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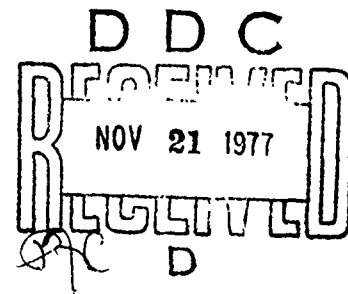


APPLICATIONS OF MULTICONDUCTOR TRANSMISSION LINE THEORY
TO THE PREDICTION OF CABLE COUPLING
Digital Computer Programs for the Analysis of
Multiconductor Transmission Lines

University of Kentucky

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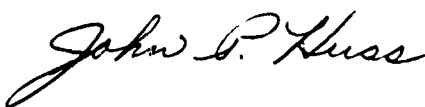
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Four digital computer programs, XTALK, XTALK2, FLATPAK, FLATPAK2, for determining the electromagnetic coupling within an (n+1) conductor, uniform transmission line are presented. Sinusoidal steady state behavior of the line as well as the TEM or "quasi-TEM" mode of propagation are assumed. XTALK and XTALK2 consider lines consisting of n wires (cylindrical conductors) and a reference conductor. The surrounding medium is homogeneous and lossless. (Con'd)		

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XTALK assumes that all $(n+1)$ conductors are perfect conductors whereas XTALK2 considers the conductors to be lossy. There are three choices for the reference conductor: a wire, a ground plane, an overall cylindrical shield.

FLATPAK and FLATPAK2 consider $(n+1)$ wire ribbon (flatpack) cables in which all wires are identical and are coated with cylindrical, dielectric insulations of identical thicknesses. All wires lie in a horizontal plane and all adjacent wires are separated by identical distances. FLATPAK considers the wires to be perfect conductors and FLATPAK2 considers the wires to be lossy. The dielectric insulations are considered to be lossless.

General termination networks are provided for at the ends of the line and the programs compute the voltages (with respect to the reference conductor) at the terminals of these termination networks for sinusoidal steady state excitation of the line.

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PREFACE

This effort was conducted by The University of Kentucky under the sponsorship of the Rome Air Development Center Post-Doctoral Program for RADC's Compatibility Branch. Mr. Jim Brodock of RADC was the task project engineer and provided overall technical direction and guidance.

The RADC Post-Doctoral Program is a cooperative venture between RADC and some sixty-five universities eligible to participate in the program. Syracuse University (Department of Electrical Engineering), Purdue University (School of Electrical Engineering), Georgia Institute of Technology (School of Electrical Engineering), and State University of New York at Buffalo (Department of Electrical Engineering) act as prime contractor schools with other schools participating via sub-contracts with the prime schools. The U.S. Air Force Academy (Department of Electrical Engineering), Air Force Institute of Technology (Department of Electrical Engineering), and the Naval Post Graduate School (Department of Electrical Engineering) also participate in the program.

The Post-Doctoral Program provides an opportunity for faculty at participating universities to spend up to one year full time on exploratory development and problem-solving efforts with the post-doctorals splitting their time between the customer location and their educational institutions. The program is totally customer-funded with current projects being undertaken for Rome Air Development Center (RADC), Space and Missile Systems Organization (SAMSO), Aeronautical Systems Division (ASD), Electronics Systems Division (FSD), Air Force Avionics Laboratory (AFAL), Foreign Technology Division (FTD), Air Force Weapons Laboratory (AFWL), Armament Development and Test Center (ADTC), Air Force Communications Service (AFCS), Aerospace Defense

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Further information about the RADC Post-Doctoral Program can be obtained from Mr. Jacob Scherer, RADC/RBC, Griffiss AFB, NY, 13441, telephone Autovon 587-2543, commercial (315) 330-2543.

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TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION -----	1
II. FORMULATION OF THE MULTICONDUCTOR TRANSMISSION LINE EQUATIONS -----	3
2.1 The Multiconductor Transmission Line Model -----	3
2.2 The Equations to be Programmed -----	14
2.3 Formulation of the Terminal Network Equations -----	22
2.4 Common Impedance Coupling and the Calculation of Conductor Self Impedances -----	28
2.5 Computation of the Per-Unit-Length Inductance and Capacitance Matrices -----	36
2.5.1 Transmission Lines Consisting of Perfect Conductors in a Lossless, Homogeneous Medium, XTALK -----	36
2.5.2 Transmission Lines Consisting of Imperfect (Lossy) Conductors in a Lossless, Homogeneous Medium, XTALK2 -----	41
2.5.3 Transmission Lines Consisting of Perfect Conductors in a Lossless, Inhomogeneous Medium, FLATPAK -----	42
2.5.4 Transmission Lines Consisting of Imperfect (Lossy) Conductors in a Lossless, Inhomogeneous Medium, FLATPAK2 -----	44
III. PROGRAM CODE DESCRIPTIONS -----	46
3.1 Program XTALK -----	46
3.2 Program XTALK2 -----	50
3.3 Program FLATPAK -----	53
3.4 Program FLATPAK2 -----	56
3.5 Required Subroutines -----	59
3.5.1 Subroutine LEQT1C -----	59
3.5.2 Subroutine EIGCC -----	61

3.5.3 Subroutines NROOT and EIGEN -----	62
IV. USER'S MANUAL -----	65
4.1 The Frequency Cards, Group III -----	65
4.2 The Termination Network Characterization Cards, Group II -----	68
4.3 Program XTALK -----	73
4.4 Program XTALK2 -----	77
4.5 Program FLATPAK -----	79
4.6 Program FLATPAK2 -----	83
4.7 Examples of Program Useage -----	83
4.7.1 Examples of the XTALK Program -----	85
4.7.2 Examples of the XTALK2 Program -----	85
4.7.3 Examples of the FLATPAK Program -----	86
4.7.4 Examples of the FLATPAK2 Program -----	86
V. SUMMARY -----	119
REFERENCES -----	120
APPENDIX A -----	123
APPENDIX B -----	133
APPENDIX C -----	145
APPENDIX D -----	152
APPENDIX E -----	163
APPENDIX F -----	167

LIST OF ILLUSTRATIONS

<u>FIGURE</u>		<u>PAGE</u>
2-1	An (n+1) conductor, uniform transmission line.	
	Sheet 1 of 2 -----	5
	Sheet 2 of 2 -----	6
2-2	The per-unit-length equivalent circuit.-----	7
2-3	The termination networks.-----	11
2-4	Example termination networks,-----	23
2-5	Example termination networks,-----	26
2-6	Illustration of common impedance coupling,-----	30
2-7	Conductor dimensions for calculating common impedance,-----	33
2-8	Lines in a homogeneous medium,-----	37
2-9	An (n+1) wire ribbon (flatpack) cable,-----	43
4-1	Type 1 structure,-----	74
4-2	Type 2 structure,-----	75
4-3	Type 3 structure,-----	76
4-4	Wire numbering for ribbon (flatpack) cables,-----	81
4-5	Input Cards, XTALK, Example 1,-----	87
4-6	Input Cards, XTALK, Example 2,-----	88
4-7	Input Cards, XTALK, Example 3,-----	89
4-8	Input Cards, XTALK, Example 4,-----	90
4-9	Output Listing, XTALK, Example 1,-----	91
4-10	Output Listing, XTALK, Example 2,-----	92
4-11	Output Listing, XTALK, Example 3,-----	93
4-12	Output Listing, XTALK, Example 4,-----	94
4-13	Input Cards, XTALK2, Example 1,-----	95

4-14	Input Cards, XTALK2, Example 2.-----	96
4-15	Input Cards, XTALK2, Example 3.-----	97
4-16	Input Cards, XTALK2, Example 4.-----	98
4-17	Output Listing, XTALK2, Example 1.-----	99
4-18	Output Listing, XTALK2; Example 2.-----	100
4-19	Output Listing, XTALK2, Example 3.-----	101
4-20	Output Listing, XTALK2, Example 4.-----	102
4-21	Input Cards, FLATPAK, Example 1.-----	103
4-22	Input Cards, FLATPAK, Example 2.-----	104
4-23	Input Cards, FLATPAK, Example 3.-----	105
4-24	Input Cards, FLATPAK, Example 4.-----	106
4-25	Output Listing, FLATPAK, Example 1.-----	107
4-26	Output Listing, FLATPAK, Example 2.-----	108
4-27	Output Listing, FLATPAK, Example 3.-----	109
4-28	Output Listing, FLATPAK, Example 4.-----	110
4-29	Input Cards, FLATPAK2,Example 1.-----	111
4-30	Input Cards, FLATPAK2,Example 2.-----	112
4-31	Input Cards, FLATPAK2,Example 3.-----	113
4-32	Input Cards, FLATPAK2,Example 4.-----	114
4-33	Output Listing, FLATPAK2, Example 1.-----	115
4-34	Output Listing, FLATPAK2, Example 2.-----	116
4-35	Output Listing, FLATPAK2, Example 3.-----	117
4-36	Output Listing, FLATPAK2, Example 4.-----	118

I. INTRODUCTION

This report is the seventh in a seven volume series documenting the Application of Multiconductor Transmission Line Theory to the Prediction of Cable Coupling. The purpose of this report is to implement the analytical techniques described in Volume I of this series [1] in the form of digital computer programs.

Crosstalk or electromagnetic coupling between wires (cylindrical conductors) in densely packed cable bundles can be a serious contributor to the degradation in performance of modern electronic systems. A recently developed digital computer program, IEMCAP, provides a general analysis capability for determining overall electromagnetic compatibility of aircraft, ground and spacecraft systems [3]. The computer programs described in this report are intended to provide a supplement to the analysis capabilities of IEMCAP by providing a more fine-grained analysis of wire-coupled interference.

IEMCAP is intended to be used to model all recognizable coupling paths on aircraft, ground and spacecraft systems. By virtue of the large size and complexity of many of these systems, detailed modeling of the coupling paths is not feasible in a program such as IEMCAP. To avoid excessive computer run times, the models of the various coupling paths used in IEMCAP are generally quite simple and represent bounds on the coupling. Consequently, the predictions of IEMCAP are generally somewhat conservative. However, once a potential wire-coupled interference problem is pinpointed by IEMCAP, the computer programs described in this report can, in many cases, be used to determine if an actual interference situation exists and the precise level of the interference.

Four programs are described: XTALK, XTALK2, FLATPAK, and FLATPAK2.

XTALK analyzes three configurations of transmission lines: (1) $(n+1)$ bare wires, (2) n bare wires above an infinite ground plane, and (3) n wires within a cylindrical shield which is filled with a homogeneous dielectric. All conductors are considered to be perfect conductors. XTALK2 analyzes the same three structural configurations as XTALK except that the conductors are considered to be imperfect conductors. FLATPAK analyzes $(n+1)$ wire ribbon cables. All wires are assumed to be perfect conductors. FLATPAK2 analyzes the same configuration as FLATPAK except that the wires are considered to be imperfect conductors. In all of the above programs, the medium (media) surrounding the conductors is assumed to be lossless. Sinusoidal, steady-state excitation of the line is considered, i.e., the transient solution is not directly obtained. Comparison of predicted to experimental results are obtained using these programs in Volume III and Volume IV of this series [4,5].

All programs are written in FORTRAN IV Language and are double precision. Changes in the programs to convert them to single precision arithmetic will be indicated. All programs have been implemented on an IBM 370/165 computer at The University of Kentucky using the Fortran IV, G level compiler and should be easily implemented on other computers.

It is, of course, difficult if not impossible to write a general computer program which will address all types of transmission line structures which the user may wish to investigate. The four programs included in this report form an initial library of analysis capabilities for wire-coupled interference problems. Other programs which address more specific structures and structures not considered by these four programs will be documented in other volumes of this series as well as in future RADC publications as they are developed.

II. FORMULATION OF THE MULTICONDUCTOR

TRANSMISSION LINE (MTL) EQUATIONS

In this chapter, the distributed parameter, multiconductor transmission line (MTL) model will be described and the programmed equations will be derived. This model is exact in the sense that interactions between all conductors in the transmission line are considered, and the distributed parameter representation (assuming the TEM mode or "quasi-TEM" mode of propagation on the line) is used. The line is assumed to be uniform in the sense that all conductors are parallel to each other and there is no variation in the cross sections of the conductors or the surrounding media along the line.

2.1 The Multiconductor Transmission Line (MTL) Model

The MTL model is described in detail in Volume I of this series [1] and in reference [2]. In this section, a brief review of the MTL model will be given and the reader should consult Volume I [1] or reference [2] for further details.

If the line is immersed in a homogeneous medium, e.g., bare wires in free space, the fundamental mode of propagation is the TEM (Transverse Electro-Magnetic) mode. If the line is immersed in an inhomogeneous medium, e.g., wires with cylindrical dielectric insulations surrounded by free space, the fundamental mode of propagation is taken to be the "quasi-TEM" mode. The essential difference in these two cases is as follows. For lines in a homogeneous medium the TEM mode assumption is legitimate. For lines in an inhomogeneous medium, the TEM mode cannot exist except in the limiting case of zero frequency (DC). However, for the inhomogeneous medium case, the assumption is made that the electric and magnetic fields are almost trans-

verse to the direction of propagation, i.e., the mode of propagation is almost TEM or "quasi-TEM".

With the assumption of the TEM mode or "quasi-TEM" mode of propagation, line voltages and currents may be defined. Consider a general $(n + 1)$ conductor, uniform transmission line shown in Figure 2-1. The $(n + 1)$ st or zero-th conductor is the reference conductor for the line voltages. For sinusoidal, steady-state excitation of the line, the line voltages, $V_i(x, t)$, (with respect to the reference, the zero-th, conductor) and line currents, $I_i(x, t)$ are

$$V_i(x, t) = V_i(x) e^{j\omega t} \quad (2-1a)$$

$$I_i(x, t) = I_i(x) e^{j\omega t} \quad (2-1b)$$

for $i = 1, \dots, n$ where $V_i(x)$ and $I_i(x)$ are the complex, phasor line voltages and currents and ω is the radian frequency of excitation of the line, $\omega = 2\pi f$. The current in the reference conductor satisfies

$$I_0(x, t) = -\sum_{i=1}^n I_i(x, t) \quad (2-2a)$$

$$I_0(x) = -\sum_{i=1}^n I_i(x) \quad (2-2b)$$

The MTL equations can be derived from the per-unit-length equivalent circuit in Figure 2-2 and are a set of $2n$, complex-valued, first order, ordinary differential equations

$$\frac{d}{dx} \begin{bmatrix} V(x) \\ I(x) \end{bmatrix} = - \begin{bmatrix} 0 & Z \\ Y & 0 \end{bmatrix} \begin{bmatrix} V(x) \\ I(x) \end{bmatrix} + \begin{bmatrix} V_s(x) \\ I_s(x) \end{bmatrix} \quad (2-3)$$

A matrix M with m rows and p columns is said to be $m \times p$ and the element in the i -th row and j -th column is designated by $[M]_{ij}$ with $i = 1, \dots, m$

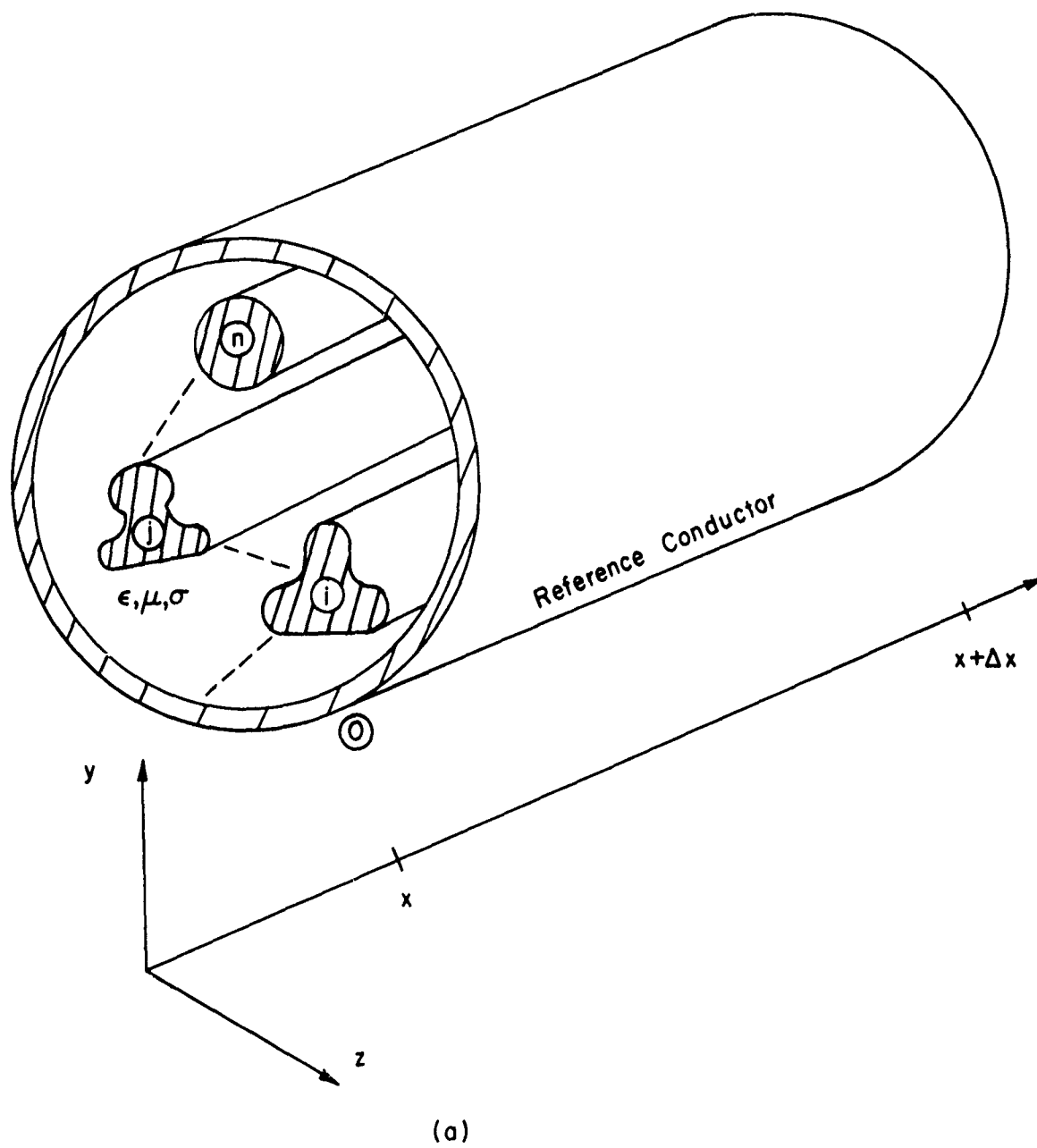
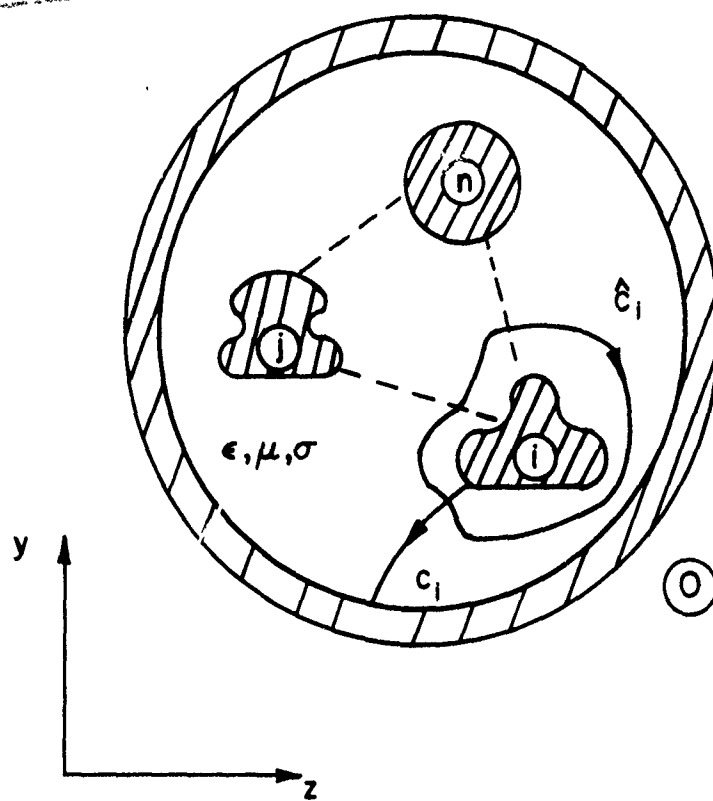
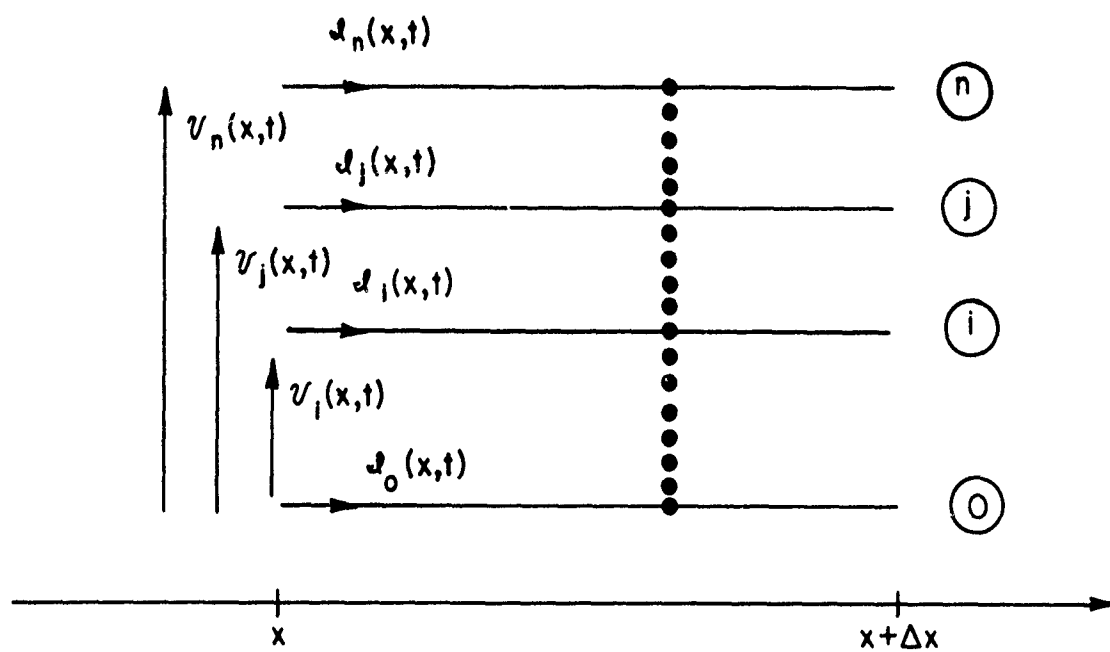


Fig. 2-1(cont.). An $(n+1)$ conductor, uniform transmission line.



(b)



(c)

Fig. 2-1. An $(n+1)$ conductor, uniform transmission line.

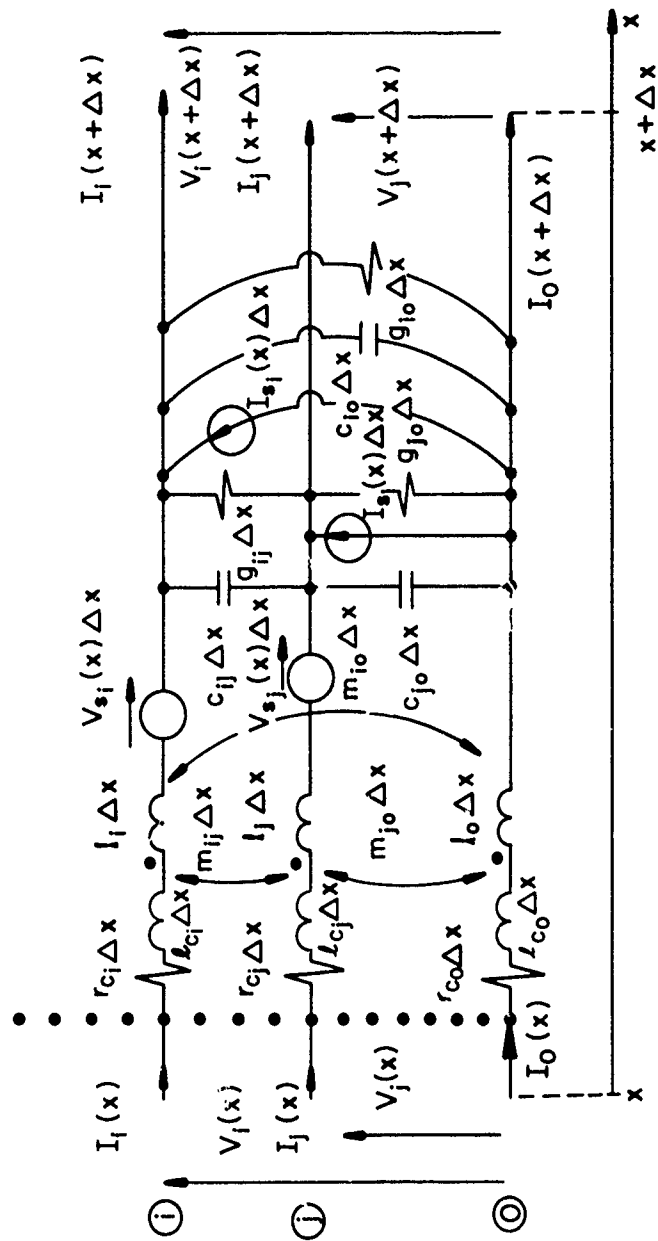


Fig. 2-2. The per-unit-length equivalent circuit.

and $j = 1, \dots, p$. An $n \times 1$ vector is denoted with a bar, e.g., $\underline{V}$, with the entry in the i -th row denoted by $[\underline{V}]_i = V_i$. The matrix $\underline{0}_{m \times p}$ is the $m \times p$ zero matrix with zeros in every position, i.e., $[\underline{0}_{m \times p}]_{ij} = 0$ for $i = 1, \dots, m$ and $j = 1, \dots, p$. The complex-valued phasor line voltages with respect to the reference conductor (the zero-th conductor), $V_i(x)$, and line currents, $I_i(x)$, are given by $[\underline{V}(x)]_i = V_i(x)$ and $[\underline{I}(x)]_i = I_i(x)$.

The $n \times n$ complex-valued, symmetric matrices, $\underline{Z}$ and $\underline{Y}$, are the per-unit-length impedance and admittance matrices of the line, respectively. Since the line is assumed to be uniform, these matrices are independent of x . These per-unit-length matrices are separable as

$$\underline{Z} = \underline{R}_c + j\omega \underline{L}_c + j\omega \underline{L} \quad (2-4a)$$

$$\underline{Y} = \underline{G} + j\omega \underline{C} \quad (2-4b)$$

where the $n \times n$ real, symmetric matrices $\underline{R}_c$, $\underline{L}_c$, $\underline{L}$, $\underline{G}$, $\underline{C}$ are the per-unit-length conductor resistance, conductor internal inductance, external inductance, conductance and capacitance matrices, respectively. The entries in these matrices may be straightforwardly obtained in terms of the elements of the per-unit-length equivalent circuit in Figure 2-2 as

$$[\underline{R}_c]_{ii} = r_{c_i} + r_{c_0}, [\underline{R}_c]_{ij} = r_{c_0} \quad (2-5a)$$

$$i \neq j$$

$$[\underline{L}_c]_{ii} = \ell_{c_i} + \ell_{c_0}, [\underline{L}_c]_{ij} = \ell_{c_0} \quad (2-5b)$$

$$i \neq j$$

$$[\underline{L}]_{ii} = \ell_i + \ell_0 - 2m_{i0}, [\underline{L}]_{ij} = \ell_0 + m_{ij} - m_{i0} - m_{j0} \quad (2-5c)$$

$$i \neq j$$

$$[\underline{G}]_{ii} = g_{i0} + \sum_{j=1}^n g_{ij}, [\underline{G}]_{ij} = -g_{ij} \quad (2-5d)$$

$$i \neq j$$

$$[\underline{C}]_{ii} = c_{i0} + \sum_{\substack{j=1 \\ i \neq j}}^n c_{ij}, \quad [\underline{C}]_{ij} = -c_{ij}. \quad (2-5e)$$

The $n \times 1$ column vectors, $\underline{V}_s(x)$ and $\underline{I}_s(x)$ contain per-unit-length equivalent voltage and current sources, $[\underline{V}_s(x)]_i = V_{s_i}(x)$ and $[\underline{I}_s(x)]_i = I_{s_i}(x)$, which are included to represent the effects of the spectral components of incident electromagnetic field sources which illuminate the line. These entries are complex-valued functions of frequency and position, x , along the line. In this report, no external incident fields are considered and these sources are set equal to zero, i.e., $\underline{V}_s(x) = \underline{0}_{n-1}$ and $\underline{I}_s(x) = \underline{0}_{n-1}$.

The solution to (2-3) is

$$\begin{aligned} \begin{bmatrix} \underline{V}(x) \\ \underline{I}(x) \end{bmatrix} &= \underline{\Phi}(x, x_0) \begin{bmatrix} \underline{V}(x_0) \\ \underline{I}(x_0) \end{bmatrix} + \int_{x_0}^x \underline{\Phi}(x, \hat{x}) \begin{bmatrix} \underline{V}_s(\hat{x}) \\ \underline{I}_s(\hat{x}) \end{bmatrix} d\hat{x} \\ &= \underline{\Phi}(x, x_0) \begin{bmatrix} \underline{V}(x_0) \\ \underline{I}(x_0) \end{bmatrix} + \begin{bmatrix} \hat{\underline{V}}_s(x) \\ \hat{\underline{I}}_s(x) \end{bmatrix} \end{aligned} \quad (2-6)$$

where $\underline{\Phi}(x, x_0)$ is the $2n \times 2n$ chain parameter matrix (or state transition matrix) and x_0 is some arbitrary position along the line $x \geq x_0$. The chain parameter matrix can be partitioned as

$$\underline{\Phi}(x, x_0) = \begin{bmatrix} \underline{\Phi}_{11}(x, x_0) & \underline{\Phi}_{12}(x, x_0) \\ \underline{\Phi}_{21}(x, x_0) & \underline{\Phi}_{22}(x, x_0) \end{bmatrix} \quad (2-7)$$

where $\underline{\Phi}_{ij}(x, x_0)$ are $n \times n$ for $i, j=1, 2$. Thus (2-6) can be written as

$$\underline{V}(x) = \underline{\Phi}_{11}(x, x_0) \underline{V}(x_0) + \underline{\Phi}_{12}(x, x_0) \underline{I}(x_0) + \hat{\underline{V}}_s(x) \quad (2-8a)$$

$$\underline{I}(x) = \underline{\Phi}_{21}(x, x_0) \underline{V}(x_0) + \underline{\Phi}_{22}(x, x_0) \underline{I}(x_0) + \hat{\underline{I}}_s(x) \quad (2-8b)$$

The entries $\underline{\Phi}_{ij}(x, x_0)$ are given by

$$\Phi_{11}(x, x_0) = 1/2 \tilde{Y}^{-1} \tilde{T} (e^{\tilde{Y}(x-x_0)} + e^{-\tilde{Y}(x-x_0)}) \tilde{T}^{-1} \tilde{Y} \quad (2-9a)$$

$$\Phi_{12}(x, x_0) = -1/2 \tilde{Y}^{-1} \tilde{T} \tilde{Y} (e^{\tilde{Y}(x-x_0)} - e^{-\tilde{Y}(x-x_0)}) \tilde{T}^{-1} \quad (2-9b)$$

$$\Phi_{21}(x, x_0) = -1/2 \tilde{T} (e^{\tilde{Y}(x-x_0)} - e^{-\tilde{Y}(x-x_0)}) \tilde{Y}^{-1} \tilde{T}^{-1} \tilde{Y} \quad (2-9c)$$

$$\Phi_{22}(x, x_0) = 1/2 \tilde{T} (e^{\tilde{Y}(x-x_0)} + e^{-\tilde{Y}(x-x_0)}) \tilde{T}^{-1} \quad (2-9d)$$

where $e^{\tilde{Y}(x-x_0)}$ is an $n \times n$ diagonal matrix with $[e^{\tilde{Y}(x-x_0)}]_{ii} = e^{\gamma_i(x-x_0)}$ and $[e^{\tilde{Y}(x-x_0)}]_{ij} = 0$ for $i, j=1, \dots, n$ and $i \neq j$. The matrix $\tilde{T}$ is an $n \times n$, complex-valued matrix which diagonalizes the matrix product $\tilde{Y}\tilde{Z}$ as

$$\tilde{T}^{-1} \tilde{Y} \tilde{Z} \tilde{T} = \tilde{Y}^2 \quad (2-10)$$

where $\tilde{Y}^2$ is an $n \times n$ diagonal matrix with $[\tilde{Y}^2]_{ii} = \gamma_i^2$ and $[\tilde{Y}^2]_{ij} = 0$ for $i, j=1, \dots, n$ and $i \neq j$. The $n \times n$ characteristic impedance matrix, $\tilde{Z}_C$, is given by

$$\tilde{Z}_C = \tilde{Y}^{-1} \tilde{T} \tilde{Y} \tilde{T}^{-1} = \tilde{Z} \tilde{T} \tilde{Y}^{-1} \tilde{T}^{-1} \quad (2-11)$$

The transmission line is of length $\mathcal{L}$ with termination networks at $x = 0$ and at $x = \mathcal{L}$ as shown in Fig. 2-3. For generality, the termination networks are considered to be in the form of linear n -ports and are characterizable by "Generalized Thevenin Equivalents" as

$$\underline{V}(0) = \underline{V}_0 - \tilde{Z}_0 \underline{I}(0) \quad (2-12a)$$

$$\underline{V}(\mathcal{L}) = \underline{V}_{\mathcal{L}} + \tilde{Z}_{\mathcal{L}} \underline{I}(\mathcal{L}) \quad (2-12b)$$

where $\underline{V}_0$ and $\underline{V}_{\mathcal{L}}$ are $n \times 1$ complex-valued vectors of equivalent, open-circuit, port excitation voltages (with respect to the reference conductor) and $\tilde{Z}_0$

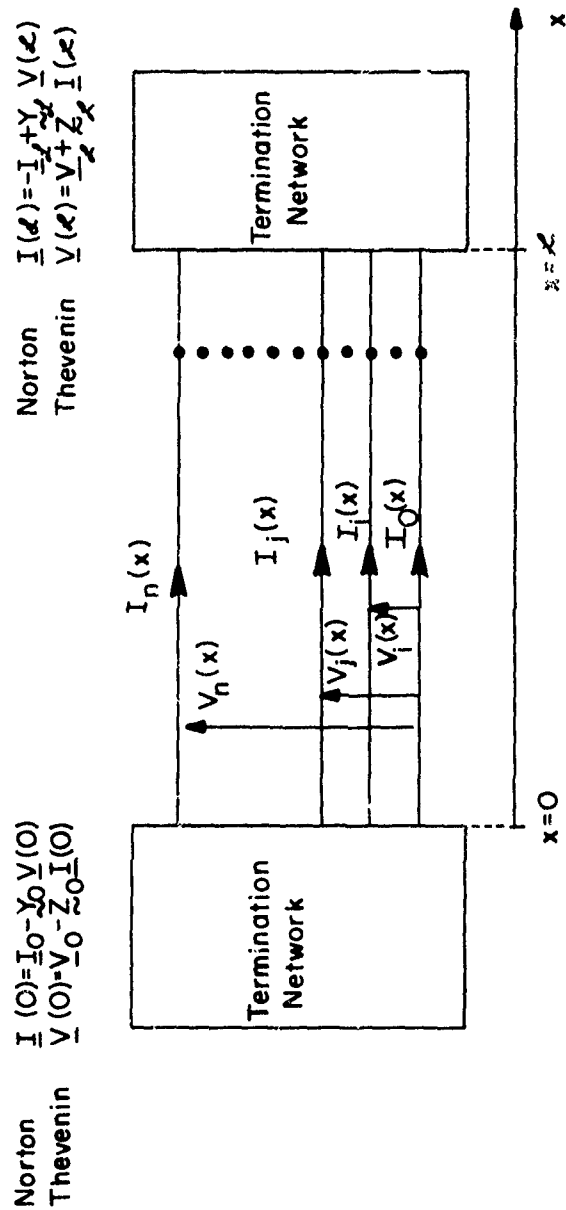


Fig. 2-3. The termination networks.

and $\underline{Z}_x$ are $n \times n$ symmetric, complex-valued port impedance matrices.

As an alternate characterization, (2-12) may be written as "Generalized Norton Equivalents" by multiplying (2-12a) on the left by $\underline{Z}_0^{-1}$ and (2-12b) on the left by $\underline{Z}_x^{-1}$ and rearranging as

$$\underline{I}(0) = \underline{I}_0 - \underline{Y}_0 \underline{V}(0) \quad (2-13a)$$

$$\underline{I}(x) = -\underline{I}_x + \underline{Y}_x \underline{V}(x) \quad (2-13b)$$

where $\underline{I}_0$ and $\underline{I}_x$ are equivalent, short-circuit, port excitation current sources.

The $n \times n$ port admittance matrices $\underline{Y}_0$ and $\underline{Y}_x$ are given by $\underline{Y}_0 = \underline{Z}_0^{-1}$ and $\underline{Y}_x = \underline{Z}_x^{-1}$ where the inverse of an $n \times n$ matrix $\underline{M}$ is denoted by $\underline{M}^{-1}$ and $\underline{I}_0 = \underline{Y}_0 \underline{V}_0$, $\underline{I}_x = \underline{Y}_x \underline{V}_x$. These port admittance matrices can be found by treating the line

currents $\underline{I}(0)$ or $\underline{I}(x)$ as independent sources and writing the node voltage equations for the termination networks. The transmission line voltages, $\underline{V}(0)$ or $\underline{V}(x)$, will comprise subsets of the node voltages of the termination networks. The additional node voltages can be eliminated from the node voltage equations describing the networks to yield (2-13). If the termination networks at $x = 0$ and $x = x$ consist only of admittances between the i -th and j -th

wires, $Y_{0_{ij}}$ and $Y_{x_{ij}}$, respectively, and between the i -th wire and the reference conductor, $Y_{0_{ii}}$ and $Y_{x_{ii}}$, respectively, then the entries in $\underline{Y}_0$ and $\underline{Y}_x$ become $[Y_0]_{ii} = Y_{0_{ii}} + \sum_{j=1}^n Y_{0_{ij}}$, $[Y_0]_{ij} = -Y_{0_{ij}}$, $[Y_x]_{ii} = Y_{x_{ii}} + \sum_{j=1}^n Y_{x_{ij}}$, $[Y_x]_{ij} = -Y_{x_{ij}}$ for $i, j=1, \dots, n$ and $i \neq j$.

With $x = x$ and $x_0 = 0$ in (2-8), one can straightforwardly obtain using the "Generalized Thevenin Equivalent" characterization of the termination networks given in (2-12)²

²In (2-8a) with $x=x_0=0$ substitute (2-12a) for $\underline{V}(0)$ and (2-12b) for $\underline{V}(x)$. Then substitute $\underline{I}(x)$ from (2-8b) with $x=x_0=0$ into the result and rearrange into the form in (2-14a). Substitute $\underline{V}(0)$ from (2-12a) into (2-8b) and rearrange to yield (2-14b).

$$[Z_{f,22}(x) - Z_{f,21}(x) Z_0 - \Phi_{12}(x) + \Phi_{11}(x) Z_0] I(0) = \quad (2-14a)$$

$$[\Phi_{11}(x) - Z_{f,21}(x)] V_0 - V_x + \hat{V}_s(x) - Z_{f,1s}(x)$$

$$I(x) = \Phi_{21}(x) V_0 + [\Phi_{22}(x) - \Phi_{21}(x) Z_0] I(0) + \hat{I}_s(x) \quad (2-14b)$$

where $\Phi(x,0) \triangleq \Phi(x)$. $V(x)$ and $I(x)$ can be obtained for any x , $0 \leq x \leq L$, from (2-8) with $I(0)$ from the solution of (2-14a) and $V(0)$ determined from (2-12a). Generally, we are only interested in the terminal voltages and currents, $V(0)$, $V(L)$, $I(0)$, $I(L)$. The terminal currents, $I(0)$ and $I(L)$, can be obtained from (2-14) and the terminal voltages, $V(0)$ and $V(L)$, can be obtained from (2-12). Here one only needs to solve n equations in n unknowns (equation 2-14a)).

The Φ_{ij} submatrices of the chain parameter matrix in (2-7) satisfy certain fundamental identities, [1,2]. These identities can be used to formulate (2-14a) in an alternate form [1,2]:

$$\begin{aligned} & \{ \{ \Phi_{21}(x) Z_x - \Phi_{22}(x) \} \{ \Phi_{21}(x) Z_0 - \Phi_{22}(x) \} - \frac{1}{n} \} I(0) = \\ & \Phi_{21}(x) V_x + \{ \Phi_{21}(x) Z_x - \Phi_{22}(x) \} \Phi_{21}(x) V_0 - \Phi_{21}(x) \cdot \\ & [\hat{V}_s(x) - Z_{f,1s}(x)] \end{aligned} \quad (2-15)$$

where $\frac{1}{n}$ is the $n \times n$ identity matrix with $[\frac{1}{n}]_{ii} = 1$ and $[\frac{1}{n}]_{ij} = 0$ for $i, j=1, \dots, n$ and $i \neq j$. Note that the formulations in (2-15) and (2-14b) require computation of only two of the four chain parameter submatrices, $\Phi_{21}(x)$ and $\Phi_{22}(x)$.

As an alternate formulation, the above equations can be written in terms

of the "Generalized Norton Equivalent" representation of the termination networks given in (2-13). Rather than rederiving the above equations it is much simpler to note the direct similarity of the Norton equivalent representation in (2-13) and the Thevenin equivalent representation in (2-12). By noting the analogous variables in (2-13) and (2-12) and observing the form of (2-8), we may simply make certain substitutions of these analogous variables in (2-14) and (2-15) as shown in Table 1. The result is

$$[\tilde{Y}_{11}(z) - \tilde{Y}_{12}(z) \tilde{Y}_0 - \tilde{\Phi}_{21}(z) + \tilde{\Phi}_{22}(z) \tilde{Y}_0] \underline{V}(0) = \quad (2-16a)$$

$$[\tilde{\Phi}_{22}(z) - \tilde{Y}_{12}(z)] \underline{I}_0 + \underline{I}_z + \hat{\underline{I}}_s(z) - \tilde{Y}_{12} \hat{\underline{V}}_s(z)$$

$$\underline{V}(z) = \tilde{\Phi}_{12}(z) \underline{I}_0 + [\tilde{\Phi}_{11}(z) - \tilde{\Phi}_{12}(z) \tilde{Y}_0] \underline{V}(0) + \hat{\underline{V}}_s(z) \quad (2-16b)$$

$$\begin{aligned} & \{[\tilde{\Phi}_{12}(z) \tilde{Y}_z - \tilde{\Phi}_{11}(z)]\{\tilde{\Phi}_{12}(z) \tilde{Y}_0 - \tilde{\Phi}_{11}(z)\} - \underline{1}_n\} \underline{V}(0) = \\ & - \tilde{\Phi}_{12}(z) \underline{I}_z + [\tilde{\Phi}_{12}(z) \tilde{Y}_z - \tilde{\Phi}_{11}(z)] \tilde{\Phi}_{12}(z) \underline{I}_0 \\ & - \tilde{\Phi}_{12}(z) [\hat{\underline{I}}_s(z) - \tilde{Y}_{12} \hat{\underline{V}}_s(z)] \end{aligned} \quad (2-16c)$$

2.2 The Equations to Be Programmed

The equations for $\underline{I}(z)$ and $\underline{V}(z)$ are given in (2-14b) and (2-16b), respectively. Either (2-14a) or (2-15) could be used for determining $\underline{I}(0)$ and either (2-16a) or (2-16c) could be used for determining $\underline{V}(0)$. However, (2-14a) and (2-16a) will be selected for determining $\underline{I}(0)$ and $\underline{V}(0)$, respectively. Since no external incident fields are considered, $\hat{\underline{V}}_s(z)$ and $\hat{\underline{I}}_s(z)$ in (2-14), (2-15) and (2-16) will be zero, i.e., $\hat{\underline{V}}_s(z) = \hat{\underline{I}}_s(z) = \underline{0}_{n-1}$.

Certain modifications to these equations will be made to produce the final equations. The matrix chain parameters given in (2-9) for a line of

TABLE 1

Analogous variables in the Generalized Thevenin Equivalent (2-12) and Generalized Norton Equivalent (2-13) representation of the termination networks. The analogous variables are substituted in equations (2-14) and (2-15) to obtain equations (2-16).

Generalized Thevenin Equivalent (2-12)	Generalized Norton Equivalent (2-13)
$\underline{I}(0)$	$\underline{V}(0)$
$\underline{I}(z)$	$\underline{V}(z)$
$\underline{Z}_0$	$\underline{Y}_0$
$\underline{Z}_z$	$\underline{Y}_z$
$\underline{V}(0)$	$\underline{I}(0)$
$\underline{V}(z)$	$-\underline{I}(z)$
$\underline{\Phi}_{11}(z)$	$\underline{\Phi}_{22}(z)$
$\underline{\Phi}_{12}(z)$	$\underline{\Phi}_{21}(z)$
$\underline{\Phi}_{21}(z)$	$\underline{\Phi}_{12}(z)$
$\underline{\Phi}_{22}(z)$	$\underline{\Phi}_{11}(z)$
$\underline{\hat{V}}_s(z)$	$\underline{\hat{I}}_s(z)$
$\underline{\hat{I}}_s(z)$	$\underline{\hat{V}}_s(z)$

total length $\mathcal{L}(x_0 = 0, x = \mathcal{L})$ become

$$\tilde{\Phi}_{11}(\mathcal{L}) = \tilde{Y}^{-1} \tilde{T} \tilde{E}^+ \tilde{T}^{-1} \tilde{Y} \quad (2-17a)$$

$$\tilde{\Phi}_{12}(\mathcal{L}) = -\tilde{Y}^{-1} \tilde{T} \tilde{Y} \tilde{E}^- \tilde{T}^{-1} \quad (2-17b)$$

$$\tilde{\Phi}_{21}(\mathcal{L}) = -\tilde{T} \tilde{E}^- \tilde{Y}^{-1} \tilde{T}^{-1} \tilde{Y} \quad (2-17c)$$

$$\tilde{\Phi}_{22}(\mathcal{L}) = \tilde{T} \tilde{E}^+ \tilde{T}^{-1} \quad (2-17d)$$

where the $n \times n$ diagonal matrices $\tilde{E}^+$ and $\tilde{E}^-$ are given by

$$\tilde{E}^+ = \frac{1}{2} (\tilde{e}^{\tilde{Y}\mathcal{L}} + \tilde{e}^{-\tilde{Y}\mathcal{L}}) \quad (2-18a)$$

$$\tilde{E}^- = \frac{1}{2} (\tilde{e}^{\tilde{Y}\mathcal{L}} - \tilde{e}^{-\tilde{Y}\mathcal{L}}) \quad (2-18b)$$

Substituting (2-17) into (2-14a) and (2-14b) yields, for the Thevenin Equivalent representation of the termination networks

$$[\tilde{Z} \tilde{Y} \tilde{T} \tilde{E}^+ \tilde{T}^{-1} + \tilde{Z} \tilde{Y} \tilde{T} \tilde{E}^- \tilde{Y}^{-1} \tilde{T}^{-1} \tilde{Y} \tilde{Z}_0] \tilde{I}(0) \quad (2-19a)$$

$$+ \tilde{Y}^{-1} \tilde{T} \tilde{Y} \tilde{E}^- \tilde{T}^{-1} + \tilde{Y}^{-1} \tilde{T} \tilde{E}^+ \tilde{T}^{-1} \tilde{Y} \tilde{Z}_0] \tilde{I}(0) \\ = [\tilde{Y}^{-1} \tilde{T} \tilde{E}^+ \tilde{T}^{-1} \tilde{Y} + \tilde{Z} \tilde{Y} \tilde{T} \tilde{E}^- \tilde{Y}^{-1} \tilde{T}^{-1} \tilde{Y}] \tilde{V}_0 - \tilde{V}\mathcal{L}$$

$$\tilde{I}(\mathcal{L}) = -\tilde{T} \tilde{E}^- \tilde{Y}^{-1} \tilde{T}^{-1} \tilde{Y} \tilde{V}_0 \quad (2-19b)$$

$$+ [\tilde{T} \tilde{E}^+ \tilde{T}^{-1} + \tilde{T} \tilde{E}^- \tilde{Y}^{-1} \tilde{T}^{-1} \tilde{Y} \tilde{Z}_0] \tilde{I}(0)$$

Similarly, substituting (2-17) into (2-16a) and (2-16b) yields, for the Norton Equivalent representation of the termination networks,

$$[\tilde{Y} \tilde{Z} \tilde{Y}^{-1} \tilde{T} \tilde{E}^+ \tilde{T}^{-1} \tilde{Y} + \tilde{Y} \tilde{Z} \tilde{Y}^{-1} \tilde{T} \tilde{Y} \tilde{E}^- \tilde{T}^{-1} \tilde{Y}_0] \tilde{V}(0) \quad (2-20a)$$

$$+ \tilde{T} \tilde{E}^- \tilde{Y}^{-1} \tilde{T}^{-1} \tilde{Y} + \tilde{T} \tilde{E}^+ \tilde{T}^{-1} \tilde{Y}_0] \tilde{V}(0)$$

$$= [\tilde{T} \tilde{E}^+ \tilde{T}^{-1} + \tilde{Y} \tilde{Z} \tilde{Y}^{-1} \tilde{T} \tilde{Y} \tilde{E}^- \tilde{T}^{-1}] \tilde{I}_0 + \tilde{I}\mathcal{L}$$

$$\tilde{V}(\mathcal{L}) = -\tilde{Y}^{-1} \tilde{T} \tilde{Y} \tilde{E}^- \tilde{T}^{-1} \tilde{I}_0 + [\tilde{Y}^{-1} \tilde{T} \tilde{E}^+ \tilde{T}^{-1} \tilde{Y} + \tilde{Y}^{-1} \tilde{T} \tilde{Y} \tilde{E}^- \tilde{T}^{-1} \tilde{Y}_0] \tilde{V}(0) \quad (2-20b)$$

The medium surrounding all conductors is assumed throughout this report to be lossless. Therefore the per-unit-length conductance matrix, $\tilde{G}$, which represents these losses in (2-4b) is zero, i.e., $\tilde{G} = \tilde{0}_{n \times n}$. Therefore the per-unit-length admittance matrix becomes

$$\tilde{Y} = j \omega \tilde{C} \quad (2-21)$$

The per-unit-length impedance matrix is

$$\tilde{Z} = \tilde{R}_c + j \omega \tilde{L}_c + j \omega \tilde{L} \quad (2-22)$$

where $\tilde{R}_c$ and $\tilde{L}_c$ are zero matrices, i.e., $\tilde{0}_{n \times n}$, when perfect conductors are assumed.

To reduce the number of matrix multiplications, the above equations will be placed in an alternate form. For the Norton Equivalent representation in (2-20), define

$$\tilde{Y}_z^* = \tilde{T}^{-1} \tilde{Y}_z \tilde{C}^{-1} \tilde{T} \quad (2-23a)$$

$$\tilde{Y}_0^* = \tilde{T}^{-1} \tilde{Y}_0 \tilde{C}^{-1} \tilde{T} \quad (2-23b)$$

$$\tilde{V}^*(z) = \tilde{T}^{-1} \tilde{C} \tilde{V}(z) \quad (2-23c)$$

$$\tilde{V}^*(0) = \tilde{T}^{-1} \tilde{C} \tilde{V}(0) \quad (2-23d)$$

$$\tilde{I}_z^* = \tilde{T}^{-1} \tilde{I}_z \quad (2-23e)$$

$$\tilde{I}_0^* = \tilde{T}^{-1} \tilde{I}_0 \quad (2-23f)$$

$$\tilde{\gamma} = j \omega \tilde{\Lambda} \quad (2-23g)$$

Equations (2-20) can then be written as

$$\begin{aligned} & [\tilde{Y}_z^* \tilde{E}^+ + \tilde{Y}_z^* \tilde{\Lambda} \tilde{E}^- \tilde{Y}_0^* + \tilde{E}^- \tilde{\Lambda}^{-1} + \tilde{E}^+ \tilde{Y}_0^*] \tilde{V}^*(0) \\ & = [\tilde{E}^+ + \tilde{Y}_z^* \tilde{\Lambda} \tilde{E}^-] \tilde{I}_0^* + \tilde{I}_z^* \end{aligned} \quad (2-24a)$$

$$\underline{V}^*(z) = -\underline{\Lambda} \underline{E}^- \underline{I}_0^* + [\underline{E}^+ + \underline{\Lambda} \underline{E}^- \underline{Y}_0^*] \underline{V}^*(0) \quad (2-24b)$$

and the actual termination voltages can be determined by solving (2-24) for $\underline{V}^*(0)$ and $\underline{V}^*(z)$ and using (2-23c) and (2-23d) to obtain

$$\underline{V}(0) = \underline{C}^{-1} \underline{T} \underline{V}^*(0) \quad (2-25a)$$

$$\underline{V}(z) = \underline{C}^{-1} \underline{T} \underline{V}^*(z) \quad (2-25b)$$

These equations are summarized in Table 2.

Similarly, equations (2-19) for the Thevenin Equivalent representation of the terminal networks can be reduced to an equivalent form by defining

$$\underline{Z}_L^* = \underline{T}^{-1} \underline{C} \underline{Z}_L \underline{T} \quad (2-26a)$$

$$\underline{Z}_0^* = \underline{T}^{-1} \underline{C} \underline{Z}_0 \underline{T} \quad (2-26b)$$

$$\underline{I}^*(z) = \underline{T}^{-1} \underline{I}(z) \quad (2-26c)$$

$$\underline{I}^*(0) = \underline{T}^{-1} \underline{I}(0) \quad (2-26d)$$

$$\underline{V}_L^* = \underline{T}^{-1} \underline{C} \underline{V}_L \quad (2-26e)$$

$$\underline{V}_0^* = \underline{T}^{-1} \underline{C} \underline{V}_0 \quad (2-26f)$$

$$\underline{\gamma} = j \omega \underline{\Lambda} \quad (2-26g)$$

Equations (2-19) can then be written as

$$\begin{aligned} & [\underline{Z}_L^* \underline{E}^+ + \underline{Z}_L^* \underline{E}^- \underline{\Lambda}^{-1} \underline{Z}_0^* + \underline{\Lambda} \underline{E}^- + \underline{E}^+ \underline{Z}_0^*] \underline{I}^*(0) \\ & = [\underline{E}^+ + \underline{Z}_L^* \underline{E}^- \underline{\Lambda}^{-1}] \underline{V}_0^* - \underline{V}_L^* \end{aligned} \quad (2-27a)$$

$$\underline{I}^*(z) = -\underline{E}^- \underline{\Lambda}^{-1} \underline{V}_0^* + [\underline{E}^+ + \underline{E}^- \underline{\Lambda}^{-1} \underline{Z}_0^*] \underline{I}^*(0) \quad (2-27b)$$

and the actual termination currents can be obtained by solving (2-27) for $\underline{I}^*(0)$ and $\underline{I}^*(z)$ and using (2-26c) and (2-26d) to obtain

$$\underline{I}(0) = \underline{T} \underline{I}^*(0) \quad (2-28a)$$

$$\underline{I}(\omega) = \underline{T} \underline{I}^*(\omega) \quad (2-28b)$$

These equations are summarized in Table 3.

There are two reasons for using the equivalent representations in Table 2 and Table 3 rather than the representations in (2-20) and (2-19). First of all, note the direct similarity of the equations in Table 2 and Table 3. The only differences (other than symbols) between equations (1) and (2) in Table 2 and the corresponding equations (1) and (2) in Table 3 is that $\underline{\Lambda}$ used in Table 2 corresponds to $\underline{\Lambda}^{-1}$ in Table 3, and $\underline{I}_\omega^*$ in Table 2 corresponds to $-\underline{V}_\omega^*$ in Table 3. (Note that since $\underline{\Lambda}$, $\underline{\Lambda}^{-1}$ and $\underline{E}^-$ are diagonal, $\underline{E}^- \underline{\Lambda}^{-1} = \underline{\Lambda}^{-1} \underline{E}^-$ and $\underline{E}^- \underline{\Lambda} = \underline{\Lambda} \underline{E}^-$.) Therefore we may form the Norton Equivalent equations in the programs and not need to write a duplicate set for the Thevenin Equivalent representations.

The second reason for using the representations in Table 2 and Table 3 is that if the termination networks are purely resistive, i.e., $\underline{Z}_0$, $\underline{Z}_\omega$, $\underline{Y}_0$ and $\underline{Y}_\omega$ are real, and the transformation matrix, $\underline{T}$, is frequency independent, i.e., perfect conductors are assumed (as in XTALK and FLATPAK), then the matrix multiplications as well as the inversion of $\underline{T}$ to form $\underline{T}^{-1}$ needed to obtain $\underline{Y}_0^*$, $\underline{Y}_\omega^*$, $\underline{Z}_0^*$, $\underline{Z}_\omega^*$ need only be performed once and need not be changed as the frequency is changed. Only equations (1) and (2) in Table 2 and Table 3 need be reformulated for each frequency. This can represent a significant savings in computation time when the line response for many frequencies is desired (as it usually is) since n^3 operations (multiplications or divisions) are required to multiply two "full" $n \times n$ matrices which is the minimum number of operations required to obtain the inverse of a general $n \times n$ matrix [1].

TABLE 2

Programmed Equations for the Generalized

Norton Equivalent Representation

- $$\begin{aligned}
 (1) \quad & [\underline{Y}_L^* \underline{E}^+ + \underline{Y}_L^* \underline{\Lambda} \underline{E}^- \underline{Y}_0^* + \underline{E}^- \underline{\Lambda}^{-1} + \underline{E}^+ \underline{Y}_0^*] \underline{V}^*(0) \\
 & = [\underline{E}^+ + \underline{Y}_L^* \underline{\Lambda} \underline{E}^-] \underline{I}_0^* + \underline{I}_L^* \\
 (2) \quad & \underline{V}^*(\mathcal{L}) = -\underline{\Lambda} \underline{E}^- \underline{I}_0^* + [\underline{E}^+ + \underline{\Lambda} \underline{E}^- \underline{Y}_0^*] \underline{V}^*(0) \\
 (3) \quad & \underline{T}^{-1} \underline{Y} \underline{Z} \underline{T} = \underline{T}^{-1} \{j\omega C[\underline{R}_c + j\omega \underline{L}_c + j\omega \underline{L}] \} \underline{T} = \underline{Y}^2 \\
 (4) \quad & \underline{\gamma} = j\omega \underline{\Lambda} \\
 (5) \quad & \underline{I}(0) = \underline{I}_0 - \underline{Y}_0 \underline{V}(0) \quad , \quad \underline{I}(\mathcal{L}) = -\underline{I}_L + \underline{Y}_L \underline{V}(\mathcal{L}) \\
 (6) \quad & \underline{Y}_0^* = \underline{T}^{-1} \underline{Y}_0 \underline{C}^{-1} \underline{T} \quad , \quad \underline{Y}_L^* = \underline{T}^{-1} \underline{Y}_L \underline{C}^{-1} \underline{T} \\
 (7) \quad & \underline{I}_0^* = \underline{T}^{-1} \underline{I}_0 \quad , \quad \underline{I}_L^* = \underline{T}^{-1} \underline{I}_L \\
 (8) \quad & \underline{E}^+ = \frac{1}{2} (\underline{e}^{\underline{\gamma} \mathcal{L}} + \underline{e}^{-\underline{\gamma} \mathcal{L}}) \quad , \quad \underline{E}^- = \frac{1}{2} (\underline{e}^{\underline{\gamma} \mathcal{L}} - \underline{e}^{-\underline{\gamma} \mathcal{L}}) \\
 (9) \quad & \underline{V}(0) = \underline{C}^{-1} \underline{T} \underline{V}^*(0) \quad , \quad \underline{V}(\mathcal{L}) = \underline{C}^{-1} \underline{T} \underline{V}^*(\mathcal{L})
 \end{aligned}$$

TABLE 3

Programmed Equations for the Generalized
Thevenin Equivalent Representation

- $$\begin{aligned}
 (1) \quad & [\underline{Z}_{\mathcal{L}}^* \underline{E}^+ + \underline{Z}_{\mathcal{L}}^* \underline{E}^- \underline{\Lambda}^{-1} \underline{Z}_0^* + \underline{\Lambda} \underline{E}^- + \underline{E}^+ \underline{Z}_0^*] \underline{I}^*(0) \\
 & = [\underline{E}^+ + \underline{Z}_{\mathcal{L}}^* \underline{E}^- \underline{\Lambda}^{-1}] \underline{V}_0^* - \underline{V}_{\mathcal{L}}^* \\
 (2) \quad & \underline{I}^*(\mathcal{L}) = -\underline{E}^- \underline{\Lambda}^{-1} \underline{V}_0^* + [\underline{E}^+ + \underline{E}^- \underline{\Lambda}^{-1} \underline{Z}_0^*] \underline{I}^*(0) \\
 (3) \quad & \underline{T}^{-1} \underline{Y} \underline{Z} \underline{T} = \underline{T}^{-1} \{j\omega \underline{C} [\underline{R}_c + j\omega \underline{L}_c + j\omega \underline{L}] \} \underline{T} = \underline{\gamma}^2 \\
 (4) \quad & \underline{\gamma} = j\omega \underline{\Lambda} \\
 (5) \quad & \underline{V}(0) = \underline{V}_0 - \underline{Z}_0 \underline{I}(0) \quad , \quad \underline{V}(\mathcal{L}) = \underline{V}_{\mathcal{L}} + \underline{Z}_{\mathcal{L}} \underline{I}(\mathcal{L}) \\
 (6) \quad & \underline{Z}_0^* = \underline{T}^{-1} \underline{C} \underline{Z}_0 \underline{T} \quad , \quad \underline{Z}_{\mathcal{L}}^* = \underline{T}^{-1} \underline{C} \underline{Z}_{\mathcal{L}} \underline{T} \\
 (7) \quad & \underline{V}_0^* = \underline{T}^{-1} \underline{C} \underline{V}_0 \quad , \quad \underline{V}_{\mathcal{L}}^* = \underline{T}^{-1} \underline{C} \underline{V}_{\mathcal{L}} \\
 (8) \quad & \underline{E}^+ = \frac{1}{2} (\underline{e}^{\underline{\gamma} \mathcal{L}} + \underline{e}^{-\underline{\gamma} \mathcal{L}}) \quad , \quad \underline{E}^- = \frac{1}{2} (\underline{e}^{\underline{\gamma} \mathcal{L}} - \underline{e}^{-\underline{\gamma} \mathcal{L}}) \\
 (9) \quad & \underline{I}(0) = \underline{T} \underline{I}^*(0) \quad , \quad \underline{I}(\mathcal{L}) = \underline{T} \underline{I}^*(\mathcal{L})
 \end{aligned}$$

Note: $\underline{V}^*(0) = \underline{V}_0^* - \underline{Z}_0^* \underline{I}^*(0) \quad , \quad \underline{V}^*(\mathcal{L}) = \underline{V}_{\mathcal{L}}^* + \underline{Z}_{\mathcal{L}}^* \underline{I}^*(\mathcal{L})$
 where: $\underline{V}^*(0) = \underline{T}^{-1} \underline{C} \underline{V}(0) \quad , \quad \underline{V}^*(\mathcal{L}) = \underline{T}^{-1} \underline{C} \underline{V}(\mathcal{L})$

2.3 Formulation of the Terminal Network Equations

The previous formulation requires that one determine the entries in the $n \times n$ matrices $\underline{Z}_0$, $\underline{Z}_1$, $\underline{Y}_0$ and $\underline{Y}_1$, and the $n \times 1$ vectors, $\underline{V}_0$, $\underline{V}_1$, $\underline{I}_0$ and $\underline{I}_1$, in the Thevenin and Norton Equivalent representations of the terminal networks in (2-12) and (2-13), respectively. In this section, some examples will be given to aid in determining these quantities.

To illustrate this, four examples will be used. The first example, Example 1, is shown in Figure 2-4a. In this example, there is no cross-coupling between the port terminals within the termination networks, i.e., at each end of the line, each endpoint of a wire is terminated directly to the reference conductor and is not physically connected to the endpoints of other wires at the same end of the line. Writing the following equations:

$$\underline{V}_1(0) = 1 - 1 \underline{I}_1(0) \quad (2-29a)$$

$$\underline{V}_2(0) = -10 \underline{I}_2(0) \quad (2-29b)$$

$$\underline{V}_1(x) = 10^3 \underline{I}_1(x) \quad (2-29c)$$

$$\underline{V}_2(x) = 10^4 \underline{I}_2(x) + 1 \quad (2-29d)$$

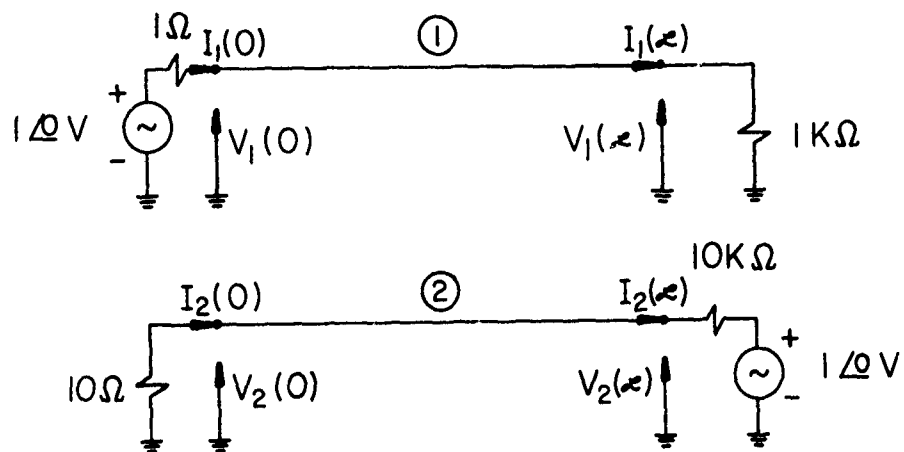
and comparing these equations to the Thevenin Equivalent representation

$$\underline{V}(0) = \underline{V}_0 - \underline{Z}_0 \underline{I}(0) \quad (2-30a)$$

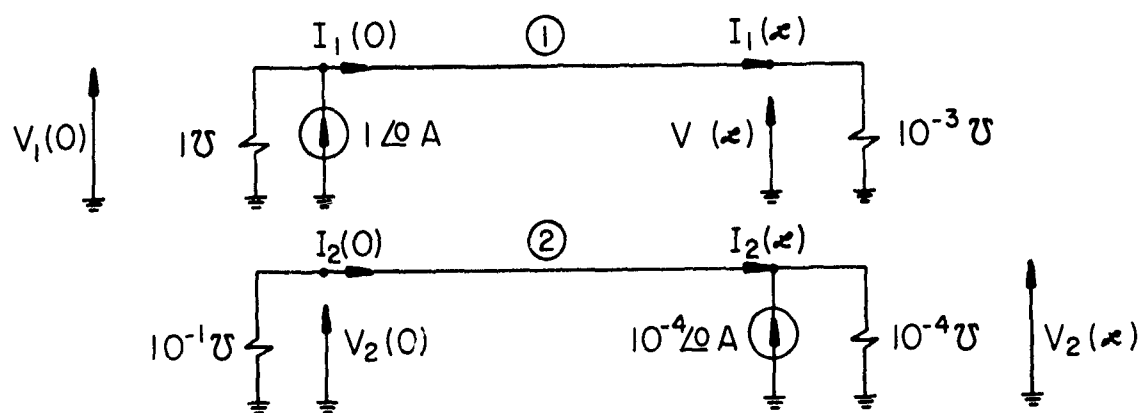
$$\underline{V}(x) = \underline{V}_x + \underline{Z}_x \underline{I}(x) \quad (2-30b)$$

where

$$\begin{aligned} \underline{V}(0) &= \begin{bmatrix} \underline{V}_1(0) \\ \underline{V}_2(0) \end{bmatrix} & \underline{V}(x) &= \begin{bmatrix} \underline{V}_1(x) \\ \underline{V}_2(x) \end{bmatrix} \\ \underline{I}(0) &= \begin{bmatrix} \underline{I}_1(0) \\ \underline{I}_2(0) \end{bmatrix} & \underline{I}(x) &= \begin{bmatrix} \underline{I}_1(x) \\ \underline{I}_2(x) \end{bmatrix} \end{aligned} \quad (2-31)$$



(a) Example 1



(b) Example 2

Fig. 2-4. Example termination networks. (No cross-coupling)

one can readily identify

$$\begin{aligned} \underline{V}_0 &= \begin{bmatrix} 1 \\ 0 \end{bmatrix} & \underline{Z}_0 &= \begin{bmatrix} 1 & 0 \\ 0 & 10 \end{bmatrix} \\ \underline{V}_1 &= \begin{bmatrix} 0 \\ 1 \end{bmatrix} & \underline{Z}_1 &= \begin{bmatrix} 10^3 & 0 \\ 0 & 10^4 \end{bmatrix} \end{aligned} \quad (2-32)$$

Similarly, one can convert the termination networks to a Norton equivalent representation in Figure 2-4b and obtain (Example 2)

$$I_2(0) = 1 - 1 V_1(0) \quad (2-33a)$$

$$I_2(0) = -10^{-1} V_2(0) \quad (2-33b)$$

$$I_1(1) = 10^{-3} V_1(1) \quad (2-33c)$$

$$I_2(1) = -10^{-4} + 10^{-4} V_2(1) \quad (2-33d)$$

Comparing these equations to the Norton Equivalent representation

$$\underline{I}(0) = \underline{I}_0 - \underline{Y}_0 \underline{V}(0) \quad (2-34a)$$

$$\underline{I}(1) = -\underline{I}_1 + \underline{Y}_1 \underline{V}(1) \quad (2-34b)$$

where $\underline{I}(0)$, $\underline{I}(1)$, $\underline{V}(0)$, $\underline{V}(1)$ are given in (2-31), one can readily identify for Example 2

$$\begin{aligned} \underline{I}_0 &= \begin{bmatrix} 1 \\ 0 \end{bmatrix} & \underline{Y}_0 &= \begin{bmatrix} 1 & 0 \\ 0 & 10^{-1} \end{bmatrix} \\ \underline{I}_1 &= \begin{bmatrix} 0 \\ 10^{-4} \end{bmatrix} & \underline{Y}_1 &= \begin{bmatrix} 10^{-3} & 0 \\ 0 & 10^{-4} \end{bmatrix} \end{aligned} \quad (2-35)$$

Note that

$$\underline{I}_0 = \underline{Z}_0^{-1} \underline{V}_0 \quad (2-36a)$$

$$\underline{Y}_0 = \underline{Z}_0^{-1} \quad (2-36b)$$

$$\underline{I}_z = \underline{Z}_z^{-1} \underline{V}_z \quad (2-36c)$$

$$\underline{Y}_z = \underline{Z}_z^{-1} \quad (2-36d)$$

Note also that as far as the network terminal characteristics are concerned, the termination networks in Figure 2-4a are the same as those in Figure 2-4b.

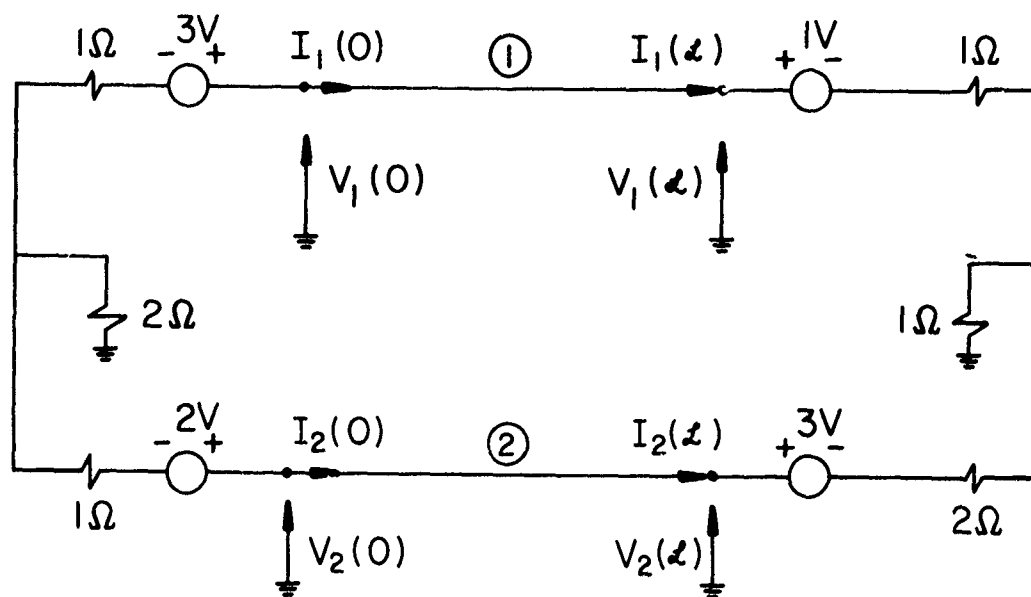
The third and fourth examples, Example 3 and Example 4, are shown in Figure 2-5. As far as terminal characteristics are concerned, the terminations in Figure 2-5a and in Figure 2-5b are the same as shown by the following. First, write the Norton Equivalent characterization for the terminations in Figure 2-5b as (treat the terminal currents as independent sources and write the node-voltage circuit equations of the networks)

$$\underbrace{\begin{bmatrix} I_1(0) \\ I_2(0) \end{bmatrix}}_{\underline{I}(0)} = \underbrace{\begin{bmatrix} 1 \\ 0 \end{bmatrix}}_{\underline{I}_0} - \underbrace{\begin{bmatrix} .6 & -.4 \\ -.4 & .6 \end{bmatrix}}_{\underline{Y}_0} \underbrace{\begin{bmatrix} V_1(0) \\ V_2(0) \end{bmatrix}}_{\underline{V}_0} \quad (2-37a)$$

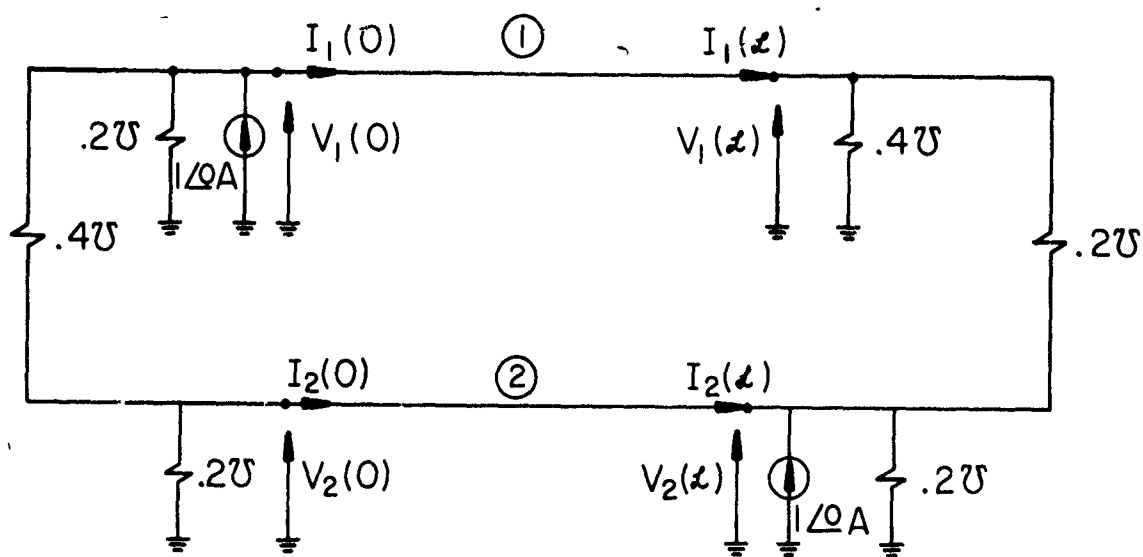
$$\underbrace{\begin{bmatrix} I_1(z) \\ I_2(z) \end{bmatrix}}_{\underline{I}(z)} = \underbrace{\begin{bmatrix} 0 \\ 1 \end{bmatrix}}_{\underline{I}_z} + \underbrace{\begin{bmatrix} .6 & -.2 \\ -.2 & .4 \end{bmatrix}}_{\underline{Y}_z} \underbrace{\begin{bmatrix} V_1(z) \\ V_2(z) \end{bmatrix}}_{\underline{V}_z} \quad (2-37b)$$

Similarly, from Figure 2-5a write the Thevenin Equivalent characterization as (treat the terminal voltages as independent sources and write the loop current circuit equations of the networks)

$$\underbrace{\begin{bmatrix} V_1(0) \\ V_2(0) \end{bmatrix}}_{\underline{V}(0)} = \underbrace{\begin{bmatrix} 3 \\ 2 \end{bmatrix}}_{\underline{V}_0} - \underbrace{\begin{bmatrix} 3 & 2 \\ 2 & 3 \end{bmatrix}}_{\underline{Z}_0} \underbrace{\begin{bmatrix} I_1(0) \\ I_2(0) \end{bmatrix}}_{\underline{I}(0)} \quad (2-38a)$$



(a) Example 3



(b) Example 4

Fig. 2-5. Example termination networks. (cross-coupling)

$$\begin{bmatrix} \underline{V}_1(z) \\ \underline{V}_2(z) \end{bmatrix} = \begin{bmatrix} 1 \\ 3 \end{bmatrix} + \underbrace{\begin{bmatrix} 2 & 1 \\ 1 & 3 \end{bmatrix}}_{\underline{Z}_z} \begin{bmatrix} \underline{I}_1(z) \\ \underline{I}_2(z) \end{bmatrix} \quad (2-38b)$$

$\underline{V}(z) \qquad \underline{V}_z \qquad \underline{Z}_z \qquad \underline{I}(z)$

Note that

$$\underline{Y}_0 = \underline{Z}_0^{-1} \quad (2-39a)$$

$$\underline{Y}_z = \underline{Z}_z^{-1} \quad (2-39b)$$

$$\underline{I}_0 = \underline{Y}_0 \underline{V}_0 \quad (2-39c)$$

$$\underline{I}_z = \underline{Y}_z \underline{V}_z \quad (2-39d)$$

and as far as the terminal characteristics of the networks are concerned, the termination networks in Figure 2-5a are the same as those in Figure 2-5b.

The above examples will serve a dual purpose. Each of the computer programs will be run for each of the above four examples for the same transmission line structure. Typical solution printouts will be shown for these results. This will serve as a partial check on the proper functioning of the programs since the corresponding terminal voltages ($\underline{V}_1(0)$, $\underline{V}_2(0)$, $\underline{V}_1(z)$, $\underline{V}_2(z)$) for Example 1 should equal those for Example 2. Similarly the corresponding terminal voltages for Example 3 should equal those for Example 4.

As can be seen from the above examples, if there is no cross-coupling within the termination networks, then formulation of the entries in $\underline{V}_0$, $\underline{V}_z$, $\underline{Z}_0$ and $\underline{Z}_z$ or $\underline{I}_0$, $\underline{I}_z$, $\underline{Y}_0$ and $\underline{Y}_z$ is particularly simple. The situation in which there is no cross-coupling within the termination networks is generally the problem of interest in wire-coupled interference calculations.

However, it was felt that the more general case of allowing cross-coupling within the terminal networks be included in the capabilities of the programs.

To save computer time, one has four options for inputting the terminal data: OPTIONS 11, 12, 21, or 22. The first digit in each number indicates to each program that the terminal characterization chosen is either the Thevenin Equivalent (1) or Norton Equivalent (2). The second digit indicates to the program whether the admittance ($\underline{Y}_0$ and $\underline{Y}_1$) or impedance ($\underline{Z}_0$ and $\underline{Z}_1$) matrices are diagonal (1), i.e., no cross-coupling, or full (2), i.e., cross-coupling. For example, OPTION 11 indicates Thevenin Equivalent, diagonal impedance matrices; OPTION 22 indicates Norton Equivalent, full admittance matrices; OPTION 12 indicates Thevenin Equivalent, full impedance matrices, and OPTION 21 indicates Norton Equivalent, diagonal admittance matrices.

This saves computer time and user effort in inputting the data. For example, in cases where $\underline{Z}_0$ (or $\underline{Z}_1$, or $\underline{Y}_0$ or $\underline{Y}_1$) must be multiplied by another $n \times n$ matrix such as in $\underline{T} \underline{Z}_0$, if $\underline{Z}_0$ is diagonal one only needs n^2 multiplications to form this product whereas if $\underline{Z}_0$ is full, n^3 multiplications are needed to form the product. The programs are written to take advantage of this. In addition, if the terminal admittance or impedance matrices are in fact diagonal, then the user need only input the entries on the main diagonal and is saved the drudgery of inputting the remaining zero entries. The specific details for inputting this termination network data will be given in Chapter IV, the User's Manual.

2.4 Common Impedance Coupling and the Calculation of Conductor Self Impedances

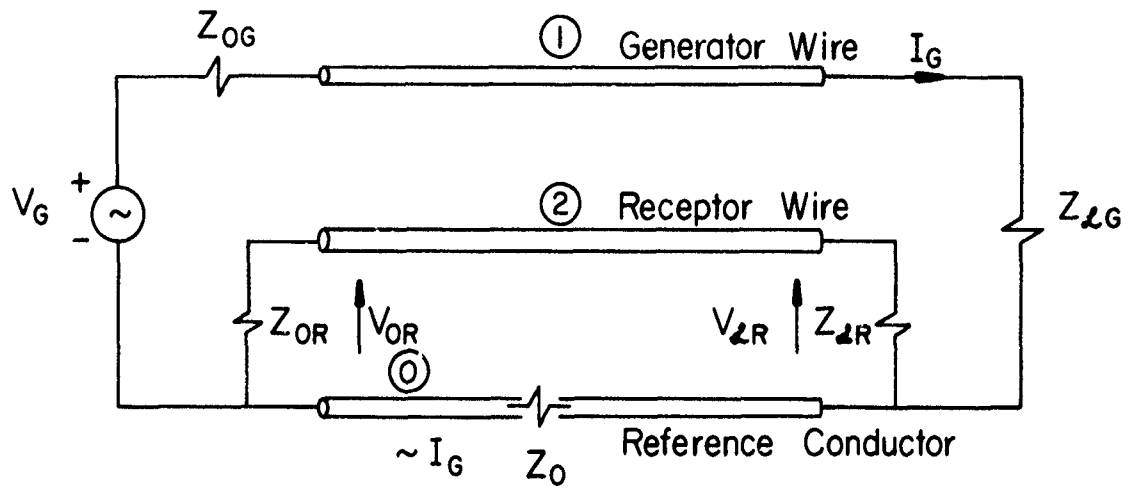
Programs XTALK and FLATPAK assume that all conductors are perfect conductors. Programs XTALK2 and FLATPAK2, however, do not assume perfect conductors and these programs include the per-unit-length conductor resistance and internal inductance, the items r_{c_i} and ℓ_{c_i} , respectively, in Figure 2-2 and (2-5) as well as the reference conductor resistance, r_{c_0} , and

inductance, ℓ_{c_0} .

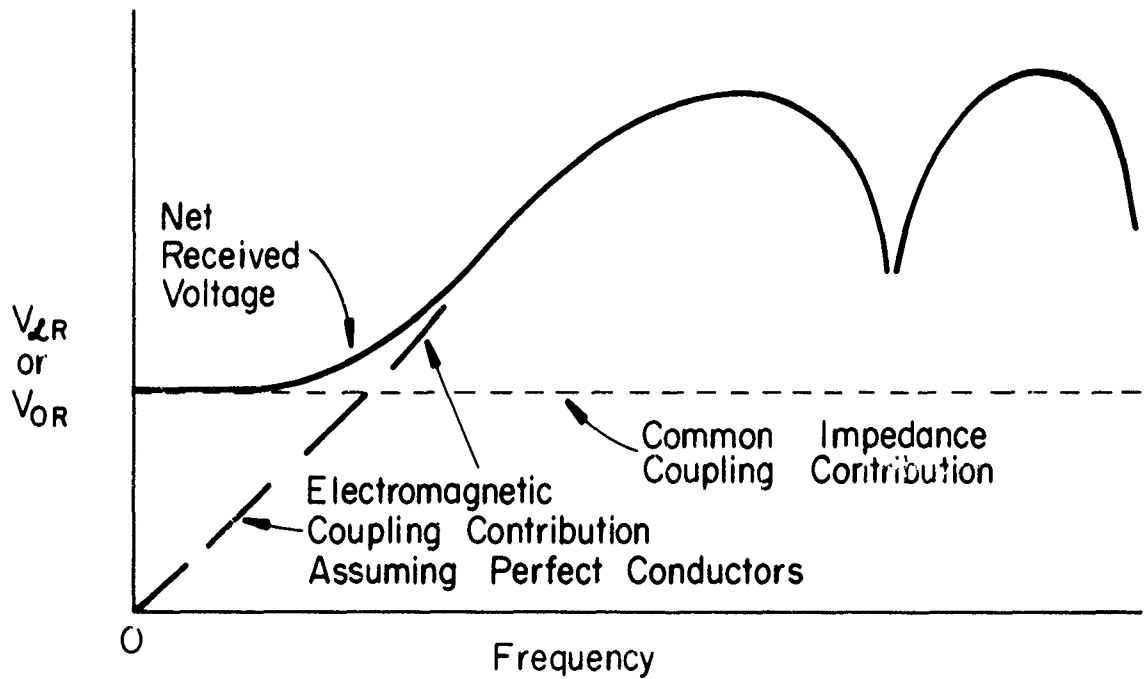
The reason for writing two separate programs to consider the same transmission line structure such as XTALK and XTALK2 is that the inclusion of conductor losses in the transmission line solution requires a longer computer run time and more array storage than when perfect conductors are assumed. This can be seen in Tables 2 and 3 in that the transformation matrix $\tilde{T}$ will be frequency dependent (and complex) when losses are included, whereas $\tilde{T}$ will be frequency independent (and real) when perfect conductors are assumed, i.e., $\tilde{R}_c = \tilde{L}_c = \tilde{0}_{nn}$. Therefore when perfect conductors are assumed (in XTALK and FLATPAK), one need only compute $\tilde{T}$ once per problem and the same $\tilde{T}$ can be used throughout the frequency iteration. When lossy conductors are considered (in XTALK2 and FLATPAK2), one must recompute $\tilde{T}$ at each frequency in addition to reforming at each frequency those matrix products involving $\tilde{T}$ in Table 2 and Table 3.

The primary effect of imperfect conductors is to introduce common impedance coupling. Consider a transmission line in which there is no cross-coupling within the termination networks. In this case, clearly the voltages induced via electromagnetic field coupling at the ends of a "receptor" circuit consisting of one conductor (wire) and the reference conductor due to a "generator" circuit consisting of another wire and the reference conductor will approach zero as the frequency of excitation is reduced to zero. However, the reference conductor impedance can couple a signal into the receptor circuit even at D-C and this is usually termed common impedance coupling.

To illustrate this, consider Figure 2-6. In Figure 2-6a, a three-conductor transmission line is shown. The reference conductor has a certain total impedance, Z_0 , which may be considerably smaller in magnitude than



(a)



(b)

Fig. 2-6. Illustration of common impedance coupling.

Z_{OR} or Z_{IR} . Consequently, the current in the generator wire at frequencies approaching D-C may be determined as

$$I_G \approx \frac{V_G}{Z_{OG} + Z_{IG}} \quad (2-40)$$

The major portion of this current will pass through the reference conductor producing a voltage drop across Z_0 . This results in received voltages

$$V_{IR} \approx - \left[\frac{Z_{IR}}{Z_{IR} + Z_{OR}} \right] Z_0 I_G \quad (2-41a)$$

$$V_{OR} \approx \left[\frac{Z_{OR}}{Z_{IR} + Z_{OR}} \right] Z_0 I_G \quad (2-41b)$$

Although this portion of the total received voltage may be "small" it may nevertheless be larger than the contribution due to electromagnetic field coupling as shown in Figure 2-6b. Consequently, this common impedance coupling generates a "floor" of induced voltage where a solution assuming perfect conductors would indicate a perhaps negligibly small received voltage at the lower frequencies.

The frequency at which this common impedance coupling becomes significant depends on many factors some of which are line geometry (which affects the level of the electromagnetic portion of the coupling) and type of reference conductor. Reference conductors consisting of a #36 gauge wire or a large, thick ground plane would certainly not produce the same level of common impedance coupling.

The above separation and superposition of the two coupling mechanisms is only correct when one dominates the other by a considerable amount. To obtain a quantitatively correct answer, one must include the conductor self impedances directly in the transmission line solution and this is done in

XTALK2 and FLATPAK2.

The transmission lines considered by all programs in this report consist of n wires (cylindrical conductors) and a reference conductor. In XTALK2, there are three choices for the reference conductor; (1) a wire, (2) a finite ground plane and (3) an overall cylindrical shield surrounding the n wires. When the reference conductor is a finite ground plane, the user simply inputs the per-unit-length resistance and self inductance of the ground plane. Thus there are two cases remaining to be considered.

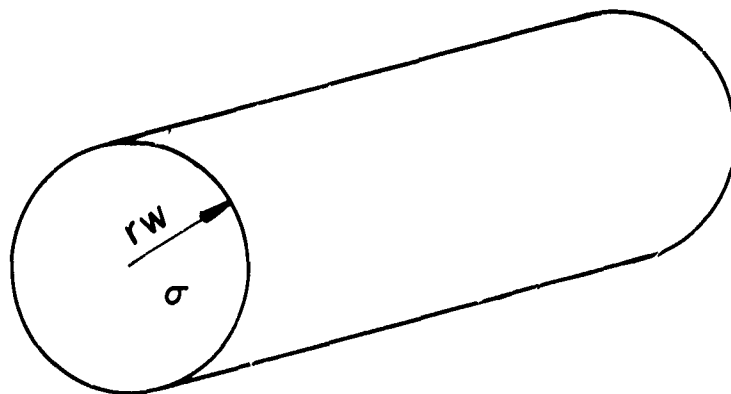
The per-unit-length self impedance of a solid cylinder of radius r_w shown in Figure 2-7a is given by the following. Define

$$\begin{aligned}\delta &= \frac{1}{\sqrt{\pi f \mu_v \sigma}} \\ &= \frac{1}{2\pi \sqrt{\sigma f} \times 10^{-7}}\end{aligned}\tag{2-42a}$$

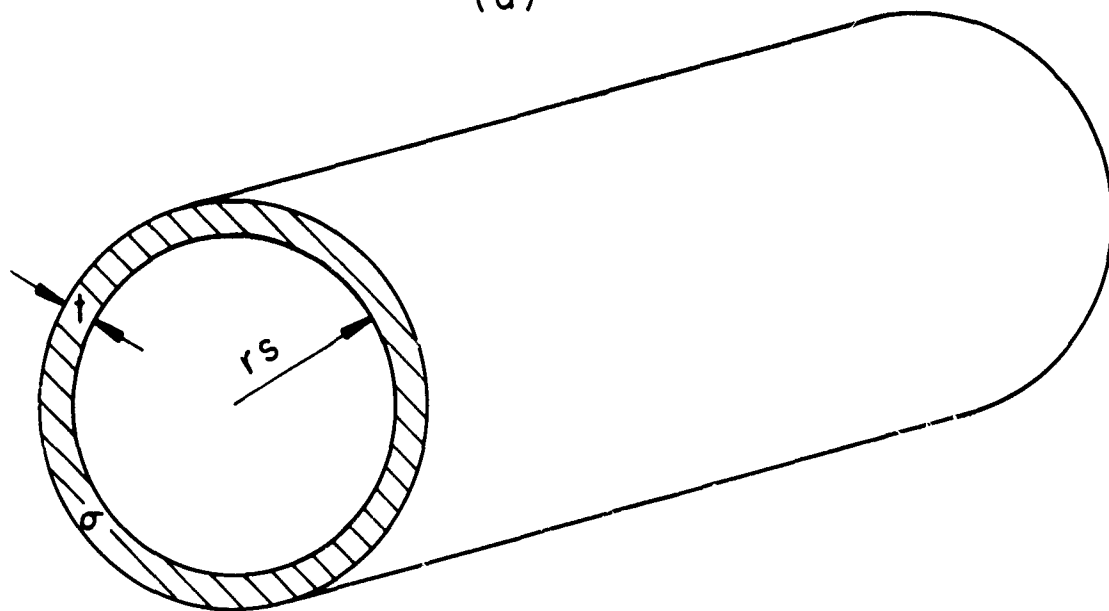
$$r_0 = \frac{1}{\pi \sigma r_w^2}\tag{2-42b}$$

$$l_0 = \frac{\mu_v}{8\pi} = .5 \times 10^{-7}\tag{2-42c}$$

where σ is the conductor conductivity, f is the frequency and μ_v is the permeability of the metal which is assumed to be that of free space ($\mu_v = 4\pi \times 10^{-7}$). The quantity δ is the conventional skin depth factor. The equations for the per-unit-length self impedance of a solid cylindrical conductor including skin effect are obtained from [6]. The equations used in the computer programs approximate the actual equations given in reference [6], pp. 78-80. The programmed equations are



(a)



(b)

Fig. 2-7. Conductor dimensions for calculating common impedance.

$$(I) \quad r_w \leq \delta$$

$$r = r_0 \quad \text{ohms/meter} \quad (2-43a)$$

$$\ell = \ell_0 \quad \text{henrys/meter} \quad (2-43b)$$

$$(II) \quad \delta < r_w < 3\delta$$

$$r = \frac{1}{4} \left(\frac{r_w}{\delta} + 3 \right) r_0 \quad \text{ohms/meter} \quad (2-44a)$$

$$\ell = \left[1.15 - .15 \left(\frac{r_w}{\delta} \right) \right] \ell_0 \quad \text{henrys/meter} \quad (2-44b)$$

$$(III) \quad r_w \geq 3\delta$$

$$r = \frac{r_w}{2\delta} r_0 \quad \text{ohms/meter} \quad (2-45a)$$

$$\ell = \frac{2\delta}{r_w} \ell_0 \quad \text{henrys/meter} \quad (2-45b)$$

These equations are used to generate the per-unit-length self impedances of the transmission line wires ($z_1 = r + j\omega\ell$) and the reference conductor when the reference conductor is also a wire ($z_0 = r + j\omega\ell$). They are stored within the program codes for XTALK2 and FLATPAK2 and the user needs to input only the physical dimensions of the wires and their conductivity.

For the purposes of computing these wire self impedances, the wires are considered to be stranded. The user inputs the radius of each strand (in mils) and the number of strands in each wire. The program then computes the per-unit-length self impedance of each strand and determines the net wire self impedance by dividing this result by the number of strands (the net resistance of the wire is considered to be the result of all strands of the wire in parallel). (All strands in a wire are considered to be identical)

The equations for the per-unit-length self impedance of the reference conductor when the reference conductor is a thin walled, overall, cylindrical

shield shown in Figure 2-7b are taken from reference [7], pp. 301-303 and include skin effect. The equations used in the computer programs are approximations of the actual equations. The skin depth, δ , is given in (2-42a). Denote the interior radius of the cylinder by r_s and its wall thickness by t . The equations become [7]

$$r_0 = \frac{1}{\pi \sigma t (2r_s + t)} \quad (2-46)$$

$$(I) \quad t \leq .5\delta$$

$$r = r_0 \quad \text{ohms/meter} \quad (2-47a)$$

$$\omega l = .4 \left(\frac{t}{\delta} \right) r_0 \quad \text{ohms/meter} \quad (2-47b)$$

$$(II) \quad t \geq 3\delta$$

$$r = \frac{1}{2\pi r_s \sigma \delta} \quad \text{ohms/meter} \quad (2-48a)$$

$$\omega l = r \quad \text{ohms/meter} \quad (2-48b)$$

$$(III) \quad .5\delta < t < 3\delta$$

$$r = \frac{1}{2\pi r_s \sigma \delta} \left[\frac{\sinh\left(\frac{2t}{\delta}\right) + \sin\left(\frac{2t}{\delta}\right)}{\cosh\left(\frac{2t}{\delta}\right) - \cos\left(\frac{2t}{\delta}\right)} \right] \quad \text{ohms/meter} \quad (2-49a)$$

$$\omega l = \frac{1}{2\pi r_s \sigma \delta} \left[\frac{\sinh\left(\frac{2t}{\delta}\right) - \sin\left(\frac{2t}{\delta}\right)}{\cosh\left(\frac{2t}{\delta}\right) - \cos\left(\frac{2t}{\delta}\right)} \right] \quad \text{ohms/meter} \quad (2-49b)$$

The per-unit-length self impedance of the shield is given by $z_0 = r + j\omega l$.

These equations are stored in the XTALK2 program code. The user only needs to input the shield interior radius, the shield thickness and the conductivity of the shield.

2.5 Computation of the Per-Unit-Length Inductance and Capacitance Matrices

All of the formulations shown in Tables 2 and 3 require the computation of the $n \times n$, real, symmetric, per-unit-length transmission line inductance and capacitance matrices, $\underline{L}$ and $\underline{C}$, respectively. The computation of these matrices will be discussed in this section.

2.5.1 Transmission Lines Consisting of Perfect Conductors in a Lossless, Homogeneous Medium, XTALK

This section considers $(n+1)$ conductor transmission lines consisting of $(n+1)$ perfect conductors in a lossless, homogeneous medium. The lines consist of n wires and three choices of reference conductor (the zero-th conductor) cross sections of which are shown in Figure 2-8. Computer program XTALK considers these cases.

The per-unit-length inductance and capacitance matrices for lines in a homogeneous medium are related by [1]

$$\underline{L} \underline{C} = \mu \epsilon \underline{1}_n \quad (2-50)$$

where μ and ϵ are the permeability and permittivity of the surrounding homogeneous medium. The per-unit-length capacitance matrix can be found from a knowledge of the per-unit-length inductance matrix from (2-50) as

$$\underline{C} = \mu \epsilon \underline{L}^{-1} \quad (2-51)$$

A logical choice for the surrounding medium in Figure 2-8(a) and 2-8(b) would be free space with permeability $\mu_v = 4\pi \times 10^{-7}$ henrys/meter and permittivity $\epsilon_v = (1/36\pi) \times 10^{-9}$ farads/meter. However, for all structure types, the homogeneous medium may be characterized, for generality, by a relative dielectric constant (permittivity) of ϵ_r and a relative permeability of μ_r . (Although the permeability of typical dielectrics is that of free space, μ_v ,

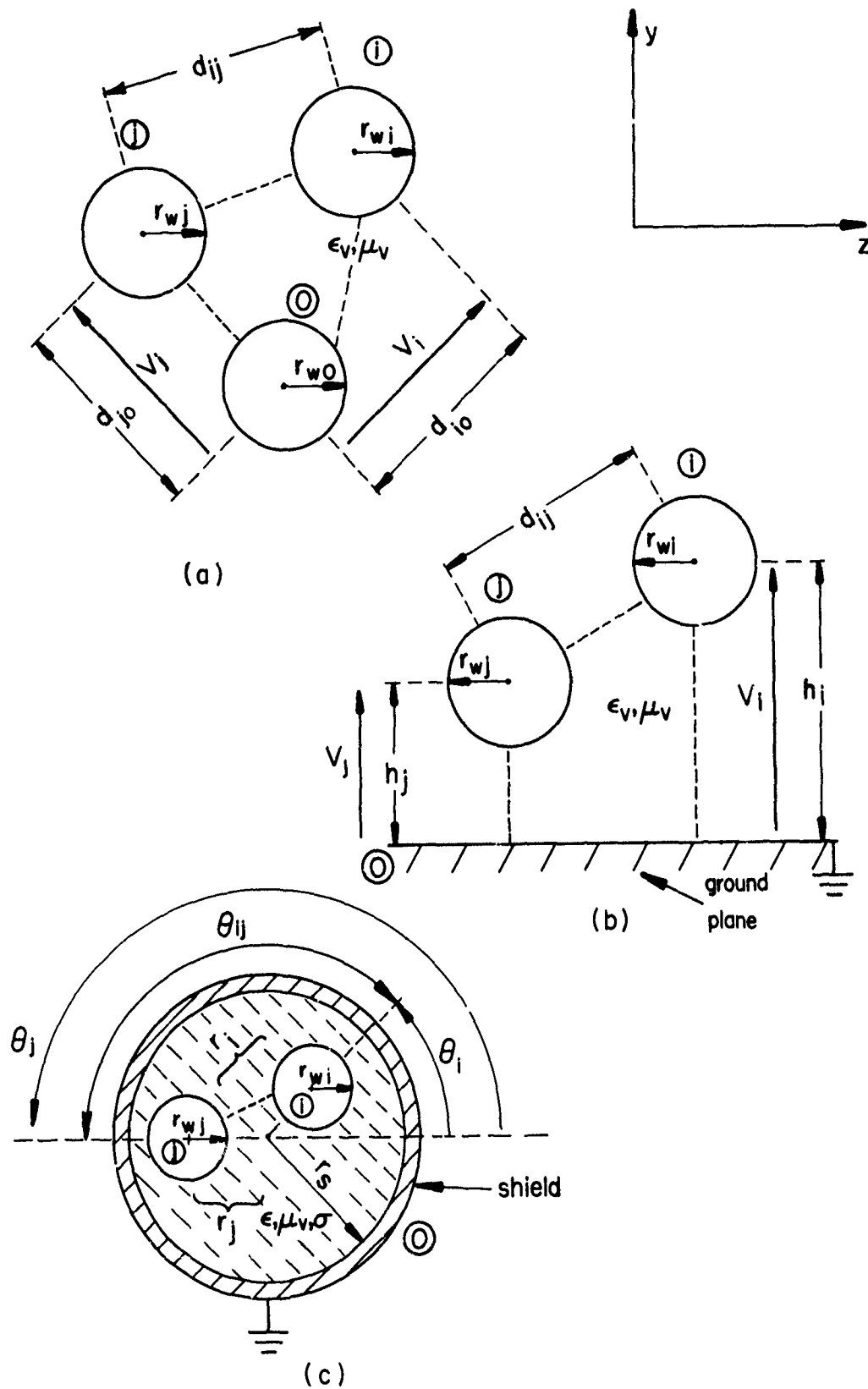


Fig. 2-8. Lines in a homogeneous medium.

the programs XTALK and XTALK2 allow for the more general case.)

For the case of lossless conductors in a lossless, homogeneous medium, the $n \times n$ characteristic impedance matrix, $\tilde{Z}_C$, in (2-11) is related to the per-unit-length inductance matrix by [1]

$$\tilde{Z}_C = \tilde{v} \tilde{L} = \frac{v_0}{\sqrt{\epsilon_r \mu_r}} \tilde{L} \quad (2-52)$$

where $\tilde{v} = 1/\sqrt{\mu\epsilon}$ is the velocity of light in the surrounding medium. The velocity of light in free space, v_0 , to 7 digits is 2.997925×10^8 meters/second.

The equations used in the programs for the entries in the per-unit-length transmission line matrix are derived in Volume I of this series [1] and are valid for "large" conductor separations. Generally this means that the smallest ratio of wire separation to wire radius should be no smaller than approximately 5. A more complete discussion of this is found in Volume I.

When the reference conductor is a wire as shown in Figure 2-8(a), the entries in the per-unit-length transmission line matrix are given by [1]

$$[\tilde{L}]_{ii} = \frac{\mu_v \mu_r}{2\pi} \ln \left(\frac{d_{i0}^2}{r_{wi} r_{w0}} \right) \quad (2-53a)$$

$$[\tilde{L}]_{ij} = \frac{\mu_v \mu_r}{2\pi} \ln \left(\frac{d_{i0} d_{j0}}{r_{w0} d_{ij}} \right) \quad (2-53b)$$

for $i, j=1, \dots, n$ and $i \neq j$ where d_{i0} is the center-to-center separation between the i -th wire and the reference conductor, d_{ij} is the center-to-center separation between the i -th and j -th wires, and r_{wi} and r_{w0} are the radii of the i -th and reference wires, respectively.

When the reference conductor is an infinite ground plane as shown in Figure 2-8(b), the entries in the per-unit-length inductance matrix are

given by [1]

$$[L]_{ii} = \frac{\mu_v \mu_r}{2\pi} \ln \left(\frac{2h_i}{r_{wi}} \right) \quad (2-54a)$$

$$[L]_{ij} = \frac{\mu_v \mu_r}{2\pi} \ln \left(\frac{\sqrt{d_{ij}^2 + 4h_i h_j}}{d_{ij}} \right) \quad (2-54b)$$

for $i, j=1, \dots, n$ and $i \neq j$ where h_i is the height of the i -th wire above the ground plane.

When the reference conductor is an overall cylindrical shield as shown in Figure 2-8(c), the entries in the per-unit-length inductance matrix are given by [1]

$$[L]_{ii} = \frac{\mu_v \mu_r}{2\pi} \ln \left(\frac{r_s^2 - r_i^2}{r_s r_{wi}} \right) \quad (2-55a)$$

$$[L]_{ij} = \frac{\mu_v \mu_r}{2\pi} \ln \left\{ \left(\frac{r_j}{r_s} \right) \sqrt{\frac{(r_i r_j)^2 + r_s^4 - 2r_i r_j r_s^2 \cos \theta_{ij}}{(r_i r_j)^2 + r_j^4 - 2r_i r_j^3 \cos \theta_{ij}}} \right\} \quad (2-55b)$$

for $i, j=1, \dots, n$ and $i \neq j$ where r_s is the interior radius of the shield, r_i is the separation of the i -th wire from the center of the shield and θ_{ij} is the angular separation between the i -th and j -th wires

For the case of lossless conductors in a lossless, homogeneous medium, the equations for the terminal voltages and currents in Table 2 and Table 3 can be further simplified. Obviously, the transformation matrix, T , which diagonalizes the matrix product $\underline{Y} \underline{Z}$ can be taken to be simply the identity matrix, i.e., $T = \underline{1}_n$, as is clear from the fact that for this case $\underline{Z} = j\omega \underline{L}$, $\underline{Y} = j\omega \underline{C}$ and

$$\begin{aligned} \underline{Y} \underline{Z} &= -\omega^2 \underline{L} \underline{C} \\ &= \frac{-\omega^2}{2} \underline{1}_n \end{aligned} \quad (2-56)$$

Also, the $n \times n$ diagonal matrix, Λ , in Tables 2 and 3 becomes

$$\Lambda = \frac{1}{v} \mathbf{1}_n \quad (2-57)$$

Therefore the equations for the terminal voltages, $\underline{V}(0)$ and $\underline{V}(L)$, for the Norton Equivalent representation of the terminal networks in Table 2 simplify to [1] (see equations (2-19) and (2-20)).

$$\begin{aligned} & [\cos(\beta L) \{ \underline{Y}_L + \underline{Y}_0 \} + j \sin(\beta L) \{ \underline{Y}_L \underline{Z}_C \underline{Y}_0 + \underline{Z}_C^{-1} \}] \underline{V}(0) \\ & = [\cos(\beta L) \mathbf{1}_n + j \sin(\beta L) \underline{Y}_L \underline{Z}_C] \underline{I}_0 + \underline{I}_L \end{aligned} \quad (2-58a)$$

$$\underline{V}(L) = -j \sin(\beta L) \underline{Z}_C \underline{I}_0 + [\cos(\beta L) \mathbf{1}_n + j \sin(\beta L) \underline{Z}_C \underline{Y}_0] \underline{V}(0) \quad (2-58b)$$

where β is the phase constant

$$\beta = \omega/v \quad (2-59)$$

and the characteristic impedance matrix $\underline{Z}_C$ is given in (2-52).

Similarly the equations for the terminal currents, $\underline{I}(0)$ and $\underline{I}(L)$, for the Thevenin Equivalent representation in Table 3 simplify to

$$\begin{aligned} & [\cos(\beta L) \{ \underline{Z}_L + \underline{Z}_0 \} + j \sin(\beta L) \{ \underline{Z}_L \underline{Z}_C^{-1} \underline{Z}_0 + \underline{Z}_C \}] \underline{I}(0) \\ & = -\underline{V}_L + [\cos(\beta L) \mathbf{1}_n + j \sin(\beta L) \underline{Z}_L \underline{Z}_C^{-1}] \underline{V}_0 \end{aligned} \quad (2-60a)$$

$$\underline{I}(L) = -j \sin(\beta L) \underline{Z}_C^{-1} \underline{V}_0 + [\cos(\beta L) \mathbf{1}_n + j \sin(\beta L) \underline{Z}_C^{-1} \underline{Z}_0] \underline{I}(0) \quad (2-60b)$$

The terminal voltages can be obtained from the solution of (2-60) for the terminal currents, $\underline{I}(0)$ and $\underline{I}(L)$, with the equations for the terminal networks

$$\underline{V}(0) = \underline{V}_0 - \underline{Z}_0 \underline{I}(0) \quad (2-61a)$$

$$\underline{V}(\underline{x}) = \underline{V}_x + \underline{Z}_x \underline{I}(\underline{x}) \quad (2-61b)$$

2.5.2 Transmission Lines Consisting of Imperfect (Lossy) Conductors in a Lossless, Homogeneous Medium, XTALK2

This section considers the (n+1) conductor transmission lines considered in the previous section and shown in Figure 2-8. However, the transmission line conductors are considered to be lossy. Computer program XTALK2 considers these cases.

The per-unit-length inductance and capacitance matrices are computed as in the previous section and satisfy the relation in (2-50). The entries in $\underline{L}$ are given in (2-53), (2-54) and (2-55). The per-unit-length admittance matrix is given by

$$\underline{Y} = j\omega \underline{C} = j \frac{\omega}{v^2} \underline{L}^{-1} \quad (2-62)$$

The per-unit-length impedance matrix is given by

$$\underline{Z} = \underline{R}_c + j\omega \underline{L}_c + j\omega \underline{L} \quad (2-63)$$

where the entries in $\underline{R}_c$ and $\underline{L}_c$ are due to imperfect conductors. The entries in $\underline{R}_c$ and $\underline{L}_c$ are given in (2-5) and these matrices can be separated as [1]

$$\underline{R}_c + j\omega \underline{L}_c = (r_{c_0} + j\omega l_{c_0}) \underline{U}_n + \underline{Z}_D \quad (2-64)$$

where $\underline{U}_n$ is the $n \times n$ unit matrix with one's in every position, i.e., $[\underline{U}_n]_{ij} = 1$, and $\underline{Z}_D$ is a diagonal matrix with

$$[\underline{Z}_D]_{ii} = r_{c_i} + j\omega l_{c_i} \quad (2-65)$$

and $[\underline{Z}_D]_{ij} = 0$ for $i, j=1, \dots, n$ and $i \neq j$. The calculation of the wire

self impedances, $r_{c_1} + j\omega l_{c_1}$, and the reference conductor self impedance, $r_{c_0} + j\omega l_{c_0}$, is discussed in section 2.4.

2.5.3 Transmission Lines Consisting of Perfect Conductors in a Lossless, Inhomogeneous Medium, FLATPAK

This section considers (n+1) conductor transmission lines consisting of (n+1) perfect conductors in a lossless, inhomogeneous medium. For example, dielectric insulations surrounding wires result in an inhomogeneous medium (dielectric insulation and the surrounding free space). The computer program FLATPAK considers a specific case of flatpack or ribbon cables. A ribbon cable consists of (n+1) identical wires with identical cylindrical dielectric insulations bonded together in a linear array as shown in Figure 2-9.

In this case, the relationship in (2-50) relating the per-unit-length inductance and capacitance matrices no longer holds. Clearly the surrounding medium does not influence the per-unit-length inductance matrix since the surrounding medium is considered to be homogeneous in its permeability characteristic, μ_v . Therefore, one may compute the per-unit-length capacitance matrix with the wire dielectric insulations removed, denoted by C_0 , and determine L through (2-50) as

$$\underline{L} = \mu_v \epsilon_v \underline{C}_0^{-1} \quad (2-66)$$

Therefore, one needs to compute the per-unit-length capacitance matrix with and without the wire dielectric insulations present. A digital computer program, GETCAP, has been written to compute the per-unit-length capacitance matrices of ribbon cables. This program is described in detail in Volume II of this series [8].

The per-unit-length impedance and admittance matrices become

$$\underline{\underline{Z}} = j\omega \underline{\underline{L}} \quad (2-67a)$$

$$\underline{\underline{Y}} = j\omega \underline{\underline{C}} \quad (2-67b)$$

The transformation matrix, $\underline{\underline{T}}$, which diagonalizes the matrix product $\underline{\underline{Y}} \underline{\underline{Z}}$ must therefore diagonalize the product $\underline{\underline{C}} \underline{\underline{L}}$ as

$$\begin{aligned} \underline{\underline{T}}^{-1} \underline{\underline{Y}} \underline{\underline{Z}} \underline{\underline{T}} &= -\omega^2 \underline{\underline{T}}^{-1} \underline{\underline{C}} \underline{\underline{L}} \underline{\underline{T}} \\ &= -\omega^2 \underline{\underline{\Lambda}}^2 \end{aligned} \quad (2-68)$$

In addition, it can be shown that [1]

$$\underline{\underline{T}}^{-1} = \underline{\underline{T}}^t \underline{\underline{C}}^{-1} \quad (2-69)$$

where $\underline{\underline{T}}^t$ is the transpose of $\underline{\underline{T}}$. A digital computer subroutine NROOT (which uses subroutine EIGEN) is used to accomplish this reduction and is discussed in a later section.

2.5.4 Transmission Lines Consisting of Imperfect (Lossy) Conductors in a Lossless, Inhomogeneous Medium, FLATPAK2

This section considers (n+1) conductor transmission lines consisting of (n+1) lossy conductors in a lossless, inhomogeneous medium. The program FLATPAK2 considers a particular case of flatpack or ribbon cables discussed in the previous section.

The per-unit-length capacitance and inductance matrices are computed assuming perfect conductors and can be obtained with GETCAP as described in the previous section.

The self impedances of the wires are identical since the wires in the ribbon cable are typically identical. Therefore the pre-unit-length

impedance and admittance matrices become

$$\underline{Z} = \underline{z}(\underline{U}_n + \underline{1}_n) + j\omega \underline{L} \quad (2-70a)$$

$$\underline{Y} = j\omega \underline{C} \quad (2-70b)$$

where $\underline{z} = r + j\omega \ell$ is the self impedance of each wire.

III. PROGRAM CODE DESCRIPTIONS

In this chapter, the content of each program will be described by card. (Each program is labeled in columns 72-80 with the card number.) All programs were written in double precision arithmetic and the program listings are given in Appendix A - Appendix D. A table is provided with each listing which shows the changes which are required to convert each program to single precision arithmetic. Listings of two of the required subroutines, NROOT and EIGEN, are provided in Appendix E - Appendix F. The remaining required subroutines, LEQT1C and EIGCC, are a part of the IMSL (International Mathematical and Statistical Library) package [9]. Appropriate alternate subroutines can be substituted for LEQT1C and EIGCC if the IMSL package is not available on the user's system.

3.1 Program XTALK

A listing of XTALK is given in Appendix A.

Cards 001 through 047 contain general comments concerning the applicability of the program. This format will be followed in the other programs.

Cards 048 through 053 are comment cards pointing out that all arrays must be properly dimensioned for each problem before using the program.

Cards 054 through 059 dimension the arrays and declare variable types.

Card 060 gives the value of π and the speed of light in free space.

Cards 061 through 065 define the complex numbers $1+j0$, $0+j0$, and $0+j1$ as well as other constants.

Cards 071 through 118 read and print an initial portion of the input data.

Cards 123 through 170 read and print the line dimensions and compute the entries in the characteristic impedance matrix. The entries in the characteristic impedance matrix, Z_C , are related to the per-unit-length inductance matrix for the three structure types given in (2-53), (2-54) and (2-55) by $Z_C = \nu L$. Cards 132 through 139 compute the main diagonal entries of Z_C . Cards 141 through 170 compute the off-diagonal entries. The $n \times 1$ complex

arrays V1 and V2 are used to temporarily store the Z_i and Y_i coordinates or the r_i and θ_i coordinates of the wires in the real parts of the arrays (see Figure 4-1, Figure 4-2, Figure 4-3). The $n \times n$ complex array M1 is used to temporarily store the characteristic impedance matrix in the real parts. Although the actual quantities stored are real, it was decided to use the real parts of these complex arrays to store these quantities rather than define additional real arrays. V1, V2 and M1 will be needed (as complex arrays) later.

Cards 175 through 181 compute the inverse of the characteristic impedance matrix which is temporarily stored in the real part of the $n \times n$ complex array M2. M2 will be needed (as a complex array) later. The matrix inverse is computed with subroutine LEQT1C which is described in section 3.5.

Cards 190 through 226 read and print the entries in the terminal impedance characterizations. These matrix characterizations are given in (2-30) for the Thevenin Equivalent characterization and in (2-34) for the Norton Equivalent characterization. The $n \times 1$ complex arrays I0 and IL store the entries in $\underline{I}(0)$ and $\underline{I}(L)$, respectively, for the Norton Equivalent in (2-34) or $\underline{V}(0)$ and $\underline{V}(L)$, respectively, for the Thevenin Equivalent in (2-30). The $n \times n$ complex arrays Y0 and YL store the entries in $\underline{Y}_0$ and $\underline{Y}_L$, respectively, for the Norton Equivalent in (2-34) or $\underline{Z}_0$ and $\underline{Z}_L$, respectively, for the Thevenin Equivalent in (2-30).

Cards 231 through 291 contain certain matrix and vector multiplications which are independent of frequency. If one requests the analysis to be done at more than one frequency (such as in computing the frequency response of the line), then these time-consuming multiplications need be computed only for the first frequency and need not be recomputed for the additional fre-

quencies. To explain these cards, consider the similarity of the forms of the equations for the Norton Equivalent characterization given in (2-58) and the Thevenin Equivalent characterization given in (2-60). The analogous variables in these two equations are summarized as:

<u>(2-58)</u>	<u>(2-60)</u>
$\underline{Y}_{\underline{I}}$	$\underline{Z}_{\underline{I}}$
$\underline{Y}_0$	$\underline{Z}_0$
$\underline{Z}_C$	$\underline{Z}_C^{-1}$
$\underline{Z}_C^{-1}$	$\underline{Z}_C$
$\underline{I}_0$	$\underline{V}_0$
$\underline{I}_{\underline{I}}$	$-\underline{V}_{\underline{I}}$
$\underline{V}(0)$	$\underline{I}(0)$
$\underline{V}(\underline{I})$	$\underline{I}(\underline{I})$

Therefore equations (2-58) can be programmed and used for both cases if analogous variables are substituted. Cards 231 through 240 swap the entries in M1 and M2 if the Thevenin Equivalent characterization is chosen. Cards 251 through 291 form the quantities in (2-58)

$\underline{Z}_C \underline{Y}_0$	<u>Array</u> M1	(3-1a)
$\underline{Y}_{\underline{I}} \underline{Z}_C \underline{Y}_0 + \underline{Z}_C^{-1}$	M2	(3-1b)
$\underline{Z}_C \underline{I}_0$	V1	(3-1c)
$\underline{Y}_{\underline{I}} \underline{Z}_C \underline{I}_0$	V2	(3-1d)

for the Norton Equivalent characterization or the quantities in (2-60)

$\underline{Z}_C^{-1} \underline{Z}_0$	<u>Array</u> M1	(3-2a)
$\underline{Z}_{\underline{I}} \underline{Z}_C^{-1} \underline{Z}_0 + \underline{Z}_C$	M2	(3-2b)

$$\underline{Z}_C^{-1} \underline{V}_0 \quad V1 \quad (3-2c)$$

$$\underline{Z}_L \underline{Z}_C^{-1} \underline{V}_0 \quad V2 \quad (3-2d)$$

for the Thevenin Equivalent characterization.

Cards 295 through 300 read the frequency and form

$$\beta \underline{L} = \frac{2\pi f}{v} \underline{L} \quad (3-3a)$$

$$\sin(\beta \underline{L}) \quad (3-3b)$$

$$\cos(\beta \underline{L}) \quad (3-3c)$$

Cards 306 through 316 form equation (2-58a) for the Norton Equivalent characterization or (2-60a) for the Thevenin Equivalent characterization. These equations are solved with subroutine LEQT1C in card 320. The solutions ($\underline{V}(0)$ for (2-58a) or $\underline{I}(0)$ for (2-60a)) are stored in the array B.

Cards 332 through 336 form equation (2-58b) or (2-60b) and the entries in $\underline{V}(\underline{L})$ for (2-58b) or $\underline{I}(\underline{L})$ for (2-60b) are stored in the array WA.

Cards 337 through 365 print the terminal voltages $\underline{V}(0)$ and $\underline{V}(\underline{L})$. Cards 337 through 352 form the terminal voltages, if the Thevenin Equivalent characterization is chosen, from

$$\underline{V}(0) = \underline{V}_0 - \underline{Z}_0 \underline{I}(0) \quad (3-4a)$$

$$\underline{V}(\underline{L}) = \underline{V}_L + \underline{Z}_L \underline{I}(\underline{L}) \quad (3-4b)$$

since the elements of the arrays B and WA are the following:

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
B	$\underline{V}(0)$	$\underline{I}(0)$
WA	$\underline{V}(\underline{L})$	$\underline{I}(\underline{L})$

Cards 353 through 365 print the resulting terminal voltages, $\underline{V}(0)$ and $\underline{V}(\underline{L})$.

3.2 Program XTALK2

A listing of XTALK2 is given in Appendix B.

Cards 001 through 190 have the same purpose and are of the same general structure as cards 001 through 181 in XTALK. The slight exceptions are that instead of computing the characteristic impedance matrix and its inverse as is done in XTALK, the per-unit-length capacitance matrix and its inverse are computed here. The per-unit-length inductance matrix, $\tilde{L}$, and capacitance matrix, $\tilde{C}$, are related by

$$\tilde{L} \tilde{C} = \frac{1}{v^2} \tilde{1}_n \quad (3-5a)$$

or

$$v \tilde{C} = \frac{1}{v} \tilde{L}^{-1} \quad (3-5b)$$

where v is the velocity of light in the surrounding medium given by

$$v = \frac{1}{\sqrt{\epsilon \mu}} = \frac{v_0}{\sqrt{\epsilon_r \mu_r}} \quad (3-5c)$$

ϵ is the permittivity of the medium, μ is the permeability of the medium, v_0 is the velocity of light in free space ($v_0 = 3 \times 10^8$ m/sec) and ϵ_r and μ_r are the relative permittivity and permeability, respectively. The characteristic impedance matrix is given by

$$\tilde{Z}_C = v \tilde{L} \quad (3-6)$$

Therefore $\tilde{C}^{-1} = v \tilde{Z}_C$. $\tilde{C}$ is stored in array C and $\tilde{C}^{-1}$ is stored in array CI.

Cards 195 through 223 read and print the characteristics of the reference conductor and the n wires to be using in calculating their self impedances.

Cards 233 through 269 read and print the termination network character-

istics and are identical to the corresponding cards in XTALK.

Cards 275 through 332 perform certain frequency independent matrix multiplications for reasons similar to those given in 3.1 for the analogous group of cards. These cards form, for the Norton or Thevenin Equivalent characterizations, certain quantities in Tables 2 and 3:

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
M1	$\underline{Y}_0 \underline{C}^{-1}$	$\underline{C} \underline{Z}_0$
M2	$\underline{Y}_{\cancel{I}} \underline{C}^{-1}$	$\underline{C} \underline{Z}_{\cancel{I}}$
V1	$\underline{I}_0$	$\underline{C} \underline{V}_0$
V2	$\underline{I}_{\cancel{I}}$	$\underline{C} \underline{V}_{\cancel{I}}$

Cards 328 through 332 form the sums of entries in each row of $\underline{C}$ and are stored in the array V3.

Cards 336 through 340 read the frequency and form the quantities $\omega=2\pi f$ and $j\omega$.

Cards 346 through 385 form the self impedances of the wires and the reference conductor. The equations for these self impedance terms are given in (2-42) through (2-49) in section 2.4. The self impedance of the reference conductor is stored as the complex variable Z_0 and the self impedances of the n wires are temporarily stored in the array B.

Cards 391 through 398 compute the eigenvalues and eigenvectors of the product of the per-unit-length admittance and impedance matrices, $\underline{YZ}$. The per-unit-length admittance matrix is given by

$$\underline{Y} = j \omega \underline{C} \quad (3-7)$$

and the per-unit-length impedance matrix is given by

$$\underline{Z} = \underline{z}_0 \underline{U}_n + \underline{Z}_D + j \omega \underline{L} \quad (3-8)$$

where $\underline{U}_n$ is an $n \times n$ unit matrix with ones in every position, z_0 is the self impedance of the reference conductor and $\underline{Z}_D$ is an $n \times n$ diagonal matrix with the self impedance of the i -th wire in the i -th row and i -th column. The matrix product becomes (with the relation in (3-5a))

$$\underline{Y} \underline{Z} = j\omega \underline{C} [z_0 \underline{U}_n + \underline{Z}_D + j\omega \underline{L}] = j\omega z_0 \underline{C} \underline{U}_n + j\omega \underline{C} \underline{Z}_D - \frac{\omega^2}{v} \underline{1}_n \quad (3-9)$$

Note that $\underline{C} \underline{U}_n$ is simply an $n \times n$ matrix with the sum of all elements in the i -th row of $\underline{C}$ in each of the entries in the i -th row of $\underline{C} \underline{U}_n$. These quantities were previously stored in the array V3. The subroutine EIGCC computes the $n \times 1$ eigenvectors of $\underline{Y} \underline{Z}$, $\underline{T}_1$, and their associated eigenvalues, γ_1^2 . The matrix $\underline{T} = [\underline{T}_1, \underline{T}_2, \dots, \underline{T}_n]$ will diagonalize $\underline{Y} \underline{Z}$ as [1]

$$\underline{T}^{-1} \underline{Y} \underline{Z} \underline{T} = \underline{\gamma}^2 \quad (3-10)$$

where $\underline{\gamma}^2$ is an $n \times n$ diagonal matrix with γ_1^2 in the i -th position on the main diagonal. This is required in Tables 2 and 3. $\underline{T}$ is stored in array T and the n entries on the main diagonal of $\underline{\gamma}^2$ are temporarily stored in the array B.

Cards 403 through 410 compute the inverse of $\underline{T}$ which is stored in array TI.

Cards 416 through 448 compute certain other quantities in Tables 2 and 3. These are

Array	Norton	Thevenin
Y0	$\underline{Y}_0^* = \underline{T}^{-1} \underline{Y}_0 \underline{C}^{-1} \underline{T}$	$\underline{Z}_0^* = \underline{T}^{-1} \underline{C} \underline{Z}_0 \underline{T}$
YL	$\underline{Y}_L^* = \underline{T}^{-1} \underline{Y}_L \underline{C}^{-1} \underline{T}$	$\underline{Z}_L^* = \underline{T}^{-1} \underline{C} \underline{Z}_L \underline{T}$
I0	$\underline{I}_0^* = \underline{T}^{-1} \underline{I}_0$	$\underline{V}_0^* = \underline{T}^{-1} \underline{C} \underline{V}_0$
IL	$\underline{I}_L^* = \underline{T}^{-1} \underline{I}_L$	$-\underline{V}_L^* = -\underline{T}^{-1} \underline{C} \underline{V}_L$

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
EP	$\tilde{E}^+ = \frac{1}{2}(\tilde{e}^{\gamma \tilde{L}} + \tilde{e}^{-\gamma \tilde{L}})$	$\tilde{E}^+ = \frac{1}{2}(\tilde{e}^{\gamma \tilde{L}} + \tilde{e}^{-\gamma \tilde{L}})$
EN	$\tilde{E}^- = \frac{1}{2}(\tilde{e}^{\gamma \tilde{L}} - \tilde{e}^{-\gamma \tilde{L}})$	$\tilde{E}^- = \frac{1}{2}(\tilde{e}^{\gamma \tilde{L}} - \tilde{e}^{-\gamma \tilde{L}})$
G	$\tilde{\Lambda} = \frac{1}{j\omega} \tilde{\gamma}$	$\tilde{\Lambda} = \frac{1}{j\omega} \tilde{\gamma}$

Cards 449 through 458 form equation (1) in Tables 2 and 3. This equation is solved with subroutine LEQTIC in card 462 with the result stored in array B as:

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
B	$\tilde{V}^*(0)$	$\tilde{I}^*(0)$

Cards 480 through 484 form equation (2) in Tables 2 and 3 with the result stored as

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
G	$\tilde{V}^*(\tilde{L})$	$\tilde{I}^*(\tilde{L})$

Cards 485 through 531 form the terminal voltages $\tilde{V}(0)$ and $\tilde{V}(\tilde{L})$ by back transforming according to equation (9) in Tables 2 and 3.

3.3 Program FLATPAK

A listing of FLATPAK is given in Appendix C.

Cards 001 through 057 are similar to corresponding cards in the previous programs.

Cards 062 through 097 read a portion of the input data describing the structure of the line. The per-unit-length capacitance matrix, $\tilde{C}$, (computed with GETCAP) is stored in array C. The per-unit-length capacitance matrix with the wire insulations removed, $\tilde{C}_0$, (computed with GETCAP) is stored in array C0.

Cards 105 through 113 compute the eigenvectors and corresponding eigen-

Values of the matrix product $\tilde{C} \tilde{L}$. Subroutine NROOT computes the matrix $\tilde{K}$ such that

$$\tilde{K}^{-1} \tilde{C}^{-1} \tilde{C}_0 \tilde{K} = \tilde{\psi} \quad (3-11)$$

such that $\tilde{\psi}$ is a diagonal matrix. $\tilde{K}$ is stored in array TI. The problem of interest is finding $\tilde{T}$ such that

$$\tilde{T}^{-1} \tilde{C} \tilde{L} \tilde{T} = \tilde{\gamma}^2 \quad (3-12)$$

where

$$\tilde{L} = \frac{1}{v_o^2} \tilde{C}_0 \quad (3-13)$$

Taking the inverse of both sides of (3-11) results in

$$\tilde{K}^{-1} \tilde{C}_0^{-1} \tilde{C} \tilde{K} = \tilde{\psi}^{-1} \quad (3-14)$$

Taking the transpose of both sides of (3-14) results in

$$\tilde{K}^t \tilde{C} \tilde{C}_0^{-1} \tilde{K}^{-1t} = \tilde{\psi}^{-1} \quad (3-15)$$

(Since $\tilde{C}$ and $\tilde{C}_0$ are symmetric, $\tilde{C}^t = \tilde{C}$ and $\tilde{C}_0^{-1t} = \tilde{C}_0^{-1}$. Also $\tilde{\psi}$ is diagonal.

Therefore $\tilde{\psi}^{-1t} = \tilde{\psi}^{-1}$.) Thus comparing (3-15) to (3-12) and using (3-13) we identify

$$\tilde{K} = \tilde{T}^{-1t} \quad (3-16a)$$

$$\frac{1}{v_o^2} \tilde{\psi}^{-1} = \tilde{\gamma}^2 \quad (3-16b)$$

and $\tilde{T}^{-1t}$ is stored in array C and array G contains the square roots of entries on the main diagonal of $\tilde{\gamma}^2$, $\tilde{\gamma}$.

Cards 114 through 128 compute $\tilde{T}$ and $\tilde{\gamma}^{-1}$ if the Thevenin Equivalent characterization is chosen. Thus, contained in arrays TI and G are:

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
TI	$\tilde{T}^{-1^t}$	$\tilde{T}$
G	$\tilde{\gamma}$	$\tilde{\gamma}^{-1}$

Cards 138 through 175 read and print the termination network characteristics and are identical to the corresponding cards in the previous programs.

Cards 182 through 220 form the following frequency independent quantities (see Tables 2 and 3)

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
Y0	$\tilde{Y}_0^* = \tilde{T}^{-1} \tilde{Y}_0 \tilde{C}^{-1} \tilde{T}$	$\tilde{Z}_0^* = \tilde{T}^{-1} \tilde{C} \tilde{Z}_0 \tilde{T}$
YL	$\tilde{Y}_L^* = \tilde{T}^{-1} \tilde{Y}_L \tilde{C}^{-1} \tilde{T}$	$\tilde{Z}_L^* = \tilde{T}^{-1} \tilde{C} \tilde{Z}_L \tilde{T}$
I0	$\tilde{I}_0^* = \tilde{T}^{-1} \tilde{I}_0$	$\tilde{V}_0^* = \tilde{T}^{-1} \tilde{C} \tilde{V}_0$
IL	$\tilde{I}_L^* = \tilde{T}^{-1} \tilde{I}_L$	$-\tilde{V}_L^* = -\tilde{T}^{-1} \tilde{C} \tilde{V}_L$

Since $\tilde{T}^{-1}$ satisfies

$$\tilde{T}^{-1} = \tilde{T}^t \tilde{C}^{-1} \quad (3-17)$$

then

$$\tilde{T}^{-1^t} = \tilde{C}^{-1} \tilde{T} \quad (3-18)$$

and these relations allow the entries in the arrays Y0, YL, I0 and IL to be more easily generated as:

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
Y0	$\tilde{Y}_0^* = \tilde{T}^{-1} \tilde{Y}_0 \tilde{T}^{-1^t}$	$\tilde{Z}_0^* = \tilde{T}^t \tilde{Z}_0 \tilde{T}$
YL	$\tilde{Y}_L^* = \tilde{T}^{-1} \tilde{Y}_L \tilde{T}^{-1^t}$	$\tilde{Z}_L^* = \tilde{T}^t \tilde{Z}_L \tilde{T}$
I0	$\tilde{I}_0^* = \tilde{T}^{-1} \tilde{I}_0$	$\tilde{V}_0^* = \tilde{T}^t \tilde{V}_0$
IL	$\tilde{I}_L^* = \tilde{T}^{-1} \tilde{I}_L$	$-\tilde{V}_L^* = -\tilde{T}^t \tilde{V}_L$

Cards 224 through 227 read the frequency and compute $\omega = 2\pi f$.

Cards 233 through 248 form equation (1) in Tables 2 and 3.

Equation (1) in Tables 2 and 3 is solved with subroutine LEQT1C in card 252.

Cards 264 through 268 form equation (2) in Tables 2 and 3. The arrays B and WA now contain, with respect to Tables 2 and 3:

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
B	$\underline{V}^*(0)$	$\underline{I}^*(0)$
WA	$\underline{V}^*(\lambda)$	$\underline{I}^*(\lambda)$

The terminal voltages, $\underline{V}(0)$ and $\underline{V}(\lambda)$ are computed in cards 269 through 286 by back transforming $\underline{V}^*(0)$ and $\underline{V}^*(\lambda)$ through (see Tables 2 and 3)

<u>Norton</u>	<u>Thevenin</u>
$\underline{V}(0) = \underline{C}^{-1} \underline{T} \underline{V}^*(0)$ $= \underline{T}^{-1t} \underline{V}^*(0)$	$\underline{V}^*(0) = \underline{V}_0^* - \underline{Z}_0^* \underline{I}^*(0)$
$\underline{V}(\lambda) = \underline{C}^{-1} \underline{T} \underline{V}^*(\lambda)$ $= \underline{T}^{-1t} \underline{V}^*(\lambda)$	$\underline{V}(0) = \underline{C}^{-1} \underline{T} \underline{V}^*(0)$ $= \underline{T}^{-1t} \underline{V}^*(0)$
	$\underline{V}^*(\lambda) = \underline{V}_\lambda^* + \underline{Z}_\lambda^* \underline{I}^*(\lambda)$
	$\underline{V}(\lambda) = \underline{C}^{-1} \underline{T} \underline{V}^*(\lambda)$ $= \underline{T}^{-1t} \underline{V}^*(\lambda)$

Cards 287 through 301 print the resulting terminal voltages.

3.4 Program FLATPAK2

A listing of FLATPAK2 is given in Appendix D.

Cards 001 through 106 are similar to corresponding cards (001 through 097) in FLATPAK.

Cards 112 through 133 compute the inverse of the per-unit-length

capacitance matrix which is stored in array C1. The per-unit-length inductance matrix, $\tilde{L}$, is also computed from the relation

$$\tilde{L} = \frac{1}{\sqrt{2}} \tilde{C}_0^{-1} \quad (3-19)$$

Cards 138 through 144 read the characteristics of the wires in the ribbon cable (all wires are assumed to be identical) for use in computing their self impedances.

Cards 154 through 191 read and print the characteristics of the termination networks and are identical to the corresponding cards in the previous programs.

Cards 197 through 262 form certain frequency independent quantities in Tables 2 and 3:

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
M1	$\tilde{Y}_0 \tilde{C}^{-1}$	$\tilde{C} \tilde{Z}_0$
M2	$\tilde{Y}_L \tilde{C}^{-1}$	$\tilde{C} \tilde{Z}_L$
V1	$\tilde{I}_0$	$\tilde{C} \tilde{V}_0$
V2	$\tilde{I}_L$	$\tilde{C} \tilde{V}_L$

Cards 251 through 262 form the quantities $\tilde{C} \tilde{L}$ which is stored in array C0 and the sums of the elements in the i-th row of $\tilde{C}$ which are stored in array V3.

Cards 266 through 270 read the frequency and form $\omega = 2\pi f$ and $j\omega$.

Cards 274 through 283 form the self impedances of the wires which are stored in the complex variable Z (all wires are identical).

Cards 289 through 295 compute the transformation matrix $\tilde{T}$ such that

$$\tilde{T}^{-1} \tilde{Y} \tilde{Z} \tilde{T} = \tilde{Y}^2 \quad (3-20)$$

where γ^2 is a diagonal matrix and

$$\begin{aligned} \tilde{Y} \tilde{Z} &= j\omega C(z \tilde{U}_n + z \tilde{1}_n + j\omega L) \\ &= j\omega z \tilde{C} \tilde{U}_n + j\omega z \tilde{C} - \omega^2 \tilde{C} \tilde{L} \end{aligned} \quad (3-21)$$

Subroutine EIGCC computes $\tilde{T}$ and stores it in array T and stores the entries on the main diagonal of γ^2 temporarily in Array B.

The inverse of $\tilde{T}$ is computed with LEQTIC in cards 300 through 307 and is stored in array TI.

Cards 313 through 345 compute certain quantities in Tables 2 and 3:

<u>Array</u>	<u>Norton</u>	<u>Thevenin</u>
Y0	$\tilde{Y}_0^* = \tilde{T}^{-1} \tilde{Y}_0 \tilde{C}^{-1} \tilde{T}$	$\tilde{Z}_0^* = \tilde{T}^{-1} \tilde{C} \tilde{Z}_0 \tilde{T}$
YL	$\tilde{Y}_L^* = \tilde{T}^{-1} \tilde{Y}_L \tilde{C}^{-1} \tilde{T}$	$\tilde{Z}_L^* = \tilde{T}^{-1} \tilde{C} \tilde{Z}_L \tilde{T}$
I0	$\tilde{I}_0^* = \tilde{T}^{-1} \tilde{I}_0$	$\tilde{V}_0^* = \tilde{T}^{-1} \tilde{C} \tilde{V}_0$
IL	$\tilde{I}_L^* = \tilde{T}^{-1} \tilde{I}_L$	$-\tilde{V}_L^* = -\tilde{T}^{-1} \tilde{C} \tilde{V}_L$
EP	$\tilde{E}^+ = \frac{1}{2}(\tilde{e}^{\gamma L} + \tilde{e}^{-\gamma L})$	$\tilde{E}^+ = \frac{1}{2}(\tilde{e}^{\gamma L} + \tilde{e}^{-\gamma L})$
EN	$\tilde{E}^- = \frac{1}{2}(\tilde{e}^{\gamma L} - \tilde{e}^{-\gamma L})$	$\tilde{E}^- = \frac{1}{2}(\tilde{e}^{\gamma L} - \tilde{e}^{-\gamma L})$
G	$\tilde{\Lambda} = \frac{1}{j\omega} \tilde{\gamma}$	$\tilde{\Lambda} = \frac{1}{j\omega} \tilde{\gamma}$

Cards 346 through 355 form equation (1) in Tables 2 and 3 which is solved with subroutine LEQTIC in card 359.

Cards 376 through 380 form equation (2) in Tables 2 and 3. Thus the arrays B and G contain:

<u>Arrays</u>	<u>Norton</u>	<u>Thevenin</u>
B	$\tilde{V}^*(0)$	$\tilde{I}^*(0)$
G	$\tilde{V}^*(L)$	$\tilde{I}^*(L)$

Cards 381 through 406 form $\underline{V}(0)$ and $\underline{V}(z)$ by back transforming $\underline{V}^*(0)$ and $\underline{V}^*(z)$ as described in FLATPAK using the relations in Table 2 and Table 3:

$$\begin{aligned}\underline{V}(0) &= \underline{C}^{-1} \underline{T} \underline{V}^*(0) \\ \underline{V}(z) &= \underline{C}^{-1} \underline{T} \underline{V}^*(z)\end{aligned}$$

Cards 407 through 427 print the terminal voltages.

3.5 Required Subroutines

The four programs require certain subroutines: LEQT1C, EIGCC, NROOT, and EIGEN. The individual programs require:

<u>Program</u>	<u>Required Subroutines</u>
XTALK	LEQT1C
XTALK2	LEQT1C, EIGCC
FLATPAK	LEQT1C, NROOT, EIGEN
FLATPAK2	LEQT1C, EIGCC

The required subroutines must follow the main program and precede the data cards.

3.5.1 Subroutine LEQT1C

Subroutine LEQT1C is a general subroutine for solving a system of n simultaneous, complex equations. The program is a part of the IMSL (International Mathematical and Statistical Library) package [9].

The subroutine solves the system of equations

$$\begin{matrix} A & X & = & B \\ \sim & \sim & & \sim \end{matrix} \quad (3-22)$$

where $\tilde{A}$ is an $n \times n$ complex matrix, $\tilde{B}$ is an $n \times m$ complex matrix and $\tilde{X}$ is an $n \times m$ complex matrix whose columns, $\tilde{X}_{-i}$, are solutions to

$$\tilde{A} \tilde{X}_{-i} = \tilde{B}_{-i} \quad (3-23)$$

where $\tilde{B}_{-i}$ is the i -th column of $\tilde{B}$.

The calling statement is

CALL LEQT1C(A,N,N,B,N,M,WA,IER)

where

$\tilde{A} \rightarrow A$

$\tilde{B} \rightarrow B$

$N \rightarrow n$

$M \rightarrow m$

and WA is a complex working vector of length n . IER is an error parameter which is returned as ¹

IER = 128 $\rightarrow$ no solution error

IER = 129 $\rightarrow$ $\tilde{A}$ is algorithmically singular [9].

The solution $\tilde{X}$ is returned in array B and the contents of array A are destroyed.

Subroutine LEQT1C can be used to find the inverse of an $n \times n$ matrix by computing

$$\tilde{A} \tilde{X} = \tilde{1}_n \quad (3-24)$$

where $\tilde{1}_n$ is the $n \times n$ identity matrix. Thus the solution is $\tilde{X} = \tilde{A}^{-1}$. LEQT1C

¹The solution error parameter is printed out whenever LEQT1C is used. The printed error is IER-128 so that the solution error should be 0.

is used in numerous places to invert real matrices by defining the real part of $\underline{A}$ to be the matrix and the imaginary part to be zero. Upon solution, the real part of $\underline{X}$ is the inverse of the real matrix, $\underline{A}$.

3.5.2 Subroutine EIGCC

Subroutine EIGCC is also a part of the IMSL subroutine package [9] and is used to find the eigenvalues and eigenvectors of an $n \times n$ complex matrix, $\underline{M}$. Denote the $n \times 1$ (complex) eigenvectors, $\underline{T}_i$, of $\underline{M}$ as $\underline{T}_1, \underline{T}_2, \dots, \underline{T}_n$ and the corresponding (complex) eigenvalues as $b_1, b_2, \dots, b_n$. EIGCC computes the $n \times n$ matrix $\underline{T} = [\underline{T}_1, \underline{T}_2, \underline{T}_3, \dots, \underline{T}_n]$ such that

$$\underline{T}^{-1} \underline{M} \underline{T} = \underline{B} \quad (3-25)$$

where $\underline{B}$ is an $n \times n$ diagonal matrix with $[\underline{B}]_{ii} = b_i$ and $[\underline{B}]_{ij} = 0$ for $i, j=1, \dots, n$ and $i \neq j$.

The calling statement is

CALL EIGCC(M,N,N,2,B,T,WK,IER)

where WK is a real working vector of length $2n(n+1)$. IER is an error parameter which is returned as $IER = 128 + J$.¹ This indicates that the routine failed to converge on the j -th eigenvalue [9]. The precision of the eigenvector, eigenvalue solution is returned in the first position of array WK, WK(1), and indicates [9]

Solution Precision
WK (1) < 1 → Excellent

1 < WK (1) < 100 → Good

WK (1) > 100 → Poor

¹The solution error is printed out as IER-128. A successful solution would then be indicated by 0.

The matrix $\tilde{T}$ is stored in the $n \times n$ array T and the eigenvalues, b_i , are stored in the $n \times 1$ array B in the same order as the columns of T.

3.5.3 Subroutines NROOT and EIGEN

Subroutines NROOT and EIGEN are a set of subroutines from the IBM Scientific Subroutine Package (SSP) [10] which compute the eigenvectors and eigenvalues of the matrix product

$$\tilde{B}^{-1} \tilde{A} \quad (3-26)$$

where $\tilde{A}$ and $\tilde{B}$ are $n \times n$ real, symmetric matrices and $\tilde{B}$ is positive definite. A listing of NROOT is provided in Appendix E and a listing of EIGEN is provided in Appendix F. These subroutines are used to find the eigenvalues and eigenvectors of the product of the per-unit-length capacitance, $\tilde{C}$, and inductance, $\tilde{L}$, matrices as

$$\tilde{C} \tilde{L} \quad (3-27)$$

Subroutine NROOT calls subroutine EIGEN.

NROOT computes the $n \times n$ real matrix $\tilde{T}$ such that

$$\tilde{T}^{-1} \tilde{B}^{-1} \tilde{A} \tilde{T} = \tilde{G} \quad (3-28)$$

where $\tilde{G}$ is an $n \times n$ diagonal matrix with $[\tilde{G}]_{ii} = g_i$ and $[\tilde{G}]_{ij} = 0$ for $i, j=1, \dots, n$ and $i \neq j$. The eigenvectors $\tilde{T}_i$ correspond to the eigenvalues g_i and $\tilde{T} = [\tilde{T}_1, \tilde{T}_2, \dots, \tilde{T}_n]$.

The calling statement is

CALL NROOT(N,A,B,G,T,N*N)

where

Array

A → A

B → B

N → n

G → G

T → T

The $n \times 1$ array G returns the eigenvalues g_i in the same sequence as the columns (corresponding eigenvectors) of T.

The subroutine operates in the following manner [1,11]. NROOT first computes the $n \times n$, real, orthogonal transformation matrix $\tilde{S}$ such that $(\tilde{S}^{-1} = \tilde{S}^t)$

$$\tilde{S}^t \tilde{B} \tilde{S} = \tilde{H} \quad (3-29)$$

where $\tilde{H}$ is an $n \times n$ diagonal matrix with $[\tilde{H}]_{ii} = h_i$ and $[\tilde{H}]_{ij} = 0$ for $i, j=1, \dots, n$. EIGEN is called for this calculation. Since $\tilde{B}$ is real, symmetric, positive definite, the eigenvalues of $\tilde{B}$, h_i , are real, nonzero and positive. Therefore NROOT forms the square root of $\tilde{H}$, $\tilde{H}^{1/2}$ and its inverse $\tilde{H}^{-1/2}$. NROOT then forms the products

$$\tilde{M} = \tilde{S} \tilde{H}^{-1/2} \quad (3-30)$$

and

$$\tilde{M}^t \tilde{A} \tilde{M} \quad (3-31)$$

which is real, symmetric. NROOT calls EIGEN once again to find the $n \times n$ real, orthogonal matrix $\tilde{W}$ such that $(\tilde{W}^{-1} = \tilde{W}^t)$

$$\tilde{W}^t [\tilde{M}^t \tilde{A} \tilde{M}] \tilde{W} = \tilde{G} \quad (3-32)$$

and $\tilde{G}$ is diagonal. The transformation matrix $\tilde{T}$ is given by

$$\tilde{T} = \tilde{S} \tilde{H}^{-1/2} \tilde{W} \quad (3-33)$$

To show that $\tilde{T}$ in fact diagonalizes $\tilde{B}^{-1} \tilde{A}$, form

$$\begin{aligned} \tilde{T}^{-1} \tilde{B}^{-1} \tilde{A} \tilde{T} &= \\ \tilde{W}^t \tilde{H}^{1/2} \tilde{S}^t \tilde{B}^{-1} \tilde{A} \tilde{S} \tilde{H}^{-1/2} \tilde{W} &= \\ \underbrace{\tilde{W}^t \tilde{H}^{1/2} \tilde{S}^t \tilde{B}^{-1} \tilde{S} \tilde{H}^{1/2}}_{\tilde{H}^{-1}} \underbrace{\tilde{H}^{-1/2} \tilde{S}^t \tilde{A} \tilde{S} \tilde{H}^{-1/2}}_{\tilde{M}^t \tilde{A} \tilde{M}} \tilde{W} &= \tilde{G} \end{aligned} \quad (3-34)$$

The NROOT subroutine used in the program FLATPAK and shown in Appendix G is slightly different from the NROOT subroutine given in SSP [10]. The difference is that the eigenvectors in NROOT in Appendix G are not normalized. This is required for NROOT to be used in FLATPAK so that the transformation matrix $\tilde{T}$ which diagonalizes the matrix product $\tilde{C} \tilde{L}$ as

$$\tilde{T}^{-1} \tilde{C} \tilde{L} \tilde{T} = \tilde{\gamma}^2 \quad (3-35)$$

will satisfy the identity

$$\tilde{T}^{-1} = \tilde{T}^t \tilde{C}^{-1} \quad (3-36)$$

If the columns of $\tilde{T}$ (the eigenvectors) are normalized, (3-36) will no longer be true.

IV. USER'S MANUAL

This section will serve as a user's manual for the use of the programs. All input data are punched on cards which must follow the main program (and any subroutines). The format of the data input cards as well as suggestions for program useage are included. All of the programs require three groups of data input:

Group I	{	Transmission Line Structure Characteristics Cards	}
Group II	{	Termination Network Characterization Cards Group II(a) Group II(b)	}
Group III	{	Frequency Cards	}

These card groups must follow the main program (and any required subroutines) in the above order. The data entries are either in Integer (I) format, e.g., 35, or in Exponential (E) format, e.g., 12.6E-3. All data entries must be right-justified in the assigned card column block.

In all four programs, the user must appropriately dimension all arrays for each problem. Comment cards are provided at the beginning of each program to assist the user in providing proper dimensions. All arrays must be properly dimensioned by repunching the dimension statement cards in a program before using the program.

4.1 The Frequency Cards, Group III

Each frequency card contains one and only one frequency for which an analysis is desired. The format of the frequency card is shown in Table 4. The frequency in Hertz is punched in columns 1-10 of each card and must be

TABLE 4

Format of the Frequency Group Cards, Group III

<u>frequency (Hertz)</u>	<u>card column</u> <u>1-10</u>	<u>format</u> <u>E</u>
--------------------------	-----------------------------------	---------------------------

Total number = unlimited

right justified in the card block consisting of card columns 1-10. For example, if one wished to input a frequency of 1 M Hz, one may punch

	1	.	E	6
	↑	↑	↑	↑
card columns	7	8	9	10

If, instead, the frequency was punched as

	1	.	E	6
	↑	↑	↑	↑
card columns	6	7	8	9

The program would take this to be a frequency of 10^{60} Hertz (zeros are added to fill out the assigned card block). This right-justification of data in an assigned card block applies to all other data entries.

More than one frequency card may be included in the frequency card group. Each program will process the data provided by Groups I and II and compute the response at the frequency on the first frequency card. It will then recompute the response at each frequency on the remaining frequency cards. The program assumes that the data on card Groups I and II are to be used for all the remaining frequencies. If this is not intended by the user, then one may only run the program for one frequency at a time. This feature, however, can be quite useful. If the termination networks are purely resistive, i.e., frequency independent, then one may use as many frequency cards as desired in this frequency card group and the program will compute the response of the line at each frequency without the necessity for the user to input the data in Groups I and II for each additional frequency. Many of the time-consuming calculations which are independent of frequency need to be computed

only once so that this mode of useage will save considerable computation time when the response at many frequencies is desired. If, however, the termination network characteristics (in Group II) are complex (which implies frequency dependent), one must run the program for only one frequency at a time.

4.2 The Termination Network Characterization Cards, Group II

This group of cards conveys the terminal characteristics of the termination networks at the ends of the line, $x = 0$ and $x = L$. The termination networks are characterized by either the Thevenin Equivalent or the Norton Equivalent characterization. These characterizations are of the form

$$\left. \begin{aligned} \underline{V}(0) &= \underline{V}_0 - \underline{Z}_0 \underline{I}(0) \\ \underline{V}(L) &= \underline{V}_L + \underline{Z}_L \underline{I}(L) \end{aligned} \right\} \begin{array}{l} \text{Thevenin} \\ \text{Equivalent} \end{array} \quad (4-1a)$$

$$\left. \begin{aligned} \underline{I}(0) &= \underline{I}_0 - \underline{Y}_0 \underline{V}(0) \\ \underline{I}(L) &= -\underline{I}_L + \underline{Y}_L \underline{V}(L) \end{aligned} \right\} \begin{array}{l} \text{Norton} \\ \text{Equivalent} \end{array} \quad (4-1b)$$

and are discussed in detail in section 2.3. The transmission line consists of n wires which are numbered from 1 to n and a reference conductor for the line voltages. The reference conductor is numbered as the zero (0) conductor. Thus $\underline{V}_0$, $\underline{V}_L$, $\underline{I}_0$, $\underline{I}_L$ are $n \times 1$ vectors and $\underline{Z}_0$, $\underline{Z}_L$, $\underline{Y}_0$, $\underline{Y}_L$ are $n \times n$ matrices which are assumed to be symmetric.

The impedance or admittance matrices, $\underline{Z}_0$ and $\underline{Z}_L$ or $\underline{Y}_0$ and $\underline{Y}_L$, respectively, may either be "full" in which all entries are not necessarily zero or may be diagonal in which only the entries on the main diagonals are not necessarily zero and the off-diagonal entries are zero. The user may select one of four options for communicating the entries in the vectors and matrices in

(4-1). These are:

OPTION = 11	{ Thevenin Equivalent representation; diagonal impedance matrices, $\underline{Z}_0$ and $\underline{Z}_x$. }
OPTION = 12	{ Thevenin Equivalent representation; full impedance matrices, $\underline{Z}_0$ and $\underline{Z}_x$. }
OPTION = 21	{ Norton Equivalent representation; diagonal admittance matrices, $\underline{Y}_0$ and $\underline{Y}_x$. }
OPTION = 22	{ Norton Equivalent representation; full admittance matrices, $\underline{Y}_0$ and $\underline{Y}_x$. }

The structure and ordering of the data in Group II are given in Table 5 and can be summarized in the following manner. The first group of cards in Group II, Group II(a), will describe the entries on the main diagonal in $\underline{Y}_0(\underline{Z}_0)$, $\underline{Y}_{0ii}(\underline{Z}_{0ii})$, and $\underline{Y}_x(\underline{Z}_x)$, $\underline{Y}_{xii}(\underline{Z}_{xii})$, and the entries in $\underline{I}_0(\underline{V}_0)$, $\underline{I}_{0i}(\underline{V}_{0i})$, and $\underline{I}_x(\underline{V}_x)$, $\underline{I}_{xi}(\underline{V}_{xi})$. These cards must be in the order from $i = 1$ to $i = n$. Each of these entries is in general, complex. Therefore two card blocks are assigned for each entry; one for the real part and one for the imaginary part. For example, consider a 4 conductor line (3 wires and a reference conductor). Here n would be 3. Suppose the Thevenin Equivalent characterization is selected, with the following entries in the characterization matrices:

$$\underline{V}_0 = \begin{bmatrix} 1 + j2 \\ 3 + j5 \\ 6 + j4 \end{bmatrix} \quad \underline{Z}_0 = \begin{bmatrix} 7+j8 & 0 & 0 \\ 0 & j9 & 0 \\ 0 & 0 & 10+j11 \end{bmatrix}$$

$$\underline{V}_x = \begin{bmatrix} 12 \\ j13 \\ 14+j15 \end{bmatrix} \quad \underline{Z}_x = \begin{bmatrix} 16 & 0 & 0 \\ 0 & 17+j18 & 0 \\ 0 & 0 & j19 \end{bmatrix}$$

TABLE 5 (cont.)

Format of the Termination Network Characterization Cards, Group II

<u>Group II(a) (total = n)</u>		<u>card column</u>	<u>format</u>
$Y_{0ii}(Z_{0ii})$	real part	1-10	E
	imaginary part	11-20	E
$I_{0i}(V_{0i})$	real part	21-30	E
	imaginary part	31-40	E
$Y_{\ell ii}(Z_{\ell ii})$	real part	41-50	E
	imaginary part	51-60	E
$I_{\ell i}(V_{\ell i})$	real part	61-70	E
	imaginary part	71-80	E

Note: A total of n cards must be present for an n wire line and must be arranged in the order:

wire 1

wire 2

.

.

.

wire n

TABLE 5

Group II(b) $\left(\begin{array}{l} \text{total} = n(n-1)/2 \text{ if OPTION} = 12 \text{ or } 22 \\ \text{total} = 0 \text{ if OPTION} = 11 \text{ or } 21 \end{array} \right)$

		card column	format
$Y_{0ij}(Z_{0ij})$	{ real part	1-10	E
	{ imaginary part	11-20	E
$Y_{lij}(Z_{lij})$	{ real part	41-50	E
	{ imaginary part	51-60	E

Note: If OPTION = 12 or 22, a total of $n(n-1)/2$ cards must be present and must follow Group II(a). If OPTION = 11 or 21, this card group is omitted. The cards must be arranged so as to describe the entries in the upper triangle portion of $Y_0(Z_0)$ and $Y_l(Z_l)$ by rows, i.e., the cards must contain the 12 entries, the 13 entries, ---, the 1n entries, the 23 entries, ---, the 2n entries, ---- etc. The ordering of the cards is therefore:

```

wires 1,2
wires 1,3
.
.
wires 1,n
wires 2,3
wires 2,4
.
.
wires 2,n
.
.
wires (n-1), n

```

One would have selected OPTION 11. The n=3 cards would be arranged (in this order)

Group II(a)	7.E0	8.E0	1.E0	2.E0	16.E0	0.E0	12.E0	0.E0
	↑	↑	↑	↑	↑	↑	↑	↑
	10	20	30	40	50	60	70	80
	0.E0	9.E0	3.E0	5.E0	17.E0	18.E0	0.E0	13.E0
	10.E0	11.E0	6.E0	4.E0	0.E0	19.E0	14.E0	15.E0

If the terminal impedance matrices were not diagonal, e.g., OPTION 12 is selected, then $n(n-1)/2$ additional cards, Group II(b), would follow the above n cards comprising Group II(a). These cards describe the entries in the upper triangle portion of the termination impedance or admittance matrices by rows. Suppose the networks are characterized by the same $\underline{V}_0$ and $\underline{V}_L$ vectors as above but the $\underline{Z}_0$ and $\underline{Z}_L$ matrices are

$$\underline{Z}_0 = \begin{bmatrix} 7 + j8 & 20 + j21 & 22 + j23 \\ 20 + j21 & j9 & 24 + j25 \\ 22 + j23 & 24 + j25 & 10 + j11 \end{bmatrix}$$

$$\underline{Z}_L = \begin{bmatrix} 16 & 26 + j27 & 28 \\ 26 + j27 & 17 + j18 & j29 \\ 28 & j29 & j19 \end{bmatrix}$$

The following $n(n-1)/2 = 3$ cards must follow the above 3 cards in the order of the 12 entries first, the 13 entries next and then the 23 entries:

Group II(b)	{	20.E0	21.E0			26.E0	27.E0		
		↑ 10	↑ 20			↑ 50	↑ 60		
		22.E0	23.E0			28.E0	0.E0		
		24.E0	25.E0			0.E0	29.E0		

4.3 Program XTALK

XTALK considers $(n+1)$ conductor transmission lines consisting of n wires in a lossless, homogeneous surrounding medium and a reference conductor for the line voltages. The n wires and the reference conductor are considered to be perfect (lossless) conductors. There are three choices for the reference conductor type:

TYPE = 1: The reference conductor is a wire.

TYPE = 2: The reference conductor is an infinite ground plane.

TYPE = 3: The reference conductor is an overall cylindrical shield.

Cross-sectional views of each of these three structure types are shown in Figure 4-1, 4-2 and 4-3, respectively.

For the TYPE 1 structure shown in Figure 4-1, an arbitrary rectangular coordinate system is established with the center of the coordinate system at the center of the reference conductor. The radii of all $(n+1)$ wires, r_{wi} , as well as the Z and Y coordinates of each of the n wires serve to completely describe the structure. Negative coordinate values must be input as negative data items. For example, Z_j and Y_j in Figure 4-1 would be negative numbers.

TYPE = I

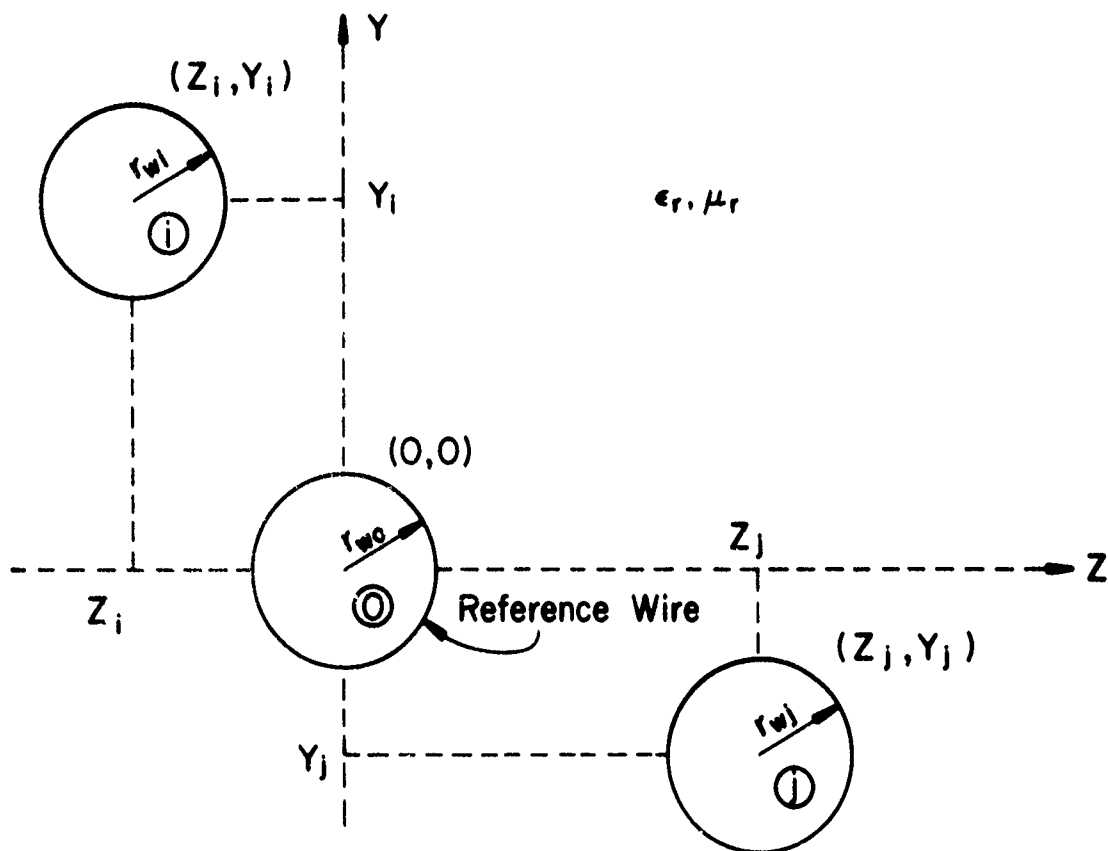


Figure 4-1. Type 1 structure.

TYPE = 2

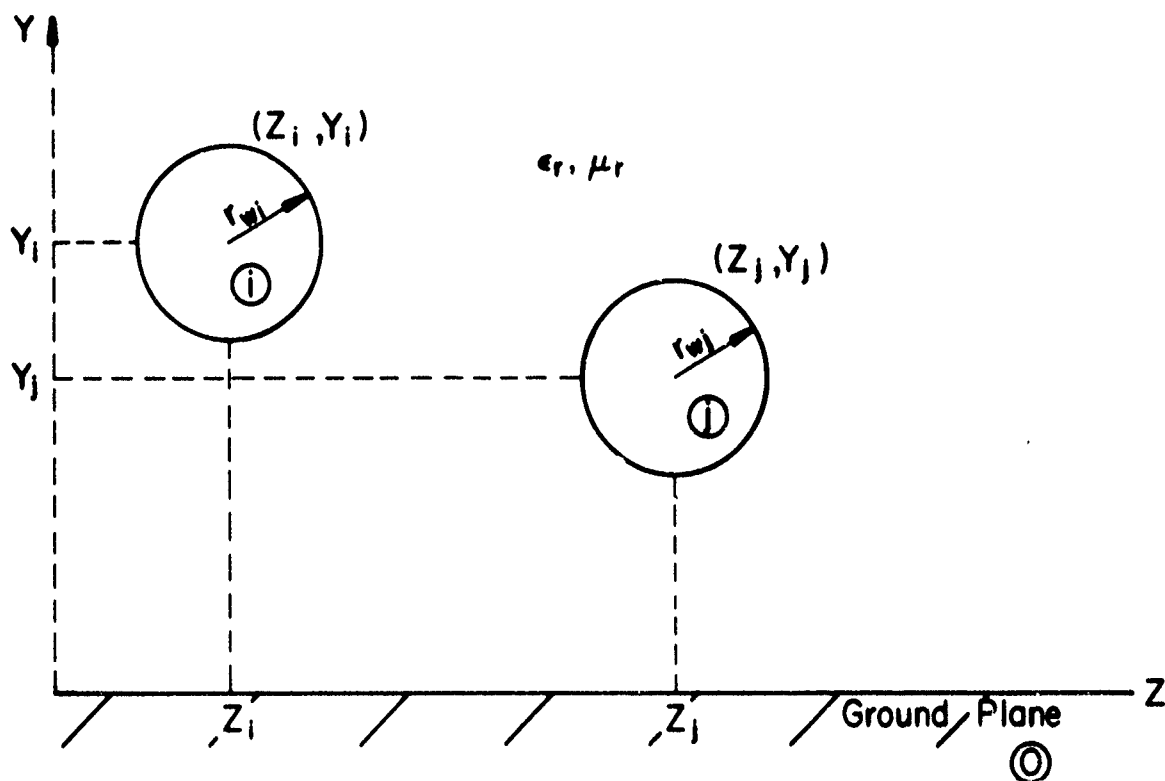


Figure 4-2. Type 2 structure.

TYPE = 3

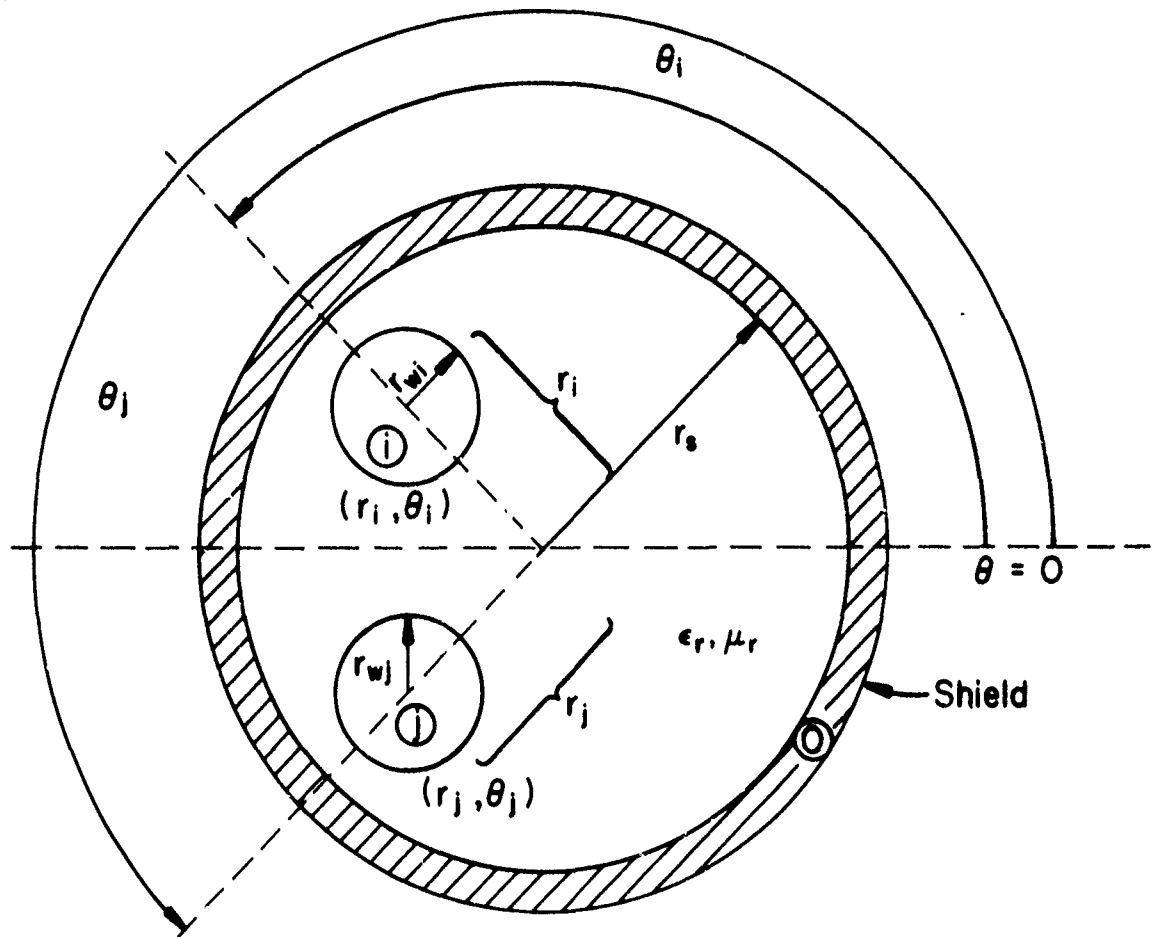


Figure 4-3. Type 3 structure.

For the TYPE 2 structure shown in Figure 4-2, an arbitrary coordinate system is established with the ground plane as the Z axis. The coordinates Y_i and Y_j (positive quantities) define the heights of the wires above the ground plane. The necessary data are the Z and Y coordinates and the radius, r_{wi} , of each wire.

For the TYPE 3 structure shown in Figure 4-3, an arbitrary angular coordinate system is established with the center of the coordinate system at the center of the shield. The necessary parameters are the radii of the wires, r_{wi} , the angular position, θ_i , and the radial position, r_i , of each wire and the interior radius of the shield, r_s .

The format of the structural characteristics cards, Group I, are shown in TABLE 6. The first card contains the structure TYPE number (1,2,or 3), the load structure OPTION number (11,12,21, or 22), the number of wires, n , the relative dielectric constant of the surrounding medium (homogeneous), ϵ_r , the relative permeability of the surrounding medium (homogeneous), μ_r , and the total length of the transmission line, L , (meters). If TYPE 1 or 3 is selected, a second card is required which contains the radius of the reference wire, r_{w0} , (mils) for TYPE 1 structures or the interior radius of the shield, r_s , (meters) for TYPE 3 structures. For TYPE 2 structures, this card is absent. These cards are followed by n cards each of which contain the radii of the wires, r_{wi} , (mils) and the Z_i and Y_i coordinates of each wire (meters) for TYPE 1 and 2 structures or the angular coordinates r_i (meters) and θ_i (degrees) of the i -th wire for TYPE 3 structures. These n cards must be arranged in the order $i = 1, i = 2, \dots, i = n$.

4.4 Program XTALK2

XTALK2 considers the same structure types as XTALK. The only difference between the programs is that XTALK2 considers imperfect conductors. This

TABLE 6

Format of the Structure Characteristics Cards, Group I, for XTALK

<u>Card Group #1 (total = 1):</u>	<u>card column</u>	<u>format</u>
(a) TYPE (1,2,3)	10	I
(b) LOAD STRUCTURE OPTION (11,12,21, or 22)	19 - 20	I
(c) n (number of wires)	29 - 30	I
(d) ϵ_r (relative dielectric constant of the surrounding medium)	36 - 45	E
(e) μ_r (relative permeability of the surrounding medium)	51 - 60	E
(f) L (line length in <u>meters</u>)	66 - 75	E
<u>Card Group #2 (total = 1 if TYPE = 1 or 3, total = 0 if TYPE = 2)</u>		
(a) TYPE = 1: r_{w0} (radius of reference wire in <u>mils</u>)	6 - 15	E
(b) TYPE = 2: absent		
(c) TYPE = 3: r_s (interior radius of shield in <u>meters</u>)	6 - 15	E
<u>Card Group #3 (total = n)</u>		
(a) r_{w1} (wire radius in <u>mils</u>)	6 - 15	E
(b) Z_i for TYPE 1 or 2 in <u>meters</u> r_i for TYPE 3 in <u>meters</u>	21 - 30	E
(c) Y_i for TYPE 1 or 2 in <u>meters</u> θ_i for TYPE 3 in <u>degrees</u>	36 - 45	E

Note: Cards in Group #3 must be arranged in the order:

wire 1
wire 2
.
.
wire n

requires an additional set of cards in Group I which must follow those in Table 6. The format of these cards is shown in Table 7.

4.5 Program FLATPAK

FLATPAK considers $(n+1)$ wire flatpak or ribbon cables as shown in Figure 4-4. The $(n+1)$ wires are considered to be perfect conductors. In addition, the surrounding media are assumed to be lossless. The required cards in the Structure Characteristics card group, Group I, are shown in Table 8.

The first card is similar to the previous programs and communicates three items to the program. The first entry on the card is the number n which is the number of wires in the cable exclusive of the reference wire. The second entry on the card is the load structure option which is to be selected from the choices 11, 12, 21, or 22 as discussed in section 3.2. The third entry on this card is the total length of the cable in meters.

Card Group 2 concerns the entries in the per-unit-length capacitance matrix, $\tilde{C}$, for the ribbon cable. Since $\tilde{C}$ is symmetric, it is only necessary to input the entries on the main diagonal of $\tilde{C}$ and the entries in the upper (or lower) triangle of $\tilde{C}$. Computer program GETCAP [8] was designed to compute these items. GETCAP has the provision for providing a punched card output of the entries in $\tilde{C}$ in the form required by FLATPAK.

A few comments are in order to assist users of GETCAP. The program is documented in Volume II of this series [8]. However, some confusion as to the wire numbering sequence in GETCAP and FLATPAK may arise. The wires in the cable are numbered from left to right with numbers from 1 to $N=n+1$ for use in the GETCAP program with the reference wire number chosen from this sequence. In the FLATPAK program, the wires are numbered from left to

TABLE 7 (Cont.)

Format of the Structure Characteristics Cards, Group I, for XTALK 2

<u>Card Group #1</u>	same as XTALK (TABLE 6)		
<u>Card Group #2</u>	same as XTALK (TABLE 6)		
<u>Card Group #3</u>	same as XTALK (TABLE 6)		
<u>Card Group #4</u> (total = 1)		<u>card column</u>	<u>format</u>
TYPE = 1: (a) radius of strands in reference wire (<u>mils</u>)		6 - 15	E
(b) conductivity of strands (<u>siemens/meter</u>)		21 - 30	E
(c) number of strands in reference wire		39 - 40	I
TYPE = 2: (a) per-unit-length resistance of ground plane (<u>ohms/meter</u>)		6 - 15	E
(b) per-unit-length inductance of ground plane (<u>henrys/meter</u>)		21 - 30	E
TYPE = 3: (a) thickness of shield (<u>meters</u>)		6 - 15	E
(b) conductivity of shield (<u>siemens/meter</u>)		21 - 30	E
<u>Card Group # 5</u> (total = n)			
(a) radius of wire strands (<u>mils</u>)		6 - 15	E
(b) conductivity of wire strands (<u>siemens/</u> <u>meter</u>)		21 - 30	E
(c) number of strands in wire		39 - 40	I

NOTE: Cards in Group #5 must be arranged for wires from 1 to n.

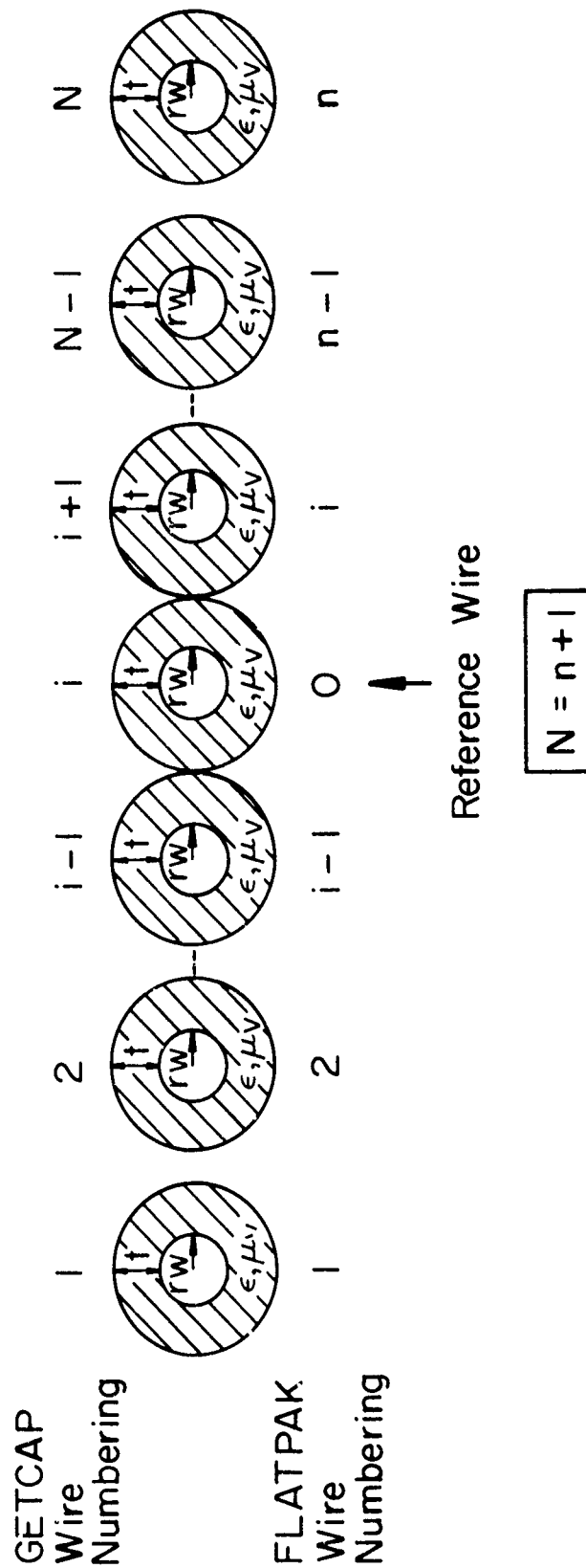


Figure 4-4. Wire numbering for ribbon (flatpack) cables.

TABLE 8

Format of the Structure Characteristics Cards, Group I, for FLATPAK

<u>Card Group #1</u> (total = 1)	<u>Card Column</u>	<u>Format</u>
(a) Number of wires (exclusive of the reference wire) (n)	9 - 10	I
(b) LOAD STRUCTURE OPTION (11,12,21, or 22)	19 - 20	I
(c) Line length (<u>meters</u>) $\mathcal{L}$	21 - 30	E
<u>Card Group #2</u> (total = $n(n+1)/2$)		
(a) i	5 - 6	I
(b) j	10 - 11	I
(c) $[C]_{ij}$ (<u>farads/meter</u>) (Entries in the per-unit-length transmission line capacitance matrix with the wire dielectric insulations in place, computed with GETCAP)	14 - 26	E
<u>Card Group #3</u> (total = $n(n+1)/2$)		
(a) i	5 - 6	I
(b) j	10 - 11	I
(c) $[C_0]_{ij}$ (<u>farads/meter</u>) (Entries in the per-unit-length transmission line capacitance matrix with the wire dielectric insulations removed, computed with GETCAP)	14 - 26	E

right with numbers from 1 to n with the reference wire numbered as the zero (0) wire as shown in Figure 4-4. Whether the cross section of the cable in Figure 4-4 is at $x=0$ looking to the right (increasing x) or at $x = L$ looking to the left (decreasing x) is irrelevant so long as the user is consistent in using the same cross section for wire numbering in GETCAP and in this program when assigning the load termination entries.

The third group of cards in Group I, Card Group #3, are the elements of the per-unit-length transmission line capacitance matrix computed with the dielectric insulations removed, C_0 . GETCAP may be used to compute these items and provide punched card output for direct use as data input for FLATPAK.

4.6 Program FLATPAK 2

FLATPAK 2 considers (n+1) wire ribbon cables as in FLATPAK. However, FLATPAK 2 considers the (n+1) wires to be imperfect (lossy) conductors.

The format of the Structure Characteristic Cards, Group I, is shown in TABLE 9. Only one additional card over those required for FLATPAK is needed. Since all wires in the cable are assumed to be identical, this card describes the characteristics of these wires for use in computing the wire self impedances.

4.7 Examples of Program Usage

In this section, some typical examples will be shown to illustrate the use of the programs. Entries on the data cards as well as typical printouts of the results will be shown.

The terminal network structures for the examples are those comprising Examples 1, 2, 3, and 4 shown in Figure 2-4 and Figure 2-5. For Examples

TABLE 9

Format of the Structure Characteristics Cards, Group I, for FLATPAK 2

	<u>Card Column</u>	<u>Format</u>
<u>Card Group #1</u>	same as FLATPAK	
<u>Card Group #2</u>	same as FLATPAK	
<u>Card Group #3</u>	same as FLATPAK	
<u>Card Group #4</u>	(total = 1)	
(a) radius of wire strands (<u>mils</u>)	6 - 15	E
(b) conductivity of wire strands (<u>siemens/meter</u>)	21 - 30	E
(c) number of strands in each wire	39 - 40	I

1 and 2, the entries in the Thevenin Equivalent characterization matrices are given in (2-32) and the entries in the Norton Equivalent characterization matrices are given in (2-35). For Examples 3 and 4, the entries in the Norton Equivalent characterization matrices are given in (2-37) and the entries in the Thevenin Equivalent characterization matrices are given in (2-38).

The terminal voltages for each wire (with respect to the reference conductor) at $x=0$ and $x=l$ are the entries in $\underline{V}(0)$ and $\underline{V}(l)$, respectively. The magnitudes and angles of the entries in $\underline{V}(0)$ ($\underline{V}(l)$) are denoted by VOM and VOA (VLM and VLA), respectively, on the computer printouts. Two frequencies will be considered, 10 MHz and 100 MHz.

4.7.1 Examples of the XTALK Program

The transmission line structure chosen for all examples in this section is that of two wires with another wire as the reference conductor. The wire radii (mils) are 6.3 mils (thousands of a inch) for wires #1 and #2 with the reference wire of radius 6.3 mils. The three wires are in a linear array with $Z_1 = 1.27$ mm, $Y_1 = 0$, $Z_2 = 2.54$ mm, $Y_2 = 0$. The line length is 5 meters and the relative dielectric constant is chosen (for the purpose of illustration) to be 3.0 with a relative permeability of 1.0.

The data cards are shown in Figure 4-5 through 4-8 and the printouts are shown in Figure 4-9 through 4-12.

4.7.2 Examples of the XTALK 2 Program

The line considered for XTALK in 4.7.1 will be used here. Each wire will be stranded, copper ($\sigma = 5.8 \times 10^7$) with 7 strands in each wire. The radius of each strand is 2.5 mils.

The data cards are shown in Figure 4-13 through 4-16 and the printouts are shown in Figure 4-17 through 4-20.

4.7.3 Examples of the FLATPAK Program

A three wire ribbon cable will be considered. The wire radii are .16002 mm, the insulation thicknesses are .3479 mm and the center-to-center separations of the wires are 1.27 mm. The insulations are polyvinyl chloride and a relative dielectric constant of 3.5 is assumed. The reference wire is the middle wire in the cable. The elements in the per-unit-length capacitance matrix (with and without the dielectric insulations) were computed with GETCAP [8].

The data cards are shown in Figure 4-21 through 4-24 and the printouts are shown in Figure 4-25 through 4-28.

4.7.4 Examples of the FLATPAK 2 Program

The three wire ribbon cable considered in the previous section with the FLATPAK program will be investigated. Each wire is stranded with 7 strands (copper) and each strand is of radius 2.5 mils.

The data cards are shown in Figure 4-29 through 4-32 and the printouts are shown in Figure 4-33 through 4-36.

XTALK									
2 PARALLEL WIRES									
TYPE OF STRUCTURE= 1									
LOAD STRUCTURE OPTION= 11									
LINE LENGTH= 5.000000 00 METERS									
DIELECTRIC CONSTANT OF THE MEDIUM= 3.0000 00									
RELATIVE PERMEABILITY OF THE MEDIUM= 1.0000 00									
REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RAD'US= 6.3000 00 MILS									
WIRE NUMBER		WIRE RADIUS (MILS)		Z COORDINATE (METERS)			Y COORDINATE (METERS)		
1		6.3000 00		1.8790-03			0.0000-01		
2		6.3000 00		2.5400-03			0.0000-01		
IMPEDANCE AT X=0				VOLTAGE SOURCE AT X=0		IMPEDANCE AT X=L		VOLTAGE SOURCE AT X=L	
(OHMS)				(VOLTS)		(OHMS)		(VOLTS)	
ENTRY		REAL	IMAG	REAL	IMAG	REAL	IMAG	REAL	IMAG
1 1		1.0000 00	0.0000-01	1.0000 00	0.0000-01	1.0000 03	0.0000-01	3.0000-01	0.0000-01
2 2		1.0000 01	0.0000-01	0.0000-01	0.0000-01	1.0000 04	0.0000-01	1.0000 00	0.0000-01
CHARACTERISTIC IMPEDANCE MATRIX INVERSION ERROR= 0									
FREQUENCY(HERTZ)= 1.00000 07 SOLUTION ERROR= 0									
WIRE		VOM(VOLTS)		VOA(DEGREES)		VLN(VOLTS)		VLA(DEGREES)	
1		0.0290-01		1.8770 06		3.51 00		-1.4790 02	
2		1.0000-01		-7.1200 01		0.35 00-01		-3.9900 01	
FREQUENCY(HERTZ)= 1.00000 08 SOLUTION ERROR= 0									
WIRE		VOM(VOLTS)		VOA(DEGREES)		VLN(VOLTS)		VLA(DEGREES)	
1		0.0010-01		0.0100-01		1.2900 00		7.0090 00	
2		0.0010-01		-0.0020 01		3.0090-02		1.0350 02	
CORE USAGE OBJECT CODE= 20336 BYTES,ARRAY AREA= 672 BYTES,TOTAL AREA AVAILABLE= 161792 BYTES									
DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 3									
COMPILE TIME= 0.54 SEC,EXECUTION TIME= 0.06 SEC, 10.44.45 TUESDAY 4 OCT 77 MATFIV - JAN 1976 VILS									

Figure 4-9. Output Listing, XTALK, Example 1.

XTALK									
2 PARALLEL WIRES									
TYPE OF STRUCTURE= 1									
LOAD STRUCTURE OPTION= 21									
LINE LENGTH= 5.000000 00 METERS									
DIELECTRIC CONSTANT OF THE MEDIUM= 5.0000 00									
RELATIVE PERMEABILITY OF THE MEDIUM= 1.0000 00									
REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS= 6.3000 00 MILS.									
WIRE NUMBER		WIRE RADIUS (MILS)		X COORDINATE (METERS)		Y COORDINATE (METERS)			
1		6.3000 00		1.2790-03		0.0000-01			
2		6.3000 00		2.5400-03		0.0000-01			
		ADMITTANCE AT X=0 (SIEMENS)		CURRENT SOURCE AT X=0 (AMPS)		ADMITTANCE AT X=L (SIEMENS)		CURRENT SOURCE AT X=L (AMPS)	
ENTRY		REAL	IMAG	REAL	IMAG	REAL	IMAG	REAL	IMAG
1 1		1.0000-00	0.0000-01	1.0000-00	0.0000-01	1.0000-03	0.0000-01	0.0000-01	0.0000-01
2 2		1.0000-01	0.0000 01	0.0000-01	0.0000-01	1.0000-04	0.0000-01	1.0000-04	0.0000-01
CHARACTERISTIC IMPEDANCE MATRIX INVERSION ERROR= 0									

FREQUENCY(HERTZ)= 1.0000E 07 SOLUTION ERROR= 0									
WIRE		VOM(VOLTS)		VOA(DEGREES)		VLM(VOLTS)		VLA(DEGREES)	
1		0.8290-01		1.8770 00		3.6100 00		-1.4760 02	
2		1.9890-01		-7.1850 01		6.7090-01		-3.9990 01	

FREQUENCY(HERTZ)= 1.0000E 08 SOLUTION ERROR= 0									
WIRE		VOM(VOLTS)		VOA(DEGREES)		VLM(VOLTS)		VLA(DEGREES)	
1		9.9810-01		4.9100-01		1.2940 00		0.0000 00	
2		9.9870-01		-8.9920 01		3.0990-02		1.0000 02	
CORE USAGE		OBJECT CODE= 20336 BYTES,ARRAY AREA=		672 BYTES,TOTAL AREA AVAILABLE=		161702 BYTES			
DIAGNOSTICS		NUMBER OF ERRORS=		0, NUMBER OF WARNINGS=		0, NUMBER OF EXTENSIONS=			
COMPILE TIME=		0.63 SEC,EXECUTION TIME=		0.07 SEC,		10.42.11		TUESDAY 4 OCT 77 WATFIV - JAN 1976 VILS	
9STOP									

Figure 4-10. Output Listing, XTALK, Example 2.

XTALK									
2 PARALLEL WIRES									
TYPE OF STRUCTURE= 1									
LOAD STRUCTURE OPTION= 22									
LINE LENGTH= 5.000000 00 METERS									
DIELECTRIC CONSTANT OF THE MEDIUM= 3.0000 00									
RELATIVE PERMEABILITY OF THE MEDIUM= 1.0000 00									
REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS= 6.3000 00 MILS									
WIRE NUMBER		WIRE RADIUS (MILS)		X COORDINATE (METERS)		Y COORDINATE (METERS)			
1		6.3000 00		1.2700-03		0.0000-01			
2		6.3000 00		2.6400-03		0.0000-01			
ADMITTANCE AT X=0			CURRENT SOURCE AT X=0		ADMITTANCE AT X=L		CURRENT SOURCE AT X=L		
(SIEMENS)			(AMPS)		(SIEMENS)		(AMPS)		
ENTRY	REAL	IMAG	REAL	IMAG	REAL	IMAG	REAL	IMAG	
1 1	0.0000-01	0.0000-01	1.0000 00	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	
2 2	0.0000-01	0.0000-01	0.0000-01	0.0000-01	4.0000-01	0.0000-01	1.0000 00	0.0000-01	
1 2	-0.0000-01	0.0000-01			-2.0000-01	0.0000-01			
CHARACTERISTIC IMPEDANCE MATRIX INVERSION ERROR= 0									
FREQUENCY(HERTZ)= 1.00000 07 SOLUTION ERROR= 0									
WIRE		VM(VOLTS)		VO(DEGREES)		VL(VOLTS)		VLA(DEGREES)	
1		2.9990 00		-7.0960-01		1.0000 00		-2.8810 00	
2		2.0000 00		-1.6090 00		2.9990 00		-6.0720-01	
FREQUENCY(HERTZ)= 1.00000 08 SOLUTION ERROR= 0									
WIRE		VM(VOLTS)		VO(DEGREES)		VL(VOLTS)		VLA(DEGREES)	
1		2.9970 00		-6.0300-01		1.0000 00		3.1790 00	
2		2.0000 00		-9.5190-01		2.9990 00		-5.0670-01	
CORE USAGE		OBJECT CODE= 20336 BYTES, ARRAY AREA= 672 BYTES, TOTAL AREA AVAILABLE= 161792 BYTES							
DIAGNOSTICS		NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 3							
COMPILE TIME=		0.60 SEC, EXECUTION TIME= 0.06 SEC, 10.41.25 TUESDAY 4 OCT 77 NATFIV - JAN 1976 VILS							
STOP									

Figure 4-12. Output Listing, XTALK, Example 4.

Figure 4-13. Input Cards, XTALK2, Example 1.

[illegible]

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Figure 4-16. Input Cards, XTALK2, Example 4.

XTALK2									
2 PARALLEL WIRES									
TYPE OF STRUCTURE= 1									
LOAD STRUCTURE OPTION= 11									
LINE LENGTH= 5.000000 00 METERS									
DIELECTRIC CONSTANT OF THE MEDIUM= 3.0000 00									
RELATIVE PERMEABILITY OF THE MEDIUM= 1.0000 00									
REFERENCE CONDUCTOR FOR LINE VOLTAGE IS A WIRE WITH RADIUS= 6.3000 00 MILS									
WIRE NUMBER	WIRE RADIUS (MILS)			Z COORDINATE (METERS)			Y COORDINATE (METERS)		
1	6.3000 00			-1.2700-93			0.0000-01		
2	6.3000 00			2.8400-03			0.0000-01		
PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0									
REFERENCE WIRE RADIUS WITH EACH STRAND OF RADIUS= 2.0000 00 MILS									
CONDUCTIVITY OF REFERENCE WIRE STRANDS= 6.0000 07 SIEMENS PER METER									
NUMBER OF STRANDS= 7									
WIRE NUMBER	WIRE STRAND RADIUS (MILS)			CONDUCTIVITY (SIEMENS PER METER)			NUMBER OF STRANDS		
1	2.0000 00			6.0000 07			7		
2	2.0000 00			6.0000 07			7		
ENTRY		IMPEDANCE AT X=0 (OHMS)		VOLTAGE SOURCE AT X=0 (VOLTS)		IMPEDANCE AT X=L (OHMS)		VOLTAGE SOURCE AT X=L (VOLTS)	
		REAL	IMAG	REAL	IMAG	REAL	IMAG	REAL	IMAG
1	1	1.0000 00	0.0000-01	1.0000 00	0.0000-01	1.0000 03	0.0000-01	0.0000-01	0.0000-01
2	2	1.0000 01	0.0000-01	0.0000-01	0.0000-01	1.0000 04	0.0000-01	1.0000 00	0.0000-01
FREQUENCY(HERTZ)= 1.00000 07 SOLUTION ERROR= 0									
EIGEN SOLUTION ERROR= 0									
EIGEN SOLUTION PRECISION= 3.4360-02									
TRANSFORMATION MATRIX INVERSION ERROR= 0									
WIRE	V0M(VOLTS)		V0A(DEGREES)		VL4(VOLTS)		VLA(DEGREES)		
1	9.8310-01		1.7380 00		3.3300 00		-1.4700 02		
2	1.8380-01		-8.2710 01		5.8760-01		-3.3380 01		
FREQUENCY(HERTZ)= 1.00000 16 SOLUTION ERROR= 0									
EIGEN SOLUTION ERROR= 0									
EIGEN SOLUTION PRECISION= 4.8160-01									
TRANSFORMATION MATRIX INVERSION ERROR= 0									
WIRE	V0M(VOLTS)		V0A(DEGREES)		VL4(VOLTS)		VLA(DEGREES)		
1	9.9760-01		4.4750-01		1.2470 00		8.1070 00		
2	4.0500-02		-7.9900 01		2.8890-02		1.0550 02		
CORE USAGE	OBJECT CODE= 59496 BYTES, ARRAY AREA= 1312 BYTES, TOTAL AREA AVAILABLE= 161792 BYTES								
DIAGNOSTICS	NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 25								
COMPILE TIME=	1.25 SEC, EXECUTION TIME= 0.12 SEC, 10.45.14 TUESDAY 4 OCT 77 MATFIV - JAN 1976 VILS								
STOP									

Figure 4-17. Output Listing, XTALK2, Example 1.

XTALK2									
2 PARALLEL WIRES									
TYPE OF STRUCTURE= 1									
LOAD STRUCTURE OPTION= 12									
LINE LENGTH= 5.000000 00 METERS									
DIELECTRIC CONSTANT OF THE MEDIUM= 3.0000 00									
RELATIVE PERMEABILITY OF THE MEDIUM= 1.0000 00									
REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS= 6.3000 00 MILS									
9									
WIRE NUMBER		WIRE RADIUS (MILS)		X COORDINATE (METERS)		Y COORDINATE (METERS)			
1		6.3000 00		1.2700-03		0.0000-01			
2		6.3000 00		2.5400-03		0.0000-01			
PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0									
REFERENCE WIRE IS STRANDED WITH EACH STRAND OF RADIUS= 2.5000 00 MILS									
CONDUCTIVITY OF REFERENCE WIRE STRANDS= 5.0000 07 SIEMENS PER METER									
NUMBER OF STRANDS= 7									
WIRE NUMBER		WIRE STRAND RADIUS (MILS)		CONDUCTIVITY (SIEMENS PER METER)		NUMBER OF STRANDS			
1		2.5000 00		5.0000 07		7			
2		2.5000 00		5.0000 07		7			
ENTRY		IMPEDANCE AT X=0 (OHMS)		VOLTAGE SOURCE AT X=0 (VOLTS)		IMPEDANCE AT X=L (OHMS)		VOLTAGE SOURCE AT X=L (VOLTS)	
		REAL		IMAG		REAL		IMAG	
1 1		3.0000 00		0.0000-01		3.0000 00		0.0000-01	
2 2		3.0000 00		0.0000-01		3.0000 00		0.0000-01	
1 2		2.0000 00		0.0000-01		2.0000 00		0.0000-01	
FREQUENCY(HERTZ)= 1.00000 07 SOLUTION ERROR= 0									
EIGEN SOLUTION ERROR= 0									
EIGEN SOLUTION PRECISION= 3.4380-02									
TRANSFORMATION MATRIX INVERSION ERROR= 0									
WIRE		V0M(VOLTS)		V0A(DEGREES)		VLM(VOLTS)		VLA(DEGREES)	
1		2.9990 00		-7.2040-01		1.0000 00		-8.8740 00	
2		2.0000 00		-1.6150 00		2.9990 00		-8.8740-01	
FREQUENCY(HERTZ)= 1.00000 00 SOLUTION ERROR= 0									
EIGEN SOLUTION ERROR= 0									
EIGEN SOLUTION PRECISION= 4.6160-03									
TRANSFORMATION MATRIX INVERSION ERROR= 0									
WIRE		V0M(VOLTS)		V0A(DEGREES)		VLM(VOLTS)		VLA(DEGREES)	
1		2.9990 00		-8.7480-01		1.0000 00		3.2740 00	
2		1.9990 00		5.2990-01		2.9990 00		-8.8740-01	
CORE USAGE OBJECT CODE= 59696 BYTES, AREA= 131 BYTES, TOTAL AREA AVAILABLE= 161792 BYTES									
DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 26									
COMPILE TIME= 1.27 SEC, EXECUTION TIME= 0.13 SEC, 10.46.26 TUESDAY 4 OCT 77 MAYFIV - JAN 1976 VILS									
STOP									

Figure 4-19. Output Listing, XTALK2, Example 3.

XTALK2									
2 PARALLEL WIRES									
TYPE OF STRUCTURE= 1									
LOAD STRUCTURE OPTION= 22									
LINE LENGTH= 5.000000 00 METERS									
DIELECTRIC CONSTANT OF THE MEDIUM= 5.0000 00									
RELATIVE PERMEABILITY OF THE MEDIUM= 1.0000 00									
REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS= 6.3000 00 MILS									
WIRE NUMBER WIRE RADIUS (MILS) X COORDINATE (METERS) Y COORDINATE (METERS)									
1 6.3000 00 1.2700-03 0.0000-01									
2 6.3000 00 2.6400-03 0.0000-01									
PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0									
REFERENCE WIRE IS 3-STRANDED WITH EACH STRAND OF RADIUS= 2.0000 00 MILS									
CONDUCTIVITY OF REFERENCE WIRE STRANDS= 5.0000 07 SIEMENS PER METER									
NUMBER OF STRANDS= 7									
WIRE NUMBER WIRE STRAND RADIUS (MILS) CONDUCTIVITY (SIEMENS PER METER) NUMBER OF STRANDS									
1 2.0000 00 5.0000 07 7									
2 2.0000 00 5.0000 07 7									
ADMITTANCE AT X=0 CURRENT SOURCE AT X=0 ADMITTANCE AT X=L CURRENT SOURCE AT X=L									
(SIEMENS) (AMPS) (SIEMENS) (AMPS)									
ENTRY REAL IMAG REAL IMAG REAL IMAG REAL IMAG									
1 1 0.0000-01 0.0000-01 1.0000 00 0.0000-01 0.0000-01 0.0000-01 0.0000-01									
2 2 0.0000-01 0.0000-01 0.0000-01 0.0000-01 4.0000-01 0.0000-01 1.0000 00 0.0000-01									
1 2 -4.0000-01 0.0000-01 -2.0000-01 0.0000-01									
FREQUENCY(HERTZ)= 1.00000 07 SOLUTION ERROR= 0									
EIGEN SOLUTION ERROR= 0									
EIGEN SOLUTION PRECISION= 3.4350-02									
TRANSFORMATION MATRIX INVERSION ERROR= 0									
WIRE V0M(VOLTS) V0A(DEGREES) V1M(VOLTS) V1A(DEGREES)									
1 2.9990 00 -7.2040-01 1.0000 00 -2.9740 00									
2 2.0000 00 -1.5180 00 2.9990 00 -0.5340-01									
FREQUENCY(HERTZ)= 1.00000 08 SOLUTION ERROR= 0									
EIGEN SOLUTION ERROR= 0									
EIGEN SOLUTION PRECISION= 4.8160-03									
TRANSFORMATION MATRIX INVERSION ERROR= 0									
WIRE V0M(VOLTS) V0A(DEGREES) V1M(VOLTS) V1A(DEGREES)									
1 2.9930 00 -8.7580-01 1.0070 00 3.2740 00									
2 1.9990 00 -5.2920-01 2.9940 00 -2.4630-01									
CORE USAGE OBJECT CODE= 59696 BYTES,ARRAY AREA= 1312 BYTES,TOTAL AREA AVAILABLE= 161792 BYTES									
DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF VARNINGS= 0, NUMBER OF EXTENSIONS= 26									
COMPILE TIME= 1.29 SEC,EXECUTION TIME= 0.13 SEC, 10.47.52 TUESDAY 6 OCT 77 MATFIV - JAN 1976 MILS									
SSTOP									


```

.....1,58.....
.....1,52.....
.....2,958.....2,958.....1,958.....2,958.....
.....2,958.....2,958.....2,958.....2,958.....2,958.....2,958.....2,958.....2,958.....
.....2,958.....2,958.....2,958.....2,958.....2,958.....2,958.....1,958.....2,958.....
C...2...2...1,5266775-11.....
C...1...2...-7,1277775-12.....
C...1...1...1,5266775-11.....
C...2...2...2,6545905-11.....
C...1...2...-6,1228815-12.....
C...1...1...2,6544905-11.....
.....2.....12.....2,958.....

```

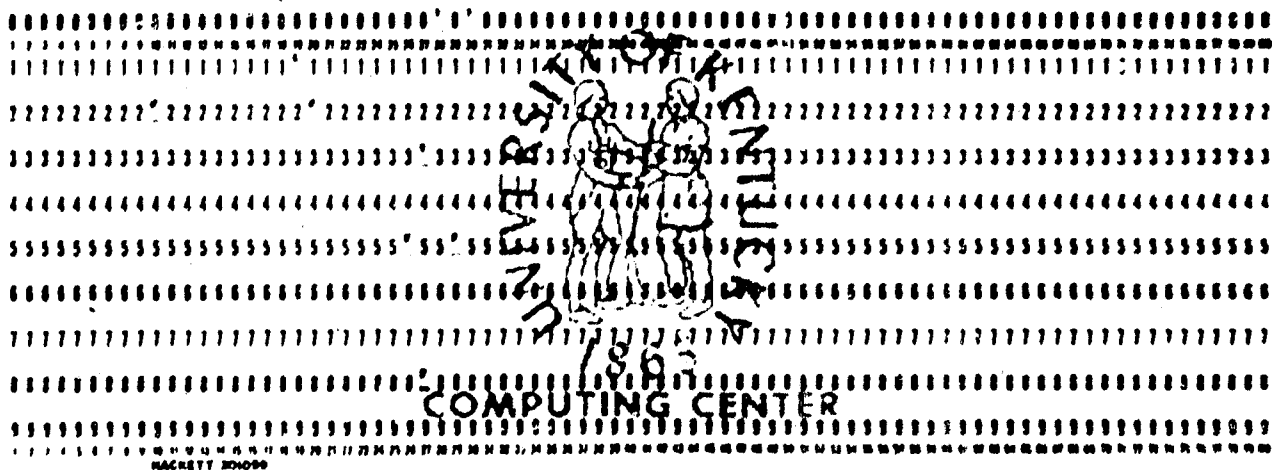


Figure 4-23. Input Cards PLATPAI, Example 1.

```

.....1,50.....
.....1,52.....
.....-9,450.....0,050.....-0,250.....0,050.....
.....0,450.....0,050.....0,050.....0,050.....0,450.....0,050.....1,050.....0,050
.....0,450.....0,050.....1,050.....0,050.....0,450.....0,050.....0,050.....0,450
C...2...2...1,7864875=-11.....
C...1...2...2,1877925=-12.....
C...1...1...1,5864875=-11.....
C...2...2...2,6548875=-11.....
C...1...2...-6,1229945=-16.....
C...1...1...2,6544875=-11.....
.....2.....2.....5,050.....

```

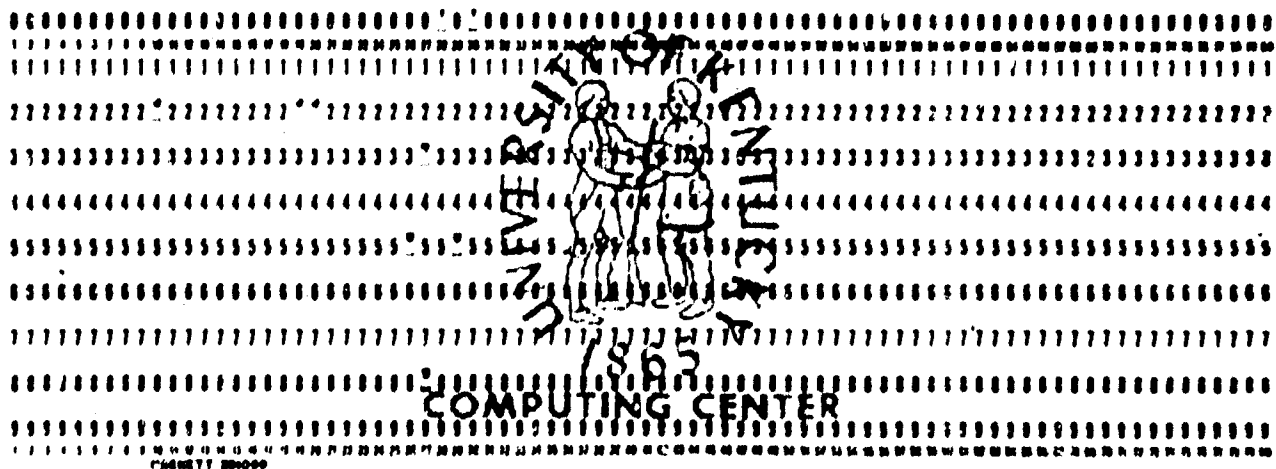


Figure 4-24. Input Cards, FLATPAK, Example 4.

FLATPAK									
3 PARALLEL WIRES									
LINE LENGTH= 3.000000 00 METERS									
LOAD STRUCTURE OPTION= 11									
TRANSFORMATION MATRIX INVERSION ERROR= 9									

Figure 4-25. Output Listing, FLATPAK, Example 1.

FLATPAK									
1 W/ALLEN WIRES									
LINE LENGTH= 5.000000 00 METERS									
LOAD STRUCTURE OPTION= 21									
		ADMITTANCE AT X=0 (SIEMENS)		CURRENT SOURCE AT X=0 (AMPS)		ADMITTANCE AT X=L (SIEMENS)		CURRENT SOURCE AT X=L (AMPS)	
ENTRY		REAL	IMAG	REAL	IMAG	REAL	IMAG	REAL	IMAG
1	1	1.0000 00	0.0000-01	1.0000 00	0.0000-01	1.0000-03	0.0000-01	0.0000-01	0.0000-01
2	2	1.0000-01	0.0000-01	0.0000-01	0.0000-01	1.0000-04	0.0000-01	1.0000-04	0.0000-01

FREQUENCY(HERTZ)= 1.00000 07					SOLUTION ERROR= 0				
WIRE		VMM(VOLTS)	VMA(DEGREES)		VLM(VOLTS)		VLA(DEGREES)		
1		9.8360-01	-8.0690-01		3.8970 00		-8.3730 01		
2		7.2070-07	1.1960 02		1.5780 00		-1.0690 02		

FREQUENCY(HERTZ)= 1.00000 08					SOLUTION ERROR= 0				
WIRE		VMM(VOLTS)	VMA(DEGREES)		VLM(VOLTS)		VLA(DEGREES)		
1		9.9910-01	-8.0690-02		2.9890-01		-1.3210 02		
2		6.6690-02	9.2290 01		1.5470 00		-1.7710 02		

CORE USAGE= 23402 BYTES,ARRAY AREA= 664 BYTES,TOTAL AREA AVAILABLE= 161702 BYTES									
DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF WARNING= 0, NUMBER OF EXTENSIONS= 3									
COMPILE TIME= 1.07 SEC,EXECUTION TIME= 0.05 SEC, 15.24.20 TUESDAY 4 JUL 77 DAYTIV - JAN 1976 VILB									
STOP									

Figure 4-26. Output Listing, FLATPAK, Example 2.

FLATPAK									
3 PARALLEL WIRES									
LINE LENGTH= 5.00000000 METERS									
LOAD STRUCTURE OPTION= 12									
TRANSPORTATION MATRIX INVERSION ERROR= 0									
ENTRY		IMPEDANCE AT X=0 (OHMS)		VOLTAGE SOURCE AT X=0 (VOLTS)		IMPEDANCE AT X=L (OHMS)		VOLTAGE SOURCE AT X=L (VOLTS)	
		REAL	IMAG	REAL	IMAG	REAL	IMAG	REAL	IMAG
1	1	3.0000 00	0.0000-01	3.0000 00	0.0000-01	2.0000 00	0.0000-01	1.0000 00	0.0000-01
2	2	3.0000 00	0.0000-01	2.0000 00	0.0000-01	3.0000 00	0.0000-01	3.0000 00	0.0000-01
1	2	2.0000 00	0.0000-01			1.0000 00	0.0000-01		

FREQUENCY (HERTZ)= 1.00000 07		SOLUTION ERROR= 0			
WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)	
1	2.9990 00	-8.4990-01	1.0000 00	-2.0390 00	
2	2.0000 00	-1.3170 00	2.9990 00	-5.3170-01	

FREQUENCY (HERTZ)= 1.00000 08		SOLUTION ERROR= 0			
WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)	
1	2.9990 00	-1.3170 00	1.0000 00	-3.9830 00	
	2.0000 00	-2.9480 00	2.9970 00	-9.1020-01	

CORE USAGE	OBJECT CODE=	23992 BYTES, ARRAY AREA=	664 BYTES, TOTAL AREA AVAILABLE=	161792 BYTES
DIAGNOSTICS	NUMBER OF ERRORS=	0, NUMBER OF WARNINGS=	0, NUMBER OF EXTENSIONS=	3
COMPILE TIME=	0.52 SEC, EXECUTION TIME=	0.05 SEC,	10.26.52	TUESDAY 4 OCT 77 WATPIV - JAN 1976 VILS
ASTOP				

Figure 4-27. Output Listing, FLATPAK, Example 3.

FLATPAK															
3 PARALLEL WIRES															
LINE LENGTH= 9.000000D 00 METERS															
LOAD STRUCTURE OPTION= 22															
ADMITTANCE AT X=0 (SIEMENS)				CURRENT SOURCE AT X=0 (AMPS)				ADMITTANCE AT X=L (SIEMENS)				CURRENT SOURCE AT X=L (AMPS)			
ENTRY		REAL	IMAG	REAL		IMAG		REAL		IMAG		REAL		IMAG	
1	1	0.0000-01	0.0000-01	1.0000 00	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01
2	2	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	0.0000-01	1.0000 00	0.0000-01	0.0000-01	0.0000-01
1	2	-4.0000-01	0.0000-01					-2.0000-01	0.0000-01	0.0000-01	0.0000-01				

FREQUENCY(HERTZ)= 1.00000 07						SOLUTION ERROR= 0					
WIRE		V01(VOLTS)		V01(DEGREES)		V02(VOLTS)		V02(DEGREES)			
1		2.9990 00	-8.4280-01	1.0000 00	-8.0380 00						
2		2.0000 00	-1.3370 00	2.0000 00	-8.3170-01						

FREQUENCY(HERTZ)= 1.00000 08						SOLUTION ERROR= 0					
WIRE		V01(VOLTS)		V01(DEGREES)		V02(VOLTS)		V02(DEGREES)			
1		2.9990 00	-1.3870 00	1.0010 00	-3.9830 00						
2		2.0000 00	-2.9450 00	2.0070 00	-9.1020-01						
CORE USAGE OBJECT CODE= 23692 BYTES, ARRAY AREA= 664 BYTES, TOTAL AREA AVAILABLE= 121702 BYTES											
DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 3											
COMPILE TIME= 0.07 SEC, EXECUTION TIME= 0.00 SEC, 10.29.16 TUESDAY 4 OCT 77 WATPIV - JAN 1978 VILS											
STOP											

Figure 4-28. Output Listing, FLATPAK, Example 4.

Figure 4-30. Input Cards, FLATPAK2, Example 2.

FLATPAK2									
7 PARALLEL WIRES									
LINE LENGTH= 9.000000 00 METERS									
LOAD STRUCTURE OPTION= 11									
PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0									
PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0									
WIRES ARE STRANDED WITH EACH STRAND OF RADIUS= 9.0000 00 MILS									
CONDUCTIVITY OF WIRE STRANDS= 9.0000 07 SIEMENS PER METER									
NUMBER OF STRANDS= 7									

Figure 4-33. Output Listing, FLATPAK2, Example 1.

PLATPAK2

3 PARALLEL WIRES

LINE LENGTH= 5.000000 00 METERS

LOAD STRUCTURE OPTION= 21

PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0

PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0

WIRES ARE STRANDED WITH EACH STRAND OF RADIUS= 2.5000 00 MILS

CONDUCTIVITY OF WIRE STRANDS= 5.8000 07 SIEMENS PER METER

NUMBER OF STRANDS= 7

		ADMITTANCE AT X=0		CURRENT SOURCE AT X=0		ADMITTANCE AT X=L		CURRENT SOURCE AT X=L	
		(SIEMENS)		(AMPS)		(SIEMENS)		(AMPS)	
ENTRY		REAL	IMAG	REAL	IMAG	REAL	IMAG	REAL	IMAG
1	1	1.0000 00	0.0000-01	1.0000 00	0.0000-01	1.0000-03	0.0000-01	0.0000-01	0.0000-01
2	2	1.0000-01	0.0000-01	0.0000-01	0.0000-01	1.0000-04	0.0000-01	1.0000-01	0.0000-01

FREQUENCY (HERTZ)= 1.00000 07 SOLUTION ERROR= 0

EIGEN SOLUTION ERROR= 0

EIGEN SOLUTION PRECISION= 1.2460-02

TRANSFORMATION MATRIX INVERSION ERROR= 0

WIRE	VOL(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	9.6370-01	-7.6170-01	3.7920 00	-8.6180 01
2	7.7490-02	1.1560 02	1.0130 00	-1.1330 02

FREQUENCY (HERTZ)= 1.00000 08 SOLUTION ERROR= 0

EIGEN SOLUTION ERROR= 0

EIGEN SOLUTION PRECISION= 8.4180-03

TRANSFORMATION MATRIX INVERSION ERROR= 0

WIRE	VOL(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	9.9880-01	-6.0460-02	2.4210-01	-1.1730 02
2	0.5090-02	9.1440 01	1.5080 00	-1.7700 02

CORE USAGE OBJECT CODE= 53296 BYTES, ARRAY AREA= 1296 BYTES, TOTAL AREA AVAILABLE= 161792 BYTES

DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 25

COMPILE TIME= 1.32 SEC, EXECUTION TIME= 0.11 SEC, 10.33.30 TUESDAY 4 OCT 77 WATFIV - JAN 1976 V1L6

STOP

Figure 4-34. Output Listing, FLATPAK2, Example 2.

FLATPAK2									
3 PARALLEL WIRES									
LINE LENGTH= 5.000000 00 METERS									
LOAD STRUCTURE OPTION= 12									
PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0									
PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0									
WIRES ARE STRANDED WITH EACH STRAND OF RADIUS= 2.0000 00 MILS									
CONDUCTIVITY OF WIRE STRANDS= 5.0000 07 SIEMENS PER METER									
NUMBER OF STRANDS= 7									

Figure 4-35. Output Listing, FLATPAK2, Example 3.

FLATPAK2									
3 PARALLEL WIRES									
LINE LENGTH= 3.000000 00 METERS									
LOAD STRUCTURE OPTION= 22									
PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0									
PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0									
WIRES ARE STRANDED WITH EACH STRAND OF RADIUS= 2.8000 00 MILS									
CONDUCTIVITY OF WIRE STRANDS= 5.8000 07 SIEMENS PER METER									
NUMBER OF STRANDS= 7									

Figure 4-36. Output Listing, FLATPAK2, Example 4.

V. SUMMARY

Four digital computer programs, XTALK, XTALK 2, FLATPAK, FLATPAK 2, for determining the electromagnetic coupling within an $(n+1)$ conductor, uniform transmission line are presented. Sinusoidal steady state behavior of the line as well as the TEM or "quasi-TEM" mode of propagation are assumed.

XTALK and XTALK 2 consider lines consisting of n wires (cylindrical conductors) and a reference conductor. The surrounding medium is homogeneous and lossless. XTALK assumes that all $(n+1)$ conductors are perfect conductors whereas XTALK 2 considers the conductors to be lossy. There are three choices for the reference conductor: a wire, a ground plane, an overall cylindrical shield.

FLATPAK and FLATPAK 2 consider $(n+1)$ wire ribbon (flatpack) cables in which all wires are identical and are coated with cylindrical, dielectric insulations of identical thicknesses. All wires lie in a horizontal plane and all adjacent wires are separated by identical distances. FLATPAK considers the wires to be perfect conductors and FLATPAK 2 considers the wires to be lossy. The dielectric insulations are considered to be lossless.

General termination networks are provided for at the ends of the line and the programs compute the voltages (with respect to the reference conductor) at the terminals of these termination networks for sinusoidal steady state excitation of the line.

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APPENDICES

APPENDIX A

XTALK

Program Listing

```

C*****XTALK001
C                                     XTALK002
C      PROGRAM XTALK                 XTALK003
C      (FORTRAN IV, DOUBLE PRECISION) XTALK004
C      WRITTEN BY                     XTALK005
C      CLAYTON R. PAUL               XTALK006
C      DEPARTMENT OF ELECTRICAL ENGINEERING XTALK007
C      UNIVERSITY OF KENTUCKY         XTALK008
C      LEXINGTON, KENTUCKY 40506     XTALK009
C                                     XTALK010
C      A DIGITAL COMPUTER PROGRAM TO COMPUTE THE TERMINAL VOLTAGES XTALK011
C      (WITH RESPECT TO THE REFERENCE CONDUCTOR) AT THE ENDS OF A XTALK012
C      MULTICONDUCTOR TRANSMISSION LINE FOR THE TEN MODE OF XTALK013
C      PROPAGATION.                  XTALK014
C                                     XTALK015
C      THE DISTRIBUTED PARAMETER, MULTICONDUCTOR TRANSMISSION LINE XTALK016
C      EQUATIONS ARE SOLVED FOR STEADY STATE, SINUSOIDAL EXCITATION XTALK017
C      OF THE LINE.                  XTALK018
C                                     XTALK019
C      THE LINE CONSISTS OF N WIRES (CYLINDRICAL CONDUCTORS) AND A XTALK020
C      REFERENCE CONDUCTOR. THE REFERENCE CONDUCTOR MAY BE A WIRE XTALK021
C      (TYPE=1), AN INFINITE GROUND PLANE (TYPE=2), OR AN OVERALL XTALK022
C      CYLINDRICAL SHIELD (TYPE=3)  XTALK023
C                                     XTALK024
C      THE N WIRES ARE ASSUMED TO BE PARALLEL TO EACH OTHER AND THE XTALK025
C      REFERENCE CONDUCTOR.         XTALK026
C                                     XTALK027
C      THE N WIRES AND THE REFERENCE CONDUCTOR ARE ASSUMED TO BE XTALK028
C      PERFECT CONDUCTORS.          XTALK029
C                                     XTALK030
C      THE LINE IS IMMERSSED IN A LINEAR, ISOTROPIC, AND HOMOGENEOUS XTALK031
C      MEDIUM WITH A RELATIVE PERMEABILITY OF  $\mu_0$  AND A RELATIVE XTALK032
C      DIELECTRIC CONSTANT OF  $\epsilon_0$ . THE MEDIUM IS ASSUMED TO BE LOSSLESS. XTALK033
C                                     XTALK034
C      LOAD STRUCTURE OPTION DEFINITIONS: XTALK035
C      OPTION=11,THEVENIN EQUIVALENT LOAD STRUCTURES WITH DIAGONAL XTALK036
C      IMPEDANCE MATRICES           XTALK037
C      OPTION=12,THEVENIN EQUIVALENT LOAD STRUCTURES WITH FULL XTALK038
C      IMPEDANCE MATRICES           XTALK039
C      OPTION=21,NORTON EQUIVALENT LOAD STRUCTURES WITH DIAGONAL XTALK040
C      ADMITTANCE MATRICES          XTALK041
C      OPTION=22,NORTON EQUIVALENT LOAD STRUCTURES WITH FULL XTALK042
C      ADMITTANCE MATRICES          XTALK043
C                                     XTALK044
C      SUBROUTINES USED: LEQT1C     XTALK045
C                                     XTALK046
C*****XTALK047
C      ALL VECTORS AND MATRICES IN THE FOLLOWING DIMENSION STATEMENTS XTALK048
C      SHOULD BE OF SIZE N WHERE N IS THE NUMBER OF WIRES (EXCLUSIVE OF XTALK049
C      THE REFERENCE CONDUCTOR), I. E., IO(N), IL(N), YO(N,N), YL(N,N), B(N), XTALK050
C      A(N,N), WA(N), M1(N,N), M2(N,N), V1(N), V2(N) XTALK051
C                                     XTALK052
C      IMPLICIT REAL*8 (A-H,O-Z)    XTALK053
C      INTEGER TYPE,OPTION          XTALK054
C      REAL*8 L,MUO2PI,MUR          XTALK055
C      COMPLEX*16 XJ,IO( 2),IL( 2),YO( 2, 2),YL( 2, 2),A( 2, 2),B( 2), XTALK056
C      WA( 2),M1( 2, 2),M2( 2, 2),V1( 2),V2( 2),SUMO,SUML,VO,VL,ZEROC, XTALK057
C      2C,A1,A2,ONEC               XTALK058
C      DATA PI/3.141592653D0/,V/2.997925D8/ XTALK059
C      DATA CMTH/2.54D-5/,MUO2PI/2.D-7/,P5/.5D0/,ZERO/0.D0/,ONE/1.D0/, XTALK060
C                                     XTALK061

```

1TWO/2.D0//,FOUR/4.D0//,ONE80/180.D0/	XTALK062
ONEC=DCMPLX(1.D0,0.D0)	XTALK063
ZEROC=DCMPLX(0.D0,0.D0)	XTALK064
ZJ=DCMPLX(0.D0,1.D0)	XTALK065
C	XTALK066
C*****FREQUENCY INDEPENDENT CALCULATIONS*****	XTALK067
C	XTALK068
C READ AND PRINT INPUT DATA	XTALK069
C	XTALK070
READ(5,1) TYPE,OPTION,N,ER,MUR,L	XTALK071
1 FORMAT(9X,I',2(8X,I2),3(5X,E10.3))	XTALK072
IF (TYPE.GE.1.AND.TYPE.LE.3) GO TO 3	XTALK073
WRITE(6,2)	XTALK074
2 FORMAT(' STRUCTURE TYPE ERROR'// ' TYPE MUST EQUAL 1,2,OR 3'///)	XTALK075
GO TO 82	XTALK076
3 IF (OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 5	XTALK077
IF (OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 5	XTALK078
WRITE(6,4)	XTALK079
4 FORMAT(' LOAD STRUCTURE OPTION ERROR'// ' OPTION MUST EQUAL 11,12,21,OR 22'///)	XTALK080
GO TO 82	XTALK081
5 WRITE(6,6) N,TYPE,OPTION,L,ER,MUR	XTALK082
6 FORMAT(1H1,50X,'XTALK'///	XTALK083
145X,I2,' PARALLEL WIRES'///	XTALK084
243X,' TYPE OF STRUCTURE= ',I1///	XTALK085
341X,' LOAD STRUCTURE OPTION= ',I2///	XTALK086
439X,' LINE LENGTH= ',1PE13.6,' METERS'///	XTALK087
532X,' DIELECTRIC CONSTANT OF THE MEDIUM= ',1PE10.3///	XTALK088
631X,' RELATIVE PERMEABILITY OF THE MEDIUM= ',1PE10.3///)	XTALK089
GO TO (7,15,11),TYPE	XTALK090
7 READ(5,8) RWO	XTALK091
8 FORMAT(5X,E10.3)	XTALK092
WRITE(6,9) RWO	XTALK093
9 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS	XTALK094
1US= ',1PE10.3,' MILS'///)	XTALK095
RWO=RWO*CHT	XTALK096
WRITE(6,10)	XTALK097
10 FORMAT(' WIRE NUMBER',4X,'WIRE RADIUS (MILS)',18X,	XTALK098
1'Z COORDINATE (METERS)',24X,'Y COORDINATE (METERS)',//)	XTALK099
GO TO 19	XTALK100
11 READ(5,12) RS	XTALK101
12 FORMAT(5X,E10.3)	XTALK102
WRITE(6,13) RS	XTALK103
13 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A CYLINDRICAL OV	XTALK104
1ERALL SHIELD WITH INTERIOR RADIUS= ',1PE10.3,' METERS'///)	XTALK105
RS2=RS*RS	XTALK106
WRITE(6,14)	XTALK107
14 FORMAT(' WIRE NUMBER',2X,'WIRE RADIUS (MILS)', 2X,'SEPAFATION BETW	XTALK108
1EEN WIRE AND CENTER OF SHIELD (METERS)',6X,'ANGULAR COORDINATE (DE	XTALK109
2GREES)'//)	XTALK110
GO TO 18	XTALK111
15 WRITE(6,16)	XTALK112
16 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS AN INFINITE GROU	XTALK113
1ND PLANE'///)	XTALK114
WRITE(6,17)	XTALK115
17 FORMAT(' WIRE NUMBER',4X,'WIRE RADIUS (MILS)',18X,	XTALK116
1'HORIZO AL COORDINATE (METERS)',16X,'WIRE HEIGHT (METERS)',//)	XTALK117
C	XTALK118
C READ AND PRINT LINE DIMENSIONS AND COMPUTE THE CHARACTERISTIC	XTALK119
C IMPEDANCE MATRIX, ZC (STORE ZC IN ARRAY M1)	XTALK120
C	XTALK121
	XTALK122

18	C=HUG2*PI*ONEC*V*DSQRT(MUR/ER)	XTALK123
	DO 24 I=1,N	XTALK124
	READ(5,19) RW,Z,Y	XTALK125
19	FORMAT(3(5X,E10.3))	XTALK126
	WRITE(6,20) I,RW,Z,Y	XTALK127
20	FORMAT(2X,I2,13X,1PE10.3,27X,1PE10.3,35X,1PE10.3/)	XTALK128
	V1(I)=ONEC*Z	XTALK129
	V2(I)=ONEC*Y	XTALK130
	RW=RW*CHTN	XTALK131
	GO TO (21,22,23),TYPE	XTALK132
21	DI2=Z*Z+Y*Y	XTALK133
	H1(I,I)=C*DLOG(DI2/(RW*RW0))	XTALK134
	GO TO 24	XTALK135
22	H1(I,I)=C*DLOG(TWO*Y/RW)	XTALK136
	GO TO 24	XTALK137
23	H1(I,I)=C*DLOG((RS2-Z*Z)/(RS*RW))	XTALK138
24	CONTINUE	XTALK139
	IF(M.EQ.1) GO TO 29	XTALK140
	K1=M-1	XTALK141
	DO 28 I=1,K1	XTALK142
	K2=I+1	XTALK143
	DO 28 J=K2,M	XTALK144
	ZI=DREAL(V1(I))	XTALK145
	ZJ=DREAL(V1(J))	XTALK146
	YI=DREAL(V2(I))	XTALK147
	YJ=DREAL(V2(J))	XTALK148
	GO TO (25,26,27),TYPE	XTALK149
25	DI2=ZI*ZI+YI*YI	XTALK150
	DJ2=ZJ*ZJ+YJ*YJ	XTALK151
	ZD=ZI-ZJ	XTALK152
	YD=YI-YJ	XTALK153
	DIJ2=ZD*ZD+YD*YD	XTALK154
	H1(I,J)=P5*C*DLOG(DI2*DJ2/(RW0*RW0*DIJ2))	XTALK155
	H1(J,I)=H1(I,J)	XTALK156
	GO TO 28	XTALK157
26	ZD=ZI-ZJ	XTALK158
	YD=YI-YJ	XTALK159
	DIJ2=ZD*ZD+YD*YD	XTALK160
	H1(I,J)=P5*C*DLOG(ONE+FOUR*YI*YJ/DIJ2)	XTALK161
	H1(J,I)=H1(I,J)	XTALK162
	GO TO 28	XTALK163
27	THETA=(YI-YJ)*PI/ONE80	XTALK164
	RI2=ZI*ZI	XTALK165
	RJ2=ZJ*ZJ	XTALK166
	H1(I,J)=P5*C*DLOG((RJ2/RS2)*(RI2*RJ2+RS2*RS2-TWO*ZI*ZJ*RS2*DCOS(THETA))/(RI2*RJ2+RJ2*RJ2-TWO*ZI*ZJ*RJ2*DCOS(THETA)))	XTALK167
	H1(J,I)=H1(I,J)	XTALK168
28	CONTINUE	XTALK169
		XTALK170
C	COMPUTE THE INVERSE OF THE CHARACTERISTIC IMPEDANCE MATRIX, ZCINV	XTALK171
C	(STORE ZCINV IN ARRAY M2)	XTALK172
C		XTALK173
	29 DO 31 I=1,N	XTALK174
	DO 30 J=1,N	XTALK175
	A(I,J)=H1(I,J)	XTALK176
30	M2(I,J)=ZEROC	XTALK177
31	M2(I,I)=ONEC	XTALK178
	CALL LEQT1C(A,N,N,M2,N,N,0,WA,KER)	XTALK179
	KER=KER-128	XTALK180
C		XTALK181
C	READ AND PRINT ENTRIES IN LOAD ADMITTANCE(IMPEDANCE) MATRICES	XTALK182
		XTALK183

C	AND SHORT CIRCUIT CURRENT SOURCE (OPEN CIRCUIT VOLTAGE SOURCE)	XTALK184
C	VECTORS (STORE ADMITTANCE (IMPEDANCE) MATRICES AT X=0 IN ARRAY Y0	XTALK185
C	AND THOSE AT X=L IN ARRAY YL. STORE SHORT CIRCUIT CURRENT SOURCE	XTALK186
C	(OPEN CIRCUIT VOLTAGE SOURCE) VECTORS AT X=0 IN ARRAY I0 AND	XTALK187
C	THOSE AT X=L IN ARRAY IL.)	XTALK188
C		XTALK189
	IF (OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 34	XTALK190
	WRITE(6,32)	XTALK191
32	FORMAT(/,18X,'ADMITTANCE AT X=0',30X,'CURRENT SOURCE AT X=0',	XTALK192
	112X,'ADMITTANCE AT X=L',10X,'CURRENT SOURCE AT X=L'/)	XTALK193
	WRITE(6,33)	XTALK194
33	FORMAT(21X,' (SIEMENS) ',23X,' (AMPS) ',22X,' (SIEMENS) ',23X,' (AMPS) ')/	XTALK195
	GO TO 37	XTALK196
34	WRITE(6,35)	XTALK197
35	FORMAT(/,18X,'IMPEDANCE AT X=0',11X,'VOLTAGE SOURCE AT X=0',	XTALK198
	112X,'IMPEDANCE AT X=L',11X,'VOLTAGE SOURCE AT X=L'/)	XTALK199
	WRITE(6,36)	XTALK200
36	FORMAT(23X,' (OHMS) ',23X,' (VOLTS) ',24X,' (OHMS) ',23X,' (VOLTS) ')/	XTALK201
37	WRITE(6,38)	XTALK202
38	FORMAT(' ENTRY',10X,'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG',11X,	XTALK203
	1'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG'//)	XTALK204
	DO 41 I=1,N	XTALK205
	READ(5,39) Y0I,Y0I,I0(I),YLI,YLI,IL(I)	XTALK206
39	FORMAT(8(E10.3))	XTALK207
	Y0(I,I)=Y0I+XJ*Y0I	XTALK208
	YL(I,I)=YLI+XJ*YLI	XTALK209
	WRITE(6,40) I,I,Y0(I,I),I0(I),YL(I,I),IL(I)	XTALK210
40	FORMAT(1X,I2,2X,I2,8(5X,1PE10.3)/)	XTALK211
41	CONTINUE	XTALK212
	IF (OPTION.EQ.11.OR.OPTION.EQ.21) GO TO 45	XTALK213
	IF (N.EQ.1) GO TO 45	XTALK214
	DO 44 I=1,K1	XTALK215
	K2=I+1	XTALK216
	DO 45 J=K2,N	XTALK217
	READ(5,42) Y0I,Y0I,YLI,YLI	XTALK218
42	FORMAT(2(E10.3),20X,2(E10.3))	XTALK219
	Y0(I,J)=Y0I+XJ*Y0I	XTALK220
	YL(I,J)=YLI+XJ*YLI	XTALK221
	Y0(J,I)=Y0(I,J)	XTALK222
	YL(J,I)=YL(I,J)	XTALK223
	WRITE(6,43) I,J,Y0(I,J),YL(I,J)	XTALK224
43	FORMAT(1X,I2,2X,I2,2(5X,1PE10.3),30X,2(5X,1PE10.3))	XTALK225
44	CONTINUE	XTALK226
C		XTALK227
C	IF THEVENIN EQUIVALENT IS SPECIFIED, SWAP ENTRIES IN N1 AND N2.	XTALK228
C	N1 WILL CONTAIN ZCINV AND N2 WILL CONTAIN ZC.	XTALK229
C		XTALK230
45	IF (OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 48	XTALK231
	DO 47 I=1,N	XTALK232
	DO 46 J=1,N	XTALK233
	A1=N1(I,J)	XTALK234
	A2=N2(I,J)	XTALK235
	N1(I,J)=A2	XTALK236
	N1(J,I)=A2	XTALK237
	N2(I,J)=A1	XTALK238
46	N2(J,I)=A1	XTALK239
47	IL(I)=-IL(I)	XTALK240
C		XTALK241
C	COMPUTE THE MATRIX ZC+ZL*ZCINV*Z0 FOR THE THEVENIN EQUIVALENT	XTALK242
C	OR ZCINV+YL*ZC*Y0 FOR THE NORTON EQUIVALENT. STORE IN ARRAY N2.	XTALK243
C	COMPUTE THE MATRIX ZCINV*Z0 FOR THE THEVENIN EQUIVALENT OR	XTALK244

C	ZC*Y0 FOR THE NORTON EQUIVALENT. STORE IN ARRAY N1.	XTALK245
C	COMPUTE THE VECTOR ZL*ZCINV*V0 FOR THE THEVENIN EQUIVALENT OR	XTALK246
C	YL*ZC*IO FOR THE NORTON EQUIVALENT. STORE IN ARRAY V2.	XTALK247
C	COMPUTE THE VECTOR ZCINV*V0 FOR THE THEVENIN EQUIVALENT OR	XTALK248
C	ZC*IO FOR THE NORTON EQUIVALENT. STORE IN ARRAY V1.	XTALK249
C		XTALK250
	48 IF (OPTION.EQ.12.OR.OPTION.EQ.22) GO TO 54	XTALK251
	DO 50 I=1,N	XTALK252
	SUM0=ZEROC	XTALK253
	DO 49 J=1,N	XTALK254
	A(I,J)=N1(I,J)*Y0(J,J)	XTALK255
	49 SUM0=SUM0+N1(I,J)*IO(J)	XTALK256
	50 V1(I)=SUM0	XTALK257
	DO 52 I=1,N	XTALK258
	DO 51 J=1,N	XTALK259
	51 N2(I,J)=YL(I,I)*A(I,J)+N2(I,J)	XTALK260
	52 V2(I)=YL(I,I)*V1(I)	XTALK261
	DO 53 I=1,N	XTALK262
	DO 53 J=1,N	XTALK263
	53 N1(I,J)=A(I,J)	XTALK264
	GO TO 62	XTALK265
	54 DO 57 I=1,N	XTALK266
	SUM0=ZEROC	XTALK267
	DO 56 J=1,N	XTALK268
	SUML=ZEROC	XTALK269
	DO 55 K=1,N	XTALK270
	55 SUML=SUML+N1(I,K)*Y0(K,J)	XTALK271
	SUM0=SUM0+N1(I,J)*IO(J)	XTALK272
	56 A(I,J)=SUML	XTALK273
	57 V1(I)=SUM0	XTALK274
	DO 60 I=1,N	XTALK275
	SUM0=ZEROC	XTALK276
	DO 59 J=1,N	XTALK277
	SUML=ZEROC	XTALK278
	DO 58 K=1,N	XTALK279
	58 SUML=SUML+YL(I,K)*A(K,J)	XTALK280
	N2(I,J)=SUML+N2(I,J)	XTALK281
	59 SUM0=SUM0+YL(I,J)*V1(J)	XTALK282
	60 V2(I)=SUM0	XTALK283
	DO 61 I=1,N	XTALK284
	DO 61 J=1,N	XTALK285
	61 N1(I,J)=A(I,J)	XTALK286
	62 BL=TWO*PI*DSQRT(MUR*ER)*L/V	XTALK287
	IF (KER.NE.1) KER=0	XTALK288
	WRITE(6,63) KER	XTALK289
	63 FORMAT (//, ' CHARACTERISTIC IMPEDANCE MATRIX INVERSION ERROR= ',I2	XTALK290
	1//)	XTALK291
C		XTALK292
C	C*****FREQUENCY DEPENDENT CALCULATIONS*****XTALK293	XTALK293
C		XTALK294
	64 CONTINUE	XTALK295
	READ(5,65,END=82) F	XTALK296
	65 FORMAT (E10.3)	XTALK297
	BETAL=BL*F	XTALK298
	DS=DSIN(BETAL)	XTALK299
	DC=DCOS(BETAL)	XTALK300
C		XTALK301
C	COMPUTE THE TERMINAL VOLTAGES	XTALK302
C		XTALK303
C	FORM THE EQUATIONS	XTALK304
C		XTALK305

IF (OPTION.EQ.12.OR.OPTION.EQ.22) GO TO 68	XTALK306
DO 67 I=1,N	XTALK307
DO 66 J=1,N	XTALK308
66 A(I,J)=XJ*DS*M2(I,J)	XTALK309
A(I,I)=DC*(Y0(I,I)+YL(I,I))+A(I,I)	XTALK310
67 B(I)=DC*I0(I)+XJ*DS*V2(I)+IL(I)	XTALK311
GO TO 71	XTALK312
68 DO 70 I=1,N	XTALK313
DO 69 J=1,N	XTALK314
69 A(I,J)=XJ*DS*M2(I,J)+DC*(Y0(I,J)+YL(I,J))	XTALK315
70 B(I)=DC*I0(I)+XJ*DS*V2(I)+IL(I)	XTALK316
C SOLVE THE EQUATIONS	XTALK317
71 CALL LEQ1C(A,N,N,B,1,N,0,WA,IER)	XTALK318
IER=IER-128	XTALK319
IF (IER.NE.1) IER=0	XTALK320
WRITE(5,72) F,IER	XTALK321
72 FORMAT(1H1,' FREQUENCY (HERTZ)= ',1PE11.4,10X,' SOLUTION ERROR= ',	XTALK322
12X,I2///)	XTALK323
WRITE(6,73)	XTALK324
73 FORMAT(16X,' WIRE',8X,' VOM (VOLTS) ',3X,' VOA (DEGREES) ',8X,	XTALK325
' VLM (VOLTS) ',3X,' VLA (DEGREES) '///)	XTALK326
C COMPUTE AND PRINT THE TERMINAL VOLTAGES	XTALK327
DO 75 I=1,N	XTALK328
SUM0=ZEROC	XTALK329
DO 74 J=1,N	XTALK330
74 SUM0=SUM0+M1(I,J)*B(J)	XTALK331
75 WA(I)=XJ*DS*(SUM0-V1(I))+DC*B(I)	XTALK332
DO 81 I=1,N	XTALK333
IF (OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 76	XTALK334
V0=B(I)	XTALK335
VL=WA(I)	XTALK336
GO TO 79	XTALK337
76 IF (OPTION.EQ.12) GO TO 77	XTALK338
V0=I0(I)-Y0(I,I)*B(I)	XTALK339
VL=-IL(I)+YL(I,I)*WA(I)	XTALK340
GO TO 79	XTALK341
77 SUM0=ZEROC	XTALK342
SUML=ZEROC	XTALK343
DO 78 J=1,N	XTALK344
SUM0=SUM0+Y0(I,J)*B(J)	XTALK345
78 SUML=SUML+YL(I,J)*WA(J)	XTALK346
V0=I0(I)-SUM0	XTALK347
VL=-IL(I)+SUML	XTALK348
79 VOM=CDABS(V0)	XTALK349
VLM=CDABS(VL)	XTALK350
VOR=DREAL(V0)	XTALK351
VOI=DIMAG(V0)	XTALK352
VLR=DREAL(VL)	XTALK353
VLI=DIMAG(VL)	XTALK354
IF (VOR.EQ.ZERO.AND.VOI.EQ.ZERO) VOR=CNE	XTALK355
IF (VLR.EQ.ZERO.AND.VLI.EQ.ZERO) VLR=CNE	XTALK356
VOA=DATAN2(VOI,VOR)*ONE80/PI	XTALK357
VLA=DATAN2(VLI,VLR)*ONE80/PI	XTALK358
WRITE(6,80) I,VOM,VOA,VLM,VLA	XTALK359
80 FORMAT(17X,I2,8X,1PE10.3,3X,1PE10.3,10X,1PE10.3,3X,1PE10.3/)	XTALK360
81 CONTINUE	XTALK361
GO TO 64	XTALK362
	XTALK363
	XTALK364
	XTALK365
	XTALK366

82 STOP
END

XTALK367
XTALK368

TABLE A-1

Changes in XTALK to Convert
to Single Precision Arithmetic

Delete Card 054

<u>Card Number</u>		<u>Double</u>		<u>Single</u>
056		REAL *8		REAL
057		COMPLEX *16		COMPLEX
060		3.141592653D0		3.1415926E0
060		2.997925D8		2.997925E8
061-062	change all	D's	to	E's
063		DCMPLX(1.D0,0.D0)		CMPLX(1.E0,0.E0)
064		DCMPLX(0.D0,0.D0)		CMPLX(0.E0,0.E0)
065		DCMPLX(0.D0,1.D0)		CMPLX(0.E0,1.E0)
123		DSQRT		SQRT
134		DLOG		ALOG
136		DLOG		ALOG
138		DLOG		ALOG
145		DREAL		REAL
146		DREAL		REAL
147		DREAL		REAL
148		DREAL		REAL
155		DLOG		ALOG
161		DLOG		ALOG
167		DLOG		ALOG
168		DCOS		COS
168		DCOS		COS

<u>Card Number</u>	<u>Double</u>	<u>Single</u>
287	DSQRT	SQRT
299	DSIN	SIN
300	DCOS	COS
353	CDABS	CABS
354	CDABS	CABS
355	DREAL	REAL
356	DIMAG	AIMAG
357	DREAL	REAL
358	DIMAG	AIMAG
361	DATAN2	ATAN2
362	DATAN2	ATAN2

APPENDIX B

XTALK2

Program Listing

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C*****XTALK001
C                                     XTALK002
C      PROGRAM XTALK2                 XTALK003
C      (FORTRAN IV, DOUBLE PRECISION) XTALK004
C      WRITTEN BY                     XTALK005
C      CLAYTON R. PAUL                XTALK006
C      DEPARTMENT OF ELECTRICAL ENGINEERING XTALK007
C      UNIVERSITY OF KENTUCKY          XTALK008
C      LEXINGTON, KENTUCKY 40506      XTALK009
C                                     XTALK010
C      A DIGITAL COMPUTER PROGRAM TO COMPUTE THE TERMINAL VOLTAGES XTALK011
C      (WITH RESPECT TO THE REFERENCE CONDUCTOR) AT THE ENDS OF A XTALK012
C      MULTICONDUCTOR TRANSMISSION LINE FOR THE TEM MODE OF XTALK013
C      PROPAGATION.                   XTALK014
C                                     XTALK015
C      THE DISTRIBUTED PARAMETERS, MULTICONDUCTOR TRANSMISSION LINE XTALK016
C      EQUATIONS ARE SOLVED FOR STEADY STATE, SINUSOIDAL EXCITATION XTALK017
C      OF THE LINE.                   XTALK018
C                                     XTALK019
C      THE LINE CONSISTS OF N WIRES (CYLINDRICAL CONDUCTORS) AND A XTALK020
C      REFERENCE CONDUCTOR. THE REFERENCE CONDUCTOR MAY BE A WIRE XTALK021
C      (TYPE=1), AN INFINITE GROUND PLANE (TYPE=2), OR AN OVERALL XTALK022
C      CYLINDRICAL SHIELD (TYPE=3).   XTALK023
C                                     XTALK024
C      THE N WIRES ARE ASSUMED TO BE PARALLEL TO EACH OTHER AND THE XTALK025
C      REFERENCE CONDUCTOR.           XTALK026
C                                     XTALK027
C      THE N WIRES AND THE REFERENCE CONDUCTOR ARE CONSIDERED TO BE XTALK028
C      IMPERFECT CONDUCTORS. THE SELF IMPEDANCES OF EACH WIRE AND THE XTALK029
C      REFERENCE CONDUCTOR INCLUDE SKIN EFFECT. XTALK030
C                                     XTALK031
C      THE LINE IS IMMERSED IN A LINEAR, ISOTROPIC, AND HOMOGENEOUS XTALK032
C      MEDIUM WITH A RELATIVE PERMEABILITY OF  $\mu_{R}$  AND A RELATIVE XTALK033
C      DIELECTRIC CONSTANT OF  $\epsilon_{R}$ . THE MEDIUM IS ASSUMED TO BE LOSSLESS. XTALK034
C                                     XTALK035
C      LOAD STRUCTURE OPTION DEFINITIONS: XTALK036
C      OPTION=11,THEVENIN EQUIVALENT LOAD STRUCTURES WITH DIAGONAL XTALK037
C      IMPEDANCE MATRICES              XTALK038
C      OPTION=12,THEVENIN EQUIVALENT LOAD STRUCTURES WITH FULL XTALK039
C      IMPEDANCE MATRICES              XTALK040
C      OPTION=21,NORTON EQUIVALENT LOAD STRUCTURES WITH DIAGONAL XTALK041
C      ADMITTANCE MATRICES             XTALK042
C      OPTION=22,NORTON EQUIVALENT LOAD STRUCTURES WITH FULL XTALK043
C      ADMITTANCE MATRICES             XTALK044
C                                     XTALK045
C      SUBROUTINES USED: LEQ1C,EIGCC   XTALK046
C                                     XTALK047
C*****XTALK048
C                                     XTALK049
C      ALL VECTORS AND MATRICES IN THE FOLLOWING DIMENSION STATEMENTS XTALK050
C      SHOULD BE OF SIZE N WHERE N IS THE NUMBER OF WIRES (EXCLUSIVE OF XTALK051
C      THE REFERENCE CONDUCTOR), I. E., NS(N),C(N,N),Z(N),Y(N),CI(N,N), XTALK052
C      IO(N),IL(N),YO(N,N),YL(N,N),B(N),A(N,N),P(N,N),EN(N),EP(N), XTALK053
C      N1(N,N),N2(N,N),V1(N),V2(N),T(N,N),TI(N,N),G(N),V3(N),WA(N) XTALK054
C      THE VECTOR WK MUST BE OF LENGTH 2N(N+1) XTALK055
C                                     XTALK056
C      IMPLICIT REAL*8 (A-H,O-Z)      XTALK057
C      INTEGER TYPE,OPTION,NS( 2)    XTALK058
C      REAL*8 L,LDC,LGP,C( 2, 2),Z( 2),Y( 2),CI( 2, 2),V3( 2),WK( 12), XTALK059
C      1NU02PI,NU04PI,NU08PI,MUR     XTALK060
C      COMPLEX*16 XJ,SUM0,SUML,S0,SL,V0,VL,Z0,EPP,BNN,GAM,JOMEGA XTALK061

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1,IO(2),IL(2),YO(2, 2),YL(2, 2),B(2),A(2, 2),WA(2),G(2),	XTALK062
2P(2, 2),EP(2),EN(2),M1(2, 2),M2(2, 2),V1(2),V2(2),	XTALK063
3T(2, 2),TI(2, 2),ZEROC,ONEC	XTALK064
DATA PI/3.141592653D0/,V/2.997925D8/	XTALK065
DATA CMTN/2.54D-5/,MUO2PI/2.D-7/,TWO/2.D0/,P5/.5D0/,ONE/1.D0/	XTALK066
1FOUR/4.D0/,ONE80/180.D0/,ZERO/0.D0/,MUO8PI/.5D-7/,MUO4PI/1.D-7/	XTALK067
2THREE/3.D0/,P25/.25D0/,ONEP15/1.15D0/,P15/.15D0/,P4/.4D0/	XTALK068
VV=V*V	XTALK069
ZEROC=DCHPLX(0.D0,0.D0)	XTALK070
ONEC=DCHPLX(1.D0,0.D0)	XTALK071
XJ=DCHPLX(0.D0,1.D0)	XTALK072
C	XTALK073
C*****FREQUENCY INDEPENDENT CALCULATIONS*****	XTALK074
C	XTALK075
C READ AND PRINT INPUT DATA	XTALK076
C	XTALK077
READ(5,1) TYPE,OPTION,N,ER,MUR,L	XTALK078
1 FORMAT(9X,I1,2(8X,I2),3(5X,E10.3))	XTALK079
IF(TYPE.GE.1.AND.TYPE.LE.3) GO TO 3	XTALK080
WRITE(6,2)	XTALK081
2 FORMAT(' STRUCTURE TYPE ERROR'//' TYPE MUST EQUAL 1,2,OR 3'///)	XTALK082
GO TO 121	XTALK083
3 IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 5	XTALK084
IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 5	XTALK085
WRITE(6,4)	XTALK086
4 FORMAT(' LOAD STRUCTURE OPTION ERROR'//' OPTION MUST EQUAL 11,12,21,OR 22'///)	XTALK087
GO TO 121	XTALK088
5 WRITE(6,6) N,TYPE,OPTION,L,ER,MUR	XTALK089
6 FORMAT(1H1,50X,'XTALK2'///	XTALK090
145X,I2,' PARALLEL WIRES'///	XTALK091
243X,' TYPE OF STRUCTURE= ',I1///	XTALK092
341X,' LOAD STRUCTURE OPTION= ',I2///	XTALK093
439X,' LINE LENGTH= ',1PE13.6,' METERS'///	XTALK094
532X,' DIELECTRIC CONSTANT OF THE MEDIUM= ',1PE10.3///	XTALK095
631X,' RELATIVE PERMEABILITY OF THE MEDIUM= ',1PE10.3///)	XTALK096
GO TO (7,15,11),TYPE	XTALK097
7 READ(5,8) RWO	XTALK098
8 FORMAT(5X,E10.3)	XTALK099
WRITE(6,9) RWC	XTALK100
9 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADI	XTALK101
1US= ',1PE10.3,' MILS'///)	XTALK102
RWO=RWO*CMTN	XTALK103
WRITE(6,10)	XTALK104
10 FORMAT(' WIRE NUMBER',4X,'WIRE RADIUS (MILS)',18X,	XTALK105
1'Z COORDINATE (METERS)',24X,'Y COORDINATE (METERS)',//)	XTALK106
GO TO 18	XTALK107
11 READ(5,12) RS	XTALK108
12 FORMAT(5X,E10.3)	XTALK109
WRITE(6,13) RS	XTALK110
13 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A CYLINDRICAL OV	XTALK111
1ERALL SHIED WITH INTERIOR RADIUS= ',1PE10.3,' METERS'////)	XTALK112
RS2=RS*RS	XTALK113
WRITE(6,14)	XTALK114
14 FORMAT(' WIRE NUMBER',2X,'WIRE RADIUS (MILS)', 2X,'SEPARATION BETW	XTALK115
11EEN WIRE AND CENTER OF SHIELD (METERS)',6X,'ANGULAR COORDINATE (DE	XTALK116
2GREES)'//)	XTALK117
GO TO 18	XTALK118
15 WRITE(6,16)	XTALK119
16 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS AN INFINITE GROU	XTALK120
1ND PLANE'////)	XTALK121
	XTALK122

	WRITE(6,17)	XTALK123
	17 FORMAT(' WIRE NUMBER',4X,'WIRE RADIUS (MILS)',10X,	XTALK124
	1'HORIZONTAL COORDINATE (METERS)',16X,'WIRE HEIGHT (METERS)',//)	XTALK125
C		XTALK126
C	READ AND PRINT LINE DIMENSIONS AND COMPUTE THE INVERSE OF THE	XTALK127
C	PER-UNIT-LENGTH CAPACITANCE MATRIX,CINV	XTALK128
C	(STORE CINV IN ARRAY CI)	XTALK129
C		XTALK130
	18 D=HWO2PI*VV/ER	XTALK131
	DO 24 I=1,N	XTALK132
	READ(5,19) RW,Z(I),Y(I)	XTALK133
	19 FORMAT(3(5X,E10.3))	XTALK134
	WRITE(6,20) I,RW,Z(I),Y(I)	XTALK135
	20 FORMAT(2X,I2,13X,1PE10.3,27X,1PE10.3,35X,1PE10.3/)	XTALK136
	RW=RW*CHIN	XTALK137
	GO TO (21,22,23),TYPE	XTALK138
	21 DI2=Z(I)*Z(I)+Y(I)*Y(I)	XTALK139
	CI(I,I)=D*DLOG(DI2/(RW*RW0))	XTALK140
	GO TO 24	XTALK141
	22 CI(I,I)=D*DLOG(TWO*Y(I)/RW)	XTALK142
	GO TO 24	XTALK143
	23 CI(I,I)=D*DLOG((RS2-Z(I)*Z(I))/(RS*RW))	XTALK144
	24 CONTINUE	XTALK145
	IF(N.EQ.1) GO TO 29	XTALK146
	K1=N-1	XTALK147
	DO 28 I=1,K1	XTALK148
	K2=I+1	XTALK149
	DO 28 J=K2,N	XTALK150
	GO TO (25,26,27),TYPE	XTALK151
	25 DI2=Z(I)*Z(I)+Y(I)*Y(I)	XTALK152
	DJ2=Z(J)*Z(J)+Y(J)*Y(J)	XTALK153
	ZD=Z(I)-Z(J)	XTALK154
	YD=Y(I)-Y(J)	XTALK155
	DIJ2=ZD*ZD+YD*YD	XTALK156
	CI(I,J)=P5*D*DLOG(DI2*DJ2/(RW0*RW0*DIJ2))	XTALK157
	CI(J,I)=CI(I,J)	XTALK158
	GO TO 28	XTALK159
	26 ZD=Z(I)-Z(J)	XTALK160
	YD=Y(I)-Y(J)	XTALK161
	DIJ2=ZD*ZD+YD*YD	XTALK162
	CI(I,J)=P5*D*DLOG(ONE+FOUR*Y(I)*Y(J)/DIJ2)	XTALK163
	CI(J,I)=CI(I,J)	XTALK164
	GO TO 28	XTALK165
	27 THETA=(Y(I)-Y(J))*PI/ONE80	XTALK166
	RI2=Z(I)*Z(I)	XTALK167
	RJ2=Z(J)*Z(J)	XTALK168
	CI(I,J)=P5*D*DLOG((RJ2/RS2)*{RI2*RJ2+RS2*RS2-TWO*Z(I)*Z(J)*RS2*	XTALK169
	1DCOS(THETA)})/(RI2*RJ2+RJ2*RJ2-TWO*Z(I)*Z(J)*RJ2*DCOS(THETA)))	XTALK170
	CI(J,I)=CI(I,J)	XTALK171
	28 CONTINUE	XTALK172
C		XTALK173
C	COMPUTE THE PER-UNIT-LENGTH CAPACITANCE MATRIX,C	XTALK174
C	(STORE C IN ARRAY C)	XTALK175
C		XTALK176
	29 DO 31 I=1,N	XTALK177
	DO 30 J=1,N	XTALK178
	A(I,J)=CI(I,J)*ONEC	XTALK179
	30 P(I,J)=ZEROC	XTALK180
	31 P(I,I)=ONEC	XTALK181
	CALL LEQY1C(A,N,N,P,N,N,0,WA,KER)	XTALK182
	KER=KER-128	XTALK183

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IF (KER.NE.1) KER=0
WRITE(6,32) KER
32 FORMAT(//,' PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= ',
1I2//)
DO 33 I=1,N
DO 33 J=1,N
33 C(I,J)=DREAL(P(I,J))

C
C READ AND PRINT CHARACTERISTICS OF THE WIRES AND THE REFERENCE
C CONDUCTOR TO BE USED IN THE SELF IMPEDANCE CALCULATIONS
C
GO TO (34,40,37),TYPE
34 READ(5,35) RWS0,SIG0,WS0
35 FORMAT(2(5X,E10.3),8X,I2)
WRITE(6,36) RWS0,SIG0,WS0
36 FORMAT(///// 'REFERENCE WIRE IS STRANDED WITH EACH STRAND OF RADIUS
1= ',1PE10.3,' MILS'/// 'CONDUCTIVITY OF REFERENCE WIRE STRANDS= ',
21PE10.3,' SIEMENS PER METER'/// 'NUMBER OF STRANDS= ',I2////)
RWS0=RWS0*CHTN
GO TO 43
37 READ(5,38) TH,SIG0
38 FORMAT(2(5X,E10.3))
WRITE(6,39) TH,SIG0
39 FORMAT(///// 'SHIELD THICKNESS= ',1PE10.3,' METERS'/// 'SHIELD CONDUC
1CTIVITY= ',1PE10.3,' SIEMENS PER METER'////)
GO TO 43
40 READ(5,41) RGP,LGP
41 FORMAT(2(5X,E10.3))
WRITE(6,42) RGP,LGP
42 FORMAT(///// 'GROUND PLANE RESISTANCE= ',1PE10.3,' OHMS PER METER'
1/// 'GROUND PLANE INDUCTANCE= ',1PE10.3,' HENRYS PER METER'////)
43 WRITE(6,44)
44 FORMAT(///// 'WIRE NUMBER',4X,'WIRE STRAND RADIUS (MILS)',18X,
1'CONDUCTIVITY (SIEMENS PER METER)',10X,'NUMBER OF STRANDS'//)
DO 47 I=1,N
READ(5,45) Z(I),Y(I),WS(I)
45 FORMAT(2(5X,E10.3),8X,I2)
WRITE(6,46) I,Z(I),Y(I),WS(I)
46 FORMAT(2X,I2,16X,1PE10.3,35X,1PE10.3,32X,I2/)
47 Z(I)=Z(I)*CHTN

C
C READ AND PRINT ENTRIES IN LOAD ADMITTANCE(IMPEDANCE) MATRICES
C AND SHORT CIRCUIT CURRENT SOURCE(OPEN CIRCUIT VOLTAGE SOURCE)
C VECTORS.
C (STORE ADMITTANCE(IMPEDANCE) MATRICES AT X=0 IN ARRAY Y0 AND
C THOSE AT X=L IN ARRAY YL. STORE SHORT CIRCUIT CURRENT SOURCE
C (OPEN CIRCUIT VOLTAGE SOURCE) VECTORS AT X=0 IN ARRAY I0 AND
C THOSE AT X=L IN ARRAY IL.)
C
IF (OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 50
WRITE(6,48)
48 FORMAT(//,18X,'ADMITTANCE AT X=0',10X,'CURRENT SOURCE AT X=0',
112X,'ADMITTANCE AT X=L',10X,'CURRENT SOURCE AT X=L'//)
WRITE(6,49)
49 FORMAT(21X,' (SIEMENS) ',23X,' (AMPS) ',22X,' (SIEMENS) ',23X,' (AMPS)'//)
GO TO 53
50 WRITE(6,51)
51 FORMAT(//,18X,'IMPEDANCE AT X=0',11X,'VOLTAGE SOURCE AT X=0',
112X,'IMPEDANCE AT X=L',11X,'VOLTAGE SOURCE AT X=L'//)
WRITE(6,52)
52 FORMAT(23X,' (OHMS) ',23X,' (VOLTS) ',23X,' (OHMS) ',23X,' (VOLTS)'//)

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XTALK184
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53 WRITE(6,54)	XTALK245
54 FORMAT(' ENTRY',10X,'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG',11X,	XTALK246
1'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG'//)	XTALK247
DO 57 I=1,N	XTALK248
READ(5,55) YOR,YOI,I0(I),YLR,YLI,IL(I)	XTALK249
55 FORMAT(8(E10.3))	XTALK250
Y0(I,I)=YOR+XJ*YOI	XTALK251
YL(I,I)=YLR+XJ*YLI	XTALK252
WRITE(6,56) I,I,Y0(I,I),I0(I),YL(I,I),IL(I)	XTALK253
56 FORMAT(1X,I2,2X,I2,8(5X,1PE10.3)/)	XTALK254
57 CONTINUE	XTALK255
IF(OPTION.EQ.1..OR.OPTION.EQ.21) GO TO 61	XTALK256
IF(N.EQ.1) GO TO 61	XTALK257
DO 60 I=1,K1	XTALK258
K2=I+1	XTALK259
DO 60 J=K2,N	XTALK260
READ(5,58) YCR,YOI,YLR,YLI	XTALK261
58 FORMAT(2(E10.3),20X,2(E10.3))	XTALK262
Y0(I,J)=YOR+XJ*YOI	XTALK263
YL(I,J)=YLR+XJ*YLI	XTALK264
Y0(J,I)=Y0(I,J)	XTALK265
YL(J,I)=YL(I,J)	XTALK266
WRITE(6,59) I,J,Y0(I,J),YL(I,J)	XTALK267
59 FORMAT(1X,I2,2X,I2,2(5X,1PE10.3),30X,2(5X,1PE10.3))	XTALK268
60 CONTINUE	XTALK269
C	XTALK270
C COMPUTE THE MATRICES C*Y0,C*YL,C*Y0,C*YL FOR THE THEVENIN	XTALK271
C EQUIVALENT OR Y0*CINV,YL*CINV,I0,IL, FOR THE NORTON EQUIVALENT AND	XTALK272
C STORE IN ARRAYS M1,M2,V1,V2, RESPECTIVELY.	XTALK273
61 IF(OPTION.EQ.11) GO TO 62	XTALK274
IF(OPTION.EQ.12) GO TO 65	XTALK275
IF(OPTION.EQ.21) GO TO 69	XTALK276
IF(OPTION.EQ.22) GO TO 72	XTALK277
62 DO 64 I=1,N	XTALK278
S0=ZEROC	XTALK279
SL=ZEROC	XTALK280
DO 63 J=1,N	XTALK281
M1(I,J)=C(I,J)*Y0(J,J)	XTALK282
M2(I,J)=C(I,J)*YL(J,J)	XTALK283
S0=S0+C(I,J)*I0(J)	XTALK284
63 SL=SL+C(I,J)*IL(J)	XTALK285
V1(I)=S0	XTALK286
64 V2(I)=SL	XTALK287
GO TO 76	XTALK288
65 DO 68 I=1,N	XTALK289
S0=ZEROC	XTALK290
SL=ZEROC	XTALK291
DO 67 J=1,N	XTALK292
SUM0=ZEROC	XTALK293
SUPL=ZEROC	XTALK294
DO 66 K=1,N	XTALK295
SUM0=SUM0+C(I,K)*Y0(K,J)	XTALK296
66 SUML=SUML+C(I,K)*YL(K,J)	XTALK297
S0=S0+C(I,J)*I0(J)	XTALK298
SL=SL+C(I,J)*IL(J)	XTALK299
M1(I,J)=SUM0	XTALK300
67 M2(I,J)=SUML	XTALK301
V1(I)=S0	XTALK302
68 V2(I)=SL	XTALK303
GO TO 76	XTALK304
	XTALK305

69 DO 71 I=1,N	XTALK306
DO 70 J=1,N	XTALK307
M1(I,J)=Y0(I,I)*CI(I,J)	XTALK308
70 M2(I,J)=YL(I,I)*CI(I,J)	XTALK309
V1(I)=I0(I)	XTALK310
71 V2(I)=IL(I)	XTALK311
GO TO 76	XTALK312
72 DO 75 I=1,N	XTALK313
DO 74 J=1,N	XTALK314
SUM0=ZEROC	XTALK315
SUML=ZEROC	XTALK316
DO 73 K=1,N	XTALK317
SUM0=SUM0+Y0(I,K)*CI(K,J)	XTALK318
73 SUML=SUML+YL(I,K)*CI(K,J)	XTALK319
M1(I,J)=SUM0	XTALK320
74 M2(I,J)=SUML	XTALK321
V1(I)=I0(I)	XTALK322
75 V2(I)=IL(I)	XTALK323
76 CONTINUE	XTALK324
C	XTALK325
C	XTALK326
C	XTALK327
DO 78 I=1,N	XTALK328
S=ZERO	XTALK329
DO 77 J=1,N	XTALK330
77 S=S+C(I,J)	XTALK331
78 V3(I)=S	XTALK332
C	XTALK333
C*****FREQUENCY DEPENDENT CALCULATIONS*****C*****	XTALK334
C	XTALK335
79 CONTINUE	XTALK336
READ(5,80,END=121) F	XTALK337
80 FORMAT(210.3)	XTALK338
OMEGA=TWO*PI*F	XTALK339
JOMEGA=XJ*OMEGA	XTALK340
C	XTALK341
C	XTALK342
C	XTALK343
C	XTALK344
C	XTALK345
LDC=MU08PI	XTALK346
DO 83 I=1,N	XTALK347
DELTA=ONE/(TWO*PI*DSQRT(Y(I)*F*MU04PI))	XTALK348
RDC=ONE/(PI*Y(I)*(Z(I)*Z(I)))	XTALK349
IF(Z(I).LE.DELTA) GO TO 81	XTALK350
IF(Z(I).GE.THREE*DELTA) GO TO 82	XTALK351
B(I)=(P25*(Z(I)/DELTA+THREE)*RDC+JOMEGA*(ONEP15-P15*Z(I)/DELTA)	XTALK352
+LDC)/NS(I)	XTALK353
GO TO 83	XTALK354
81 B(I)=(RDC+JOMEGA*LDC)/NS(I)	XTALK355
GO TO 83	XTALK356
82 B(I)=(P5*Z(I)*RDC/DELTA+JOMEGA*TWO*DELTA*LDC/Z(I))/NS(I)	XTALK357
83 CONTINUE	XTALK358
GO TO (84,87,88),TYPE	XTALK359
84 DELTA=ONE/(TWO*PI*DSQRT(SIG0*F*MU04PI))	XTALK360
RDC=ONE/(PI*SIG0*(RWS0*RWS0))	XTALK361
IF(RWS0.LE.DELTA) GO TO 85	XTALK362
IF(RWS0.GE.THREE*DELTA) GO TO 86	XTALK363
Z0=(P25*(RWS0/DELTA+THREE)*RDC+JOMEGA*(ONEP15-P15*RWS0/DELTA)*LDC)	XTALK364
+1/NS0	XTALK365
GO TO 91	XTALK366

85	Z0=(RDC+JOMEGA*LDC)/NS0	XTALK367
	GO TO 91	XTALK368
86	Z0=(P5*EWS0*RDC/DELTA+JOMEGA*TWO*DELTA*LDC/RWS0)/NS0	XTALK369
	GO TO 91	XTALK370
87	Z0=(RGP+JOMEGA*LCF)	XTALK371
	GO TO 91	XTALK372
88	RDC=ONE/(PI*SIG0*TH*(TWO*RS+TH))	XTALK373
	DELTA=ONE/(TWO*PI*DSQRT(SIG0*F*MUO*PI))	XTALK374
	IF (TH.LE.DELTA*P5) GO TO 89	XTALK375
	IF (TH.GE.THREE*DELTA) GO TO 90	XTALK376
	X=TWO*TH/DELTA	XTALK377
	SINH=(DEXP(X)-DEXP(-X))*P5	XTALK378
	COSH=(DEXP(X)+DEXP(-X))*P5	XTALK379
	Z0=((SINH+DSIN(X))*XJ*(SINH-DSIN(X)))/(TWO*PI*RS*SIG0*DELTA*	XTALK380
	1(COSH-DCOS(X)))	XTALK381
	GO TO 91	XTALK382
89	Z0=(ONE*XJ*P4*TH/DELTA)*RDC	XTALK383
	GO TO 91	XTALK384
90	Z0=(ONE*XJ)/(TWO*PI*RS*SIG0*DELTA)	XTALK385
C		XTALK386
C	COMPUTE THE EIGENVALUES AND THE EIGENVECTORS OF THE PRODUCT YZ	XTALK387
C	(STORE THE EIGENVECTORS AS COLUMNS OF ARRAY T. STORE THE	XTALK388
C	EIGENVALUES IN ARRAY B.)	XTALK389
C		XTALK390
91	OM2=OMEGA*OMEGA	XTALK391
	DO 93 I=1,N	XTALK392
	DO 92 J=1,N	XTALK393
92	A(I,J)=JOMEGA*(V3(I)*Z0+C(I,J)*B(J))	XTALK394
93	A(I,I)=A(I,I)-OM2*MUR*ER/V1	XTALK395
	CALL EIGCC(A,N,N,2,B,T,N,WK,LER)	XTALK396
	LER=LER-128	XTALK397
	IF (LER.LT.1) LER=0	XTALK398
C		XTALK399
C	COMPUTE THE INVERSE OF THE TRANSFORMATION MATRIX, T	XTALK400
C	(STORE IN ARRAY TI)	XTALK401
C		XTALK402
	DO 95 I=1,N	XTALK403
	DO 94 J=1,N	XTALK404
	A(I,J)=T(I,J)	XTALK405
94	TI(I,J)=ZEROC	XTALK406
95	TI(I,I)=ONEC	XTALK407
	CALL LEQ1C(A,N,N,TI,N,N,0,WA,NER)	XTALK408
	NER=NER-128	XTALK409
	IF (NER.LE.1) NER=0	XTALK410
C		XTALK411
C	COMPUTE THE TERMINAL VOLTAGES	XTALK412
C		XTALK413
C	FORM THE EQUATIONS	XTALK414
C		XTALK415
	DO 98 I=1,N	XTALK416
	S0=ZEROC	XTALK417
	SL=ZEROC	XTALK418
	DO 97 J=1,N	XTALK419
	SUM0=ZEROC	XTALK420
	SUHL=ZEROC	XTALK421
	DO 96 K=1,N	XTALK422
	SUM0=SUM0+M1(I,K)*T(K,J)	XTALK423
96	SUHL=SUHL+M2(I,K)*T(K,J)	XTALK424
	S0=S0+TI(I,J)*V1(J)	XTALK425
	SL=SL+TI(I,J)*V2(J)	XTALK426
	A(I,J)=SUM0	XTALK427

97	P(I,J)=SUHL	XTALK428
	IO(I)=SO	XTALK429
	IL(I)=SL	XTALK430
	IF(OPTION.EQ.11.OR.OPTION.EQ.12) IL(I)=-IL(I)	XTALK431
	GAN=CDSQRT(B(I))	XTALK432
	EPP=CDEXP(GAN*L)*P5	XTALK433
	ENN=CDEXP(-GAN*L)*P5	XTALK434
	EP(I)=EPP*ENN	XTALK435
	EN(I)=ENN	XTALK436
	G(I)=GAN/JOMEGA	XTALK437
	IF(OPTION.EQ.11.OR.OPTION.EQ.12) G(I)=GNBC/G(I)	XTALK438
98	CONTINUE	XTALK439
	DO 100 I=1,N	XTALK440
	DO 100 J=1,N	XTALK441
	SUHO=ZERO	XTALK442
	SUHL=ZERO	XTALK443
	DO 99 K=1,N	XTALK444
	SUHO=SUHO+TI(I,K)*A(K,J)	XTALK445
99	SUHL=SUHL+TI(I,K)*P(K,J)	XTALK446
	YO(I,J)=SUHO	XTALK447
100	YL(I,J)=SUHL	XTALK448
	DO 103 I=1,N	XTALK449
	SO=ZERO	XTALK450
	DO 102 J=1,N	XTALK451
	SL=ZERO	XTALK452
	DO 101 K=1,N	XTALK453
101	SL=SL+YL(I,K)*G(K)*EN(K)*YO(K,J)	XTALK454
	A(I,J)=SL+YL(I,J)*EP(J)+YO(I,J)*EP(I)	XTALK455
102	SO=SO+YL(I,J)*G(J)*EN(J)*IO(J)	XTALK456
	A(I,I)=A(I,I)+EN(I)/G(I)	XTALK457
103	B(I)=SO+EP(I)*IO(I)+IL(I)	XTALK458
C		XTALK459
C	SOLVE THE EQUATIONS	XTALK460
C		XTALK461
	CALL LBQTC(A,N,N,B,1,N,0,WA,IER)	XTALK462
	IER=IER-128	XTALK463
	IF(IER.NE.1) IER=0	XTALK464
	WRITE(6,104) P,IER	XTALK465
104	FORMAT(1H1,' FREQUENCY (HERTZ) = ',1PE11.4,10X,' SOLUTION ERROR = ',	XTALK466
	12X,12/)	XTALK467
	PREC=WK(1)	XTALK468
	WRITE(6,105) LER,PREC	XTALK469
105	FORMAT(' EIGEN SOLUTION ERROR = ',14/ ' EIGEN SOLUTION PRECISION = ',	XTALK470
	11PE10.3/)	XTALK471
	WRITE(6,106) MER	XTALK472
106	FORMAT(' TRANSFORMATION MATRIX INVERSION ERROR = ',12/)	XTALK473
	WRITE(6,107)	XTALK474
107	FORMAT(16X,' WIRE ',8X,' VON(VOLTS) ',3X,' VOA(DEGREES) ',8X,	XTALK475
	1'VLN(VOLTS) ',3X,'VLA(DEGREES) '///)	XTALK476
C		XTALK477
C	COMPUTE AND PRINT THE TERMINAL VOLTAGES	XTALK478
C		XTALK479
	DO 109 I=1,N	XTALK480
	SO=ZERO	XTALK481
	DO 108 J=1,N	XTALK482
108	SO=SO+YO(I,J)*B(J)	XTALK483
109	G(I)=-G(I)*EN(I)*IO(I)+EP(I)*B(I)+G(I)*EN(I)*SO	XTALK484
	IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 114	XTALK485
	DO 111 I=1,N	XTALK486
	SO=ZERO	XTALK487
	SL=ZERO	XTALK488

DO 110 J=1,N	XTALK489
SO=SO-YO(I,J)*B(J)	XTALK490
110 SL=SL+YL(I,J)*G(J)	XTALK491
YO(I,I)=IO(I)+SO	XTALK492
111 YL(I,I)=-IL(I)+SL	XTALK493
DO 113 I=1,N	XTALK494
SO=ZEROC	XTALK495
SL=ZEROC	XTALK496
DO 112 J=1,N	XTALK497
SO=SO+T(I,J)*YO(J,J)	XTALK498
112 SL=SL+T(I,J)*YL(J,J)	XTALK499
P(I,I)=SO	XTALK500
113 A(I,I)=SL	XTALK501
GO TO 117	XTALK502
114 DO 116 I=1,N	XTALK503
SO=ZEROC	XTALK504
SL=ZEROC	XTALK505
DO 115 J=1,N	XTALK506
SO=SO+T(I,J)*B(J)	XTALK507
115 SL=SL+T(I,J)*G(J)	XTALK508
P(I,I)=SO	XTALK509
116 A(I,I)=SL	XTALK510
117 DO 120 I=1,N	XTALK511
SO=ZEROC	XTALK512
SL=ZEROC	XTALK513
DO 118 J=1,N	XTALK514
SO=SO+CI(I,J)*P(J,J)	XTALK515
118 SL=SL+CI(I,J)*A(J,J)	XTALK516
VO=SO	XTALK517
VL=SL	XTALK518
VOM=CDABS(VO)	XTALK519
VLH=CDABS(VL)	XTALK520
VOR=DREAL(VO)	XTALK521
VOI=DIHAG(VO)	XTALK522
VLR=DREAL(VL)	XTALK523
VLI=DIHAG(VL)	XTALK524
IF (VOR.EQ.ZERO.AND.VOI.EQ.ZERO) VOR=ONE	XTALK525
IF (VLR.EQ.ZERO.AND.VLI.EQ.ZERO) VLR=ONE	XTALK526
VOA=DATAN2(VOI,VOR)*ONE80/PI	XTALK527
VLA=DATAN2(VLI,VLR)*ONE80/PI	XTALK528
WRITE(6,119) I,VOM,VOA,VLH,VLA	XTALK529
119 FORMAT(17X,I2,8X,1PE10.3,3X,1PE10.3,10X,1PE10.3,3X,1PE10.3/)	XTALK530
120 CONTINUE	XTALK531
GO TO 79	XTALK532
121 STOP	XTALK533
END	XTALK534

TABLE B-1

Changes in XTALK2 to Convert
to Single Precision Arithmetic

Delete Card 057

<u>Card Number</u>	<u>Double</u>	<u>Single</u>
059	REAL *8	REAL
061	COMPLEX *16	COMPLEX
065	3.141592653DC	3.1415926E0
065	2.997925D8	2.997925E8
066-068	change all D's to	E's
070	DCMPLX(0.D0,0.D0)	CMPLX(0.E0,0.E0)
071	DCMPLX(1.D0,0.D0)	CMPLX(1.E0,0.E0)
072	DCMPLX(0.D0,1.D0)	CMPLX(0.E0,1.E0)
140	DLOG	ALOG
142	DLOG	ALOG
144	DLOG	ALOG
157	DLOG	ALOG
163	DLOG	ALOG
169	DLOG	ALOG
170	DCOS	COS
170	DCOS	COS
190	DREAL	REAL
348	DSQRT	SQRT
360	DSQRT	SQRT
374	DSQRT	SQRT
378	DEXP	EXP
378	DEXP	EXP

<u>Card Number</u>	<u>Double</u>	<u>Single</u>
379	DEXP	EXP
379	DEXP	EXP
380	DSIN	SIN
380	DSIN	SIN
381	DCOS	COS
432	CDSQRT	CSQRT
433	CDEXP	CEXP
434	CDEXP	CEXP
519	CDABS	CABS
520	CDABS	CABS
521	DREAL	REAL
522	DIMAG	AIMAG
523	DREAL	REAL
524	DIMAG	AIMAG
527	DATAN2	ATAN2
528	DATAN2	ATAN2

APPENDIX C

FLATPAK

Program Listing

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C*****FLATP001
C                                     FLATP002
C                                     FLATP003
C      PROGRAM FLATPAK               FLATP004
C      (FORTRAN IV, DOUBLE PRECISION) FLATP005
C      WRITTEN BY                     FLATP006
C      CLAYTON R. PAUL               FLATP007
C      DEPARTMENT OF ELECTRICAL ENGINEERING FLATP008
C      UNIVERSITY OF KENTUCKY         FLATP009
C      LEXINGTON, KENTUCKY 40506     FLATP010
C                                     FLATP011
C      A DIGITAL COMPUTER PROGRAM TO COMPUTE THE TERMINAL VOLTAGES
C      (WITH RESPECT TO THE REFERENCE WIRE) OF AN N+1 WIRE FLATPACK OR
C      RIBBON CABLE FOR THE 'QUASI-TEM' MODE OF PROPAGATION. FLATP012
C                                     FLATP013
C      THE DISTRIBUTED PARAMETER, MULTICONDUCTOR TRANSMISSION LINE
C      EQUATIONS ARE SOLVED FOR STEADY STATE, SINUSOIDAL EXCITATION
C      OF THE LINE.                  FLATP014
C                                     FLATP015
C      THE N+1 WIRES ARE ASSUMED TO BE PARALLEL TO EACH OTHER. FLATP016
C                                     FLATP017
C      THE N+1 WIRES ARE CONSIDERED TO BE PERFECT CONDUCTORS. FLATP018
C                                     FLATP019
C      THE SURROUNDING MEDIA ARE ASSUMED TO BE LOSSLESS. FLATP020
C                                     FLATP021
C      THE PER-UNIT-LENGTH CAPACITANCES OF THE CABLE (WITH AND WITHOUT
C      THE DIELECTRIC INSULATIONS PRESENT) ARE INPUT DATA AND MAY BE
C      COMPUTED WITH THE PROGRAM GETCAP. FLATP022
C                                     FLATP023
C      LOAD STRUCTURE OPTION DEFINITIONS: FLATP024
C      OPTION=11, THEVENIN EQUIVALENT LOAD STRUCTURES WITH DIAGONAL
C      IMPEDANCE MATRICES FLATP025
C      OPTION=12, THEVENIN EQUIVALENT LOAD STRUCTURES WITH FULL
C      IMPEDANCE MATRICES FLATP026
C      OPTION=21, NORTON EQUIVALENT LOAD STRUCTURES WITH DIAGONAL
C      ADMITTANCE MATRICES FLATP027
C      OPTION=22, NORTON EQUIVALENT LOAD STRUCTURES WITH FULL
C      ADMITTANCE MATRICES FLATP028
C                                     FLATP029
C      SUBROUTINES USED: LEQTC, NROOT, EIGEN FLATP030
C                                     FLATP031
C*****FLATP041
C      ALL VECTORS AND MATRICES IN THE FOLLOWING DIMENSION STATEMENTS
C      SHOULD BE OF SIZE N WHERE N IS THE NUMBER OF WIRES (EXCLUSIVE OF
C      THE REFERENCE WIRE), I.E., C(N,N), CO(N,N), TI(N,N), G(N), WA(N),
C      IO(N), IL(N), YO(N,N), YL(N,N), B(N), A(N,N), P(N,N) FLATP032
C                                     FLATP033
C      IMPLICIT REAL*8 (A-H,O-Z) FLATP034
C      INTEGER OPTION FLATP035
C      REAL*8 L,C( 2, 2),CO( 2, 2),TI( 2, 2),G( 2) FLATP036
C      COMPLEX*16 XJ,SUM0,SUML,S0,SL,V0,V1,ZEROC,ONEC,IO( 2),IL( 2),
C      YO( 2, 2),YL( 2, 2),B( 2),A( 2, 2),WA( 2),P( 2, 2) FLATP037
C      DATA PI/3.141592653D0/,V/2.997925D8/ FLATP038
C      DATA ONE/1.D0/,TWO/2.D0/,ZERO/0.D0/,ONE80/180.D0/ FLATP039
C      ZEROCD=DCMPLX(0.D0,0.D0) FLATP040
C      ONECD=DCMPLX(1.D0,0.D0) FLATP041
C      XJ=DCMPLX(0.D0,1.D0) FLATP042
C                                     FLATP043
C      C*****FREQUENCY INDEPENDENT CALCULATIONS*****FLATP059
C      READ AND PRINT INPUT DATA FLATP060
C                                     FLATP061

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C	READ(5,1) N,OPTION,L	FLATP062
	1 FORMAT(8X,I2,8X,I2,E10.3)	FLATP063
	IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 3	FLATP064
	IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 3	FLATP065
	WRITE(6,2)	FLATP066
	2 FORMAT(' LOAD STRUCTURE OPTION ERROR'/' OPTION MUST EQUAL 11,12,21,OR 22'/'/)	FLATP067
	GO TO 60	FLATP068
	3 NP=N+1	FLATP069
	WRITE(6,4) NP,L,OPTION	FLATP070
	4 FORMAT(181,49X,'FLATPAK'///	FLATP071
	145X,I2,' PARALLEL WIRES'///	FLATP072
	239X,'LINE LENGTH= ',1PE13.6,' METERS'///	FLATP073
	342X,'LOAD STRUCTURE OPTION= ',I2///)	FLATP074
		FLATP075
		FLATP076
		FLATP077
C	READ ENTRIES IN THE PER-UNIT-LENGTH TRANSMISSION LINE	FLATP078
C	CAPACITANCE MATRIX,C(COMPUTED WITH GETCAP)	FLATP079
C	(STORE C IN ARRAY C)	FLATP080
C		FLATP081
	DO 6 I=1,N	FLATP082
	DO 6 J=I,N	FLATP083
	READ(5,5) K,M,C(K,M)	FLATP084
	5 FORMAT(4X,I2,3X,I2,2X,E13.6)	FLATP085
	6 C(M,K)=C(K,M)	FLATP086
		FLATP087
C	READ ENTRIES IN THE PER-UNIT-LENGTH TRANSMISSION LINE	FLATP088
C	CAPACITANCE MATRIX WITH THE WIRE INSULATIONS REMOVED, CO,(COMPUTED WITH GETCAP)	FLATP089
C	(STORE CO IN ARRAY CO)	FLATP090
C		FLATP091
	DO 8 I=1,N	FLATP092
	DO 8 J=I,N	FLATP093
	READ(5,7) K,M,CO(K,M)	FLATP094
	7 FORMAT(4X,I2,3X,I2,2X,E13.6)	FLATP095
	8 CO(M,K)=CO(K,M)	FLATP096
		FLATP097
C	COMPUTE THE EIGENVECTORS (COLUMNS OF THE MATRIX T) AND EIGENVALUES	FLATP098
C	OF THE MATRIX PRODUCT CL	FLATP099
C	(THE ARRAYS TI AND G CONTAIN T AND THE INVERSE OF THE EIGENVALUES	FLATP100
C	FOR THE THEVENIN EQUIVALENT OR THE INVERSE OF THE TRANSPOSE OF T	FLATP101
C	AND THE EIGENVALUES FOR THE NORTON EQUIVALENT, RESPECTIVELY)	FLATP102
C		FLATP103
	IF(N.EQ.1) GO TO 9	FLATP104
	CALL NROOT(N,CO,C,G,TI,N*N)	FLATP105
	GO TO 10	FLATP106
	9 G(1)=CO(1,1)/C(1,1)	FLATP107
	TI(1,1)=ONE/DSQRT(C(1,1))	FLATP108
10	DO 12 I=1,N	FLATP109
	DO 11 J=1,N	FLATP110
	11 C(I,J)=TI(I,J)	FLATP111
	12 G(I)=ONE/(V*DSQRT(G(I)))	FLATP112
	IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 18	FLATP113
	DO 14 I=1,N	FLATP114
	DO 13 J=1,N	FLATP115
	A(I,J)=TI(I,J)*ONEC	FLATP116
13	P(I,J)=ZEROC	FLATP117
14	P(I,I)=ONEC	FLATP118
	CALL LEQ1C(A,N,N,P,N,N,O,WA,KER)	FLATP119
	KER=KER-128	FLATP120
	IF(KER.NE.1) KER=0	FLATP121
		FLATP122

WRITE(6,15) KER	FLATP123
15 FORMAT (//, ' TRANSFORMATION MATRIX INVERSION ERROR= ', I2//)	FLATP124
DO 17 I=1, N	FLATP125
DO 16 J=1, N	FLATP126
16 TI(I,J)=DREAL(P(J,I))	FLATP127
17 G(I)=ONE/G(I)	FLATP128
C READ AND PRINT ENTRIES IN LOAD ADMITTANCE(IMPEDANCE) MATRICES	FLATP129
C AND SHORT CIRCUIT CURRENT SOURCE(OPEN CIRCUIT VOLTAGE SOURCE)	FLATP130
C VECTORS	FLATP131
C (STORE ADMITTANCE(IMPEDANCE) MATRICES AT X=0 IN ARRAY Y0 AND THOSE	FLATP132
C AT X=L IN ARRAY YL. STORE SHORT CIRCUIT CURRENT SOURCE(OPEN	FLATP133
C CIRCUIT VOLTAGE SOURCE) VECTORS AT X=0 IN ARRAY IO AND THOSE	FLATP134
C AT X=L IN ARRAY IL.)	FLATP135
18 IF (OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 21	FLATP136
WRITE(6,19)	FLATP137
19 FORMAT (//, 18X, 'ADMITTANCE AT X=0', 10X, 'CURRENT SOURCE AT X=0',	FLATP138
112X, 'ADMITTANCE AT X=L', 10X, 'CURRENT SOURCE AT X=L'//)	FLATP139
WRITE(6,20)	FLATP140
20 FORMAT(21X, ' (SIEMENS) ', 23X, ' (AMPS) ', 22X, ' (SIEMENS) ', 23X, ' (AMPS) '//)	FLATP141
GO TO 24	FLATP142
21 WRITE(6,22)	FLATP143
22 FORMAT (//, 18X, 'IMPEDANCE AT X=0', 11X, 'VOLTAGE SOURCE AT X=0',	FLATP144
112X, 'IMPEDANCE AT X=L', 11X, 'VOLTAGE SOURCE AT X=L'//)	FLATP145
WRITE(6,23)	FLATP146
23 FORMAT(23X, ' (OHMS) ', 23X, ' (VOLTS) ', 24X, ' (OHMS) ', 23X, ' (VOLTS) '//)	FLATP147
24 WRITE(6,25)	FLATP148
25 FORMAT (' ENTRY', 10X, 'REAL', 11X, 'IMAG', 11X, 'REAL', 11X, 'IMAG', 11X,	FLATP149
'REAL', 11X, 'IMAG', 11X, 'REAL', 11X, 'IMAG'//)	FLATP150
DO 28 I=1, N	FLATP151
READ(5,26) YOR,YOI,IO(I),YLR,YLI,IL(I)	FLATP152
26 FORMAT(8(E10.3))	FLATP153
Y0(I,I)=YOR+XJ*YOI	FLATP154
YL(I,I)=YLR+XJ*YLI	FLATP155
WRITE(6,27) I,I,Y0(I,I),IO(I),YL(I,I),IL(I)	FLATP156
27 FORMAT(1X,I2,2X,I2,8(5X,1PE10.3) /)	FLATP157
28 CONTINUE	FLATP158
IF (OPTION.EQ.11.OR.OPTION.EQ.21) GO TO 32	FLATP159
IF (N.EQ.1) GO TO 32	FLATP160
K1=N-1	FLATP161
DO 31 I=1,K1	FLATP162
K2=I+1	FLATP163
DO 31 J=K2,N	FLATP164
READ(5,29) YOR,YOI,YLR,YLI	FLATP165
29 FORMAT(2(E10.3), 20X, 2(E10.3))	FLATP166
Y0(I,J)=YOR+XJ*YOI	FLATP167
YL(I,J)=YLR+XJ*YLI	FLATP168
Y0(J,I)=Y0(I,J)	FLATP169
YL(J,I)=YL(I,J)	FLATP170
WRITE(6,30) I,J,Y0(I,J),YL(I,J)	FLATP171
30 FORMAT(1X,I2,2X,I2,2(5X,1PE10.3), 30X, 2(5X,1PE10.3))	FLATP172
31 CONTINUE	FLATP173
C COMPUTE THE MATRICES TTRAN*ZO*T, TTRAN*ZL*T, TTRAN*VO, -TTRAN*VL	FLATP174
C FOR THE THEVENIN EQUIVALENT OR TINV*Y0*TINVTRAN, TINV*YL*TINVTRAN,	FLATP175
C TINV*IO, TINV*IL FOR THE NORTON EQUIVALENT AND STORE IN ARRAYS	FLATP176
C Y0,YL,IO,IL, RESPECTIVELY.	FLATP177
32 IF (OPTION.EQ.12.OR.OPTION.EQ.22) GO TO 35	FLATP178
DO 34 I=1, N	FLATP179
	FLATP180
	FLATP181
	FLATP182
	FLATP183

S0=ZEROC	FLATP184
SL=ZEROC	FLATP185
DO 33 J=1,N	FLATP186
A(I,J)=Y0(I,I)*TI(I,J)	FLATP187
P(I,J)=Y1(I,I)*TI(I,J)	FLATP188
S0=S0+TI(J,I)*I0(J)	FLATP189
33 SL=SL+TI(J,I)*IL(J)	FLATP190
B(I)=S0	FLATP191
34 WA(I)=SL	FLATP192
GO TO 39	FLATP193
35 DO 38 I=1,N	FLATP194
S0=ZEROC	FLATP195
SL=ZEROC	FLATP196
DO 37 J=1,N	FLATP197
SUM0=ZEROC	FLATP198
SUHL=ZEROC	FLATP199
DO 36 K=1,N	FLATP200
SUM0=SUM0+Y0(I,K)*TI(K,J)	FLATP201
36 SUHL=SUHL+Y1(I,K)*TI(K,J)	FLATP202
A(I,J)=SUM0	FLATP203
P(I,J)=SUHL	FLATP204
S0=S0+TI(J,I)*I0(J)	FLATP205
37 SL=SL+TI(J,I)*IL(J)	FLATP206
B(I)=S0	FLATP207
38 WA(I)=SL	FLATP208
39 DO 42 I=1,N	FLATP209
DO 41 J=1,N	FLATP210
S0=ZEROC	FLATP211
SL=ZEROC	FLATP212
DO 40 K=1,N	FLATP213
S0=S0+TI(K,I)*A(K,J)	FLATP214
40 SL=SL+TI(K,I)*P(K,J)	FLATP215
Y0(I,J)=S0	FLATP216
41 YL(I,J)=SL	FLATP217
I0(I)=B(I)	FLATP218
IL(I)=WA(I)	FLATP219
42 IF (OPTION.EQ.11.OR.OPTION.EQ.12) IL(I)=-IL(I)	FLATP220
C	FLATP221
C*****FREQUENCY DEPENDENT CALCULATIONS*****	FLATP222
C	FLATP223
43 CONTINUE	FLATP224
READ(5,44,END=60) F	FLATP225
44 FORMAT(E10.3)	FLATP226
OMEGA=TWO*PI*F	FLATP227
C	FLATP228
C COMPUTE THE TERMINAL VOLTAGES	FLATP229
C	FLATP230
C FORM THE EQUATIONS	FLATP231
C	FLATP232
DO 45 I=1,N	FLATP233
W=G(I)	FLATP234
IF (OPTION.EQ.11.OR.OPTION.EQ.12) W=ONE/W	FLATP235
W=OMEGA*W*I	FLATP236
CO(I,I)=DCOS(W)	FLATP237
45 P(I,I)=XJ*DSIN(W)	FLATP238
DO 48 I=1,N	FLATP239
S0=ZEROC	FLATP240
DO 47 J=1,N	FLATP241
SL=ZEROC	FLATP242
DO 46 K=1,N	FLATP243
46 SL=SL+YL(I,K)*G(K)*P(K,K)*Y0(K,J)	FLATP244

	A(I,J)=SL+YL(I,J)*C0(J,J)+Y0(I,J)*C0(I,I)	FLATP245
47	S0=S0+YL(I,J)*G(J)*P(J,J)*I0(J)	FLATP246
	A(I,I)=A(I,I)+P(I,I)/G(I)	FLATP247
48	B(I)=S0+C0(I,I)*I0(I)+IL(I)	FLATP248
C		FLATP249
C	SOLVE THE EQUATIONS	FLATP250
C		FLATP251
	CALL LEQ1C(A,N,N,B,1,N,0,WA,IER)	FLATP252
	IER=IER-128	FLATP253
	IF (IER.NE.1) IER=0	FLATP254
	WRITE(6,49) F,IER	FLATP255
49	FORMAT(1H1,' FREQUENCY (HERTZ)= ',1PE11.4,10X,' SOLUTION ERROR= ',	FLATP256
	12X,I2/)	FLATP257
	WRITE(6,50)	FLATP258
50	FORMAT(16X,' WIRE',8X,' V0H(VOLTS)',3X,' V0A(DEGREES)',8X,	FLATP259
	' V1H(VOLTS)',3X,' V1A(DEGREES)'//)	FLATP260
C		FLATP261
C	COMPUTE AND PRINT THE TERMINAL VOLTAGES	FLATP262
C		FLATP263
	DO 52 I=1,N	FLATP264
	S0=ZEROC	FLATP265
	DO 51 J=1,N	FLATP266
51	S0=S0+Y0(I,J)*B(J)	FLATP267
52	WA(I)=-G(I)*P(I,I)*I0(I)+C0(I,I)*B(I)+G(I)*P(I,I)*S0	FLATP268
	IF (OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 56	FLATP269
	DO 54 I=1,N	FLATP270
	S0=ZEROC	FLATP271
	SL=ZEROC	FLATP272
	DO 53 J=1,N	FLATP273
	S0=S0-Y0(I,J)*B(J)	FLATP274
53	SL=SL+YL(I,J)*WA(J)	FLATP275
	A(I,I)=I0(I)+S0	FLATP276
54	P(I,I)=-IL(I)+SL	FLATP277
	DO 55 I=1,N	FLATP278
	B(I)=A(I,I)	FLATP279
55	P(I,I)=P(I,I)	FLATP280
56	DO 59 I=1,N	FLATP281
	S0=ZEROC	FLATP282
	SL=ZEROC	FLATP283
	DO 57 J=1,N	FLATP284
	S0=S0+C(I,J)*B(J)	FLATP285
57	SL=SL+C(I,J)*WA(J)	FLATP286
	V0=S0	FLATP287
	V1=SL	FLATP288
	V0H=CDABS(V0)	FLATP289
	V1H=CDABS(V1)	FLATP290
	V0R=DREAL(V0)	FLATP291
	V0I=DIMAG(V0)	FLATP292
	V1R=DREAL(V1)	FLATP293
	V1I=DIMAG(V1)	FLATP294
	IF (V0R.EQ.ZERO.AND.V0I.EQ.ZERO) V0R=CNE	FLATP295
	IF (V1R.EQ.ZERO.AND.V1I.EQ.ZERO) V1R=CNE	FLATP296
	V0A=ATAN2(V0I,V0R)*ONE80/PI	FLATP297
	V1A=ATAN2(V1I,V1R)*ONE80/PI	FLATP298
	WRITE(6,58) I,V0H,V0A,V1H,V1A	FLATP299
58	FORMAT(17X,I2,8X,1PE10.3,3X,1PE10.3,10X,1PE10.3,3X,1PE10.3/)	FLATP300
59	CONTINUE	FLATP301
	GO TO 43	FLATP302
60	STOP	FLATP303
	END	FLATP304

TABLE C-1

Changes in FLATPAK to Convert
to Single Precision Arithmetic

Delete Card 048

<u>Card Number</u>	<u>Double</u>	<u>Single</u>
050	REAL *8	REAL
051	COMPLEX *16	COMPLEX
053	3.141592653D0	3.1415926E0
053	2.997925D8	2.997925E8
054	change all D's to	E's
055	DCMLPX(0.D0,0.D0)	CMPLX(0.E0,0.E0)
056	DCMLPX(1.D0,0.D0)	CMPLX(1.E0,0.E0)
057	DCMLPX(0.D0,1.D0)	CMPLX(0.E0,1.E0)
109	DSQRT	SQRT
113	DSQRT	SQRT
127	DREAL	REAL
237	DCOS	COS
238	DSIN	SIN
289	CDABS	CABS
290	CDABS	CABS
291	DREAL	REAL
292	DIMAG	AIMAG
293	DREAL	REAL
294	DIMAG	AIMAG
297	DATAN2	ATAN2
298	DATAN2	ATAN2

APPENDIX D

FLATPAK2

Program Listing

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C*****FLATP001
C                                     FLATP002
C      PROGRAM FLATPAK2               FLATP003
C      (PORTMAN IV, DOUBLE PRECISION) FLATP004
C      WRITTEN BY                     FLATP005
C      CLAYTON R. PAUL               FLATP006
C      DEPARTMENT OF ELECTRICAL ENGINEERING FLATP007
C      UNIVERSITY OF KENTUCKY        FLATP008
C      LEXINGTON, KENTUCKY 40506    FLATP009
C                                     FLATP010
C      A DIGITAL COMPUTER PROGRAM TO COMPUTE THE TERMINAL VOLTAGES FLATP011
C      (WITH RESPECT TO THE REFERENCE WIRE) OF AN N+1 WIRE FLATPACK OR FLATP012
C      RIBBON CABLE FOR THE 'QUASI-TEM' MODE OF PROPAGATION. FLATP013
C                                     FLATP014
C      THE DISTRIBUTED PARAMETER, MULTICONDUCTOR TRANSMISSION LINE FLATP015
C      EQUATIONS ARE SOLVED FOR STEADY STATE, SINUSOIDAL EXCITATION FLATP016
C      OF THE LINE. FLATP017
C                                     FLATP018
C      THE N+1 WIRES ARE ASSUMED TO BE PARALLEL TO EACH OTHER. FLATP019
C                                     FLATP020
C      THE N+1 WIRES ARE CONSIDERED TO BE IMPERFECT CONDUCTORS. THE SELF FLATP021
C      IMPEDANCES OF EACH WIRE INCLUDE SKIN EFFECT. FLATP022
C                                     FLATP023
C      THE SURROUNDING MEDIA ARE ASSUMED TO BE LOSSLESS. FLATP024
C                                     FLATP025
C      THE PER-UNIT-LENGTH CAPACITANCES OF THE CABLE(WITH AND WITHOUT FLATP026
C      THE DIELECTRIC INSULATIONS PRESENT) ARE INPUT DATA AND MAY BE FLATP027
C      COMPUTED WITH THE PROGRAM GETCAP. FLATP028
C                                     FLATP029
C      LOAD STRUCTURE OPTION DEFINITIONS: FLATP030
C      OPTION=11,THEVENIN EQUIVALENT LOAD STRUCTURES WITH DIAGONAL FLATP031
C      IMPEDANCE MATRICES FLATP032
C      OPTION=12,THEVENIN EQUIVALENT LOAD STRUCTURES WITH FULL FLATP033
C      IMPEDANCE MATRICES FLATP034
C      OPTION=21,NORTON EQUIVALENT LOAD STRUCTURES WITH DIAGONAL FLATP035
C      ADMITTANCE MATRICES FLATP036
C      OPTION=22,NORTON EQUIVALENT LOAD STRUCTURES WITH FULL FLATP037
C      ADMITTANCE MATRICES FLATP038
C                                     FLATP039
C      SUBROUTINES USED: LEQ1C,EIGCC FLATP040
C                                     FLATP041
C*****FLATP042
C                                     FLATP043
C      ALL VECTORS AND MATRICES IN THE FOLLOWING DIMENSION STATEMENTS FLATP044
C      SHOULD BE OF SIZE N WHERE N IS THE NUMBER OF WIRES (EXCLUSIVE OF FLATP045
C      THE REFERENCE WIRE), I.E., C(N,N),CO(N,N),CI(N,N) FLATP046
C      IO(N),IL(N),YO(N,N),YL(N,N),B(N),A(N,N),P(N,N),EN(N),EP(N), FLATP047
C      N1(N,N),N2(N,N),V1(N),V2(N),T(N,N),TI(N,N),G(N),V3(N),WA(N) FLATP048
C      THE VECTOR WK MUST BE OF LENGTH 2N(N+1) FLATP049
C                                     FLATP050
C      IMPLICIT REAL*8 (A-H,O-Z) FLATP051
C      INTEGER OPTION FLATP052
C      REAL*8 L,LDC,C( 2, 2),CO( 2, 2),V3( 2),CI( 2, 2),WK( 12), FLATP053
C      1NUO4PI,NUO8PI FLATP054
C      COMPLEX*16 XJ,SUM0,SUM1,SO,SL,VO,VL,ZEBOC,ONEC,Z,BPP,ENN,GAN FLATP055
C      1,IO( 2),IL( 2),YO( 2, 2),YL( 2, 2),B( 2),A( 2, 2),WA( 2),G( 2), FLATP056
C      2P( 2, 2),EP( 2),EN( 2),N1( 2, 2),N2( 2, 2),V1( 2),V2( 2), FLATP057
C      3T( 2, 2),TI( 2, 2),JOMEGA FLATP058
C      DATA PI/3.141592653D0/,V/2.997925D8/ FLATP059
C      DATA CMTM/2.54D-5/,ZERO/0.D0/,TWO/2.D0/,NUO8PI/-5D-7/,ONE/1.D0/, FLATP060
C      1NUO4PI/1.D-7/,THREE/3.D0/,P25/.25D0/,ONEP15/1.15D0/,P15/.15D0/, FLATP061

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2P5/.5D0/,ONE80/180.D0/	FLATP062
VV=V*V	FLATP063
ZEROC=DCMPLX(0.D0,0.D0)	FLATP064
ONEC=DCMPLX(1.D0,0.D0)	FLATP065
XJ=DCMPLX(0.D0,1.D0)	FLATP066
C	FLATP067
C*****FREQUENCY INDEPENDENT CALCULATIONS*****	FLATP068
C	FLATP069
C READ AND PRINT INPUT DATA	FLATP070
C	FLATP071
READ(5,1) N,OPTION,L	FLATP072
1 FORMAT(8X,I2,8X,I2,E10.3)	FLATP073
IF (OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 3	FLATP074
IF (OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 3	FLATP075
WRITE(6,2)	FLATP076
2 FORMAT(' LOAD STRUCTURE OPTION ERROR'// ' OPTION MUST EQUAL 11,12,21,22')	FLATP077
GO TO 81	FLATP078
3 NP=N+1	FLATP079
WRITE(6,4) NP,L,OPTION	FLATP080
4 FORMAT(1H1,49X,'FLATPAK2'///	FLATP081
145X,I2,' PARALLEL WIRES'///	FLATP082
239X,'LINE LENGTH= ',1PE13.6,' METRES'///	FLATP083
342X,'LOAD STRUCTURE OPTION= ',I2///)	FLATP084
C	FLATP085
C READ ENTRIES IN THE PER-UNIT-LENGTH TRANSMISSION LINE	FLATP086
C CAPACITANCE MATRIX,C (COMPUTED WITH GETCAP)	FLATP087
C (STORE C IN ARRAY C)	FLATP088
C	FLATP089
DO 6 I=1,N	FLATP090
DO 6 J=1,N	FLATP091
READ(5,5) K,M,C(K,M)	FLATP092
5 FORMAT(4X,I2,3X,I2,2X,E13.6)	FLATP093
6 C(M,K)=C(K,M)	FLATP094
C	FLATP095
C READ ENTRIES IN THE PER-UNIT-LENGTH TRANSMISSION LINE	FLATP096
C CAPACITANCE MATRIX WITH THE WIRE INSULATIONS REMOVED,C0 (COMPUTED	FLATP097
C WITH GETCAP)	FLATP098
C (STORE C0 IN ARRAY C0)	FLATP099
C	FLATP100
DO 8 I=1,N	FLATP101
DO 8 J=1,N	FLATP102
READ(5,7) K,M,C0(K,M)	FLATP103
7 FORMAT(4X,I2,3X,I2,2X,E13.6)	FLATP104
8 C0(M,K)=C0(K,M)	FLATP105
C	FLATP106
C COMPUTE THE PER-UNIT-LENGTH TRANSMISSION LINE INDUCTANCE MATRIX,L,	FLATP107
C AND THE INVERSE OF THE CAPACITANCE MATRIX,CI	FLATP108
C (STORE CI IN ARRAY CI AND L IN ARRAY C0)	FLATP109
C	FLATP110
DO 10 I=1,N	FLATP111
DO 9 J=1,N	FLATP112
T(I,J)=C(I,J)*ONEC	FLATP113
A(I,J)=C0(I,J)*ONEC	FLATP114
TI(I,J)=ZEROC	FLATP115
9 P(I,J)=ZEROC	FLATP116
TI(I,I)=CNEC	FLATP117
10 P(I,I)=ONEC	FLATP118
CALL LEQT1C(A,N,S,P,N,M,0,WA,KER)	FLATP119
CALL LEQT1C(T,N,M,TI,N,M,0,WA,NES)	FLATP120
KER=KER-128	FLATP121
	FLATP122

	NER=NER-128	FLATP123
	IF (KER.NE.1) KER=0	FLATP124
	IF (NER.NE.1) NER=0	FLATP125
	WRITE(6,11) KER	FLATP126
	WRITE(6,11) NER	FLATP127
	11 FORMAT (//,' PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= ',	FLATP128
	1I2//)	FLATP129
	DO 12 I=1,N	FLATP130
	DO 12 J=1,N	FLATP131
	CI(I,J)=DREAL(TI(I,J))	FLATP132
	12 CO(I,J)=DREAL(P(I,J))/VV	FLATP133
C		FLATP134
C	READ AND PRINT CHARACTERISTICS OF THE WIRES TO BE USED IN THE SELF	FLATP135
C	IMPEDANCE CALCULATIONS	FLATP136
C		FLATP137
	READ(5,13) RWS,SIG,NS	FLATP138
	13 FORMAT(2(5X,E10.3),8X,I2)	FLATP139
	WRITE(6,14) RWS,SIG,NS	FLATP140
	14 FORMAT (////' WIRES ARE STRANDED WITH EACH STRAND OF RADIUS= ',	FLATP141
	11PE10.3,' MILS'/' CONDUCTIVITY OF WIRE STRANDS= ',	FLATP142
	21PE10.3,' SIEMENS PER METER'/' NUMBER OF STRANDS= ',I2////)	FLATP143
	RWS=RWS*CHT	FLATP144
C		FLATP145
C	READ AND PRINT ENTRIES IN LOAD ADMITTANCE(IMPEDANCE) MATRICES	FLATP146
C	AND SHORT CIRCUIT CURRENT SOURCE(OPEN CIRCUIT VOLTAGE SOURCE)	FLATP147
C	VECTORS	FLATP148
C	(STORE ADMITTANCE(IMPEDANCE) MATRICES AT X=0 IN ARRAY Y0 AND	FLATP149
C	THOSE AT X=L IN ARRAY YL. STORE SHORT CIRCUIT CURRENT SOURCE	FLATP150
C	(OPEN CIRCUIT VOLTAGE SOURCE) VECTORS AT X=0 IN ARRAY I0 AND	FLATP151
C	THOSE AT X=L IN ARRAY IL.)	FLATP152
C		FLATP153
	IF (OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 17	FLATP154
	WRITE(6,15)	FLATP155
	15 FORMAT (//,18X,'ADMITTANCE AT X=0',10X,'CURRENT SOURCE AT X=0',	FLATP156
	112X,'ADMITTANCE AT X=L',10X,'CURRENT SOURCE AT X=L'//)	FLATP157
	WRITE(6,16)	FLATP158
	16 FORMAT (21X,' (SIEMENS) ',23X,' (AMPS) ',22X,' (SIEMENS) ',23X,' (AMPS) '//)	FLATP159
	GO TO 20	FLATP160
	17 WRITE(6,18)	FLATP161
	18 FORMAT (//,18X,'IMPEDANCE AT X=0',11X,'VOLTAGE SOURCE AT X=0',	FLATP162
	112X,'IMPEDANCE AT X=L',11X,'VOLTAGE SOURCE AT X=L'//)	FLATP163
	WRITE(6,19)	FLATP164
	19 FORMAT (23X,' (OHMS) ',23X,' (VOLTS) ',24X,' (OHMS) ',23X,' (VOLTS) '//)	FLATP165
	20 WRITE(6,21)	FLATP166
	21 FORMAT (' ENTRY',10X,'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG',11X,	FLATP167
	1'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG'//)	FLATP168
	DO 24 I=1,N	FLATP169
	READ(5,22) Y0R,Y0I,I0(I),YLR,YLI,IL(I)	FLATP170
	22 FORMAT(8(E10.3))	FLATP171
	Y0(I,I)=Y0R+XJ*Y0I	FLATP172
	YL(I,I)=YLR+XJ*YLI	FLATP173
	WRITE(6,23) I,I,Y0(I,I),I0(I),YL(I,I),IL(I)	FLATP174
	23 FORMAT(1X,I2,2X,I2,8(5X,1PE10.3) /)	FLATP175
	24 CONTINUE	FLATP176
	IF (OPTION.EQ.11.OR.OPTION.EQ.21) GO TO 28	FLATP177
	IF (N.EQ.1) GO TO 28	FLATP178
	K1=N-1	FLATP179
	DO 27 I=1,K1	FLATP180
	K2=I+1	FLATP181
	DO 27 J=K2,N	FLATP182
	READ(5,25) Y0R,Y0I,YLR,YLI	FLATP183

25	FORMAT (2 (E10.3), 20X, 2 (E10.3))	PLATP184
	Y0 (I,J)=Y0B+XJ*Y0I	PLATP185
	YL (I,J)=YLB+XJ*YLI	PLATP186
	Y0 (J,I)=Y0 (I,J)	PLATP187
	YL (J,I)=YL (I,J)	PLATP188
	WRITE (6,26) I,J,Y0 (I,J),YL (I,J)	PLATP189
26	FORMAT (1X,I2,2X,I2,2 (5X,1PE10.3),30X,2 (5X,1PE10.3))	PLATP190
27	CONTINUE	PLATP191
C		PLATP192
C	COMPUTE AND STORE THE MATRICES AND VECTORS C*Z0, C*ZL, C*V0, C*VL	PLATP193
C	FOR THE THEVENIN EQUIVALENT OR Y0*CINV, YL*CINV, I0, IL FOR THE	PLATP194
C	NORTON EQUIVALENT IN ARRAYS M1,M2,V1,V2, RESPECTIVELY	PLATP195
C		PLATP196
28	IF (OPTION.EQ.11) GO TO 29	PLATP197
	IF (OPTION.EQ.12) GO TO 32	PLATP198
	IF (OPTION.EQ.21) GO TO 36	PLATP199
	IF (OPTION.EQ.22) GO TO 39	PLATP200
29	DO 31 I=1,N	PLATP201
	S0=ZEROC	PLATP202
	SL=ZEROC	PLATP203
	DO 30 J=1,N	PLATP204
	M1 (I,J)=C (I,J)*Y0 (J,J)	PLATP205
	M2 (I,J)=C (I,J)*YL (J,J)	PLATP206
	S0=S0+C (I,J)*I0 (J)	PLATP207
30	SL=SL+C (I,J)*IL (J)	PLATP208
	V1 (I)=S0	PLATP209
31	V2 (I)=SL	PLATP210
	GO TO 43	PLATP211
32	DO 35 I=1,N	PLATP212
	S0=ZEROC	PLATP213
	SL=ZEROC	PLATP214
	DO 34 J=1,N	PLATP215
	SUM0=ZEROC	PLATP216
	SUML=ZEROC	PLATP217
	DO 33 K=1,N	PLATP218
	SUM0=SUM0+C (I,K)*Y0 (K,J)	PLATP219
33	SUML=SUML+C (I,K)*YL (K,J)	PLATP220
	S0=S0+C (I,J)*I0 (J)	PLATP221
	SL=SL+C (I,J)*IL (J)	PLATP222
	M1 (I,J)=SUM0	PLATP223
34	M2 (I,J)=SUML	PLATP224
	V1 (I)=S0	PLATP225
35	V2 (I)=SL	PLATP226
	GO TO 43	PLATP227
36	DO 38 I=1,N	PLATP228
	DO 37 J=1,N	PLATP229
	M1 (I,J)=Y0 (I,I)*CI (I,J)	PLATP230
37	M2 (I,J)=YL (I,I)*CI (I,J)	PLATP231
	V1 (I)=I0 (I)	PLATP232
38	V2 (I)=IL (I)	PLATP233
	GO TO 43	PLATP234
39	DO 42 I=1,N	PLATP235
	DO 41 J=1,N	PLATP236
	SUM0=ZEROC	PLATP237
	SUML=ZEROC	PLATP238
	DO 40 K=1,N	PLATP239
	SUM0=SUM0+Y0 (I,K)*CI (K,J)	PLATP240
40	SUML=SUML+YL (I,K)*CI (K,J)	PLATP241
	M1 (I,J)=SUM0	PLATP242
41	M2 (I,J)=SUML	PLATP243
	V1 (I)=I0 (I)	PLATP244

42	V2(I)=IL(I)	FLATP245
43	CONTIN E	FLATP246
C		FLATP247
C	COMPUTE THE MATRIX C*L AND STORE IN ARRAY CO. COMPUTE THE SUMS	FLATP248
C	OF ELEMENTS IN EACH ROW OF C AND STORE IN ARRAY V3.	FLATP249
C		FLATP250
	DO 46 I=1,N	FLATP251
	S=ZERO	FLATP252
	DO 45 J=1,N	FLATP253
	SS=ZERO	FLATP254
	DO 44 K=1,N	FLATP255
44	SS=SS+C(I,K)*CO(K,J)	FLATP256
	P(I,J)=SS*ONEC	FLATP257
45	S=S+C(I,J)	FLATP258
46	V3(I)=S	FLATP259
	DO 47 I=1,N	FLATP260
	DO 47 J=1,N	FLATP261
47	CO(I,J)=DREAL(P(I,J))	FLATP262
C		FLATP263
C	*****FREQUENCY DEPENDENT CALCULATIONS*****	FLATP264
C		FLATP265
48	CONTINUE	FLATP266
	READ(5,49,END=81) F	FLATP267
49	FORMAT (E10.3)	FLATP268
	OMEGA=TWC*PI*F	FLATP269
	JOMEGA=XJ*OMEGA	FLATP270
C		FLATP271
C	COMPUTE THE WIRE SELF IMPEDANCES	FLATP272
C		FLATP273
	LDC=HWO8PI	FLATP274
	DELTA=ONE/(TWO*PI*DSQRT(SIG*F*HWO4PI))	FLATP275
	RDC=ONE/(PI*SIG*RWS*RWS)	FLATP276
	IF(RWS.LE.DELTA) GO TO 50	FLATP277
	IF(RWS.GE.THREE*DELTA) GO TO 51	FLATP278
	Z=(P25*(RWS/DELTA+THREE)*RDC+JOMEGA*(ONEP15-P15*RWS/DELTA)*LDC)/NS	FLATP279
	GO TO 52	FLATP280
50	Z=(RDC+JOMEGA*LDC)/NS	FLATP281
	GO TO 52	FLATP282
51	Z=(P5*RWS*RDC/DELTA+JOMEGA*TWO*DELTA*LDC/RWS)/NS	FLATP283
C		FLATP284
C	COMPUTE THE EIGENVALUES AND THE EIGENVECTORS OF THE PRODUCT YZ	FLATP285
C	(STORE THE EIGENVECTORS AS COLUMNS OF ARRAY T AND THE EIGENVALUES	FLATP286
C	IN ARRAY B)	FLATP287
C		FLATP288
52	OM2=OMEGA*OMEGA	FLATP289
	DO 53 I=1,N	FLATP290
	DO 53 J=1,N	FLATP291
53	A(I,J)=JOMEGA*Z*(V3(I)+C(I,J))-OM2*CO(I,J)	FLATP292
	CALL EIGCC(A,N,N,2,B,T,N,WK,LER)	FLATP293
	LER=LER-128	FLATP294
	IF(LER.LT.1) LER=0	FLATP295
C		FLATP296
C	COMPUTE THE INVERSE OF THE TRANSFORMATION MATRIX, T	FLATP297
C	(STORE THE INVERSE IN ARRAY TI)	FLATP298
C		FLATP299
	DO 55 I=1,N	FLATP300
	DO 54 J=1,N	FLATP301
	A(I,J)=T(I,J)	FLATP302
54	TI(I,J)=ZEROC	FLATP303
55	TI(I,I)=ONEC	FLATP304
	CALL LEQTIC(A,N,N,TI,N,N,0,WA,HER)	FLATP305

	NER=NER-128	FLATP306
	IF (NER.NE.1) NER=0	FLATP307
C		FLATP308
C	COMPUTE THE TERMINAL VOLTAGES	FLATP309
C		FLATP310
C	FORM THE EQUATIONS	FLATP311
		FLATP312
	DO 58 I=1,N	FLATP313
	S0=ZEROC	FLATP314
	SL=ZEROC	FLATP315
	DO 57 J=1,N	FLATP316
	SUN0=ZEROC	FLATP317
	SUNL=ZEROC	FLATP318
	DO 56 K=1,N	FLATP319
	SUN0=SUN0+H1(I,K)*T(K,J)	FLATP320
56	SUNL=SUNL+H2(I,K)*T(K,J)	FLATP321
	S0=S0+TI(I,J)*V1(J)	FLATP322
	SL=SL+TI(I,J)*V2(J)	FLATP323
	A(I,J)=SUN0	FLATP324
57	P(I,J)=SUNL	FLATP325
	IO(I)=S0	FLATP326
	IL(I)=SL	FLATP327
	IF (OPTION.EQ.11.OR.OPTION.EQ.12) IL(I)=-IL(I)	FLATP328
	GAM=CDSQRT(B(I))	FLATP329
	EPP=CDEXP(GAM*L)*P5	FLATP330
	ENN=CDEXP(-GAM*L)*P5	FLATP331
	EP(I)=EPP+ENN	FLATP332
	EN(I)=EPP-ENN	FLATP333
	G(I)=GAM/JOMEGA	FLATP334
	IF (OPTION.EQ.11.OR.OPTION.EQ.12) G(I)=ONEC/G(I)	FLATP335
58	CONTINUE	FLATP336
	DO 60 I=1,N	FLATP337
	DO 60 J=1,N	FLATP338
	SUN0=ZEROC	FLATP339
	SUNL=ZEROC	FLATP340
	DO 59 K=1,N	FLATP341
	SUN0=SUN0+TI(I,K)*A(K,J)	FLATP342
59	SUNL=SUNL+TI(I,K)*P(K,J)	FLATP343
	YO(I,J)=SUN0	FLATP344
60	YL(I,J)=SUNL	FLATP345
	DO 63 I=1,N	FLATP346
	S0=ZEROC	FLATP347
	DO 62 J=1,N	FLATP348
	SL=ZEROC	FLATP349
	DO 61 K=1,N	FLATP350
61	SL=SL+YL(I,K)*G(K)*EN(K)*YO(K,J)	FLATP351
	A(I,J)=SI+YL(I,J)*EP(J)+YO(I,J)*EP(I)	FLATP352
62	S0=S0+YL(I,J)*G(J)*EN(J)*IO(J)	FLATP353
	A(I,I)=A(I,I)+EN(I)/G(I)	FLATP354
63	B(I)=S0+EP(I)*IO(I)+IL(I)	FLATP355
C		FLATP356
C	SOLVE THE EQUATIONS	FLATP357
		FLATP358
	CALL LEQ1C(A,N,N,B,1,N,0,WA,IER)	FLATP359
	IER=IER-128	FLATP360
	IF (IER.NE.1) IER=0	FLATP361
	WRITE(6,64) P,IER	FLATP362
64	FORMAT(1H1,' FREQUENCY(HERTZ)= ',1PE11.4,10X,' SOLUTION ERROR= ',	FLATP363
	12X,12/)	FLATP364
	WRITE(6,65) IER,WK(1)	FLATP365
65	FORMAT(' EIGEN SOLUTION ERROR= ',14/ ' EIGEN SOLUTION PRECISION= ',	FLATP366

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11PE10.3/)
WRITE(6,66) NER
66 FORMAT(' TRANSFORMATION MATRIX INVERSION ERROR= ',I2//)
WRITE(6,67)
67 FORMAT(16X,'WIRE',8X,'VON(VOLTS)',3X,'VOA(DEGREES)',8X,
1'VLN(VOLTS)',3X,'VLA(DEGREES)')///)
C
C COMPUTE AND PRINT THE TERMINAL VOLTAGES
C
DO 69 I=1,N
S0=ZEROC
DO 68 J=1,N
68 S0=S0+Y0(I,J)*B(J)
69 G(I)=-G(I)*EN(I)+IO(I)-EP(I)*B(I)+G(I)*EN(I)*S0
IF (OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 74
DO 71 I=1,N
S0=ZEROC
SL=ZEROC
DO 70 J=1,N
S0=S0-Y0(I,J)*B(J)
70 SL=SL+YL(I,J)*G(J)
Y0(I,I)=IO(I)+S0
71 YL(I,I)=-IL(I)+SL
DO 73 I=1,N
S0=ZEROC
SL=ZEROC
DO 72 J=1,N
S0=S0+T(I,J)*Y0(J,J)
72 SL=SL+T(I,J)*YL(J,J)
P(I,I)=S0
73 A(I,I)=SL
GO TO 77
74 DO 76 I=1,N
S0=ZEROC
SL=ZEROC
DO 75 J=1,N
S0=S0+T(I,J)*B(J)
75 SL=SL+T(I,J)*G(J)
P(I,I)=S0
76 A(I,I)=SL
77 DO 80 I=1,N
S0=ZEROC
SL=ZEROC
DO 78 J=1,N
S0=S0+CI(I,J)*P(J,J)
78 SL=SL+CI(I,J)*A(J,J)
V0=S0
VL=SL
VON=CDABS(V0)
VLN=CDABS(VL)
VOR=DREAL(V0)
VOI=DIMAG(V0)
VLR=DREAL(VL)
VLI=DIMAG(VL)
IF (VOR.EQ.ZERO.AND.VOI.EQ.ZERO) VOR=CNE
IF (VLR.EQ.ZERO.AND.VLI.EQ.ZERO) VLR=CNE
VOA=DATAN2(VOI,VOR)*ONE80/PI
VLA=DATAN2(VLI,VLR)*ONE80/PI
WRITE(6,79) I,VON,VOA,VLN,VLA
79 FORMAT(17X,I2,8X,1PE10.3,3X,1PE10.3,10X,1PE10.3,3X,1PE10.3/)
80 CONTINUE

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FLATP367
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FLATP427

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GO TO 48
81 STOP
END

FLATP428
FLATP429
FLATP430

TABLE D-1Changes in FLATPAK2 to Convert
to Single Precision Arithmetic

Delete Card 051

<u>Card Number</u>	<u>Double</u>	<u>Single</u>
053	REAL *8	REAL
055	COMPLEX *16	COMPLEX
059	3.141592653D0	3.1415926E0
059	2.997925D8	2.997925E8
060-062	change all D's to	E's
064	DCMPLX(0.D0,0.D0)	CMPLX(0.E0,0.E0)
065	DCMPLX(1.D0,0.D0)	CMPLX(1.E0,0.E0)
066	DCMPLX(0.D0,1.D0)	CMPLX(0.E0,1.E0)
132	DREAL	REAL
133	DREAL	REAL
262	DREAL	REAL
275	DSQRT	SQRT
329	CDSQRT	CSQRT
330	CDEXP	CEXP
331	CDEXP	CEXP
415	CDABS	CABS
416	CDABS	CABS
417	DREAL	REAL
418	DIMAG	AIMAG
419	DREAL	REAL
420	DIMAG	AIMAG

Card Number

Double

Single

423

DATAN2

ATAN2

424

DATAN2

ATAN2

APPENDIX E

NROOT

Subroutine Listing

```

SUBROUTINE NROOT(M,A,B,XL,X,MA)
REAL*8 A(MA),B(MA),XL(M),X(MA),SUMV,ZERO,ONE
DATA ZERO/0.D0/,ONE/1.D0/
K=1
DO 1 J=2,M
  I=M*(J-1)
  DO 1 I=1,J
    L=L+1
    K=K+1
1  B(K)=B(L)
  MV=0
  CALL EIGEN(B,X,M,MV,M*M)
  L=0
  DO 2 J=1,M
    L=L+J
2  XL(J)=ONE/DSQRT(DABS(B(L)))
  K=0
  DO 3 J=1,M
    DO 3 I=1,M
      K=K+1
3  B(K)=X(K)*XL(J)
  DO 4 I=1,M
    N2=0
    DO 4 J=1,M
      N1=M*(I-1)
      L=M*(J-1)+I
      X(L)=ZERO
      DO 4 K=1,M
        N1=N1+1
        N2=N2+1
4  X(L)=X(L)+B(N1)*A(N2)
  L=0
  DO 5 J=1,M
    DO 5 I=1,J
      N1=I-M
      N2=K*(J-1)
      L=L+1
      A(L)=ZERO
      DO 5 K=1,M
        N1=N1+M
        N2=N2+1
5  A(L)=A(L)+X(N1)*B(N2)
  CALL EIGEN(A,X,M,MV,M*M)
  L=0
  DO 6 I=1,M
    L=L+I
6  XL(I)=A(L)
  DO 7 I=1,M
    N2=0
    DO 7 J=1,M
      N1=I-M
      L=M*(J-1)+I
      A(L)=ZERO
      DO 7 K=1,M
        N1=N1+M
        N2=N2+1
7  A(L)=A(L)+B(N1)*X(N2)
  K=0
  DO 8 J=1,M
    DO 8 I=1,M
      K=K+1

```

NROOT001
 NROOT002
 NROOT003
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 NROOT061

8 X(K)=A(K)
RETURN
END

NR00T062
NR00T063
NR00T064

TABLE E-1

Changes in NROOT to Convert
to Single Precision Arithmetic

<u>Card Number</u>		<u>Double</u>		<u>Single</u>
002		REAL *8		REAL
003	change all	D's	to	E's
016		DSQRT		SQRT
016		DABS		ABS

APPENDIX F

EICEN

Subroutine Listing

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SUBROUTINE EIGEN(A,R,N,HV,HA)
REAL*8 A(HA),R(HA),ANORM,ANRMX,THR,X,Y,SINX,SINX2,COSX,COSX2,
1SINCS,RANGE,ZERO,ONE,P5,TWO
DATA ZERO/0.D0/,ONE/1.D0/,P5/.5D0/,TWO/2.D0/
1 RANGE=1.0D-12
IF(HV-1) 2,5,2
2 IQ=-N
DO 4 J=1,N
IQ=IQ+N
DO 4 I=1,N
IJ=IQ+I
R(IJ)=ZERO
IF(I-J) 4,3,4
3 R(IJ)=ONE
4 CONTINUE
5 ANORM=ZERO
DO 7 I=1,N
DO 7 J=I,N
IF(I-J) 6,7,6
6 IA=I+(J-J-J)/2
ANORM=ANORM+A(IA)*A(IA)
7 CONTINUE
IF(ANORM) 36,36,8
8 ANORM=DSQRT(TWO)*DSQRT(ANORM)
ANRMX=ANORM*RANGE/FLOAT(N)
IND=0
THR=ANORM
9 THR=THR/FLOAT(N)
10 L=1
11 M=L+1
12 HQ=(M*M-M)/2
LQ=(L*L-L)/2
MH=M+AQ
13 IF(DABS(A(LM))-THR) 29,14,14
14 IND=1
LL=L+1Q
MM=M+MQ
X=P5*(A(LL)-A(MM))
15 Y=-A(LM)/DSQRT(A(LM)*A(LM)+X*X)
IF(X) 16,17,17
16 Y=-Y
17 SINX=Y/DSQRT(TWO*(ONE+(DSQRT(ONE-Y*Y))))
SINX2=SINX*SINX
18 COSX=DSQRT(ONE-SINX2)
COSX2=COSX*COSX
SINCS=SINX*COSX
ILQ=M*(L-1)
INQ=M*(M-1)
DO 28 I=1,N
IQ=(I*I-I)/2
IF(I-L) 19,26,19
19 IF(I-M) 20,26,21
20 IM=I+MQ
GO TO 22
21 IM=M+IQ
22 IF(I-L) 23,24,24
23 IL=I+LQ
GO TO 25
24 IL=L+IQ
25 X=A(IL)*COSX-A(IM)*SINX
A(IM)=A(IL)*SINX+A(IM)*COSX

```

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EIGEN001
EIGEN002
EIGEN003
EIGEN004
EIGEN005
EIGEN006
EIGEN007
EIGEN008
EIGEN009
EIGEN010
EIGEN011
EIGEN012
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EIGEN014
EIGEN015
EIGEN016
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EIGEN054
EIGEN055
EIGEN056
EIGEN057
EIGEN058
EIGEN059
EIGEN060
EIGEN061

```

A(IL)=X	EIGEN062
26 IF (NV-1) 27,28,27	EIGEN063
27 ILR=ILQ+I	EIGEN064
INR=INQ+I	EIGEN065
X=R(ILR)*COSX-R(INR)*SINX	EIGEN066
R(INR)=R(ILR)*SINX+R(INR)*COSX	EIGEN067
R(ILR)=X	EIGEN068
28 CONTINUE	EIGEN069
X=TWO*A(LH)*SINCS	EIGEN070
Y=A(LL)*COSX2+A(HH)*SINX2-X	EIGEN071
X=A(LL)*SINX2+A(HH)*COSX2+Y	EIGEN072
A(LH)=(A(LL)-A(HH))*SINCS+A(LH)*(COSX2-SINX2)	EIGEN073
A(LL)=Y	EIGEN074
A(HH)=X	EIGEN075
29 IF (H-M) 30,31,30	EIGEN076
30 H=H+1	EIGEN077
GO TO 12	EIGEN078
31 IF (L-(N-1)) 32,33,32	EIGEN079
32 L=L+1	EIGEN080
GO TO 11	EIGEN081
33 IF (IND-1) 35,34,35	EIGEN082
34 IND=0	EIGEN083
GO TO 10	EIGEN084
35 IF (THR-ANRNX) 36,36,9	EIGEN085
36 IQ=-N	EIGEN086
DO 20 I=1,N	EIGEN087
IQ=I+N	EIGEN088
LL=I-(I*I-I)/2	EIGEN089
JQ=N*(I-2)	EIGEN090
DO 40 J=1,N	EIGEN091
JQ=JQ+N	EIGEN092
HH=J+(J*J-J)/2	EIGEN093
IF (A(LL)-A(HH)) 37,40,40	EIGEN094
37 X=A(LL)	EIGEN095
A(LL)=A(HH)	EIGEN096
A(HH)=X	EIGEN097
IF (NV-1) 38,40,38	EIGEN098
38 DO 39 K=1,N	EIGEN099
ILR=IQ+K	EIGEN100
INR=JQ+K	EIGEN101
X=R(ILR)	EIGEN102
R(ILR)=R(INR)	EIGEN103
39 R(INR)=X	EIGEN104
40 CONTINUE	EIGEN105
RETURN	EIGEN106
END	EIGEN107

TABLE F-1
Changes in EIGEN to Convert
to Single Precision Arithmetic

<u>Card Number</u>		<u>Double</u>		<u>Single</u>
002		REAL *8		REAL
004	change all	D's	to	E's
005		1.0D-12		1.0E-6
024		DSQRT		SQRT
024		DSQRT		SQRT
034		DABS		ABS
039		DSQRT		SQRT
042		DSQRT		SQRT
042		DSQRT		SQRT
044		DSQRT		SQRT