NASAP-70
USER'S AND PROGRAMMER'S MANUAL
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NASAP-70 USER'S AND PROGRAMMER'S MANUAL

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PREFACE

The study for this report was carried out in the Computer Science Department, University of California, Los Angeles, under National Aeronautics and Space Administration Contract NAS 12-2138.

The development of the program and the preparation of this manual was a cooperative effort. We acknowledge the cooperation, patience, and understanding of Dr. W. W. Happ of the Electronics Research Center of NASA. We also express our appreciation to our sister universities and other NASAP-70 participants for their suggestions and help.

Within UCLA the cooperative spirit has also prevailed. Our thanks and appreciation go to: Alfred Tyrill, who programmed the Fast Fourier Transform and plotter; David Paletz, who programmed the algorithm for building optimum circuit trees at a given frequency and the transfer function printout, Steve Grandi, who programmed the sensitivity analysis routines, Mrs. Donnamae Meyerhoff for her excellent survey of transient models and the background study in radiation effects in solid state devices, Dennis Sesar for this critical review of the computational errors and run time limitations of NASAP-70, and Michael Wilson who investigated the application of NASAP-70 to large scale problems.
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CHAPTER 1
THE NASAP-70 PROJECT

1.0 Introduction

NASAP-70 is a digital circuit analysis program developed at UCLA with the cooperation and advice of a number of University, industrial, and governmental research groups located in virtually all sections of the United States. The program consists of a number of commonly required circuit analysis routines that are based upon the flowgraph techniques and algorithms of W. W. Happ and others.\(^1\) As was pointed out by Happ, two distinct advantages can be realized (1) The requirement for writing a set of independent circuit equations is eliminated, and (2) the resulting flowgraph is unique. Because of these characteristics and the modular manner in which the program is constructed, algorithms can easily be mechanized, changed, and expanded for digital computation.

The program documented herein is the final installment of this cooperative project initiated by the Electronics Research Center of NASA four years ago.

1.1 Capabilities and Limitations

NASAP-70 can handle linear circuits consisting of constant-value passive elements, independent and dependent current sources, and independent and dependent voltage sources. The dependent sources must be linearly related to a voltage or current located in another part of the circuit. Nonlinear functional relationships (dependencies) and time-varying parameters cannot be handled in general. However, provisions have been included to accommodate a single nonlinear or external characteristic in resistors as advanced by Haag and Weber\(^4\)
Central to the NASAP-70 program is its capability to formulate transfer functions from a topological description of the circuit and its numerical specification of components. The format of the input code, selected by a user, dictate the manner by which a transfer function is derived by the program. The following input codes, identified by the names NASAP, TREE, and CIRCUIT, can be employed

1. **NASAP** - directs the program to form its own tree and transfer function.
2. **TREE** - allows a user to define his own tree from which a transfer function can then be constructed by the program.
3. **CIRCUIT** - directs the program to select a tree by which a transfer function is constructed according to a user specified frequency to assure relatively accurate coefficients.

With one minor, but practical exception, a transfer function, relating a voltage across or a current through an element to either a driving voltage or current source, can in general be requested. Any number of transfer function requests can be made in any given computer run. The transfer function formulations are printed out as a ratio of two polynomials in S with numerical coefficients.

In conjunction with a particular transfer function request, a user can ask for

1. **The sensitivity of a transfer function to changes in circuit parameters** - A maximum of twenty valid sensitivity requests can be processed for each circuit. The sensitivity function is printed as a ratio of two polynomials in S with numerical coefficients.
2. **A worst case analysis** - For circuits of twenty elements or less (not counting independent voltage or current sources) a worst case analysis can be formulated as a ratio of two polynomials in S with numerical coefficients. Tolerances for each element can be user-specified or defaulted automatically with 10% values by the program.
3. **Poles and zeros of all transfer functions**

4. **The sensitivity of poles** - When pole sensitivity is requested, it is implied that it is formulated for all elements for which a sensitivity request had been issued.

5. **Transient response** - A user can request a transient response of any transfer function for an impulse, a step function, a sine wave, an exponential, a biased pulse, or pulse train driving function.

6. **An A.C. frequency response (Bode Plot)**

The output format for the transient, A.C. frequency response, sensitivity and worst case analysis functions can be presented by either tables, printer plots or both. The input data is written on a free-field format. Diagnostics are provided for reading the input circuit description cards. If mistakes are relatively minor, corrections are made automatically by the program and are printed out to inform the user of the changes made. The program will not abort a run unless a serious error (one which cannot be easily interpreted) is encountered. The normal input is by cards. An on-line version of NASAP-70 has been developed but is not documented here.

NASAP-70 has been written completely in FORTRAN IV and has been developed on the IBM 360/91 and run on the SDS Sigma Seven Digital Computers at UCLA. It has been successfully converted to other machines by other research groups at installations across the country. By means of overlays, approximately 32K of core memory is required to handle circuits consisting of 30 elements.

The maximum number of elements that NASAP-70 can accommodate in practice is determined by the number of bits in the computer word. Even though computer words, in essence, are extended by software, circuits with more than 30 elements cannot be handled efficiently by the 32 bit IBM machines. Other machines with longer data words, such as the CDC 6600, can accommodate larger circuit problems.
1.2 Historical Perspective

To properly understand the place that NASAP-70 takes in the computer-aided design field, it is fitting to trace the development of the field, in general, and contrast it with NASAP-70. Typical circuit design programs, such as ECAP, SCEPTRE, NET-1, and CIRCUS derive their conceptual foundation from the treatise of Gabriel Kron, who was the first person to systematize circuit equations for solution by digital techniques.\(^5\)

Kron noted that the topological-algebraic structure of networks could be treated separately in formulating mesh, nodal, and branch equations from a primitive set of ohmic relations. Even to this day, the influence of Kron's pioneering efforts are still being felt in all the major circuit program developments, including NASAP-70.

Kron's ideas, which were presented from an engineering point of view, were formally studied by J. Paul Roth who proved the interrelationship of the topological-algebraic structure of networks from an abstract mathematical position.\(^6\) Even though Kron's work was known for a couple of decades, it never achieved popularity until Seshu and Reed published their papers and a book in which a rigorous proof of network theory was presented in a manner palatable to engineers.\(^7\),\(^8\)

Since that time, the field of computer-aided circuit design has exploded attracting outstanding investigators from many engineering and science fields. Noteworthy among the investigators are Branin, Bashkow, Calahan, Katzenelson, Malmberg, Kuh, Rohrer, Desoer, and many others.\(^9\)\(^-\)\(^16\)

All of these researches advocated the matrix or state space method dealing with circuit problems. NASAP-70, on the other hand, with its flowgraph approach, traces its origin to Claude Shannon who discovered
the topological gain formula while investigating the functional operation of an analog computer.\footnote{During World War II, Claude Shannon developed his formula. But because of wartime restrictions, his work was not published and was virtually unknown to the academic community. In 1952, Samuel Mason rediscovered the same formula.} Shannon's formula which is an analytic equation for calculating the gain for an open loop system (circuit) was generalized by W. W. Happ to include closed systems.\footnote{During World War II, Claude Shannon developed his formula. But because of wartime restrictions, his work was not published and was virtually unknown to the academic community. In 1952, Samuel Mason rediscovered the same formula.} The Shannon-Happ formula fabricates the backbone of NASAP-70 upon which the transfer function, sensitivity, and frequency response of a large class of linear systems can be computed.

The NASAP project was started approximately four years ago at the Electronics Research Center of NASA with the Shannon-Happ formula as a programming kernel. The first year was devoted to program development which included transfer function, sensitivity, and A.C. frequency response capabilities. The second and third years brought further program development and application studies into areas of NASA research. This past year the NASAP project came to a close. The final version of the NASAP program, called NASAP-70, is documented herein. In addition, seven applications manuals are being written in the areas of Electronic Filter Design, Instrumentation Circuits, Biomedical Circuits, Communication Circuits, and others.\footnote{During World War II, Claude Shannon developed his formula. But because of wartime restrictions, his work was not published and was virtually unknown to the academic community. In 1952, Samuel Mason rediscovered the same formula.}

1.3 Format of the Manual

The manual is divided into two parts: (1) A User's Guide, which is made up of Chapters 2 and 3, and Appendices B and C, and (2) a Programmer's Manual which consists of Chapters 4 and 5, and the program listing and dictionary of program variables in Appendix A.

In Chapter 2, the fundamentals of setting up a problem for NASAP-70 are presented without any deep discussion of the theory involved. It has been written, however, to show the program can be used for large problems, and how computing time and computational errors can be predicted and reconciled.
The theory behind NASAP-70 has been reserved for Chapter 3. Appendix B describes the most popular transistor models in use today, and includes a discourse of environmental effects (radiation) on transistor models.

Chapter 4 contains a detailed description of the NASAP program. This chapter should be read in conjunction with Appendix A, the program listing and dictionary of variables. Chapter 5 describes the system requirements for implementing NASAP-70.

The format of the User's Guide and Programmer's Manual has been designed to place those topics which can usually be self-contained in an individual chapter. It is for this reason that all references pertinent to a chapter have been placed at the end of that chapter. The format of the manual also provides a convenient method to add, delete, or change portions of the manual without disrupting larger segments of the entire manual.
REFERENCES


1-7
PART I THE USER'S GUIDE

CHAPTER 2

A USER'S VIEWPOINT

2.0 Introduction

This chapter describes the step-by-step procedure of how to prepare a circuit for analysis by NASAP-70. The discussion has been restricted to an explanation of the rudiments of coding and does not include a detailed study of circuit theory or programming. That has been reserved for Chapter Chapters 3, 4 and 5. Examples have been dispersed throughout the discussion. Also included are some design tips from a user's viewpoint of NASAP-70, partitioning schemes, error analysis, and nonlinear techniques.

It must be emphasized, however, that if one is to really achieve a good design, a deeper understanding of circuit theory, and the advantages and limitations of computer methods contained herein are necessary. To that end the user is encouraged to read the articles and books referenced at the end of the chapter. 1-4

2.1 Preliminary Considerations and Modeling

Before any problem is coded for a computer run, it is important to make a check on the validity of the circuit itself and the device models. Difficulty usually arises when some physical device, such as a transistor, diode, etc., is replaced by a lumped parameter model made up of some dependent active devices and passive elements, and inserted into the remaining network without really looking for such conflicts as two electrically difference current sources placed in series, or two electrically different voltage sources placed in parallel. In general, no loop in a circuit may consist entirely of voltage sources, including independent and dependent sources, nor should any node be formed entirely of branches in which only independent and dependent current sources are present. If such
a case should occur, it would mean that NASAP-70 (or any other program for that matter) would not be able to formulate a set of independent equations necessary for solution since it violates the fundamental conservation of energy law.

It is also imperative to have a circuit designer select the appropriate model for a physical device. Quite often the model chosen has been derived for one type of operation and is assumed to be valid for another. All models are restricted to some extent. There are A.C., D.C., and transient models, some are considered small signal or large signal, while others are considered low frequency or high frequency. There are also the so-called environmental and radiation-effect models. Generally speaking, all models are appropriate only for the particular application for which they were derived, and if a circuit designer places a model in a universal catch-all role, only misleading results can occur.

In Appendix B descriptions of typical transistor models have been compiled and classified according to the intended use. Also include there is a tabulation of how the model parameters can be calculated from the manufacturer's device specifications. A rather in-depth study of solid-state modeling for a radiation environment is also given.

Besides modeling, other difficulties can appear when a complicated circuit is approximated by reducing the number of circuit. All too often, entire sections of a circuit are replaced by a simple series or parallel circuit, the cumulated practice of which can eliminate critical modes of circuit operations. As is usually the case, the circuit designer is so preoccupied with establishing models or reducing the size of the circuit in order to code it for the computer that he completely loses the physical realization of the problem itself. No matter how carefully a computer program is conceived, its operation can be completely frustrated by improper use by circuit designers who consistently violate sound engineering practice for the sake of accommodating a computer program.
2.2 Circuit Preparation

Once an appropriate circuit configuration has been established, making certain that no physical inconsistencies exist, the step-by-step preparation procedure for coding NASAP-70 can then be carried out. The procedure recommended here is described by means of an example circuit problem shown in Figure 2.1(a) which calls for an A.C. transfer function relating the voltage $V_{\text{out}}$ across the inductor to the input voltage $V_{\text{in}}^4$. The A.C. equivalent circuit is shown in Figure 2.1(b). Note that the battery has been replaced by its internal impedance of zero ohms and the transistor has been modeled by a simple input resistor and a dependent current generator placed in parallel with an output resistor. (High frequency effects are not considered here and actually are not required to illustrate the preparation procedure.)

Assuming that the circuit model in Figure 2.1(b) is adequate for the desired analysis, the initial preparation of coding for NASAP-70 requires that a unique identification be imposed on the topology of the circuit, the circuit elements, and the dependencies. Consequently, the nodes are numbered consecutively starting with the number 1 and the elements are redefined according to a letter-number format, where each component is unambiguously determined, according to type, by one of three possible coding schemes described in section 2.3. No two components can have the same code identifications. Dependencies are indicated on the circuit diagram by a dash line which designates the current or voltage variable upon which the sources are dependent. This is done only as a crutch to remind the designer not to forget it when the circuit information is actually coded.

After the nodes are assigned numbers (topology), and the circuit elements and dependencies are distinguished, as shown in Figure 2.2 for the coding scheme NASAP, the unknown directed current variables must be assigned to each circuit branch element. Generally speaking, the current
(a) CIRCUIT DIAGRAM

(b) A.C. MODEL

Figure 2.1
Figure 2.2 Prepared Circuit Diagram for Coding Scheme NASAP

V1 = 1 volt  
C2 = 10μf  
R1 = 50 ohms  
β = 98  
C1 = 10 7 μf  
R5 = 2 megohms  
R4 = 25 ohms  
R2 = 20,000 ohms  
R3 = 325 ohms  
LI = 1.7 millihenrys

Figure 2.3 Voltage-Current Relationship of Elements
direction in each passive element can be assigned arbitrarily although some caution must be exercised in assigning currents to passive elements related to dependent sources. The current directions in active devices also must be handled with care so that the proper voltage-current relationship can be established.

**Voltage Sources.** The current direction associated with either an independent or dependent voltage source should be established in the positive sense of the voltage rise – from minus to plus – as shown in Figure 2.3(a). (An opposite rule could have been assumed but this would have required that a negative voltage value be read in with the input data. Since such a practice is somewhat unnatural to most circuit designers, it has been avoided here as a matter of good practice rather not that it cannot be done.) Following the current assignment rule as stated presents no difficulty when independent voltage sources are being considered, in general, the same rule can be applied to dependent voltage sources provided the dependency relationships are consistent with the physical phenomena involved. (A number of examples consisting of dependent sources have been included in this chapter and are described in sufficient detail to illustrate how the common current assignment rule for both dependent and independent voltage sources can be adopted.)

**Current Source** In dealing with either dependent or independent current sources, the positive voltage sense is taken in the direction of positive current flow as shown in Figure 2.3(b). Similar to the discussion concerning dependent voltage sources, the positive sense of the voltage across the dependent current source is the same as that defined for the independent current source provided the dependency relationship is consistent with the physical phenomenon. Examples are included to illustrate the procedure to be employed.

Figure 2.3 summarizes the current-voltage relationship for the dependent and independent active devices and passive elements. If the assignment of the current direction is in agreement with these configurations -
including the dependency considerations described below - the NASAP-70 program can then be properly coded.

Dependencies. A major concern of the NASAP-70 in programming dependency relationships is to assure that the proper sign is attached to the coded dependency parameter. Consider the transistor model shown in Figure 2.4(a) which has been extracted from the diagram of Figure 2.2. For this common emitter circuit, if a current flows into r_1, the dependent current source I_β will generate positive current flow as indicated in Figure 2.4(a). For the case depicted β is taken as a positive number, and thus the current can be expressed as I_β = βI_r_1. If the assigned current direction in r_1 is taken as in Figure 2.4(b) while the I_β direction of flow is retained, then the dependency parameter would be -β, a negative number. Therefore it is important that the physical dependency phenomenon be clearly understood for each device that is being modeled.

Another dependency example is shown in Figure 2.4(c). For this case a dependent voltage source V_µ is considered, where V_µ is linearly related to the voltage v_1 developed across the resistor r_1 as shown. In order to maintain the positive value of the parameter µ in the relation V_µ = µV_1, it is necessary that the positive sense of V_1 be taken across r_1 as the physical phenomenon dictates. Thus, this requires that the current through r_1 be assigned so that the desired voltage polarity of V_1 is produced.

Alternative measures can be taken, but practicality dictates that it is best to follow one rule because it leads to fewer errors and presents a better means for debugging. The user must be cognizant of the dependency relationship involved and code according to the plan best suited to his own tastes.

Once all the preparation steps are completed to uniquely identify the topology, the circuit elements, and the dependencies, and to assign the current direction in all the circuit elements - the circuit diagram is then ready for coding. Notice, for example, in Figure 2.2 that all the nodes
Figure 24 Dependency Parameters

\[ I_\beta = \beta I_{r_i} \]

\[ V_\mu = \mu V_1 \]
are numbered consecutively starting with the number 1. Zero and negative node numbers are not permitted. Also note that all circuit elements have been redefined to conform to the NASAP letter-number coding scheme (see Section 2.31). It must be emphasized that even though some of the elements could have the same value, they still have to be assigned different numbers in their respective letter-number symbol. The dependency relationship is illustrated by a broken line with the associated dependency parameter value placed in the middle of it.

2.3 Coding Mechanics

The general order of a NASAP-70 program deck is shown in Figure 2.5. The first group of cards allows a user to head the output listing with the title information punched on them. No more than ten cards are permitted.

The second group of cards contains the topology information, element designators, the values of the elements, and dependencies of the circuit to be analyzed. Three different circuit description coding rules can be utilized.

The last group of cards contain the desired output requests.

The title, circuit description, and output request cards are separated from each other by control cards. The necessary control card information is dictated by the circuit description format selected by a user.

Any number of individual problems can be processed during a computer run. However, the above mentioned order must be maintained for each problem. The last card of the entire group of cards must be a STOP card. Only one STOP card is allowed.

2.3.1 Circuit Description Codes

The circuit description coding rules are based upon a free-field format whereby each element identifier is written on a programming sheet, one to a line, with its corresponding topological, numerical, and dependency information. Thus a circuit composed of, say, 15 elements will require 15 cards, exclusive of the control and output request cards.
Title Cards

Control Card #1

Circuit Description
Cards
Topology
Element Identification
Numerical Values
Dependencies

Control Card #2

Output Request Cards:
Transfer Function
Pole Sensitivity
Parameter Sensitivity
Worst Case
Transient Response
Poles and Zeros
Frequency Response
Nonlinear Parametric
Response

Control Card #3

STOP Card

Figure 25
The three different code formats available in defining a circuit to NASAP-70 are identified to the program by punching one of the words: NASAP, TREE, or CIRCUIT on control card #1.

**NASAP**: For compatibility with other versions of NASAP, control card #1, with NASAP punched on it, will cause the program to accept the circuit description in the form presented in *A USER'S GUIDE AND PROGRAMMER'S MANUAL FOR NASAP* and *CODING INSTRUCTIONS FOR NASAP 69/I*. The NASAP coding of a circuit relieves the user of selecting a tree. Instead, the program automatically builds a tree that results in a transfer function being formed in a minimum of computation time.

The circuit coding requires that six fields of information be set down on each card, and since a free field format is employed, the ordering of the information must be taken into account. This is done by inserting at least one blank to separate the fields from each other, permitting the information to be inputted without regard to column orientation.

The general form of the circuit input data is:

\[
(\text{ELEMENT DESIGNATOR}) (\text{ORIGIN NODE}) (\text{TARGET NODE}) \begin{pmatrix} \text{NUMERICAL OR DEPENDENCY VALUE} \\ \text{UNITS (OPTIONAL)} \end{pmatrix} \text{DEPENDENCY DESIGNATOR}
\]

The parentheses are not allowed on the coding sheets, but are placed here for clarity sake.

The first letter of each ELEMENT DESIGNATOR must conform to the following relationship:

<table>
<thead>
<tr>
<th>Designator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Voltage Source</td>
</tr>
<tr>
<td>I</td>
<td>Current Source</td>
</tr>
<tr>
<td>C</td>
<td>Capacitor</td>
</tr>
<tr>
<td>L</td>
<td>Inductor</td>
</tr>
<tr>
<td>R</td>
<td>Resistor</td>
</tr>
</tbody>
</table>

Table 2.1
Any of those letters may be followed by up to 11 alphanumeric characters to bring the total number of characters in the ELEMENT DESIGNATOR to not more than 12.

The second and third fields contain the numbers of the origin node and the target (terminal) node, respectively, of the assigned current flow through the element. The fourth field accepts the numerical value of the circuit element, if the element is not a dependent source, and accepts the dependency parameter value if it is. The numerical values can be expressed in either decimal numbers with or without a decimal point, or in Fortran E-format.

The fifth field is an optional units field that allows a user to operate in other than the MKS system of units. In effect the units field is a scale factor multiplier to the numerical value field. The accepted symbols are given in Table 2.2. No mixing or interchanging of scale factors are permitted. If UNITS is not specified, MKS units are assumed.

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>SCALE FACTOR</th>
<th>MULTIPLIER</th>
</tr>
</thead>
<tbody>
<tr>
<td>RESISTOR</td>
<td>K</td>
<td>$10^3$</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>$10^6$</td>
</tr>
<tr>
<td>CAPACITOR</td>
<td>PF</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>UF</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>INDUCTOR</td>
<td>UH</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>MH</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

The sixth field position is employed only if a dependency exists, which is indicated by writing either an I, for current, or V, for voltage, followed by the element identifier of the element upon which the dependency exists.
With the "NASAP" coding rules, the prepared circuit diagram of Figure 2.2 can be coded as shown below:

<table>
<thead>
<tr>
<th>ELEMENT DESIGNATOR</th>
<th>ORIGIN NODE</th>
<th>TARGET NODE</th>
<th>PARAMETER VALUE</th>
<th>UNITS</th>
<th>DEPENDENCY DESIGNATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>6</td>
<td>1</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>6</td>
<td>5</td>
<td>10.7 PF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4</td>
<td>5</td>
<td>3</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3</td>
<td>3</td>
<td>1</td>
<td>325</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>3</td>
<td>1</td>
<td>10 UF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I1</td>
<td>4</td>
<td>3</td>
<td>98 IR4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R5</td>
<td>4</td>
<td>3</td>
<td>2 M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2</td>
<td>2</td>
<td>4</td>
<td>20 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>2</td>
<td>1</td>
<td>1.7 MH</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note the coding peculiar to the dependent current source I1. Since I1 is related to current flow in the resistor R4, the dependency relation is indicated in the sixth field position as IR4 with the dependency parameter $\beta$ (which is equal to a value of 98) coded in the fourth field. If other dependent sources were present, they too would follow the identical coding scheme.

Control card #2, for the NASAP coding rules, must contain either the word OUTPUT or the word END.

TREE The TREE input code can be employed by a user who wishes to form a transfer function based upon a user-defined tree. Control card #1, with the word TREE on it, alerts the program that the circuit description that follows contains a user specified tree in addition to the topological, elemental, and dependency information.

The general format of the circuit coding is:

\[
\text{ELEMENT IDENTIFIER/DEPENDENCY (ORIGIN-TARGET) = VALUE UNITS}
\]
To obtain a worst case function, a card must be inserted immediately after control card #2 (the END or OUTPUT cards), with the word, WORST. Tolerance cards must also be provided, since the variation of each element must be known. Tolerance cards have the following format

\[ \text{TOL} = \text{ELEMENT DESIGNATOR} = \text{VALUE} \]

where ELEMENT DESIGNATOR is a circuit element, and VALUE is the relative tolerance \( \frac{\Delta Q}{Q} \) of the element \( Q \). If no TOLERANCE card is provided for an element, a default value of 0.1 (10%) is assumed.

When a WORST CASE Function is requested, the sensitivity functions for all elements are also printed out automatically. Therefore no SENSITIVITY cards can be present when a WORST card is present. A typical WORST CASE analysis is given in the examples in Appendix C.

POLE SENSITIVITY The sensitivity of the poles of the transfer function is obtained by adding the word POLES to the ROOTS card:

\[ \text{ROOTS, POLES.} \]

Pole sensitivity in NASAP-70 is defined as

\[ \text{PS} = \frac{dS_1}{dQ} Q \]

where \( S_1 \) is a pole and \( Q \) is a circuit parameter whose value changes causing a change in the root \( S_1 \). The sensitivity of the poles are produced for all elements for which a sensitivity request is made (or for all elements if a WORST card is included).
Pole sensitivity function is printed as the ratio of two polynomials in S, just like the parameter sensitivity function and is interpreted similarly.

**Plot Requests:** Printer plots can be requested of NASAP-70 to produce:
1. transient responses of transfer functions from a group of user-specified standard input functions,
2. a bounded frequency response of transfer functions,
3. and (3) bounded (parameter, pole, and worst case) sensitivity responses.

The plot request is a single card of the form

```
PLOT (option 1 / option 2 ......)
```

where the options are types, parameters, and limits of the printer plots. All options for any one plot request must appear on one card since continuation cards are not allowed. Not all the options are required since defaults are provided. Options may appear in any order on the plot card.

A transient response can be obtained for an impulse, step, sine, exponential, pulse, and pulse train by specifying an option according to

<table>
<thead>
<tr>
<th>OPTION FORMAT</th>
<th>DESIRED INPUT RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE = IMPULSE</td>
<td>Impulse</td>
</tr>
<tr>
<td>TYPE = STEP</td>
<td>Step function</td>
</tr>
<tr>
<td>TYPE = SINE</td>
<td>Sine Wave</td>
</tr>
<tr>
<td>TYPE = EXPONENTIAL</td>
<td>Exponential</td>
</tr>
<tr>
<td>TYPE = PULSE</td>
<td>Pulse or Pulse train</td>
</tr>
</tbody>
</table>

To provide control over the format of the printer plot itself the following options can be included
Table 2.7

<table>
<thead>
<tr>
<th>Option Format</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMPLITUDE = a number</td>
<td>Represents the magnitude of any of the waveforms in Table 2.7</td>
</tr>
<tr>
<td>DENSITY = a number</td>
<td>Specifies the number of calculations per plotted output point</td>
</tr>
<tr>
<td>TIME = a number (in secs)</td>
<td>Specifies the duration of the applied input, it must always be present for any transient response request</td>
</tr>
<tr>
<td>STEP = a number (in secs)</td>
<td>Specifies the time between individual calculated points</td>
</tr>
</tbody>
</table>

For the PULSE type option, the following additional options can be employed

Table 2.8

<table>
<thead>
<tr>
<th>Option Format</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIAS = a number</td>
<td>Used in conjunction with the AMPLITUDE option to produce a train of positive and negative pulses</td>
</tr>
<tr>
<td>WIDTH = a number (in secs)</td>
<td>Specifies the duration of a pulse</td>
</tr>
<tr>
<td>CYCLE = a number (in secs)</td>
<td>Specifies the time of one cycle</td>
</tr>
</tbody>
</table>

To illustrate how some of the pulse options are combined, consider the plot statement

PLOT(TYPE=PULSE/AMPLITUDE=10/BIAS=-2/WIDTH=10/CYCLE=15/TIME=30)

The program interprets this statement to mean a pulse train of two pulses (TIME = 30 seconds) where each pulse alternates between +8 and -2 (from AMPLITUDE = 10, BIAS = -2) and each pulse duration is 15 seconds (CYCLE = 15) with a change from a positive to negative amplitude 10 seconds from the beginning of the cycle (WIDTH = 10). Figure 2.12 illustrates the waveform involved.
Options associated with other type inputs are as follows:

<table>
<thead>
<tr>
<th>TYPE OPTION</th>
<th>INTERPRETATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONSTANT = a number</td>
<td>Used only with EXPONENTIAL input. It represents the a in Ke^at</td>
</tr>
<tr>
<td>FREQUENCY = a number</td>
<td>Used only with the SINE input to specify the frequency of the sine wave</td>
</tr>
</tbody>
</table>

Table 2.10 summarizes all the type input options and their permissible function and printer graph parameters. Only the first two letters of each word are needed. For instance, AM may be used to abbreviate AMPLITUDE, IM for IMPULSE, etc.

The following default conditions apply
Table 2.10

<table>
<thead>
<tr>
<th>TYPE</th>
<th>AMPLITUDE</th>
<th>BIAS</th>
<th>CONSTANT</th>
<th>FREQUENCY(^1)</th>
<th>DENSITY</th>
<th>TIME</th>
<th>WIDTH</th>
<th>CYCLE</th>
<th>STEP(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMPULSE</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>STEP(^2)</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>SINE</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>EXPON</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>PULSE</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>(PULSE-TRAIN)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

1. The option "frequency" is used here in conjunction with the TYPE option SINE, it is also used as a TYPE option in generating a frequency response (see Table 2.12).

2. Step is used in three senses as a TYPE option to denote a step function, as an increment between plot points (in secs) for transient responses, and as an increment between plot points (in CPS) as given in Table 2.12.
Table 2.11

<table>
<thead>
<tr>
<th>OPTION</th>
<th>DEFAULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE</td>
<td>IMPULSE</td>
</tr>
<tr>
<td>TIME</td>
<td>1 second</td>
</tr>
<tr>
<td>STEP</td>
<td>.01</td>
</tr>
<tr>
<td>AMPLITUDE</td>
<td>1</td>
</tr>
<tr>
<td>DENSITY</td>
<td>1</td>
</tr>
<tr>
<td>CONSTANT</td>
<td>1</td>
</tr>
<tr>
<td>FREQUENCY</td>
<td>1</td>
</tr>
</tbody>
</table>

Inconsistent requests will be ignored and are defaulted from left to right, e.g.,

PLOT(TYPE = IMPULSE/FREQ = 2) yields an impulse response.

The printer plot capability can also be employed to produce a frequency plot (Bode) of a transfer function and sensitivity functions. The PLOT instruction include the appropriate codes shown below
Table 2.12

<table>
<thead>
<tr>
<th>FORMAT</th>
<th>INTERPRETATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE = FREQUENCY</td>
<td>Plots the magnitude and phase of the transfer function</td>
</tr>
<tr>
<td>TYPE = SENSITIVITY</td>
<td>Plots the magnitude and phase of the sensitivity function</td>
</tr>
<tr>
<td>TYPE = WORST</td>
<td>Plots the magnitude of the square worst case tolerance function</td>
</tr>
</tbody>
</table>

| EL = Element Designator | Specifies to the program which particular sensitivity function request should be plotted (from a 'SENSITIVITY' or 'WORST' card) |
| FROM = a number (in CPS) | Specifies the beginning of a frequency, sensitivity, or worst case response plot |
| TO = a number (in CPS) | Specifies the end of a frequency, sensitivity, or worst case response plot |
| STEP = a number (in CPS) | Indicates the frequency step increment between individual calculated points |

Note that the keyword STEP is used in a different context here than in the transient response case.

To illustrate how the PLOT options can be used, consider the plot statements

PLOT(TY = FR/FR = 10/TO =1E3/ST = 1.122)

PLOT(TY = SE/EL = C3/FR = 10/TO =1ES/ST = 1.22)

taken from the output request statements in Figure 2.7. The first statement requests a frequency plot of the transfer function VR4/VV1, to encompass
the frequency range from 10 to 1000 cps in increments of 1.122 cps. The second statement requests a plot of the sensitivity function of the transfer function \( V_{R4}/V_{V1} \) with respect to the element \( C3 \). The frequency range is the same as the first plot statement. Figures 2.13 and 2.14 are plot and table outputs of the two PLOT requests.

Note that the PLOT requests always refer to the previous transfer function request, if more than one such request is made. The sensitivity plot request must include an element option since more than one sensitivity request can be called for in conjunction with a transfer function request. Both the magnitude and phase are printed out.

Control Card #3 can have either the word EXECUTE or END on it.

As another example problem describing PLOT requests, consider the circuit shown in Figure 2.15 taken from the report by Moe and Schwartz.7 The input code is shown in Figure 2.16 where the transfer function of the voltage across \( C7 \) to the drawing voltage source \( V1 \) is requested. There are three transients plots requested (1) an impulse response of .5 sec duration, (2) a step response of .5 sec duration, and (3) a 4 cps sine wave response, outputted every .005 second until 9 seconds is reached.

The output plots and tabular data are shown in Figures 2.17 through 2.22.

Figure 2.23 shows a typical deck setup for multiple circuit problems for one computer run. The three different coding schemes are illustrated.

Complete input and output listing of another sample problem can be found in Appendix C. Note only one STOP appears — at the end of the deck.
The transform of the response is ---

<table>
<thead>
<tr>
<th>EXP. OF X</th>
<th>NUMER. COEFFS.</th>
<th>DENOM. COEFFS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-4.53399E-02</td>
<td>1.07795E-03</td>
</tr>
<tr>
<td>1</td>
<td>-2.61157E-03</td>
<td>1.90822E-02</td>
</tr>
<tr>
<td>2</td>
<td>4.57050E-10</td>
<td>3.10779E-03</td>
</tr>
<tr>
<td>3</td>
<td>4.96394E-16</td>
<td>2.16136E-05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FREQ</th>
<th>MAG</th>
<th>FREQ</th>
<th>MAG</th>
<th>FREQ</th>
<th>MAG</th>
<th>FREQ</th>
<th>MAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.712E-01</td>
<td>1.34726E-01</td>
<td>7.947E-01</td>
<td>2.07490E-01</td>
<td>2.132E-02</td>
<td>1.02776E-01</td>
<td>3.54600E-02</td>
<td>3.59398E-02</td>
</tr>
<tr>
<td>1.016E-01</td>
<td>2.37412E-01</td>
<td>3.694E-01</td>
<td>2.83722E-01</td>
<td>1.299E-02</td>
<td>2.77417E-01</td>
<td>3.166E-02</td>
<td>3.52103E-02</td>
</tr>
<tr>
<td>1.945E-01</td>
<td>1.56406E-01</td>
<td>4.648E-01</td>
<td>2.67280E-01</td>
<td>6.310E-02</td>
<td>2.79346E-01</td>
<td>5.628E-02</td>
<td>6.51299E-02</td>
</tr>
<tr>
<td>1.294E-01</td>
<td>1.43579E-01</td>
<td>7.947E-01</td>
<td>2.07490E-01</td>
<td>2.193E-02</td>
<td>1.93679E-01</td>
<td>6.306E-02</td>
<td>6.92907E-02</td>
</tr>
<tr>
<td>2.343E-01</td>
<td>1.18591E-01</td>
<td>5.371E-01</td>
<td>6.94530E-01</td>
<td>2.324E-02</td>
<td>2.64144E-02</td>
<td>7.015E-02</td>
<td>7.15933E-02</td>
</tr>
<tr>
<td>1.522E-01</td>
<td>1.41655E-01</td>
<td>7.947E-01</td>
<td>2.07490E-01</td>
<td>2.83722E-01</td>
<td>3.166E-02</td>
<td>3.52103E-02</td>
<td>4.17395E-02</td>
</tr>
<tr>
<td>2.812E-01</td>
<td>1.63288E-01</td>
<td>8.947E-01</td>
<td>4.30263E-01</td>
<td>2.817E-02</td>
<td>4.77371E-02</td>
<td>8.906E-02</td>
<td>1.38509E-02</td>
</tr>
</tbody>
</table>

GREATEST VALUE = 6.94530E-01
LOWEST VALUE = 0.0
INTERVAL = 6.81264E-03

---

Figure 2.13a
<table>
<thead>
<tr>
<th>FREQ</th>
<th>PHA</th>
<th>FREQ</th>
<th>PHA</th>
<th>FREQ</th>
<th>PHA</th>
<th>FREQ</th>
<th>PHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00E 01</td>
<td>0.798E 02</td>
<td>3.162E 01</td>
<td>-1.63E 02</td>
<td>9.99E 01</td>
<td>8.797E 01</td>
<td>3.161E 02</td>
<td>8.23E 01</td>
</tr>
<tr>
<td>1.2E 01</td>
<td>0.731E 02</td>
<td>3.94E 01</td>
<td>-1.62E 02</td>
<td>1.12E 02</td>
<td>7.937E 01</td>
<td>3.04E 02</td>
<td>8.36E 01</td>
</tr>
<tr>
<td>1.7E 01</td>
<td>0.31E 02</td>
<td>3.49E 01</td>
<td>-1.61E 02</td>
<td>1.22E 02</td>
<td>7.733E 01</td>
<td>3.04E 02</td>
<td>8.36E 01</td>
</tr>
<tr>
<td>1.9E 01</td>
<td>0.794E 02</td>
<td>5.41E 01</td>
<td>-1.6E 02</td>
<td>1.59E 02</td>
<td>7.622E 01</td>
<td>3.09E 02</td>
<td>8.11E 01</td>
</tr>
<tr>
<td>2.1E 01</td>
<td>0.699E 02</td>
<td>6.36E 01</td>
<td>-1.6E 02</td>
<td>1.77E 02</td>
<td>6.89E 01</td>
<td>3.02E 02</td>
<td>8.50E 01</td>
</tr>
<tr>
<td>2.2E 01</td>
<td>0.675E 02</td>
<td>6.27E 01</td>
<td>-1.55E 02</td>
<td>2.23E 02</td>
<td>6.64E 01</td>
<td>3.07E 02</td>
<td>8.64E 01</td>
</tr>
<tr>
<td>2.3E 01</td>
<td>0.655E 02</td>
<td>7.14E 01</td>
<td>-1.17E 02</td>
<td>2.31E 02</td>
<td>8.05E 01</td>
<td>3.98E 02</td>
<td>8.68E 01</td>
</tr>
<tr>
<td>2.5E 01</td>
<td>0.471E 02</td>
<td>4.85E 01</td>
<td>-1.3E 02</td>
<td>2.66E 02</td>
<td>3.43E 02</td>
<td>8.25E 01</td>
<td></td>
</tr>
</tbody>
</table>

GREATEST VALUE = 1.0540E 02  
LOWEST VALUE = -1.7903E 02  
INTERVAL = 3.09E 02

---

Figure 2 13b

- 2-37
SENSITIVITY WITH RESPECT TO C3

THE TRANSFORM OF THE RESPONSE IS:

<table>
<thead>
<tr>
<th>EXP. OF S</th>
<th>ALRED. COEFFS.</th>
<th>DEACO. COEFFS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.45050E 05</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.08387E 03</td>
<td>1.12738E 04</td>
</tr>
<tr>
<td>2</td>
<td>4.0315E 03</td>
<td>1.4515E 01</td>
</tr>
<tr>
<td>3</td>
<td>3.2262E 03</td>
<td>3.1736E 02</td>
</tr>
<tr>
<td>4</td>
<td>3.1221E 03</td>
<td>1.2347E 04</td>
</tr>
<tr>
<td>5</td>
<td>4.6249E 03</td>
<td>3.6923E 00</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>-1.6946E 15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FREQ</th>
<th>MAG</th>
<th>FREQ</th>
<th>MAG</th>
<th>FREQ</th>
<th>MAG</th>
<th>FREQ</th>
<th>MAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000E 01</td>
<td>1.17848E-02</td>
<td>3.144E-01</td>
<td>1.01107E 01</td>
<td>9.666E 01</td>
<td>3.01039E 01</td>
<td>5.1610 02</td>
<td>5.6631E 01</td>
</tr>
<tr>
<td>3.122E 01</td>
<td>2.35103E-02</td>
<td>3.844E-01</td>
<td>1.33019E 01</td>
<td>3.1250E 02</td>
<td>1.2007E 00</td>
<td>5.8504E 02</td>
<td>5.4760E 01</td>
</tr>
<tr>
<td>1.246E 01</td>
<td>2.62707E-02</td>
<td>5.344E-01</td>
<td>1.43241E 00</td>
<td>1.4289E 02</td>
<td>5.2594E 00</td>
<td>4.8277E 01</td>
<td>5.2950E 00</td>
</tr>
<tr>
<td>3.412E 01</td>
<td>3.7143E-02</td>
<td>5.444E-01</td>
<td>1.46615E 00</td>
<td>1.4670E 02</td>
<td>8.3017E 00</td>
<td>4.9464E 00</td>
<td>5.9120E 00</td>
</tr>
<tr>
<td>1.050E 01</td>
<td>4.6934E-02</td>
<td>5.014E-01</td>
<td>1.29208E 00</td>
<td>1.2977E 02</td>
<td>7.0370E 00</td>
<td>5.0432E 00</td>
<td>5.8287E 00</td>
</tr>
<tr>
<td>1.790E 01</td>
<td>5.92104E-02</td>
<td>5.624E-01</td>
<td>1.17164E 00</td>
<td>1.1750E 02</td>
<td>6.9413E 00</td>
<td>4.9505E 00</td>
<td>5.4940E 00</td>
</tr>
<tr>
<td>4.954E 01</td>
<td>7.51181E-02</td>
<td>6.364E-01</td>
<td>1.01416E 00</td>
<td>1.0164E 02</td>
<td>6.4641E 00</td>
<td>5.1620E 00</td>
<td>5.7180E 00</td>
</tr>
<tr>
<td>2.106E 01</td>
<td>9.53329E-02</td>
<td>7.678E-01</td>
<td>2.24730E 00</td>
<td>2.2500E 02</td>
<td>6.6604E 00</td>
<td>7.0792E 00</td>
<td>6.0148E 00</td>
</tr>
<tr>
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<td>1.21654E-01</td>
<td>7.944E-01</td>
<td>2.37866E 00</td>
<td>2.3800E 02</td>
<td>5.9613E 00</td>
<td>7.0238E 00</td>
<td>5.9907E 00</td>
</tr>
<tr>
<td>2.640E 01</td>
<td>2.9450C-01</td>
<td>6.946E-01</td>
<td>1.43777E 00</td>
<td>1.4400E 02</td>
<td>5.4760E 00</td>
<td>5.0740E 00</td>
<td>5.0940E 00</td>
</tr>
</tbody>
</table>

GREATEST VALUE = 2.30763E 00  LOWEST VALUE = 0.0  INTERVAL = 2.0766E-02

Figure 2.14a
<table>
<thead>
<tr>
<th>FREQ</th>
<th>PHA</th>
<th>FREQ</th>
<th>PHA</th>
<th>FREQ</th>
<th>PHA</th>
<th>FREQ</th>
<th>PHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000E+00</td>
<td>1.506E+00</td>
<td>3.142E-01</td>
<td>1.251E+00</td>
<td>0.079E+00</td>
<td>9.66E-01</td>
<td>9.66E-02</td>
<td>1.346E+00</td>
</tr>
<tr>
<td>1.100E+00</td>
<td>1.546E+00</td>
<td>3.147E-01</td>
<td>1.251E+00</td>
<td>1.132E+00</td>
<td>7.52E+00</td>
<td>7.52E+00</td>
<td>1.346E+00</td>
</tr>
<tr>
<td>1.100E+00</td>
<td>1.506E+00</td>
<td>3.142E-01</td>
<td>1.251E+00</td>
<td>1.132E+00</td>
<td>7.52E+00</td>
<td>7.52E+00</td>
<td>1.346E+00</td>
</tr>
<tr>
<td>1.100E+00</td>
<td>1.506E+00</td>
<td>3.142E-01</td>
<td>1.251E+00</td>
<td>1.132E+00</td>
<td>7.52E+00</td>
<td>7.52E+00</td>
<td>1.346E+00</td>
</tr>
<tr>
<td>1.100E+00</td>
<td>1.506E+00</td>
<td>3.142E-01</td>
<td>1.251E+00</td>
<td>1.132E+00</td>
<td>7.52E+00</td>
<td>7.52E+00</td>
<td>1.346E+00</td>
</tr>
</tbody>
</table>

Greatest value = 1.601E+00  Lowest value = -6.318E+00  Interval = 1.464E+00
Figure 2.15 Complete Simplified Circuit for Anal.
Complete EOG System with a Four
NASAP (SIMPLIFIED EDG SYSTEM WITH BLINK INPUT)

V1 1 2 0.1166
R1 2 3 1.0
C1 2 3 0.2265F
R2 3 1 0.876
V2 1 4 2.14 VR2
R3 4 5 1.0
C2 5 1 0.0580F
I 1 1 6 1 VC2
I 2 6 1 1 VC4
C3 6 1 0.04459F
V3 1 7 1.0 VC3
R4 7 8 0.02275
C4 8 1 1.0F
V4 1 9 10.99 VC4
R5 9 10 1.0
C5 10 1 0.007496F
V5 1 11 50 VC5
R6 11 12 0.1
R7 12 13 14K
C6 13 14 1.6UF
R8 14 1 15, 4K
R9 16 14 1M
R10 14 15 10K
R11 12 16 14K,
R12 15 1 200
I 3 1 15 500 VR9
R13 15 16 10K
C7 16 1 2.0UF
OUTPUT
VC7/VV1
PLOT(TY=IM/TI=0.5)
PLOT(TY=ST/TI=0.5)
PLOT(TY=SI/FR=4/TI=1.0/ST=.005)
EXECUTE
STOP

Figure 2.16  NASAP – 70 Input Coding
**TRANSFER FUNCTION**

\[
- 8.181E 08 -1.833E 06 - 1.000E 00 S^2 + 0.0 - 0.0 - 0.0 - 0.0 - 0.0 - 0.0
\]

\[
= 1.000E 09 + 1.100F 01 C8 + 1.270E 05 C8^3 + 1.050E 07 + 1.000E 05 + 1.430E 04 + 2.000E 02 + 1.000E 00
\]

The function factor = \(-2.6294E 06\)

---

**Figure 2.17**
Figure 2.18
CONTROL CARD

TITLE CARD

NASAP

VINPUT 1 2 1

IOUTPUT 3 4 1 IR1

R1 2 4 .37M

C23 2 3 2E10 PF

LO 1 4 33

CONTROL CARD

OUTPUT

WORST CASE

TOL=LO= 50

V I OUTPUT / VVINPUT

ROOTS, POLES

PLOT (TYPE = IMPULSE / TIME = 10)

PLOT (TYPE = FR/FR = .01/TO = 1E2)

PLOT (TYPE = WORST/FR = .01/TO = 1E2)

VR-/VVINPUT

CONTROL CARD

EXECUTE

ANOTHER OPTIONAL TITLE CARD

CONTROL CARD

TREE

E1 (1-2) = 1

DJ2/IRE1 (3-4) = 1

RE1 (2-4) = .37M

CE, (2-3) = 2E10 PF

LJ, (1-4) = 33

CONTROL CARD

END

SENS=RE1

SENS=LJ

VLJ/VE1

PLOT (TY = SI/AM = 2/FR = 10)

PLOT (TY = SE/FR = 1E-3/TO = 1E6/EL = RE1)

END

PRECEDING PAGE BLANK NOT FILMED

2-55
CIRC (5E6)  
E1 (1-2) = 1  
R2 (2-3) = 2  
L3 (3-1) = 1  
C4 (3-1) = 4  

CONTROL CARD -> END  
IC4/VE1  
ROOTS  

CONTROL CARD -> END  
STOP  

Figure 2.23  Sample Data Decks for NASAP-70

Figure 2.24  Example of Outputs Taken Across Two or More Circuit Elements
2.4 Coding Tips

As is usually the case with any application program, a number of design tricks will evolve as the circuit designers become familiar with its operation. Some of these tips are described here.

Outputs Taken Across Two or More Circuit Elements

Quite often a circuit designer needs the transfer function expression taken across more than one circuit element, and with the capabilities of NASAP-70, as many computer runs as there are circuit output elements will be required. To circumvent this difficulty, an extra current source can be inserted across the desired output terminals and the output voltage measured across it (see for example Figure 2.24). This element can be viewed as an ideal voltmeter, that is, a device that extracts a constant value (which is always zero) of current from the circuit. By adding the output current source (I = 0), provision has been made for a general method of solution.

(As an added note, an ideal ammeter which is a short circuit is a voltage source whose voltage is a constant value of zero.)

Total Output Response

This design tip is really a reminder to the circuit designer of how the output response of a circuit should be handled when a number of active devices and energy storage elements are present. For such cases NASAP-70 requires that as many transfer functions as there are active devices and elements with energy stored in them be computed, relating these devices to the output requested. The transient response associated for each transfer function is then computed and summed all together to form the total output response. It is important to note that any charged capacitor with $V_0$ volts has to be replaced by an uncharged capacitor in series with a battery of $V_0$ volts.
Also, any inductor $L$ with an initial current of $I_0$ through it has to be replaced by an inductor placed in parallel with a current source $I_0$.

These sources are considered like any other active device, and thus their presence must be reflected in the desired output response.

There are approximation-oriented guidelines by which a tree selection procedure should be implemented. For low frequency approximation, capacitors should be chosen as links while inductors should be chosen branches (as much as possible while still retaining a tree structure.) Conversely, high frequency approximation results in inductors chosen as links while capacitors are chosen as branches. The practical underlying
reason is that while a zero is well represented and well behaved on a computer, $\infty \rightarrow 1/0$ causes error and havoc on the machine and thus will not be accepted by the algorithm. This means that if one requires low as well as high frequency approximations for the same problem, this problem should be submitted as two problems with two different trees. Similarly, elements with relatively large impedances compared with the circuit (for example, grid-plate tube impedance) should always be chosen links. (To set $I \rightarrow 0$ which means grid current equal zero.) On the other hand, elements with relatively small input impedances ($r_1$ in some transistors) should always be chosen branches (To set $V \rightarrow 0$).

In an approximation, branches can be collapsed or links can be opened without disturbing the tree structure. This fact can be verified by observing the example problems. Hence, by carefully selecting elements to be links or branches, foresight in design can be incorporated into circuit description and a great deal of flexibility in calculations can be achieved.

2.5 **NASAP Analysis of Nonlinear DC Circuits**

The basic procedure for analyzing four classes of nonlinear dependencies is described: (1) Nonlinear controlled source dependent on current or voltage in the circuit, (2) Nonlinear controlled source dependent on a parameter external to the circuit such as temperature, (3) Nonlinear resistor dependent on current or voltage associated with its terminals, and (4) Nonlinear resistor dependent on a parameter external to the circuit.

A method for obtaining models for nonlinear elements is presented and is used to establish a model for an exponential nonlinearity. This model is used in the analysis of transistor bias circuits.

Also included are the analysis procedures for power supply regulator circuits using the real $s$ evaluation option. This analysis produces results related to the load and line regulation properties of the regulator.

*This section has been taken from the work presented in references 9 and 10.
2.5.1 Modeling Circuit Element Variations

Linear and nonlinear circuit element variations in a resistive circuit can be simulated with the use of the PLOT(TYPE=RE) capabilities of the NASAP program which results in a real variable evaluation of the transfer function. Consider a variable circuit element \( A(x) \) where \( A \) may be a resistor, a current source, or a voltage source and \( x \) may be a current, a voltage, or some external parameter such as temperature. The function \( A(x) \) is approximated by a ratio of polynomials using either approximation methods or trial and error.

\[
A(x) = \frac{P(x)}{Q(x)}
\]  

(2.1)

The variable \( x \) is replaced by \( s \) and a circuit is synthesized which has a transfer function or an input impedance given by \( P(s)/Q(s) \). When the TYPE=REAL option is used, this circuit will simulate the variation of the circuit element \( A(x) \) if the range of \( s \) is the same as the expected range of \( x \). It should be noted that since the circuit is used for simulation purposes only, it does not have to be physically realizable, i.e., controlled sources or negative circuit elements may be used.

The method for using this model in computer analysis of a circuit depends on the circuit element and variable which \( A \) and \( x \) represent. In Cases I and II of the discussion which follows it is assumed that \( P(s)/Q(s) \) is realized as an input impedance. If the realization is an input admittance or a transfer function, relatively minor modifications are required.

Case I

\( A \) is a controlled voltage or a current source and \( x \) is a voltage or a current in the circuit.

The dependency function \( A(s) \) is synthesized as an impedance and a current generator of value unity is connected to the impedance. This auxiliary network is hinged to the network which is to be analyzed. The nonlinear dependent source in the network is replaced by a source which is
dependent on the voltage across the auxiliary network. The transfer function \( x/\text{independent source} \) is specified and the \texttt{TYPE=REAL} option is used. The solution for the circuit is obtained from the tabular printout or the graphical plot as the value where \( x = s \). If \( x \) is not the desired output variable, the circuit is recoded with \( A(x) \) replaced by its known value from the above solution. The auxiliary network is eliminated and the desired output variable is specified.

This analysis is applicable when the circuit contains no more than one variable source.

To illustrate the method, consider the circuit of Figure 2.25. Let \( R = 2 \) and assume that \( V \) is a function of \( I_1 \) and is adequately approximated by

\[
V(I_1) = \frac{I_1^2 + I_1 - 5}{I_1 + 1} \quad 0 \leq I_1 \leq 1
\]  

(2.2)

A pencil and paper solution results in

\[
I_1 = .921 \quad V_0 = .0795
\]  

(2.3)

For computer analysis an impedance is synthesized for which

\[
Z(s) = \frac{s^2 + s - 5}{s + 1} = s - \frac{5}{s + 1}
\]  

(2.4)

A circuit realization of this impedance is shown in Figure 2.26. The auxiliary network is hinged to the basic circuit with \( R_2 = 2, I_1 = I R_7 \) and \( V_2 = V R_6 \). Note that the \( R_5, R_6 \) resistance combination is used for voltage measurement only and could be replaced by a single, large valued resistance. The transfer function \( IR_1/VV_1 \) is specified and a frequency of .915 to .925 in steps of .001 is specified. The frequency range is chosen on the basis of the expected "ballpark" value of the current \( IR_1 \). If a good estimate of \( IR_1 \) cannot be made, a larger frequency range is specified with larger
increments and more than one pass on the computer may be necessary to obtain IR1 to the desired degree of accuracy.

The computer analysis results in

\[ \frac{IR_1}{V_{V1}} = -0.25 \left( \frac{-7 - s + s^2}{1 + s} \right) \]  

(2.5)

and the printout table gives IR1 = s for s = 0.921. The value of V2 is then obtained as V2 = -1.682. The basic circuit is then coded using this value of V2 and the result is VR3/VV1 = 0.0795.
Case II

A is a controlled voltage or current source and $x$ is an external parameter which is known to vary over a specified range.

In this case, the controlled source is generally dependent on a current or voltage in the circuit (denoted by $y$ in this discussion) and the dependency factor is a function of an external parameter $x$. The $h_{FE}I_E$ generator in the transistor dc equivalent circuit where $h_{FE}$ is temperature dependent is an example of this situation. The circuit is coded with $yA(x)$ replaced by a generator, $V(s)$, which is dependent on the voltage across the auxiliary network. The desired transfer function is specified and the SIGMA option is used. The computer solution gives the relation between the output variable and $x$ in functional (replace $s$ by $x$), tabular and graphical forms. This method is applicable for any number of variable sources in the circuit which depend on the same external parameter $x$.

The circuit of Figure 2.25 is used to illustrate the procedure with $R = 2$ and $V$ dependent on $I_1$ and temperature according to

$$V = I_1 \frac{T^2 + T - 5}{T + 1} \quad 10 \leq T \leq 50$$

(2.6)

A hand solution results in

$$V_o = \frac{T^2 + 3T - 3}{T^2 + 5T - 1}$$

(2.7)

For computer analysis the nonlinear dependency has the same functional form as in Case I and therefore $Z(s)$ of Figure 2.26 simulates the temperature dependency. The auxiliary network is hinged to the basic circuit with $I_1 = IR1$ and $V2 = VR6$. The transfer function $VR3/VV1$ is requested and a frequency range of 10 to 50 in steps of 1 is specified. The result is

$$\frac{VR3}{VV1} = -3 + 3s + s^2$$

(2.8)
A table is printed out and a graph of the function over the range
s = 10 to s = 50 is plotted.

Case III

A is a resistor and x is the voltage across or the current through
the resistor.

The circuit is coded with R(x) replaced by Z(s). The transfer function
x/independent source is specified and the TYPE=REAL option is used. The
solution for the circuit is obtained from the tabular printout or the graphical
plot as the value where x = s. If x is not the desired output variable, the
circuit is recoded with R(x) replaced by its known value and the desired
transfer function is specified. This analysis is applicable when the circuit
contains no more than one nonlinear resistance.

In the circuit of Figure 2.25, let V = -2 and R be dependent on I2.

\[ R(I_2) = \frac{I_2^2 + I_2 - 5}{I_2 + 1} \quad 2 \leq I_2 \leq 4 \]  

(2.9)

The solution is

\[ I_2 = 2.155, \quad V_o = -.771 \]  

(2.10)

For computer analysis, the basic circuit of Figure 2.26 is used with R2
replaced by Z(s) and V2 = -2 IR7. The transfer function IL1/VV1 is requested
and a frequency range of 2.15 to 2.16 in steps of .001 is specified. As in
Case I, it may require more than one pass on the computer to determine the
proper frequency range and increment which will result in the desired degree
of accuracy for IL1. The computer analysis gives

\[ \frac{IL1}{VV1} = 2.67 \frac{1 + s}{-4.333 + 1.667s + s^2} \]  

(2.11)

for which IL1 = s at s = 2.155. The value of R(I2) is evaluated as R(I2) = .5702.
The basic circuit is recoded using this value of R and the above value for V.
The analysis results in VR3/VV1 = -.771.

2-54
Case IV

A is a resistor and \( x \) is an external parameter which is known to vary over a specified range.

The circuit is coded with \( R(x) \) replaced by \( Z(s) \) and the desired transfer function is specified. The computer solution gives the relation between the output variable and \( x \). This method is applicable for any number of variable resistances in the circuit which depend on the same external parameter \( x \).

As an example, let \( V = 2 \) and \( R \) be a function of temperature in the circuit of Figure 2.25.

\[
R(T) = \frac{T^2 + T - 5}{T + 1} \quad 10 \leq T \leq 50
\]  

(2.12)

A hand solution gives

\[
V_o = 0.667 \frac{T^2 + 3T - 3}{T^2 + 1.667T - 4.333}
\]  

(2.13)

In the computer analysis, the basic circuit of Figure 2.26 is used with \( R_2 \) replaced by \( Z(s) \) and \( V_2 = 2IR_7 \). The frequency range 10 to 50 in steps of 1 is specified and the computer output is

\[
\frac{V_{R3}}{VV1} = 0.667 \frac{-3 + 3s + s^2}{-4.333 + 1.667s + s^2}
\]  

(2.14)

A table is printed out and a graph of the function over the range \( s = 10 \) to \( s = 50 \) is plotted.

2.5.2 Modeling Temperature Variations of Transistor Parameters

The parameters of the transistor dc equivalent circuit, \( h_{FE}, VBE \) and \( I_{CO} \), are temperature dependent. The functional form of the dependence may vary depending on the construction of the transistor. Generally, graphical plots of the dependencies are available from the manufacturer on request.
Analytical investigations predict the following nominal temperature variations.

\[
h_{FE}(T) = h_{FEo}(1 - 25B + BT) \tag{2.15}
\]

where \(h_{FEo}\) is the value of \(h_{FE}\) at 25°C

\[T\] is expressed in °C

\[B = 0.02\] for Ge and 0.013 for Si

\[
V_{BE}(T) = V_{BEo} + 25D - DT \tag{2.16}
\]

where \(V_{BEo}\) is the value of \(V_{BE}\) at 25°C

\[D = 0.002\text{ to } 0.0025\]

\[
I_{co}(T) = I_{co0}2^{\frac{T-25}{F}} \tag{2.17}
\]

where \(I_{co0}\) is the value of \(I_{co}\) at 25°C

\[F = 10\] for Ge and 7 for Si

The model for temperature variation of \(h_{FE}\) requires

\[
Z(s) = 1 - 25B + Bs \tag{2.18}
\]

while the \(V_{BE}\) model must satisfy

\[
Z(s) = V_{BEo} + 25D - Ds \tag{2.19}
\]

Simple series RL circuits will satisfy these relations with \(R = 1 - 25B\) and \(L = B\) for the \(h_{FE}\) model and \(R = V_{BEo} + 25D\) and \(L = -D\) for the \(V_{BE}\) model.

The current generators used to complete the auxiliary networks will have value \(h_{FEo}I_{B}\) for the \(h_{FE}\) model and unity for the \(V_{BE}\) model.

The circuit to simulate \(I_{co}\) variation is somewhat more complicated than the \(h_{FE}\) and \(V_{BE}\) models. As indicated by Equation (2.17), \(I_{co}\) doubles every 10°C for germanium and every 7°C for silicon. A trial and error method results in the following approximating functions for the temperature range 0°C to 75°C.
\[ I_{\text{coGe}}(T) = I_{\text{coo}} \frac{T + 0.471698}{T^2 - 159.394T + 6332.58} \]  
(2.20)

\[ I_{\text{coSi}}(T) = I_{\text{coo}} \frac{T - 12.5480}{T^2 - 149.500T + 5690.00} \]  
(2.21)

Figure 2.27 shows a possible synthesis of the normalized approximating function \( I_{\text{co}}(s)/I_{\text{coo}} \). The values of the elements are listed below.

<table>
<thead>
<tr>
<th>Ge</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C )</td>
<td>.007783</td>
</tr>
<tr>
<td>( R_1 )</td>
<td>-1.8037</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>.0090349</td>
</tr>
<tr>
<td>( L )</td>
<td>.019154</td>
</tr>
</tbody>
</table>

Although these circuits model temperature variation of \( I_{\text{co}} \), they do not satisfy the transistor model since \((h_{\text{FE}} + 1)I_{\text{co}}\) is required and \( h_{\text{FE}} \) is also temperature dependent. This product can be modeled with the configuration shown in Figure 2.28. If \( \frac{1}{Y_h(s)} \gg Z(s) \) for the real \( s \) range of interest, then

\[ I = h_{\text{FEo}} Y_h(s) Z_{I_{\text{co}}} \]  
(2.22)

The control variable which is required for the transistor model is

\[ I = \left[ h_{\text{FE}}(s) + 1 \right] I_{\text{co}}(s) \]  
(2.23)

since \( Z_{I_{\text{co}}}(s) = I_{\text{coo}}(s)/I_{\text{coo}} \), the correspondence is

\[ h_{\text{FEo}} Y_h(s) = \left[ h_{\text{FE}}(s) + 1 \right] I_{\text{coo}} \]

or

\[ Y_h(s) = \frac{h_{\text{FE}}(1-25B+Bs) + 1}{h_{\text{FE}}} I_{\text{coo}} \]  
(2.24)

A summary of the models is presented in Figure 2.29 where a complete transistor circuit is modeled. The V1, R1 combination is included.
in this model so that V2, I4 and I5 can be constant amplitude controlled sources. If a plot of the collector current is required, the transfer function \( IR_5/VV1 \) is specified. A typical printout for the circuit shown in Figure 2.29 using the (TYPE=REAL) option is included in Appendix C.

2.5.3 Regulation Curves for Power Supply Regulators

The TYPE=REAL option of the NASA-70 program is useful in obtaining power supply regulation curves. In the circuit of Figure 2.30, R2 is a large valued resistor which is used for measuring voltage across the auxiliary network. The voltage across R1 is constant, the voltage across L1 varies linearly with \( s \), and the voltage across R2 is the sum of VR1 and VL1. For
Figure 2.29 Model for Simulation of Temperature Variation Effects in a Transistor Circuit

*Resistors Included in Model for Voltage Measurement
**Resistor Included in Model for Current Measurement

GERMANIUM TRANSISTOR

- $h_{ie} = 1 \text{K}$
- $h_{oe} = 25 \times 10^6 \text{ mho}$
- $h_{fe} = 50$
- $V_{be} = 2 \text{v}$
- $I_{co} = 1 \mu\text{a}$
load regulation data, \( V \) is made dependent on \( V_{R1} \) and \( I \) is made dependent on \( V_{L1} \). Line regulation information is obtained if \( V \) depends on \( V_{R2} \) and \( I \) depends on \( V_{R1} \). If \( V \) depends on \( V_{R2} \) and \( I \) depends on \( V_{L1} \), a regulation curve is obtained for simultaneous variation of line voltage and load current.

2.6 Network Partitioning Schemes for NASAP-70

Assume a general network is partitioned into several smaller sub-networks as shown in Figure 2.31. The input and output variables, \( X_1 \) and \( X_2 \), can be located arbitrarily. Note that the partitioning conveniently lends itself to transfer function formulations. Subnetwork 1 ports are identified by \( X_1 \), \( I_2 \), and \( I_3 \); the other subnetwork ports are numbered similarly.

2.6.1 N-Port Interconnection Methods

Some interconnection methods are briefly described here to make the discussion self-contained. A detailed description can be found in reference 12.

Laemmel Method The Laemmel Method is employed to connect two sub-networks in cascade as shown in Figure 2.31. This technique utilizes the open circuit impedances of the network. The input and output ports of \( N_1 \) and \( N_2 \) are in groups of a and b, respectively. The network \( N_c \) obtained by cascading \( N_1 \) and \( N_2 \) has its input and output ports in group a of \( N_1 \) and group b of \( N_2 \), respectively.
The impedance matrix of subnetwork $N_1$ is defined as
\[
U = \begin{bmatrix}
U^{aa} & U^{ab} \\
U^{ba} & U^{bb}
\end{bmatrix}
\] (2.25)

where
\[
U^{aa} = (u_{ij}^{aa} \mid i=1 \ldots q, j=1 \ldots q), \quad U^{ab} = (u_{ij}^{ab} \mid i=1 \ldots q, j=q+1 \ldots r),
\]
\[
U^{ba} = (u_{ij}^{ba} \mid i=q+1 \ldots r, j=1 \ldots q), \quad U^{bb} = (u_{ij}^{bb} \mid i=q+1 \ldots r, j=q+1 \ldots r)
\]
are the open circuit impedances relating ports of the subnetworks. Note that the $U$ matrix, and succeeding matrices, are partitioned according to the grouping of the input and output ports.

In a similar manner, the open loop impedance matrix for $N_2$ is
\[
T = \begin{bmatrix}
T^{aa} & T^{ab} \\
T^{ba} & T^{bb}
\end{bmatrix}
\] (2.26)

where
\[
T^{aa} = (t_{ij}^{aa} \mid i=1 \ldots s, j=1 \ldots s), \quad T^{ab} = (t_{ij}^{ab} \mid i=1 \ldots s, j=s+1 \ldots w).
\]
are open circuit impedances relating ports in $N_2$.

![Diagram of connecting two N Port Subnetworks in Cascade](image)

The overall open circuit impedance of $N_c$, obtained by interconnecting $N_1$ and $N_2$ (Figure 2.32), can be computed by Laemmel's relations

\[
Z_{aa} = U_{aa} - U_{ab} (U_{bb} + T_{aa})^{-1} U_{ba} \\
Z_{ab} = U_{ab} (U_{bb} + T_{aa})^{-1} T_{ab} \\
Z_{ba} = T_{ba} (U_{bb} + T_{aa})^{-1} U_{ba} \\
Z_{bb} = -T_{ba} (U_{bb} + T_{aa})^{-1} T_{ab} + T_{bb}
\]

where

\[
T = \begin{bmatrix} Z_{aa} & Z_{ab} \\ Z_{ba} & Z_{bb} \end{bmatrix}
\]

Laemmel's relations can be applied repeatedly to interconnect subnetworks of the form shown in Figure 2.31. For example, consider the first three subnetworks of row 1. Subnetworks 1 and 2 are combined to form subnetwork 1, 2 as in Figure 2.33(b). Subnetwork 1, 2 is rearranged and connected with subnetwork 3 to form subnetwork 1, 2, 3 of Figure 2.33(d). This process is continued until all subnetworks of row 1 have been interconnected. In an identical manner, the subnetworks of rows 2 are interconnected, producing $t$ subnetworks. This is depicted in Figure 2.34. The subnetworks are interconnected to reconstruct the original network.
The total number of times the Laemmel method is applied in forming the original network from the group of subnetworks given in Figure 2. 31 is $t_{\text{r}} - 1$, where $t$ is number of rows and $r$ is the number of columns of the subnetworks.

The following guidelines should be adhered to in subdividing a network for an analysis by the Laemmel Method:

1. No mutual coupling should exist between components of different subnetworks,
2. A dependency relationship must be contained within a subnetwork,
3. The port of a subnetwork must be taken across an element which is part of a closed mesh, such as shown in Figure 2. 35. (This restriction is due to NASAP-70 rather than to the methods themselves).

**Cascade Parameter Method** When a network can be partitioned into cascade subnetworks as shown in Figure 2. 36, the cascade parameter method is usually employed to compute transfer functions rather than the Laemmel method because of the reduction in computing time achieved. The cascade parameters relate the terminal voltages and currents for the overall network by the expression...
The transmission parameters $A_i$, $B_i$, $C_i$, and $D_i$ for each subnetwork are the inverse voltage transfer ratio, negative inverse of the transfer admittance, the inverse transfer impedance, and the negative inverse current transfer ratio, respectively, of the input port to the output port. $A_i$ and $C_i$ are calculated with the output port open, $B_i$ and $D_i$ are calculated with the output port shorted. The transmission parameters can be computed by NASAP-70 and are in general ratios of polynomials in $S$. 
Parallel Interconnection Method Another means of network interconnection is the paralleling of ports of networks as shown in Figure 2.37. Murti and Thulasiraman show that two n-port networks described by short circuit admittances and having no internal vertices, can be combined in parallel if their edge and port orientations are identical, and also if their modified cut set matrices with identical row and column order are equal.

Let the short circuit admittance matrices of networks $N_1$ and $N_2$ be

$$Y_1 = \begin{vmatrix} Y_{aa}^{1} & Y_{ab}^{1} \\ Y_{ba}^{1} & Y_{bb}^{1} \end{vmatrix} \quad (2.34)$$

and

$$Y_2 = \begin{vmatrix} Y_{aa}^{2} & Y_{ab}^{2} \\ Y_{ba}^{2} & Y_{bb}^{2} \end{vmatrix} \quad (2.35)$$

The individual entries of these matrices are defined similar to the Laemmel matrices except that short-circuit admittances are involved.

Assuming the interconnection criteria are satisfied, the short circuit admittance matrix of the combined network is
2.6.2 Network Interconnection Examples

The network shown in Figure 2.38 was arbitrarily constructed to illustrate Laemmel's Method. Assume that $V_2/I_1$ is required. Let this network be subdivided into two subnetworks as shown in Figure 2.39.
The port equations for subnetwork $U$ are

\[
\begin{bmatrix}
V_a^U \\
V_b^U
\end{bmatrix} =
\begin{bmatrix}
U^{aa} & U^{ab} \\
U^{ba} & U^{bb}
\end{bmatrix}
\begin{bmatrix}
I_a^U \\
I_b^U
\end{bmatrix}
\]

(2.37)

where

\[
U^{aa} = (u_{ij} i = 1, j = 1), \quad U^{ab} = (u_{ij} i = 1, j = 2, 3),
\]
\[
U^{ba} = (u_{ij} i = 2, 3, j = 1), \quad U^{bb} = (u_{ij} i = 2, 3, j = 2, 3),
\]
\[
V_a^U = V_1^U, \quad V_b^U = V_2^U, \quad V_3^U I_a^U = I_1^U, \quad I_b^U = I_2^U I_3^U
\]

The port equations for subnetwork $T$ are

\[
\begin{bmatrix}
V_a^T \\
V_b^T
\end{bmatrix} =
\begin{bmatrix}
T^{aa} & T^{ab} \\
T^{ba} & T^{bb}
\end{bmatrix}
\begin{bmatrix}
I_a^T \\
I_b^T
\end{bmatrix}
\]

(2.38)

and those for network $Z$ are

\[
\begin{bmatrix}
V_a^Z \\
V_b^Z
\end{bmatrix} =
\begin{bmatrix}
Z^{aa} & Z^{ab} \\
Z^{ba} & Z^{bb}
\end{bmatrix}
\begin{bmatrix}
I_a^Z \\
I_b^Z
\end{bmatrix}
\]

(2.39)
The matrices of (2.38) and (2.39) can readily be defined by an examination of Figures 2.38 and 2.39.

The desired transfer function is

$$\frac{V_2}{I_1} \bigg|_{I_2=0} = Z_{21} = Z_{ba},$$  \hspace{1cm} (2.40)

From Equation (2.29) \(Z^{ba} = T^{ba}(U^{bb} + T^{aa})^{-1} U^{ba}\). Therefore the following impedance parameters are computed utilizing NASAP-70 \(t_{31}, t_{32}, t_{11}, t_{12}, t_{21}, t_{22}, u_{22}, u_{32}, u_{33}, u_{21}, \) and \(u_{31}\). Since the subnetworks are lumped, linear and passive, then \(t_{12} = t_{21}\) and \(u_{23} = u_{32}\), hence \(t_{21}\) and \(u_{32}\) need not be computed. The parameters computed are listed.

$$u_{12} = \frac{+6.872E+10S + 1.000E+09S^3}{+1.000E+18 + 3.000E+15S + 1.002E+12S^2 + 3.000E+06S^3 + 1.000E+05S^4}$$  \hspace{1cm} (2.41)

Let the denominator of \(u_{12}\) be equal to \(u_{\text{den}}\) then

$$u_{12} = \frac{+6.872E+10S + 1.000E+09S^3}{u_{\text{den}}}$$  \hspace{1cm} (2.42)

$$u_{13} = U_{31} = \frac{1.000E+21 + 1.000E+18S + 1.000E+12S^2}{u_{\text{den}}}$$  \hspace{1cm} (2.43)

$$u_{22} = \frac{1.000E+15S + 3.000E+12S^2 + 1.001E+09S^3 + 1.000E+3S^4}{u_{\text{den}}}$$  \hspace{1cm} (2.44)

$$u_{23} = U_{32} = \frac{-1.000E + 12S^2}{u_{\text{den}}}$$

$$u_{33} = \frac{2.000E+21 + 1.001E+18S + 3.000E+12S^2 + 1.000E+06S^3}{u_{\text{den}}}$$  \hspace{1cm} (2.45)

$$t_{11} = \frac{1.000E+06 + 1.002E+03S + 3.000E-03S^2 + 1.000E-08S^3}{1.000E+03 + 2.002E+00S + 5.000E-06S^2 + 1.000E-12S^3}$$

Let the denominator of \(t_{11}\) to be equal to \(t_{\text{den}}\) then

2-78
\[
\begin{align*}
t_{11} &= \frac{1.000E+06 + 1.002E+03 + 3.000E-03S^2 + 1.000E-09S^3}{t_{\text{den}}} \\
t_{12} &= T_{21} = \frac{-1.000E-09S^3}{t_{\text{den}}} \\
t_{13} &= \frac{1.000E+03S + 2.000E-03S^2}{t_{\text{den}}} \\
t_{22} &= \frac{1.000E+03S + 2.000E-03S^2 + 3.000E-09S^3}{t_{\text{den}}} \\
t_{23} &= T_{32} = \frac{1.000E-09S^3}{t_{\text{den}}}
\end{align*}
\]

Substituting the appropriate matrices elements of (2.37) and (2.38) into (2.29), the transfer impedance \( Z_{21} \) is computed

\[
Z_{21} = Z_{ba} = \begin{vmatrix} T_{31} & T_{32} \end{vmatrix} \begin{bmatrix} U_{22} & U_{23} \\ U_{32} & U_{33} \end{bmatrix} + \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}^{-1} \begin{bmatrix} U_{21} \\ U_{31} \end{bmatrix}
\]

\[
Z_{21} = \frac{+1.34+4E+38S^2 + 1.001E+39S^3 + 5.010E+36S^4 + 0.036E+33S^5}{+2.000E+48S^0 + 1.301E+46S^1 + 3.009E+43S^2 + 3.026E+40S^3 + 1.333E+38S^4 + 2.052E+35S^5 + 2.414E+28S^6 + 2.086E+21S^7 + 1.313E+16S^8 + 2.189E+13S^9 + 2.908E+10S^{10} + 2.602E+04S^{11} + 9.002E+03S^{12} + 1.000E+09S^{13} + 2.602E+04S^{11} + 9.002E+03S^{12} + 1.000E+09S^{13}}
\]

Also \( Z_{21} \) was computed directly for network \( Z \) by means of NASAP-70.

This result is

\[
2-79
\]
The frequency response of Equations (2.52) and (2.53) was plotted as shown in Figure 2.40. A comparison of the two curves of Figure 2.40 gives an indication of the relative error between the two methods for computing $Z_{21}$. The peak at the upper frequency range of the curve for (2.52) is a result of solving each of the two networks separately and then combining these results to obtain the solution for the interconnected networks. One possible explanation for this is loss of significance error which can occur when two numbers of similar magnitudes are added.
A cascade connection example illustrates how the computation time increases as the number of cascaded stages increases. The circuit for each stage is shown in Figure 2.41.

The desired transfer function, $I_{out}/I_{in}$, can be calculated using NASAP-70. This was done first for one stage, then an identical stage was connected in cascade with this first stage to form a two stage amplifier. A coupling capacitor was placed between the collector of the first stage and the base of the second stage to provide DC isolation. NASAP-70 was again used to compute the transfer function $I_{out}/I_{in}$, where $I_{out}$ is the current through the collector resistor of the last stage. This process was continued until five stages had been cascaded. The results, which were calculated by an IBM 360 computer are plotted in Figure 2.42.

![Figure 2.41 A Single Stage Amplifier](image)

![Figure 2.42 Results of Cascading Amplifier Stages](image)

From this curve it can be seen that the computer time required increases rapidly as the number of cascaded stages is increased.
Calculations were made to predict the approximate theoretical time required to compute the desired transfer function when the cascaded stages are interconnected by the Cascade Parameter method. It was assumed that 1.1 seconds of CPU time was required to compute each parameter. The CPU time required to multiply the matrices of the individual stages was neglected.

If two stages were cascaded the resultant overall matrix would be

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} =
\begin{bmatrix}
A_1 & B_1 \\
C_1 & D_1
\end{bmatrix}
\begin{bmatrix}
A_2 & B_2 \\
C_2 & D_2
\end{bmatrix}
\]

The desired parameter is, \( D = B_2 C_1 + D_1 D_2 \). To compute \( D \), only \( B_2, C_1, D_1 \), and \( D_2 \) need to be calculated. Hence, the total assumed time required to compute \( D \) is \( 4 \times 1.1 = 4.4 \) seconds. The \( D \) parameter for three, four and five cascaded stages was computed in a similar manner. These theoretical computation times are plotted in Figure 2.42. It is evident that if more than four stages are cascaded, then a definite time savings will result if the desired transfer function is computed by the Cascade Parameter method. In the preceding example, the transfer function \( \frac{V_{\text{out}}}{I_{\text{in}}} \) was computed, whereas the parameter \( D \) is defined as, \( D = \frac{-I_{\text{in}}}{I_{\text{out}}} \mid V_{\text{out}} = 0 \). However, the parameter \( D \) can be computed and then inverted to give the desired transfer function.

2.7 Computational Errors

This section is concerned with the computational errors associated with NASAP-70. The impact and effect of errors at individual stages of computation are given, and in some cases recommendations regarding their minimization are also included.

2.7.1 Flowgraph Algorithm Errors

If the flowgraph algorithm and application of the Shannon-Happ formula were implemented utilizing a symbolic, or tagging approach no errors would be introduced into the derived transfer function. The NASAP-70
program discussed here performs all operations on numerical data. Thus, the constraint of digital computing introduces errors. Definition of these errors and how they relate to NASAP-70 follows.

**Input/Output Errors**

Circuit parameters are input to NASAP-70 in decimal floating point notation. Binary arithmetic units require that the input data be converted to floating point notation compatible with the machine. Errors are introduced in program working data because there is no one-to-one correspondence between fractions of different radicies when operations are restricted to a finite wordlength. The magnitude of the error is dependent on machine hardware and the algorithm used to perform the conversion.

After required calculations are completed, the internal binary results are converted back to decimal notation. The conversion effects only the last significant digit of each coefficient and is quite minor. Also, conversion is not performed when further operations are carried out in the transfer function. For these reasons, no attempt is made here to analyze these errors.

An example of actual input/output errors (IBM 360/75) is shown in Figure 2.43.

\[
\begin{align*}
T &= \frac{V_O}{V_F} \\
L_2 &= 4.9999905 \times 10^0 \\
L_3 &= 4.9999821 \times 10^{-1} \\
C_4 &= 1.3329828 \times 10^0 \\
R_5 &= 1.0000000 \times 10^0
\end{align*}
\]

**Figure 2.43**

**Round-off Error**

Round-off errors result directly from the finite wordlength of the machine. Errors can occur after both additive and multiplicative operations. The severe additive type errors are called significance loss, and will be described later.

2-83
Multiplying two numbers, each with \( n \) significant digits yields a product significant to \( 2n \) places. To store the product it is rounded to \( n \) significant digits. Wilkinson\(^{17}\) has shown that in a binary rounding system the floating point computation, \( F\lambda(X_1, X_2 \ldots X_n) \), produces the error bound \( E \),

\[
|E| \leq (n-1)2^{-t} + \frac{(n-1)(n-2)2^{-2t}}{2!} + \ldots
\]  

(2-54)

where

\[
F\lambda(X_1, X_2 \ldots X_n) = X_1 \cdot X_2 \ldots X_n (1+E)
\]

When computing high order loops, the flowgraph technique requires a number of consecutive multiplications. The round-off errors introduced can contribute significantly to the noise contained in the coefficients of a computed transfer functions. Relation (2-54) shows that increasing the word-length, \( t \), results in a decreasing error ratio, \( E \). It is proposed that double precision arithmetic be utilized in carrying out all required flowgraph multiplications. The round-off noise is located in the lower order digits. In most cases, results of multiplicative operations can be guaranteed to the significance of input data.

An example of round-off error is shown in Figure 2.44. The errors are totally attributed to round-off error because (1) Component values were selected such that the binary equivalent of the input data was exact, (2) Number of calculations and element values indicate no significant loss could have taken place.

Output requested. \( \frac{I}{V} = T \)

\[ T_{\text{True}} = \frac{I}{V} = \frac{1}{3} \]

\[ T_{\text{NASAP}} = \frac{1}{3 + \frac{2 \times 10^{-5}}{3S^2 + 0.667S + 3 709 \times 10^{-2}}} \]
Loss of Significance Errors

Loss of significance errors occur during floating point addition operations involving two numbers of opposite sign. The maximum error, E, resulting from the floating point addition \( X + Y \) is bounded by

\[
|E| \leq \left( 1 + \frac{1}{2} \right) 2^{-t}
\]

where

\[
F_E(X + Y) = (X + Y)(1 + E)
\]

The error impact is largely dependent on the magnitude and polarity of the parameters involved, and the order in which computations are carried out. Two situations demonstrate the extent of significance loss. First consider a simple floating point addition of two numbers of opposite sign but comparable magnitudes. The resulting sum is located in the low order positions, the same locations affected by conversion and round-off errors. When the sum is left-shift normalized, the true precision of the result is disguised. The second case involves a set of repeated additions where the order of calculation can introduce loss of significance.

Significance loss errors can occur in the calculations associated with the flowgraph technique. Circuits containing elements with values covering a wide range are especially prone. The table below presents three ways in which significance loss can be detected, controlled or eliminated.

<table>
<thead>
<tr>
<th>METHOD</th>
<th>PURPOSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compare results of normalized and non-normalized arithmetic</td>
<td>Detection</td>
</tr>
<tr>
<td>Time scaling</td>
<td>Minimization or Elimination</td>
</tr>
<tr>
<td>Optimum tree</td>
<td>Minimization or Elimination</td>
</tr>
</tbody>
</table>
The first approach employs a two pass system with the first pass utilizing regular floating point arithmetic. During the second pass, the arithmetic is changed such that sums are not left-shift normalized. When the number is subsequently required in another calculation, the appropriate number of zeros (necessary to align the two operands) are shifted into the least significant bit positions. This scheme defines a lower bound for the calculation. The results of the two passes are examined and significance loss has occurred if these numbers are not equivalent. The significance of the calculation is considered to be equal to the number of digits which are identical. The calculation of Figure 2.43 is not prone to significance loss,

\[
T = \left( \frac{V_1}{V_R} \right) \text{ normalized} = \frac{1.00025}{1.00000S^3 + 2.00000S^2 + 2.00050S + 1.00025}
\]

\[
T = \left( \frac{V_1}{V_R} \right) \text{ unnormalized} = \frac{1.00025}{1.00000S^3 + 2.00000S^2 + 2.00050S + 1.00025}
\]

Figure 2.45 is a problem vulnerable to significance loss as is demonstrated below

\[
T = \left( \frac{V_1}{I_1} \right) \text{ normalized} = \frac{2.04000 \times 10^{-11}S^2 + 1.10709 \times 10^{-1}S + 7.19903 \times 10^7}{2.04000 \times 10^{-13}S^2 + 7.67740 \times 10^{-4}S + 1.16400 \times 10^4}
\]

\[
T = \left( \frac{V_1}{I_1} \right) \text{ unnormalized} = \frac{2.04000 \times 10^{-11}S^2 + 1.10709 \times 10^{-1}S + 7.19903 \times 10^7}{2.04000 \times 10^{-13}S^2 + 7.67827 \times 10^{-4}S + 1.16640 \times 10^4}
\]

Figure 2.46 shows how the span of element magnitudes in Figure 2.45 changes as the time scale is decreased. The particular transfer function was computed and checked for significance loss at the various time scales. The results of the technique although inconclusive, tend to show that time scaling in one technique to combat significance loss.16
\[ I_1 = 1 \, \text{mA} \]
\[ R_2 = 1 \, \Omega \]
\[ R_3 = -1 \, \Omega \]
\[ R_4 = 100 \, \Omega \]
\[ R_5 = 1 \times 10^6 \, \Omega \]
\[ C_6 = 6 \, \text{pf} \]
\[ C_7 = 200 \, \text{pf} \]
\[ R_8 = 150 \, \Omega \]
\[ D_9 = 0.4 \]
\[ R_{10} = 1 \times 10^4 \, \Omega \]
\[ R_{11} = 100 \, \Omega \]

Compute \[ T = \frac{V_{R2}}{I_1} \]

Figure 2.45

![Graph](image)

Figure 2.46

2-87
Another way of reducing significance loss in the computation of Figure 2.45 is to select an optimal tree. An optimal tree is defined as the tree which, if selected, displays to the program the minimum variance between the magnitudes of the input data. The results of optimal tree selection are plotted above.

Different input trees generally result in varying computational orders. The above definition can be used as a means for reducing computational errors, although the method itself is not foolproof. The third data point in Figure 2.47
is assumed to result from a favorable computational order for the particular tree selected and, contradictory to the definition of an optimum tree, a comparably good transfer function was calculated.

**Error Prediction**

It was shown that the errors associated with transfer function coefficients are related directly to the number of loops of all orders in the flowgraph and the number and range of computations required for each loop. It is desirable to obtain a measure of these parameters before an attempt is made to derive a particular transfer function. Given the flowgraph model described by Figure 2.48, it can be shown that there exists, \( F_n = \frac{1}{\sqrt{5}} \left[ (1 + \sqrt{5}/2)^{n+2} - (1 - \sqrt{5}/2)^{n+2} \right] \) loops of all orders, where \( n = 2m - 1 \) (the number of passive elements minus one) and \( F_n \) = Fibonacci number of order \( n \).

If flowgraph loops of all orders are assumed to have numerical values of the same magnitude, then the equation below is an estimate of the maximum round-off error contained in a calculated transfer function coefficient

\[
\frac{\Delta \Sigma(n)}{\Sigma(n)} \approx \frac{2^{-t}}{F_n} \left[ \sum_{N=1}^{N_{\text{max}}} \frac{(n-N+1)!}{N!(n-2N+1)!} (NK-1) \right]
\]

where

1. \( \Sigma(n) \) is the sum of all loop values of all orders
2. \( K \) is the number of circuit elements in a particular first order loop (=2 for the specific model)
3. \( N_{\text{max}} = n+1/2 \) if \( n \) is odd
   \( N_{\text{max}} = n/2 \) if \( n \) is even.
In an attempt to predict errors for those circuits which do not exactly correspond to the flowgraph model, Figure 2.49 has been drawn for various values of K. Experience has shown that for practical problems, a good average value of K lies between 2 and 3.

![Figure 2.49](image)

2.7.2 Impact of Coefficient Errors on AC Analysis

The NASAP version utilizes a straightforward technique in deriving the AC Bode plot. The programs produce a frequency response of the form

\[
F(s) = \frac{N(s)}{D(s)} = \frac{\sum_{i=0}^{p} a_i s^i}{\sum_{j=0}^{q} b_j s^j}
\]
The computed coefficients, $a_i$ and $b_j$, can be expressed as,

$$a_i = a_i^T + \Delta a_i$$

$$b_j = b_j^T + \Delta b_j$$

where $a_i$ and $b_j$ represent the accumulated coefficient errors $a_i^T$ and $b_j^T$ are the true coefficients, and $F(s)$ as

$$F(s) = F^T(s) + \Delta F(s) = \frac{N^T(s)}{D^T(s)} + \Delta F(s).$$

If $F(s)$ is assumed to be a function of its coefficients $a, b$ for any $s$, then since

$$f(a^T + \Delta a, b^T + \Delta b) \approx f(a^T, b^T) + \frac{\partial f}{\partial a} \Delta a + \frac{\partial f}{\partial b} \Delta b$$

for $\Delta a \ll a$, $\Delta b \ll b$,

it can be shown that

$$\Delta F(s) = \sum_{i=0}^{p} \frac{\Delta a_i}{D^T(s)} s^i - \sum_{j=0}^{p} \frac{F^T(s)}{D^T(s)} \Delta b s^j.$$

The computational errors in $F(s)$ are approximated from an initial estimate of coefficient errors by substituting $D(s)$ and $F(s)$ for $D^T(s)$ and $F^T(s)$. These substitutions become quite laborious for functions which are a ratio of two high order polynomials. An alternate approach is taken.

Coefficient errors are not likely to exceed 15 percent of the true coefficient values (this statement is predicated on the assumption that any "large" problems have been partitioned and the steps have been taken to avoid severe significance loss). By randomly perturbing the transfer function coefficient not more than ± 15 percent and plotting the frequency response curves, the results of the above can be simulated. A band which
most probably contains the true response curve will result. For example, the frequency response curve of Figure 2.50 can be obtained from the circuit shown in Figure 2.43.

![Figure 2.50](image)

### 2.7.3 Transient Response Errors

Errors contained in a final time domain solution after application of the Fast Fourier Transform can be attributed to original coefficient errors and algorithm errors.

Given the results of Section 2.7.2

\[
f(t) = \mathcal{F}[F(s)] = \mathcal{F}[F^T(s) + \Delta F(s)]
\]

\[
= \mathcal{F}[F^T(s)] + \mathcal{F}[\Delta F(s)]
\]

\[
= f^T(t) + \Delta f(t)
\]

Since the errors due to coefficient deviations are simply an additive function to the time response, an initial approximation of these errors can be transformed directly into an estimate of time response errors.
The digital implementation of the Fast Fourier Transform introduces round-off, discretization and band limiting errors.

Gentleman and Sande $^{20}$ have described the Fast Fourier Transform round-off error found in a digital environment in terms of the ratio of the Euclidian norm of the error sequence to the Euclidian norm of the input data sequence. Using the Fast Fourier Transform yield an upper bound for the associated Euclidian norm of

$$ R \leq 1.06 \sqrt{N} K(2n)^{3/2} 2^{-b} $$

where $N$ is the number of discrete steps taken, $n = N$ (for NASAP-70 $n=2$, $k=12$), and $b$ equals the number of bits in the calculation mantissa.

Figure 2.51 shows how discretization and band limiting errors affect the results of a Fast Fourier Transformation. For each curve, the function $F(s) = s/s + \omega$, was inverted. Discretization errors are demonstrated by the more noisy 'o' curve. Band limiting errors are shown by the poor initial points of both curves.

It should be noted that the errors resulting from coefficient errors dominate those introduced by the Fast Fourier algorithm.

Based upon the error analysis of a typical circuit analysis program such as NASAP-70 the user must be aware of the computational aspects of the algorithms before the results can be considered reliable.
Figure 2.51
Note also that the definition numbers that when the branches are removed from the parent graph, the structure of the cut-set remains intact when the removal of all but any one branch of any cut-set results in two separate parts, and at the same time permits the graph to be connected.

The basic properties of linear graph theory which pertain directly to the connected parts of a separated graph are subgraphs.

Given a linear graph, a graph G is said to be a subgraph of G if it contains only branches and nodes of the original graph.

The current direction of a cut-set is shown in Figure 3. Note also that the seven current elements and four junction points result in seven seven schemes is shown with its corresponding linear graph in Figure 3 (b).

A graph represents a physical connection of function point in the system and

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A graph represents a physical connection of function point in the system and
(a) CIRCUIT DIAGRAM

(b) LINEAR GRAPH

(c) ORIENTED GRAPH (G)

(d) TREE (T)

Figure 3.2
REFERENCES

6. Gaertner Research Incorporated, "Coding Instructions for NASAP 69/1," Revision No. 1, Contract No. NAS 12-663, Stamford, Conn.


CHAPTER 3
THEORETICAL FOUNDATIONS

3.0 Introduction

Fundamental to any meaningful discussion of a computer-aided circuit analysis/design program is the systematic treatment of the basic concepts behind it. As shown in Figure 3.1, the theoretical treatment for NASAP can be separated into the disciplines of linear graph theory, flowgraph theory, sensitivity analysis, and the relevant numerical techniques and supporting computer algorithms.

Each discipline plays a distinctive role in the operation of the program. Linear graph theory is employed as a convenient mathematical tool to bridge the gap between the circuit designer and the computer. A computer subroutine then transforms the linear graph description of a circuit into flowgraph terms forming the basis of the computer algorithms for subsequent output requests. The transfer function, the principal output request of NASAP-70, is computed from the flowgraph description by means of the Shannon-Happ formula, the other user requests are based upon the transfer function formulation.

As shown in Figure 3.1, the description of each discipline in NASAP is taken in the order of implementation thus the sections are numbered accordingly.

3.1 Linear Graph Theory

The initial step in the formulation of the flowgraph relations is the identification of circuit elements in topological terms. Since this requires some background in linear graph theory, a few definitions and some basic concepts of how they pertain to circuit theory should be stated first. A more elaborate treatment of graph theory can be found in a number of textbooks. A complete exposition can be found in Kuh and Desoer.

The essential constituents of a linear graph are branches and nodes. Each branch, symbolized by a line, represents a physical element of the system from which it is abstracted with its electrical properties. A node in
Figure 3.1

3.1 Linear Graph Theory
3.2 Transformation
3.3 Flowgraph Theory
3.5 Sensitivity Analysis (Parameter, Worst Case, Pole)
3.4 Transfer Function
3.6 Roots Zeros
3.7 AC Analysis (Bode Plot)
3.8 Transient Response

Designer

Man-Machine Interface

Computer
that a hinged linear graph of Figure 3.4 violates the cut-set definition at the "hinge" and thus circuits of this type should be avoided or separated into two problems.

In simple terms a loop is defined as a collection of branches which form a closed path (ignoring the direction of flow in the branches). A more formal definition can be stated: a set of $n$ nodes $A(A_1------A_n)$ and a set of $n$ branches $B(B_1------B_n)$ which are connected constitutes a loop in a graph $G$ if $A$ is in $G$ and $B$ is in $G$, and each branch in $B$ is incident to two nodes in $A$ and each node in $A$ has two branches in $B$ incident to it. The branches 1-2, 3-2, 4-3, 4-1 form a loop as shown in Figure 3.5. Note that a loop is defined independent of the direction of the arrows.

If a subgraph $G'$ of a graph $G$ can be selected such that it consists of only branches and all nodes of $G$, is connected, and contains no loops, then the subgraph $G'$ is called a tree ($G' = T$) (See Figure 3.2(d)). The branches of a tree are called tree branches or just branches, and those branches in $G$ but not in $T$ are name links.

A number of fundamental properties concerning trees are now stated without proof. If a connected graph $G$ has $n$ nodes and $b$ branches, then

1. The Tree has $(n-1)$ tree branches and $(b-n+1)$ links,
2. A unique path exists along the tree between any two nodes (neglecting the direction of the arrows if it is an oriented graph),
3. Fundamental loops (tie sets) can be formed by taking each link with the unique path in the tree that exists between the two nodes of the link,
4. Fundamental cut sets can be formed by grouping the set of connected links about a tree branch thus forming $(n-1)$ cut sets,
5. The cut set relations form a complementary set to the tie set relation (in matrix notation one is the transpose of the other),
6. Cut set and tie set relations can be expressed unilaterally. Branch currents can be expressed as a function of link currents and link voltages as a function of branch voltages.
3.2 Transformation of a Linear Graph to a Flowgraph — Disjoint Current and Voltage Relationships

Algorithms must provide for the computer a means of producing a consistent set of determinable variables. To a circuit designer this usually means either applying Kirchhoff's voltage law in conjunction with the impedance relationships (Ohm's law) or Kirchhoff's current law in conjunction with the admittance relationships. Another approach has been advocated (originally by Kirchhoff himself) and is used in this manual. Basically it requires that Kirchhoff's current law be applied first, then Kirchhoff's voltage law, and finally Ohm's law and dependencies.

The first step in the procedure requires that all circuit elements, active or passive, dependent or independent, be divided into two groups of current-type or voltage-type elements. Naturally, a voltage source will remain a voltage-type element, and a current source will remain a current-type element. Passive elements, which are bilateral in nature, will be replaced by either a voltage-type or current-type element (i.e., replace Ohm's law \( I = \frac{V}{Z} \) by either \( I = \frac{V}{A} \) or \( V = I \cdot Z \)), the choice being somewhat arbitrary and subject to the conditions that Kirchhoff's two laws have to be applied independently. (Some guidelines will be presented in the example problem of section 3.3.) It should be emphasized that by assigning a voltage or current type element in place of a passive element, the bilateral characteristic is replaced by a unilateral relation.

In the following selection process, Kirchhoff's laws will be applied to two sets of disjoint circuit relations. Tree-link partitioning is accomplished by using a tree structure \( T \) in a graph \( G \), where the voltage-current equations are separated into two complimentary sets. The graph \( G \) contains as its branches all the circuit elements. The arrow direction corresponds to the direction of assigned current flow. The branches of a tree \( T \) (Figure 3.2(d)) are selected to be the voltage elements. The remaining elements (links in \( T \)) are chosen to be current elements. For this selection, a voltage at any point...
can be calculated as a function of voltage-type elements only. Currents and
impedances need not be considered. Similarly, the current at any element
can be determined as a function of current-type elements only, and therefore
is independent of voltage-type elements and impedances.

Note that the tree-link partition does not restrict one from determining
the voltage of a voltage-type element as a function of currents, voltages, and
Ohm's law. It is particularly important to realize that expressing a voltage as
a function of voltage-type elements does not render a voltage across these elements
constant. It does mean, however, that a consistent set of Kiekhoff's equations can
be written as a function of any voltage in terms of voltage type elements. A sim-
ilar statement can be made concerning the current type elements. Namely,
the current expressed as a function of current-type elements does not render
the current through current-type elements constant

Consider \( R \) as a voltage element. The voltage at \( R \) \( (V_{\text{in}}) \) is set as a
known variable and the current as an unknown variable, then the applica-
tions of Kiekhoff's laws will yield in the form \( V_{\text{in}} = I_{\text{out}} R \) \( + \) the
function of other currents

In summary, the NASAP algorithms make use of the following

1. A tree \( T \) in graph \( G \) divides the elements into two disjoint sets,
2. A tree \( T \) in graph \( G \) allows writing of \((n-1)\) independent current
equations of one set (voltage) in terms of the other (current) by
writing current equations for any \((n-1)\) out of \( n \) nodes,
3. By Gaussian elimination one obtains \((n-1)\) cut set equations
These equations can be expressed as unilateral current relations,
(this will be elaborated in the example),
4. Since a cut set and tie set are complementary, one obtains Kiek-
hoff's voltage equations in a unilateral form as a complement of
the unilateral current relations,
Current-voltage relations can be made functionally dependent by a set of unilateral elements provided that for each element one of the quantities (current or voltage) is known and the second quantity (voltage or current) is unknown. These are exactly the conditions that the two disjoint current-voltage sets provide.

3.3 Flowgraph Theory: Shannon-Happ Formula

For a set of linear relations that satisfy consistency criteria (to be explained later) there exists a formula by which the solution can be obtained in a noniterative substitution and does not require stability criteria for each relation. This formula was originally developed by Claude Shannon while investigating the functional operation of an analog computer. Essentially the same formula was rediscovered by S. Mason in 1952.* Shannon's Formula is an analytic expression for calculating the gain of an interconnected set of amplifiers in an analog computing network. W. W. Happ generalized Shannon's work for topologically closed systems. The Shannon-Happ Formula is valid in deriving transfer functions, sensitivities, and error functions. For the particular use intended for this formula, the sensitivity factor $H$ is set equal to zero.

Flowgraph Notation

Before the Shannon-Happ Formula can be defined explicitly, it is necessary to define the basic concepts of flowgraph for which the equation was derived. The fundamental terms of a flowgraph, namely, node, transmittance, and loop, and how they interact can best be described by example. Consider the equations,

$$a_{11}x_1 + a_{22}x_2 + x_1 = x_1$$
$$a_{21}x_1 + a_{22}x_2 + c_2 = x_2$$

and the corresponding flowgraph shown in Figure 3-6.

---

*During World War II Claude Shannon developed his formula. Because of wartime restrictions, his work was not published, and was virtually unknown to the academic community. In 1952, Samuel Mason rediscovered the same formula.
Each node represents a variable, thus $x_1$ and $x_2$ are variables and $c_1$ and $c_2$ are considered constant inputs. The nodes $c_1$ and $c_2$ are called independent nodes. If the arrows leading from $c_1$ or $c_2$ were reversed, these nodes would be dependent nodes.

A transmittance is a value assigned to the directed path between two nodes. The node at which the directed line begins is called the origin node, whereas the node at the receiving end is the target node. The transmittance relates the origin node variable. Therefore, in reading the flowgraph, the functional relationship of a variable is the summation of the product of respective incoming transmittances with their node variables. This can be verified by writing out the equation associated with the flowgraph (Figure 3.6) and the original equations. Note that a flowgraph transmittance function such as

$$ A \cdot b \rightarrow C $$

will be written as $A - b \times C$ on a programming sheet.

A directed loop is defined as a closed path consisting of a sequence of transmittances taken in the direction of the arrow. The sequence must be
taken such that no node is traversed more than once in the closed path. The
value of a directed loop is the product of the transmittances forming the di­
rected loop. In the example, three directed loops exist, \((a_{12}, a_{21}), (a_{11}),
(a_{22})\). (Note that loop in a flowgraph does depend upon direction whereas
in linear graph theory this was not required.)

Distinct types of loops must be defined in the Shannon-Happ Formula

(a) a first-order loop is a simple directed loop as defined above
(b) an Nth-order loop is composed of N disjoint first order loops
   (none of the nodes are common between loops) The value of
an Nth order loop is the product of the N first-order loop values
comprising the Nth-order loop. In the example, only one second-
order loop combination exists, namely, \((a_{11} a_{22})\)
(c) a zeroth-order loop is by definition equal to a value one and has
   no flowgraph significance. It is a mathematical convenience
employed in the Shannon-Happ Formula

**Shannon-Happ Formula**

If \(L(0)\) is the value of the zeroth-order loop (always equals one) and
\(L(N)\) is the sum of the values of all the loops whose order is \(N\), the Shannon-
Happ formula can be expressed as

\[
H = L(0) - L(1) + \cdots + (-1)^N L(N) = 0
\]

which can be written in expanded form

\[
H = 1 + \sum_{r=1}^{N} \sum_{i=1}^{R} L_i(r)(-1)^r = 0
\]

where \(R = \text{the number of } r\text{-order loops in the system and } N = \text{the order of}
the highest loop in the system.

3.4 Transfer Function Formulation

The circuit shown in Figure 3.7 is used to illustrate the circuit analysis
techniques. The AC model of this circuit using only linear elements is
shown in Figure 3.8. Note that an extra current source has been inserted at the output (across L). This element can be viewed as a voltmeter as described in section 2.
For the circuit in Figure 3.7, the output voltage is taken across the inductor L. Since the voltage across L is one of the variables, the output voltage, \( V_{out} \), can be expressed directly, that is, \( V_{out} = V_L \). By adding the output current source (I = 0) in Figure 3.8, provision has been made for a general method of solution.

After the equivalent circuit is constructed, its corresponding directed linear graph must be drawn with the assigned current direction in the circuit elements. In the linear graph G one selects a tree structure T which must contain all voltage sources (dependent or independent). If the voltage sources form a loop, the circuit's definition is ambiguous and hence cannot be solved. Assuming that the voltage sources do not form a loop, passive elements must be added to complete the tree. To this end, some of the passive devices are made voltage-type elements and thus provide the remaining constituents for the tree (See Figure 3.9). Finally, the current sources and the rest of the passive elements form links. (This operation constitutes the particular selection of either a voltage or current relation for each passive element.)
The next step requires one to obtain the current at the branches (voltage-type elements) as a function of the currents in the links (current-type elements). This entails writing the current equations for \( (n-1) \) out of \( n \) nodes of \( T \). Then, the current in each branch is found as a function of link currents only by the Gaussian elimination process. By finding branch current as a function of link currents one forms the \( (n-1) \) cut sets.

The current equations are written by setting the branch currents on the left-hand side of the equals sign and the link currents on the right-hand side. For Figure 3.9, the node current equations can be written as

| Node 6 | \(-I_{V_{in}}\) | = | \(-I_{R_1}\) | \(-I_{C_1}\) |
| Node 5 | \(I_{r_1}\) | = | \(I_{C_1}\) |
| Node 4 | \(I_{r_0}\) | = | \(-I_\beta\) | \(+I_{R_2}\) |
| Node 3 | \(-I_{r_1}\) | \(-I_{r_0}\) | \(I_{R_3}\) | = | \(I_\beta\) | \(-I_{C_2}\) |
| Node 2 | \(I_L\) | = | \(I_0\) | \(-I_{R_2}\) |

In compact matrix notation

\[
\begin{bmatrix}
-1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & -1 & 1 & 0 \\
0 & 0 & 0 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
I_{V_{in}} \\
I_{r_1} \\
I_{C_1} \\
I_{r_0} \\
I_{R_3} \\
I_L \\
I_{R_2}
\end{bmatrix}
= 
\begin{bmatrix}
-1 & -1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 & 1 \\
0 & 0 & 1 & -1 & 0 & 0 \\
0 & 0 & 0 & 1 & -1
\end{bmatrix}
\begin{bmatrix}
I_\beta \\
I_{C_2} \\
I_0 \\
I_{R_2}
\end{bmatrix}
\]

or

\[
A_T \mathbf{I}_T = B_L \mathbf{I}_L
\]

where
A is an \((n-1)\times(n-1)\) matrix \((n-1)\) is the number of branches of the tree, \(I_T\) is a column vector of \(n\) branch currents, 
\(B\) is an \((n-1)\times(m)\) matrix \((m=b-m+1\) is the number of links), 
\(I_L\) is a column vector of \(m\) link currents

After matrix \(A\) is diagonalized, performing the same operations on \(B\) as an \(A\), the current equations take the form

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
I_{V_{in}} \\
I_{R_1} \\
I_{R_0} \\
I_{R_3} \\
I_L
\end{bmatrix} = \begin{bmatrix}
1 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 \\
0 & 1 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
I_{R_1} \\
I_{C_1} \\
I_{\beta} \\
I_{C_2} \\
I_0 \\
I_{R_2}
\end{bmatrix}
\]

Note that the Gaussian elimination is performed on a set of integers, 
\((+1, 0, -1)\) and will not entail any loss of significance or introduce any truncation errors.

Following the Gaussian elimination that transforms the current equations into a unilateral set, the flowgraph can be constructed. The first step is forming the current flowgraph relations as shown in the lower part of Figure 3.10. In the diagram (Figure 3.10), two flowgraph nodes are assigned to each element. The bottom nodes correspond to the currents in the elements and the top nodes correspond to the voltage across the elements.
The flowgraph voltage relations are constructed by an imaging method based on the current relations. The rules for this technique are:

1. Consider two elements for which there exists current transmittance connecting two current nodes. Form a transmittance connecting the two corresponding voltage nodes. The direction of the voltage transmittance arrow is the reverse of the corresponding current transmittance.

2. If one element is passive and the other is active, the sign attached to the voltage transmittance is the same as the corresponding current transmittance. The sign is reversed if both elements are the same type, that is, both passive or both active. The use of the imaging technique is a consequence of the fact that disjoint sets of current and voltage also form complementary sets since they are complementary cut and tie sets. (The difference in the sign reversal between active and passive elements is due to the fact that conventionally used Kirchhoff's equations are not written in a complementary form, that is, currents are summed to zero \((I_1 + I_2 + I_n = 0)\) while voltages are summed to a nonzero quantity \((V_1 + V_2 + V_n = E)\). Also Kirchhoff originally stated them in a complementary form.)

After Kirchhoff's current law and Kirchhoff's voltage law have been applied, the current-voltage relations and dependencies and requested transfer...
function are determined by making the input dependent on the output by the relation \[ \text{Input} \leftrightarrow P \cdot \text{Output} \]. This forms a closed flowgraph. The forward transfer function \( T = 1/P \) can then be arrived at since the total gain \( P \cdot T = 1 \) as evaluated by use of the Shannon-Happ Formula (for \( P \) unknown). This evaluation can be done by separation of products containing \( P \) and those terms which do not contain \( P \) since no higher powers of \( P \) than \( P^1 \) can occur.

A transfer function can be evaluated only as a function of a free variable (it cannot be found as a function of a variable which was already set as a determinable variable). The free variables are defined as: (1) the current in the independent current source and (2) the voltage across an independent voltage source. The transmittance \( P \) will cause one of the free variables to become a determinable variable (that is, it can be included in the evaluation of the Shannon Happ Formula). The rest of the free variables will be set to zero for the evaluation of the function. A comparison between Figures 3.10 and 3.11 will indicate how this is accomplished. Note that the current-voltage relations in passive elements are taken as impedances for branches and admittances for links.

![Diagram](image-url)
It is important to emphasize the uniqueness of transformations achieved by the algorithm presented herein and its advantages over techniques which are based on solutions of a set of equations. This means that from the representations such as that presented in Figure 3.11 one can reconstruct the original system, thus showing that the algorithmic procedure described above does not incur information loss.

The transfer function $\frac{V_{\text{out}}}{V_{\text{in}}}$ is calculated by use of the Shannon-Happ Formula. In the present example there are nine first-order loops, which are summarized with their node sequence and loop transmittances in Table 3.1.

The higher-order loops are unions of first-order loops that do not intersect and the loop value is the product of the corresponding first-order loop values. Loop substitution into the Shannon-Happ Formula, and the setting of $H = 0$, followed by solving for $T = 1/P$ yields the requested transfer function,

$$
\frac{V_{\text{out}}}{V_{\text{in}}} = T \left[ \frac{L_8}{P} (1 - L_2) + \frac{L_9}{P} \right] \left[ 1 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7) 
+ (L_1 L_2 + L_1 L_4 + L_1 L_5 + L_1 L_6 + L_2 L_5 + L_2 L_6 + L_3 L_5 + L_3 L_6)
- (L_1 L_2 L_5 + L_1 L_2 L_6) \right]
= - \left[ \left( \frac{\beta C_1 L_r C_2 R_3}{R_2} \right) S^3 + \left( \frac{\beta C_1 L_r}{R_2} - \frac{C_1 L R_3}{R_2} \right) S^2 \right] 
+ \left[ \frac{C_1 C_2 L r_1 R_3}{R_2} S^3 + \left( \frac{C_1 C_2 r_1 R_3}{R_2} + \frac{C_1 L r_1}{R_2} + \frac{C_1 L R_3}{R_2} + \frac{C_1 L R_3}{R_2} \right) S^2 \right] 
+ \left( \frac{C_1 r_1 R_3}{R_2} + \frac{C_1 r_1}{R_2} + \frac{C_1 L r_3}{R_2} + \frac{C_1 r_3 R_3}{R_2} \right) S + \left( \frac{R_3}{R_2} + \frac{r_o}{R_2} \right) \right]
$$

*Although the proof is rather involved (thus not presented here), note that the information necessary to reconstruct the original circuit is given by the flowgraph and by preserving the $I_T$ and $I_L$ vectors in the arrangement of the flowgraph nodes.*
The solution $T = 1/P$ is obtained by placing the loops containing $P$ and their products in the numerator and those devoid of $P$ in the denominator.

Since the only arithmetic in the entire algorithm is used in calculating the transfer function performed at the end of the algorithm and essentially is the sum of products, one can control the error and make the solution as accurate as desired. Furthermore, comparison between values of loops is

<table>
<thead>
<tr>
<th>Loop Number</th>
<th>Node Sequence</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>$V_{C_1} I_{C_1} I_{r_1} V_{r_1}$</td>
<td>$-C_1 r_1 S$</td>
</tr>
<tr>
<td>$L_2$</td>
<td>$V_{C_2} I_{C_2} I_{R_3} V_{R_3}$</td>
<td>$-C_2 R_3 S$</td>
</tr>
<tr>
<td>$L_3$</td>
<td>$V_{C_1} I_{C_1} I_{R_3} V_{R_3}$</td>
<td>$-C_1 R_3 S$</td>
</tr>
<tr>
<td>$L_4$</td>
<td>$V_{R_3} V_{R_2} I_{R_2} I_{r_0}$</td>
<td>$-R_3/R_2$</td>
</tr>
<tr>
<td>$L_5$</td>
<td>$V_{r_0} V_{R_2} I_{R_2} I_{r_0}$</td>
<td>$-r_0/R_2$</td>
</tr>
<tr>
<td>$L_6$</td>
<td>$V_{R_2} I_{R_2} I_{L} V_{L}$</td>
<td>$-\frac{L S}{R_2}$</td>
</tr>
<tr>
<td>$L_7$</td>
<td>$I_{r_1} I_{r_0} V_{r_0} V_{r_2} r_{r_2} V_{r_3} V_{C_1} I_{C_1}$</td>
<td>$-\frac{\beta C_{1} r_0 R_3 S}{R_2}$</td>
</tr>
<tr>
<td>$L_8$</td>
<td>$V_{in} V_{C_1} I_{C_1} I_{r_0} I_{r_0} V_{r_0} V_{R_2} I_{R_2} I_{L} V_{L} V_{i_0}$</td>
<td>$-P \left(\frac{\beta C_{1} L r_0}{R_2} S^2\right)$</td>
</tr>
<tr>
<td>$L_9$</td>
<td>$V_{in} V_{C_1} I_{C_1} I_{R_3} V_{R_3} V_{R_2} I_{R_2} I_{L} V_{L} V_{i_0}$</td>
<td>$P \left(\frac{C_{1} L R_3}{R_2} S^2\right)$</td>
</tr>
</tbody>
</table>

indicative of the significance of each element in the transfer function and is helpful in omitting the elements which have a negligible effect on the final transfer function.
3.5 Sensitivities Concepts

There are three basic sensitivity algorithms employed in NASAP-70. These are parameter sensitivity, worst case (tolerance) analysis, and pole sensitivity. A description of each follows.

3.5.1 Parameter Sensitivity

In section 3.4, the transfer function \( T = \frac{1}{P} \) was obtained by keeping track of the loops that contained \( P \) and those devoid of \( P \), and forming the ratio of the two expressions. As shown below, the somewhat similar tagging technique in the computer algorithms can produce the sensitivity of the transfer function to changes in a circuit parameter.

Consider the system of Figure 3.12 where \( X \) is the input or excitation and \( Y \) is the output or response. If the input and output are connected by a transmittance \( P \), then the transfer function can be expressed in terms of \( P \) since \( P = \frac{X}{Y} = \frac{1}{T} \). This represents a closed system for which the input and output are dependent upon each other. The Shannon-Happ Formulas states that the topology equation \( H(T) \) must equal zero, thus

\[
H(T) = H(T) + TH(T') = 0
\]

where \( H(T') = \frac{dH}{dT} \) is the portion of \( H \) containing \( T \) linearly and indicated in the computer algorithm by a tag of \( T = 1 \), and

\[
H(T) + H(T=0) = \text{the portion of } H \text{ devoid of } T
\]

and indicated in the computer algorithm by a tag of \( T = 0 \).

To compute the sensitivity function, consider a circuit that contains a component \( Q \) and sustains a desired performance specification \( T \), the transfer function. It is always possible to formulate a closed system containing the two parameters \( T \) and \( Q \) linearly. The topology equation \( H = 0 \) is a constraint on the system from which the unknown \( T \) is calculated.

3-20
If the topology equation $H$ is a function of two parameters $T$ and $Q$, then

$$H(T, Q) = H(T, Q) + TH(T', Q) + QH(T, Q') + TQH(T', Q')$$

where the coefficients of $T$ and $Q$ are defined as Taylor series coefficients and the terms of the topology equation $H(T, Q)$ are defined as follows

- $H(T, Q) = H(T=0, Q=0) = H(0, 0)$
- $H(T', Q) = H(T=1, Q=0) = H(1, 0)$
- $H(T, Q') = H(T=0, Q=1) = H(0, 1)$
- $H(T', Q') = H(T=1, Q=1) = H(1, 1)$

All of these quantities refer to partial sums of the topology equation which can be tagged and identified in the computer program.

A topological derivation of sensitivity is obtained by taking the total derivation of $H(T, Q)$ above.

$$dH(T, Q) = \left| H(T', Q) + QH(T', Q') \right|dT + \left| H(T, Q') + TH(T', Q') \right|dQ = 0$$

or

$$\frac{dT}{dQ} = -\frac{H(T, Q') + TH(T', Q')}{H(T', Q) + QH(T', Q')}$$

Figure 3.12

3-21
since
\[ H(T, Q) = \left[ H(T, Q) + H(T, Q') \right] + T \left| H(T', Q) + H(T', Q') \right| = 0 \]
and
\[ H(T, Q) = \left[ H(T, Q) + H(T', Q) \right] + Q \left| H(T, Q') + H(T', Q') \right| = 0 \]
therefore,
\[ \frac{Q}{T} = \frac{[H(T, Q) + H(T', Q)] [H(T', Q) + H(T', Q')]}{[H(T, Q) + H(T, Q')] [H(T', Q') + H(T', Q')]}. \]
The parameter sensitivity is defined by
\[ \frac{dT}{d \log T} = \frac{dT}{d \log Q} = \frac{dQ}{Q} \]
or,
\[ = - \frac{H(T', Q) + H(T, Q)}{H(T, Q) + H(T, Q')} \]

3.5.2 Worst Case (Tolerance) Analysis

The sensitivity techniques outlined in section 3.5.1 may be used to perform a worst case tolerance analysis on all components of the circuit. Assume that a given circuit specification \( P \) can be specified as a function of \( n \) parameters \( Q_1, Q_2, \ldots, Q_n \)
\[ P = f(Q_1, Q_2, \ldots, Q_n) \]
Then for small changes in the parameter, the statistical tolerance \( T_P \) of \( P \) is defined as
\[ T_P = \left[ \left( \frac{\partial P}{\partial Q_1} Q_1 \right)^2 + \cdots + \left( \frac{\partial P}{\partial Q_n} Q_n \right)^2 \right]^{1/2} \]
\( T_P \) is a measure of the deviation of \( P \) from its mean value due to deviations of the components from their respective mean values.

3-22
Using the definition of sensitivity $T_p$ can be expressed in a more suitable form for utilization of the tagging technique as

$$\frac{T_p}{P} = \sum_{i=1}^{n} \left[ S_p^i \frac{dQ_n}{Q_n} \right]^2$$

where $\frac{T_p}{P}$ is the functional tolerance.

The sensitivity of $P$ with respect to each parameter $Q$ may be calculated as before, then substituted into the $\frac{T_p}{P}$ expression to derive the tolerance.

3.5.3 Root Sensitivity\(^{14}\)

When a parameter of a system changes, the locations of the poles will also change. Root sensitivity is defined as a measure of the amount of change a root undergoes, given a percent change in some system parameter.

The following analysis assumes that (1) the system is linear and time invarient, and (2) the transfer function is obtainable and can be expressed by the form

$$T(S) = \frac{A(S) + KB(S)}{C(S) + KD(S)}$$

Here, $A(S)$, $B(S)$, $C(S)$, and $D(S)$ are polynomial in $S$ and $K$ is a system parameter for which the sensitivity is desired.

For differential changes in the parameter $K$, there will be differential changes in the roots of the characteristic equation, $C(S) + KD(S)$. The definition of root sensitivity employed in NASAP-70 considers one system parameter, $K$, and one pole of the transfer function $S_1$, and is defined as

$$S_{1_K} = \frac{dS_1}{dK} K$$
If the transfer function of the system is given above for $T(S)$, then the root sensitivity can be found by evaluating the residue of the transfer function at the poles of the transfer function, or

$$S_1^S = \frac{-KD(S)}{K \frac{\partial}{\partial S} [C(S) + KD(S)]} \bigg|_{S=S_1}$$

Here $S_1$ is a pole described in the unperturbated system. This operation is performed in the program with simple tagging technique, just as in the parameter sensitivity case.

3.5.4 Sample Calculations

Given the following circuit, the following parameter sensitivity, worst case, and pole sensitive calculations are made.

![Circuit Diagram]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>1</td>
</tr>
<tr>
<td>R1</td>
<td>2</td>
</tr>
<tr>
<td>R2</td>
<td>3</td>
</tr>
<tr>
<td>C1</td>
<td>1</td>
</tr>
<tr>
<td>C2</td>
<td>3</td>
</tr>
<tr>
<td>NASAP</td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>2</td>
</tr>
<tr>
<td>R2</td>
<td>100</td>
</tr>
<tr>
<td>C1</td>
<td>4UF</td>
</tr>
<tr>
<td>END</td>
<td></td>
</tr>
<tr>
<td>VC1/VV1</td>
<td></td>
</tr>
</tbody>
</table>

**LOOP 1** contains R1, C1, P has value of $-2.5 \times 10^4 S^{-1}$

**LOOP 2** contains R1, C1 has value $2.5 \times 10^4 S^{-1}$

**ZERO ORDER LOOP** has value 1

**Parameter Sensitivity**

$$H(P') = -2.5 \times 10^4 S^{-1}$$

$$H(P) = 2.5 \times 10^4 S^{-1} + 1$$

$$H(P', R1) = 1$$

$$H(P', C1) = 0$$

$$H(P, C1) = 1$$

$$H(P', R1) = 0$$

$$H(P, R2) = 2.5 \times 10^4 S^{-1} + 1$$

$$H(P', R2) = -2.5 \times 10^4 S^{-1}$$

3-24
\[ S_P^P = \frac{H(P', \bar{Q})}{H(P')} - \frac{H(P, \bar{Q})}{H(Q)} \]

\[ S_{P1} = \frac{0}{-2.5 \times 10^4 S^{-1}} - \frac{1}{2.5 \times 10^4 S^{-1} + 1} = - \frac{1}{2.5 \times 10^4 S^{-1} + 1} \]

\[ S_{P2} = \frac{-2.5 \times 10^4 S^{-1}}{-2.5 \times 10^4 S^{-1}} - \frac{2.5 \times 10^4 S^{-1} + 1}{2.5 \times 10^4 S^{-1} + 1} = -1 \]

\[ -6.25 \times 10^8 S^{-2} - 2.5 \times 10^4 S^{-1} + 6.25 \times 10^8 S^{-2} + 2.5 \times 10^4 S^{-1} = -6.25 \times 10^8 S^{-2} - 2.5 \times 10^4 S^{-1} \]

\[ \text{TRANSFER FUNCTION} = \frac{-H(P')}{H(P)} = \frac{2.5 \times 10^4 S^{-1}}{2.5 \times 10^4 S^{-1} + 1} \]

**Pole Sensitivity**

POLE \( 2.5 \times 10^4 + S = 0 \)

\( S_1 = -2.5 \times 10^4 \)

\[ \text{Pole Sensitivity} = \frac{\partial}{\partial S} \left[ H(P') \right] \bigg|_{S=S_1} \]

\[ \frac{\partial}{\partial S} \left[ H(P') \right] = -2.5 \times 10^4 S^{-2} \]

\[ H(P', R1') = 2.5 \times 10^4 S^{-1} \]

\[ H(P', C1') = 2.5 \times 10^4 S^{-1} \]

\[ H(P', R2') = 0 \]

\[ \text{Pole Sensitivity to R1} = \frac{-2.5 \times 10^4 S^{-1}}{-2.5 \times 10^4 S^{-1}} = S_1 = -2.5 \times 10^4 \]

3-25
Pole Sensitivity to $C_1 = \frac{-2.5 \times 10^4 S^{-1}}{-2.5 \times 10^4 S^{-2}} = S_1 = -2.5 \times 10^4$

WORST CASE Analysis

$$(TP/P)^2 = \sum_{i=1}^{n} \left( S_{Q_i}^P \frac{dQ_i}{Q_i} \right)^2$$

$$\frac{dR_1}{R_1} = \frac{dC_1}{C_1} = \frac{dC_2}{C_2} = .1$$

$$(TP/P)^2 = \frac{(-1)^2 (.01)}{(2.5 \times 10^4 S^{-1} + 1)^2} + \frac{(-1)^2 (.01)}{(2.5 \times 10^4 S^{-1} + 1)^2} +$$

$$+ \frac{(0)^2 (.01)}{(-6.25 \times 10^8 S^{-2} - 2.5 \times 10^4 S^{-1})^2}$$

$$= \frac{.02}{(2.5 \times 10^4 S^{-1} + 1)^2} + \frac{0}{(2.5 \times 10^4 S^{-1} + 1)^2 (-2.5 \times 10^4 S^{-1})} =$$

$$= \frac{.02 (-2.5 \times 10^4 S^{-1})^2}{(2.5 \times 10^4 S^{-1} + 1)^2 (-2.5 \times 10^4 S^{-1})^2}$$

$$= \frac{1.25 \times 10^7 S^{-2}}{3.90625 \times 10^{17} S^{-4} + 3.125 \times 10^{13} S^{-3} + 6.25 \times 10^8 S^{-2}}$$

3.6 The Svoboda Method for Computing Roots of Polynomials

Overview of the Algorithm The flow of control among the various logical routines of the algorithm is depicted in Figure 3.13. After obtaining the input data, the Scanning Routine systematically steps over the Unit Circle evaluating the reduced polynomial at five points on each step. When a criterion for the possible existence of a root at any step is fulfilled, a transfer is made to the Home-in-Routine. The Home-in-Routine approximates the root as closely as possible and then transfers to the Root Examination Routine. Using the Round-off Routine, the Root Examination Routine
Figure 3.13 Flow of Control in Svoboda Algorithm
either rejects the root or refines it (by means of the Home-in-Routine again) and outputs it. Control then passes back to the Scanning Routine which either continues scanning or stops because the required number of roots has been obtained. When a scan is completed, if the maximum number of scans has not yet been reached, the Inversion Routine gains control to "invert" the polynomial, before returning to the Scanning Routine which continues to scan. A detailed discussion of each element of the algorithm follows.

The Scanning Routine The main routine in the Algorithm is the Scanning Routine which moves across the Unit Circle as shown in Figure 3.14. The real and imaginary axes between the ranges (-1, 0), (1, 0) and (0, -1), (0, 1) are divided into sixteenths. The Scanning Routine uses the Polynomial Evaluation Routine to find five points at each step in the scan, the central point and four points one sixteenth above, below, to the left and to the right of the central point. A test is then performed to see if this point may be near a root. The criteria for transferring to the Home-in-Routine to examine a possible root more closely are
1. The value at the central point must be less than the value of any of the four surrounding points.

2. The five points must not be equal in value.

If these criteria are not met, the scan is incremented by one sixteenth and the scanning process is resumed. Scanning is performed from left to right and from bottom to top. When a scan has been completed, that is, when the point (1, 0) has been evaluated, a check is performed to see if the number of scans has exceeded an upper limit. If not, a transfer is made to the Inversion Routine (described below) which performs the inversion of the polynomial and then returns control to the Scanning Routine.

The maximum number of scans allowable is twice the number of roots in the polynomial. Since at least one root must be obtained after each pass of both the "real" polynomial and the "inverted" polynomial (requiring a total of two scans), a number of scans no more than twice the number of roots should be required for the algorithm to work properly. (Usually, considerably fewer scans are required because several roots may be found on any one pass). If this number is exceeded, however, the routine stops automatically.

The problem of evaluating the circumference of the Unit Circle twice (once on a "real" scan and once on an "inverted" scan) is solved by taking two precautions. Firstly, all points evaluated in a "real" scan must be within the Unit Circle, while an "inverted" scan is permitted to violate the boundary of the circumference slightly. This precaution alone, however, is not sufficient to avoid a duplication of roots which lie close to the boundary, therefore, in the Root Examination Routine a check is performed to see if the root under consideration has appeared previously in another scan. This second precaution prevents roots which have been found once by a "real" scan and once by an "inverted" scan from appearing twice.

**Polynomial Calculation** The Polynomial Calculation Routine uses Horner's Technique to evaluate the polynomial complex value from the coefficients. Basically, Horner's Technique is the iterative evaluation of the expression
\[ F_{i+1} = (F_i + a_i) \cdot x \quad 1 \leq i \leq n \]

with \( F_1 = (0, 0) \) and \( F_{n+1} = F_n + a_{n+1} \) the final value, and \( a_i \) is the \( i \)'th coefficient in the polynomial

\[ P(x) = a_1 x^n + a_2 x^{n-1} + \cdots + a_n x + a_{n+1}. \]

Thus the final value is cumulatively built up in \( F \). If necessary, the complex value \( F \) is divided by previously found roots to form a reduced polynomial value

\[ F = \frac{P(x)}{(R_1 - x) (R_2 - x) \cdots (R_m - x)} \]

where \( m \) is the number of roots found previously. In order to avoid overflow, the absolute value of any of the factors \((R_i - x)\) is not allowed to be less than \(10^{-60}\). The final step is to obtain the residual (the complex absolute value) of \( F \).

\[ H = \sqrt{([\text{Re}(F)]^2 + [\text{Im}(F)]^2} \]

The residual is computed for four or five points (the Home-in-Routine does not require the central point to be evaluated each time) on each entry to the Calculation Routine. It is these four or five values \( H \) which are used by the Scanning and Home-in-Routines as the polynomial values at the test points.

**Polynomial Inversion**  In order to obtain all the roots of the polynomial

\[ P(x) = a_1 x^n + a_2 x^{n-1} + \cdots + a_n x + a_{n+1} \]

by scanning the complex plane within the Unit Circle, at some point a new polynomial is formed from the original one by reversing the order of the coefficients. The roots of this new polynomial are the reciprocals of the roots of the original polynomial, thus effectively bringing inside the Unit Circle all the roots which were previously outside. The Inverted Polynomial is
\[ P^r(y) = a_{n+1} y^n + a_n y^{n-1} + \cdots + a_2 y + a_1. \]

If \( P(r) = 0 \), it is easy to show that
\[ P(r) = 1/r^n P(r) = P^r(1/r) \]
Therefore \( y = 1/r \) is a root of the new polynomial \( p^r \).

Thus, in order to obtain all the roots of a polynomial, the program must deal effectively with two kinds of roots, "real" and "inverted", and must obtain the reciprocal of "inverted" roots before writing them on the output. The Polynomial Inversion routine, simply reverses the order of the coefficients, sets a program variable to point to either the "real" or "inverted" techniques, and returns control to the main program.

**Homing-In** Once five points have been obtained which fulfill the criterion for root examination, the homing-in procedure subdivides the distance between the central point and one of the outside points into sixteenths and, using the central points as a starting value, employs the Polynomial Evaluation Routine to compute four new outside test points. These new four points and the central point are then examined for the one having the smallest residual which becomes the central point for a new five point test. If this new central point is the same as the previous central point, the scale is subdivided into sixteenths as before so that the five point test becomes progressively more refined. At each subdivision, a new level of significance is obtained (each significant digit being a Hexadecimal digit because the scale factor is 16). This process of "homing-in" is continued until either

1. The required number of digits of accuracy is reached or,
2. The residuals of the five points do not differ by a significant amount.

In case 2, the resolution of the computing method and system has been reached and the remaining significant digits, if any, are filled with zeroes. This represents a Stopping Criterion which is independent of any formula for round-off error, but depends only on the previously mentioned resolution.
Each time a new step is taken in the Home-in-Routine, three checks are made. Firstly, if the central point should happen to be the origin (0, 0), the scale is expanded (subdivided by sixteenths), this allows for roots which may range over large orders of magnitude. Secondly, if more than sixteen steps should be taken in one direction at the same level of significance the level of significance is dropped so that larger (coarser) steps may be taken. Finally, a check is performed to ensure that the routine does not stray too far out of the Unit Circle. This safeguards against the possibility that the original location presented to the Home-in-Routine was not in the vicinity of a root, in which case it could easily wander outside the Unit Circle. If this condition should be detected, the Home-in is aborted and control is returned to the Scanning Routine.

If either case 1 or case 2 occurs, the Home-in-Routine has reached a successful completion and transfers control to the Root Examination Routine.

**Root Examination Procedures**  The Root Examination Routine first checks to see if the root just found came from the original polynomial coefficients or from a reduced polynomial. If the polynomial was a reduced one, the value of the root can be regarded merely as an approximation. The Home-in-Routine is therefore called again to repeat the latter part of the home-in procedure this time using the original polynomial and using the approximate root as a starting value. This technique ensures that every root is found from the original polynomial and that its accuracy does not depend on the accuracy with which previous roots were found.

After the final root value is obtained, a second check is made, this time on its residual. If the residual is greater than a certain value, the root is considered unreliable and is discarded. If this should occur, control is transferred back to the Scanning Routine. The maximum value of the residual is chosen arbitrarily to be one half the value of $a_{n+1}$, the constant coefficient in the polynomial.
Having passed these tests, the root value is rounded-off in the Round-off Routine (which is not discussed here because it has no bearing on the actual rootfinding algorithm). If the root is "inverted", its reciprocal is found using floating point division, and this value, after being rounded-off again, becomes the root value. A third check is then performed on the root to see if it has been found on a previous pass. (This check was mentioned previously in connection with the Unit Circle Boundary). If both real and imaginary parts fall within one significant digit of a root found on a different type of pass ("real"), it is rejected as a root but is nevertheless entered, in the same way as acceptable roots, in the list of roots used to form a reduced polynomial. (This prevents its being found again). If the root is not rejected, it is converted from its internal hexadecimal representation to decimal, rounded-off again, and is written on the output.

A final check is made to see if the required number of roots has been obtained. If not, control is returned to the Scanning Routine, otherwise the algorithm terminates.

NOTES
1. In writing this algorithm, it was intended to produce a technique for finding successive roots from the original polynomial and thus eliminate the mutual interdependence of these roots and convergence problems which are commonly found in other methods, (e.g., Newton-Raphson, Muller).\textsuperscript{16-19} However, in the course of investigating the behavior of the algorithm it was discovered that even widely dispersed roots affected the behavior of the polynomial "surface" over a wide range, and it therefore became necessary to use a reduced polynomial as a first approximation to eliminate this interference. Nevertheless, since the final root is always obtained from the original unreduced coefficients, the original algorithm has been effectively retained.
2. Since most major computing machines in this country are based on some multiple of binary arithmetic (and, in particular, hexadecimal arithmetic), a step size of sixteenths was used as the basis for the algorithm. On decimal based machines, it is likely that the algorithm would prove more effective if tenths were to be used.

3. Although no organized test of the algorithm has been performed as yet, it has performed well over a wide class of applications. In particular, 34 of the 36 roots of the 36th degree polynomial given in reference 19 were found to 5 significant digits in Single Precision Arithmetic within 60 seconds on an IBM 360/91.

3.7 A C. Analysis-Bode Plot\textsuperscript{20-21}

At this stage of the program, with the transfer function available as

\[ T = \frac{b_0 S^m + b_1 S^{m-1} + \ldots + b_m}{a_0 S^m + a_1 S^{m-1} + \ldots + a_n} , \]

where all the coefficients, \( a_1 \) and \( b_1 \), are known, the \( A C \) response is calculated by setting \( S = j\omega \) and simplifying the expression to a linear combination of real and imaginary terms

\[ T = A(\omega) + jB(\omega) \]

The magnitude of \( T \) and the angle \( \theta(\omega) \) are computed according to the equations,

\[ |T(\omega)| = \sqrt{A^2(\omega) + B^2(\omega)} , \]

and

\[ \theta(\omega) = \tan^{-1} \frac{B(\omega)}{A(\omega)} . \]

Now if \( \omega \) is made to vary, then for each value of \( \omega \) the \( |T(\omega)| \) and \( \theta(\omega) \) can be obtained over the frequency range of interest and thus can be made available for plotting. One commonly employed plot is \( |T(\omega)| \) and \( \theta(\omega) \) versus either \( \log_{10}\omega \) or \( \omega \) of Figure 3.15. Another graph, a Bode plot, (see Figure 3.16) consists of the \( |T(\omega)| \) in decibel units and \( \theta(\omega) \) in degrees versus the \( \log_{10}\omega \), taken over the frequency range specified by the user.
With the complex arithmetic capability of FORTRAN IV, the desired computation can easily be carried out in NASAP-70.

3.8 Transient Response

The transient response routine in NASAP-70 derives its theoretical basis from Fast Fourier Transform methods for the numerical inversion of Laplace Transform. Although the techniques described here follow along with the approach presented by Dubner and Abate, it was, however, developed independently at UCLA.

Theory The inverse \( f(t) \) of a Laplace Transform \( F(s) \) is given by the formula

\[
f(t) = \frac{1}{2\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} F(s) e^{st} \, ds \tag{3.1}
\]

If \( F(s) \) is a quotient of polynomials, with all coefficients real, i.e.,

\[
F(s) = \sum_{i=0}^{K} \frac{a_i s^i}{\sum_{i=0}^{n} b_i s^i} \tag{3.2}
\]

then \( f(t) \) is real, and

\[
f(t) = \frac{e^{\sigma t}}{\pi} \int_{0}^{\infty} F(\sigma + j\omega)e^{j\omega t} \, d\omega \tag{3.3}
\]

For the \( F(s) \) which are rational, i.e., have \( K > n \) in Equation (3.2), it is apparent that Equation (3.3) can be evaluated by a grathering rule for a specific \( t \), since \( \lim_{s \to \infty} F(s) = 0 \). However, if \( K > n \), a long division can be performed on \( F(s) \), to yield

\[
F(S) = C_{K-\ell} S^{K-\ell} + C_{K-\ell-1} S^{K-\ell-1} + \cdots + C_0 + R(S) \tag{3.4}
\]

where
\[ R(S) = \frac{\sum_{i=0}^{\infty} d_i S^i}{\sum_{j=0}^{\infty} b_j S^j} \]  

(3.5)

All terms of (3.4) represent impulses of varying degrees and can easily be inverted. The only concern is the inversion of \( R(S) \).

Inversion of Equation (3.3) by the trapezoidal rules, gives

\[
f(t) \approx \Delta w \left[ \text{Re}\{F(\sigma)\} \right] + \frac{e^{\sigma t}}{\pi} \sum_{K=1}^{\infty} F(\sigma + jK\Delta w)e^{jK\Delta w t} \]

(3.6)

where \( \omega \) is an appropriately chosen sampling interval, and \( \sigma \) is chosen so that the integration path is to the right of all singularities. Since \( \lim_{S \to \infty} F(S) = 0 \), an upper limit \( \nu \) can be chosen for the summation such that \( F(\sigma + jK\Delta w) \) is small for \( K > n \). Thus

\[
f(t) \approx \Delta w \left[ \text{Re}\{F(\sigma)\} \right] + \frac{e^{\sigma t}}{\pi} \sum_{K=1}^{n} F(\sigma + jk\Delta w)e^{jk\Delta w t} \]

(3.7)

(It should be noted that Equation (3.7) is the same expression obtained by Dubner and Abate, 22 except that the present derivation did not consider that when \( f(t) \) is known to be real and nonzero for \( t \geq 0 \) only, then

\[
f(t) = \frac{2e^{\sigma t}}{\pi} \int_{0}^{\infty} \text{Re}\{F(\sigma \omega)\} \cos(\omega t) d\omega \]

(3.8)

Note that if \( f(t) \) is obtained from the trapezoidal rule for \( m \) different values of \( t \), a total of \( mN \) calculations (evaluations of the term appearing...
under the summation) are required. For small \( m \), no difficulty exists, but if \( m \) is large, the machine time could be excessive.

This difficulty is overcome by the use of the Fast Fourier Transform (FFT).\(^{23,24}\) The discrete Fourier Transform pair

\[
X(K) = \Delta t \sum_{n=0}^{N-1} x(n) e^{-j2\pi \frac{nK}{N}} \tag{3.8a}
\]

\[
x(n) = \frac{\Delta \omega}{2\pi} \sum_{K=0}^{N-1} X(K) e^{2\pi i nK/N} \tag{3.8b}
\]

can be evaluated using the FFT with less than \( N \log_2 N \) calculations if \( N \) is chosen so that \( N = 2^\delta \), where \( \delta \) is a positive integer.

In Equation (3.7), if the following definitions are adopted

\[
Z_K = \left\{ \begin{array}{ll}
\frac{\text{Re}\{F(\sigma)\}}{2} & \text{if } K = 0 \\
\frac{\text{Re}\{F(\sigma+j\Delta \omega K)\}}{2} & \text{if } K > 0
\end{array} \right.
\]

and the summation limit is raised to \( N-1 \), where \( N \) is the smallest integral power of 2 greater than \( \nu \), then,

\[
f(t) \approx \frac{\Delta \omega}{\pi} e^{\sigma t} \sum_{K=0}^{N-1} Z_K e^{jK\Delta \omega t} \tag{3.9}
\]

If it is required that \( f(t) \) is evaluated only at integral multiples of some time interval \( \Delta t \), then \( f(t) \) can be defined by.

\[
f(n\Delta t) \approx \frac{\Delta \omega}{\pi} e^{\sigma n\Delta t} \sum_{K=0}^{N-1} Z_K e^{jK\Delta \omega n\Delta t} \tag{3.10}
\]

for \( n = 0, 1, 2, \ldots \)

Now, if \( \Delta t\Delta \omega = \frac{2\pi}{N} \) is introduced, Equation (3.10) becomes

3-38
It is apparent that the form of Equation (3.11) is compatible with Equation (3.8b). It should be noted that the summation in (3.11), considered as a function of \( n \), is periodic, and that \( f(n\Delta t) \) given by (3.11) is an oscillating exponential with period \( N\Delta t \), since

\[
f(n\Delta t) \approx \frac{\Delta \omega}{\pi} e^{\sigma n\Delta t} \sum_{K=0}^{N-1} Z_K e^{j2\pi \frac{nK}{N}}
\]

(3.11)

but,

\[
f[(N+n)\Delta t] \approx \frac{\Delta \omega}{\pi} e^{\sigma (N+n)\Delta t} \sum_{K=0}^{N-1} Z_K e^{j2\pi \frac{(N+n)K}{N}}
\]

(3.12)

(3.11)

Since (3.13) cannot, in general, be true a check of the validity of Equation (3.11) must be made.

If the substitutions \( n\Delta t = t \) and \( K\Delta \omega = \omega \) are made in the inverse transform relation of Equation (3.3) and the upper limit of integration is reduced to \( \omega = N\Delta \omega \), then

\[
f(n\Delta t) = \frac{e^{\sigma n\Delta t}}{\pi} \int_0^N F(\sigma + jK\Delta \omega) e^{jK\Delta \omega t} \Delta \omega dK
\]

(3.14)

Inserting the condition \( \Delta \omega = \frac{2\pi}{N} \) yields

\[
f(n\Delta t) = \frac{\Delta \omega}{\pi} e^{\sigma n\Delta t} \int_0^\infty F(\sigma + jK\Delta \omega) e^{j\frac{2\pi nK}{N}} dK
\]

(3.15)
The trapezoidal approximation of Equation (3.15) is

\[ f(n\Delta t) \approx \frac{\Delta \omega e^{\sigma n\Delta t}}{\pi} \left\{ \frac{1}{2} \text{Re} \{ F(\sigma) \} + \sum_{K=1}^{N-1} F(\sigma+jK\Delta \omega) e^{j2\pi \frac{nK}{N}} + \frac{1}{2} \text{Re} \{ F(\sigma+jN\Delta \omega) \} \right\} \tag{3.16} \]

Since it is assumed that \( F(\sigma+jN\Delta \omega) \) is small, this term can be eliminated from Equation (3.16), thus making it identical with Equation (3.11), as expected. Additionally, the validity of the approximation of Equation (3.15) by Equation (3.16) should be checked. It is a well known rule in quadrature evaluation of integrals that the summation rapidly becomes inaccurate when the sampling interval is made larger than one half the wavelength of the highest frequency component of the integrand. If it is assumed \( F(\sigma+j\omega) \) has a frequency spectrum with all its components having a wavelength much greater than \( \Delta \omega \), then the highest frequency in the integrand of Equation (3.15) will be \( \frac{n}{N} \). The sampling interval in Equation (3.11) = 1, thus the wavelength must be \( \frac{N}{n} \geq 2 \) and forcing the range of \( 0 \leq n \leq \frac{N}{2} \) on Equation (3.11). This is the same result used by Dubner and Abate.\(^{22}\)

It will be shown later that it is necessary to further restrict \( n \) so that \( 0 \leq n < \frac{N}{4} \).

It is necessary to find a value of the parameter \( \sigma \) for which (3.11) will be valid. The method employed in NASAP-70 involved repeated application of the Routh Stability criterion\(^{21}\) followed by a translation along the real axis.

The Routh criterion involved the construction of a matrix for the transfer function,

3-40
\[
F(S) = \frac{\sum_{i=0}^{K} a_i S^i}{\sum_{i=0}^{\ell} b_i S^i}
\]

The corresponding matrix is:

\[
\begin{array}{cccc}
b_0 & b_{-2} & b_{-4} & \ldots \ldots \\
b_{-1} & b_{-3} & b_{-5} & \ldots \ldots \\
d_{31} & d_{32} & d_{33} & \ldots \ldots \\
d_{41} & d_{42} & d_{43} & \ldots \ldots \\
\vdots & \vdots & \vdots & \ddots \\
\vdots & \vdots & \vdots & \ddots \\
\end{array}
\]

The first two rows are made up of the coefficients of the denominator polynomial. If \( \ell \) is odd, the final element in the first row is \( b_1 \), the second row, \( b_0 \). If \( \ell \) is even, the final element is \( b_0 \) in the first row, and zero in the second. In either case, the rows have length \( \left\lceil \frac{\ell}{2} \right\rceil + 1 \). The \( d_{ij} \) are evaluated by

\[
d_{ij} = \frac{d_{i-1,1} d_{i-2,j+1} - d_{i-2,1} d_{i-1,j+1}}{d_{i-1,1}} \quad (3.17)
\]

The meaning of \( d_{ij} \) for \( i = 1 \) or 2 is obvious. The length of nonzero elements in each row decreases as the row number increases, until in the \((\ell + 1)\) row, only \( d_{\ell+1} \) is nonzero.

After the matrix is constructed, the first element in each row is examined. If all of them are positive, no singularities are to the right of the imaginary axis. If one or more is zero or negative, then there are one or more singularities with a positive real value. To test a particular \( \sigma_o \) to determine whether it is to the right of all the poles, \( F(S) \) is shifted by \( \sigma_o \).
\[
F(S + \sigma_o) = \frac{\sum_{i=0}^{K} A_i (S + \sigma_o)^i}{\sum_{i=0}^{l} b_i (S + \sigma_o)^i}, \quad (3.18)
\]

where

\[
\sum_{i=0}^{l} b_i (S + \sigma_o)^i = \sum_{i=0}^{h} C_i S^i \quad (3.19)
\]

and

\[
C_i = \sum_{j=1}^{l} b_j \sigma_o^{j-1} \binom{j}{1}
\]

The Routh criterion can now be applied to \( C_i \), and if it is stable, then \( \sigma_o \) can be used in Equation (3.11).

Although the theory is valid at this point, a number of practical problems remain. One of these appears when \( F(S) \) contains a high order polynomial which does not go to zero until \( \omega \) is very large. In these cases, it is possible for some of the calculations involved in obtaining sample values to fall outside the range of numbers representable in a particular machine. To avoid this difficulty, the frequency scaling property of the Laplace transform is used,

\[
f(a t) = \frac{1}{a} \mathcal{L}^{-1} \{F(S)\} \quad (3.20)
\]

There also exists the inconvenience for users, resulting from the fact that the choice of \( \Delta \omega \) files \( \Delta t \). It would be much more convenient if \( \Delta t \) could be set to any desired value. To overcome this difficulty, a parameter selection procedure is used. Always setting \( \Delta t = 1 \), gives \( \Delta \omega = \frac{2\pi}{N} \). If a user desires a time step different from one second, the transform is frequency scaled according to Equation (3.20) by the time interval desired, i.e., \( a = \Delta t \).

With these changes, Equation (3.15) becomes
\[
f(na) = 2 \frac{\text{na}}{Na} \sum_{K=0}^{N-1} Z_K e^{j2\pi \frac{nK}{N}}
\]

where

\[
Z_K = \begin{cases} 
\frac{1}{2} \text{Re}[F(S)] & , K = 0 \\
\mathcal{F}(S + j2\pi \frac{K}{N}) & , K > 0 
\end{cases}
\]

\[
F(S) = (S/a)
\]

This change introduces a complication, in that the setting of \( \Delta w = \frac{2\pi}{N} \) means \( F(S) \) is sampled until \( w = \frac{2\pi}{a} \), regardless if it may be non-zero at this or higher values of \( w \).

(Note that the choice of \( N \) no longer has any effect on the upper limit of the sampling. Increasing \( N \) merely causes more samples to be taken with the sampling interval, which is set once \( a \) is chosen.

The effect of this high frequency cut-off will vary, depending upon the particular transform being inverted. The cases where the error is the greatest, however, occur near those points at which \( f(t) \) is discontinuous. In rational transforms, \( f(t) \) is discontinuous only at the origin, if at all. (If the numerator polynomial is of one degree less than the denominator, there is a discontinuity at \( f(0) \). If the difference in degree is greater than one, \( f(t) \) is continuous for all finite \( t \). The usual effect of the high frequency cutoff error is the "rounding of the corners" at \( f(0) \).

A correction procedure can be applied when this error occurs. By carrying out a long division of \( F(S) \), one obtains

\[
F(S) = \sum_{i=1}^{q} \frac{C_i}{S} + R(S)
\]

Inversion of Equation (3.22) yields,

\[3-43\]
\[
    f(t) = \sum_{i=1}^{q} C_i \frac{t^{i-1}}{(i-1)!} + \mathcal{L}^{-1} \{R(S)\}
\]

Note Equation (3.23) is a power series expansion for \( F(t) \) taken at \( t = 0 \). In NASAP-70, \( c_1 \) is evaluated with \( q = 50 \) in Equation (3.22), following by Equation (3.23) to evaluate the first five time points. During the evaluation of Equation (3.23) a check is made to determine that a smooth series fit is achieved (if the higher order terms in the summation are insignificantly small, then \( \mathcal{L}^{-1} \{R(S)\} \) is not significant because it is \( O(t^{q+1}) \) near the origin). Also checked is the possibility that some of the terms of Equation (3.23) are \( \gg f(t) \), if this is the case, there will be a loss of significance, and the error correction procedure is by-passed. If it turns out that the series is well behaved, it is used in cases where \( f(t) \) is continuous at the origin.

The theoretical foundations of NASAP just described cannot be considered extensive. But hopefully enough of the concepts have been presented to explain the underlying theme of NASAP. For those persons interested in more of an elaboration of the principle involved, they are encouraged to read the references shown at the end of the chapter.
REFERENCES


PART II  A PROGRAMMER'S MANUAL

The Programmer's Guide consists of Chapters 4 and 5 and Appendix A. Chapter 4 describes the algorithms used in NASAP-70 and the general flow of control among the NASAP-70 routines. A user intending to make any modifications to his copy of NASAP should become familiar with that chapter. The Dictionaries in Appendix A are provided to aid in easy identification of the more important names in NASAP-70.

Chapter 5 is designed as a reference for the general user. In particular, the user's attention is directed to Sections 5.4 and 5.5 which should be read before any NASAP-70 problems are run on a computer which is not an IBM 360. These sections describe some important modifications which may be required to make NASAP-70 operate properly on other computers.

Finally, Appendix A contains a program listing of NASAP-70 and Appendix C contains the output generated by sample problems.
CHAPTER 4
NASAP-70 PROGRAMMER'S GUIDE

4.0 Program Organization
4.1 General Description

The NASAP Circuit Analysis program is written entirely in Fortran IV-H. It is built around a basic program which produces a circuit tree from the user-supplied circuit data, and then uses this tree to evaluate the circuit Transfer Function. Additional modules are supplied which accept a user-defined tree (in a different data format), perform Sensitivity and Worst Case Analysis, produce Transient and Frequency Responses, find Poles and Zeroes of the Transfer Function, and perform automatic scaling on the input data.

Since NASAP-70 is written in Fortran IV, a user familiar with this language may add his own routines.

The flow of control in NASAP is shown in Figure 4.1. The Main Program first calls one of the three forms of Circuit Description Analysis. Each of these makes use of the Card Scanning Utilities. Then the Main Program can call (optionally) a Sensitivity Analysis routine if requested by the user. The Automatic Scaler may also be called at this point. The Transfer Function section is called to build the Flowgraph and compute the Transfer Function. The remaining sections, Sensitivities, Plotter, Rootfinder and the Transfer Function section again, may be called optionally. If more than one circuit description is supplied, any one of the Circuit Description Analysis routines may be called to restart the whole process.

Only one Circuit Description Analysis routine and the Transfer Function Section are absolutely required to be called during a NASAP-70 run. The remaining sections are called depending on the particular options selected by the user in his circuit data cards.
Figure 4.1 Flow of Control in NASAP-70
4.2 Algorithms and Dictionaries

In this section, the general algorithm of each subprogram is described. Instead of a statement by statement analysis of each routine, the algorithm is divided into a number of logical steps for the purpose of description. It is best to refer to a listing of the routine being studied while reading the algorithm description. (See Appendix A) The listing should be used to identify the source statements with the logical steps in the description.

For quick identification of the more important names in NASAP, a dictionary is supplied in Appendix A.

4.2.1 Main Program

The Main Program and Block Data subprogram serve to declare the more important program variables and to provide the flow of control among the modules of NASAP-70 based on the reading of certain NASAP-70 control cards from the Input Data Set.

1. In the Block Data subprogram, three Common Blocks are initialized. Common Block GAG contains an array of 20 variables which is initialized to the Sensitivity tags. These tag values are used in the Sensitivity analysis to identify flowgraph loops and the resulting Sensitivity functions with their corresponding circuit elements. Common block DATA contains an array of 32 variables which is initialized to 32 alphameric characters. Common block X contains an array of ten variables which is initialized to ten numeric characters. Common blocks DATA and X are used by the card scanning utilities (ASCAN, BSCAN, etc.) and various other routines which examine the NASAP data cards.

2. Upon entry to the Main program the important program control variables are reset beginning with NE (Number of Circuit Elements) and ending with the array SENS (The 50 Sensitivity tags). The page heading is then printed.
3. A card is read and printed, Subroutine SHIFT is called to squeeze out embedded blanks and commas, NE (which currently serves as a heading card counter) is incremented, and the first four characters on the card are checked as follows.

- If they are NASA, NE is reset and Subroutine NASAP is called, followed by a transfer to step 4 below.
- If they are TREE, NE is reset and Subroutine READ is called, followed by a transfer to step 4 below.
- If they are CIRC, NE is reset, ITREE is set (to signal that a tree is to be built by Subroutine FINE) and Subroutine READ is called. Then, provided ERR, the terminal error flag, has not been set, Subroutine FINE is called, followed by a transfer to step 4 below.
- If they are STOP, control is returned to the system monitor.
- If none of these sets of characters appear, the card is assumed to be a title card. If NE is more than ten, a warning is printed, NE is reset and control returns to step 2 above to read another card.

4. Statement 3 checks the ERR flag. If it is set, an error message is printed and control returns to Step 2 above where NASAP-70 is reinitialized. If it is reset, the checklist of elements is printed out so that the user may verify that his data were read correctly. Subroutine CALC is called to check tree legality and to create the current equations. If Subroutine CALC sets the ERR flag (e.g., due to an invalid tree), the error message is printed as before and NASAP-70 is reinitialized. Otherwise, Subroutine SCALER is called to determine if the circuit element values require scaling. If FACTOR is nonzero, then scaling was performed and the scale factor is printed out.

5. If TAG is set, then the user omitted an END card after the circuit description and therefore another card need not be read. Otherwise, a new card is read, Subroutine SHIFT is called and the following tests are made on the first four characters of this card
If they are SENS, Subroutine SENSIT is called (to analyze Sensitivity cards) and the next statement is skipped so that Subroutine WORST is not called.

If they are WORS, Subroutine WORST is called (to analyze Worst Case tolerance cards).

Subroutine GRAPH is then called to build the flowgraph (except for the unknown transmittance) which is then printed out. Subroutine REDUCE is called for each flowgraph transmittance to handle Sensitivity tags. As a final step, preparatory to servicing Output requests, NPATH (the number of flowgraph transmittances) is incremented to include the unknown transmittance, VPATH(NPATH) (its value) is set to 1.0, S(NPATH) (its tag) is set to 1000, NTIMES (the number of words per block in the BITS array) is set based on 30 bits per word, INP (the Transfer Function request flag) is reset, finally ERR is reset. By transferring to statement 10, step 6, which reads a new Output Request card, is avoided. Control goes to step 7.

6. The INP and ERR flags are reset, a new Output Request is read and Subroutine SHIFT is called.

7. Statement 10 prints the latest Output Request, calls and then analyzes the Output Request as follows

If the first three letters are END or the first two letters are EX, control goes to step 2 where NASAP is reinitialized.

If the first three letters are CIRC, TREE or NASA, it is assumed that the user omitted the END card after his Output Requests. Therefore control goes to statement 12 which prints an error message, the NASAP-70 heading, and then returns control to step 2 at a point just after a new card is read (because this card has already been read by accident).

If INP is 0, no Transfer Function request has yet been read so the next five tests are not performed.

If the first letter is V or I, this is a Transfer Function request,
therefore control goes to step 8 where the Transfer Function is formed.

If the first four letters are PLOT and ERR has not been set, Subroutine PLOT is called, and if ERR is still not set, Subroutine INVERT is called to perform the plotting. Finally ERR is reset.

If the first four letters are ROOT and ERR has not been set, Subroutine ROOTS is called. Subroutine SHIFT is then called so that the succeeding test for a Pole Sensitivity Request will operate on a card of the form ROOTS, POLES.

If the first four letters are POLE and ERR has not been set, Subroutine POLSEN is called.

Control now returns to step 6 after an error message is printed for the cards beginning with SENS, WORS, or TOL.

At this point INP = 0, which means that there has been no previous Transfer Function request. Hence, cards beginning with PLOT, ROOT, SENS, TOL or WORS are meaningless and if the current card is one of these, an error message is printed and control returns to step 6.

8. The card is now considered to be a Transfer Function request, consequently INP is set to signal that a Transfer Function request has been encountered. The number stored in NTIMES is printed and then Subroutine WHAT is called to analyze the Transfer Function request. If the ERR flag has been set, control goes to step 6 to search for another Output Request. Otherwise Subroutine INBIT is called to enter the unknown transmittance into the BITS array and then Subroutine LOOPS is called to solve for the Transfer (and Sensitivity) Functions.

9. The BITS, SMAX1 and SMIN1 arrays are reset before the Sensitivity Functions are entered. Subroutine ANSWER is called to print out the Transfer Function. If NSEN is 0, this means that no Sensitivity Functions are requested. Control then returns to step 6 (except INP and ERR are
not reset), otherwise subroutine SENSC is called. If NWORST is not 0, Subroutine WORSTC is called to evaluate the Worst Case Function, and Subroutine ANSWER is called to print it. Finally, control returns to step 6 (except INP and ERR are not reset).

4.2.2 Circuit Description Analysis

NASAP-70 offers three techniques of circuit description analysis. The technique selected is determined by the heading card read by the Main program. All the techniques make use of the card scanning utilities which perform various operations on the card image stored in an 80 word array in Common block A.

The User's Circuit Description may be supplied to NASAP-70 in one of three ways:

1. As a circuit description with a tree to be defined by the program for minimum computation time. This is the standard form of NASAP Input Data used in previous versions of the program. It is initiated by a card having the work NASAP.

2. As a circuit description with a tree to be defined by the program for optimum accuracy at a given frequency. This form of input data is new to NASAP. It is initiated by a card having the word CIRCUIT followed by a value in parentheses which represents a frequency in cycles per second.

3. As a circuit description with a user-defined tree. This option, like the CIRCUIT option, uses a new form of input data. It is initiated by a card having the word TREE.

The method of analyzing the Circuit Description Data associated with each of these forms of input is described below.

Card Scanning Utilities

There are eight routines which constitute the card scanning utilities. Subroutines ASCAN (B, I, J), BSCAN(B, I, J) and CSCAN(B, I, J) scan the
card image in Common block A starting at column I until a special character (described below) is encountered. The character is placed in B and the number of the column just before this character is placed in J.

- Subroutine ASCAN scans for \( / = \text{blank} \).
- Subroutine BSCAN scans for U blank M K P O V I.
- Subroutine CSCAN scans for \( . E + - \text{blank} \).
- Function ISORT(A) returns the fixed point numeric value of the character stored in A. If A is not numeric, FLAG is set.
- Subroutine MSG(A, I) prints a diagnostic.
- Subroutine NUMBER(N1, N2) stores the floating point value into VPATH(NE) of the number between columns N1 and N2 inclusive, irrespective of the format in which this number is written. If there is an error in the number (e.g., an invalid character), FLAG is set and the value entered into VPATH(NE) is unreliable. For instance, the following numbers are acceptable:
  
  -1 .73-7 1E2 +0.0009

  but these are not acceptable
  
  -1A 7.. 3 1B2 ++.0009

  The algorithm of Subroutine NUMBER is now described in more detail:

1. Upon entry, K (the column pointer) is set to N1, and VPATH(NE) is set to 0. Provided K is less than N2, control passes to step 3 to begin the analysis.

2. This is the error return. When this step gains control, a diagnostic is printed and control is returned to the calling routine.

3. A test is performed on the first character in the field. If it is a -, TAG is set. Subroutine CSCAN is called and if I already points to a special character this number must be less than 1, so control passes to step 5.

4. The digits which form the part of the number greater than 1 are contained between columns I and J inclusive. This step (DO 3) enters them
into VPATH(NE). If FLAG is set for any digit, the error return (step 2) is given control.

5. If the end of the number field has been reached, control passes to step 7. If the next character is not the decimal point, control passes to step 6 which checks for an exponent. Otherwise the digits of the fractional part of the number are entered into VPATH(NE) (DO 7). If FLAG is set, step 2 gets control.

6. If the next character is the E of the exponent field, the column pointer is incremented. If a - is found in the exponent field, EXPO is set. Subroutine ESCAN is called to obtain the limits of the exponent field. A diagnostic is printed if this field contains more than two digits. The rightmost two digits are used to enter the exponent value into POW. If EXPO has been set, the exponent is negative. Lastly, the value in VPATH(NE) is modified according to the value of the exponent.

7. If TAG has been set, the number was negative so the sign is reversed. Control then returns to the calling program.

- Subroutine SHIFT left adjusts all characters in Common Block A removing blanks and commas.
- Function SORT is the same as ISORT but returns a floating point value.

Subroutine NASAP

Subroutine NASAP decodes Circuit Description cards which follow a NASAP heading card. If no error is detected before the END or OUTPUT card is reached, a tree is constructed (subject to the constraint of minimum First Order Loops). Each Circuit Description Card is in the following format:

NAME ORIGIN TARGET VALUE UNITS(optional) DEPENDENCY(optional)

The Data cards are described in more detail in Sec. 4.2. The algorithm details of Subroutine NASAP follow.
1. On entry, NE (the number of elements) is reset to 0.

2. A new card is read into Common block A and Subroutine ASCAN is called repeatedly until the first non-blank character is found. If this character is E or O, this is the end of the circuit description, so control passes to step 7 where the tree is built. Otherwise NE is incremented, the element name is padded with blanks on the right and entered into the CARD array (which contains the names of all the circuit elements).

3. Subroutine ASCAN is called repeatedly to find the next non-blank character which is the start of the ORIGIN field. Function ISORT is used to enter the value of the origin node into the ORIGIN array. If FLAG is set, control transfers to step 6 which is the error return. A similar procedure is used to enter the value of the TARGET node into the TARGET array.

4. Subroutine BSCAN is called repeatedly to find the next blank character or the first character of the UNITS field, followed by a call to Subroutine NUMBER to enter the value of the VALUE field into VPATH(NE). This value is multiplied by a factor depending on the next one or two non-blank characters (which constitute the UNITS field):

\[
\begin{align*}
  U & \quad 10^{-6} \\
  P & \quad 10^{-12} \\
  K & \quad 10^{3} \\
  M & \quad 10^{6} \\
  MH & \quad 10^{-3}
\end{align*}
\]

If the character is a V or I, the DEPENDENCY field is present so Subroutine ASCAN is used to extract the name of the dependency that is then entered into the DEP array (which contains the names of controlling elements). If a DEPENDENCY field is not present, a string of blank characters is entered into the DEP array.

5. GENER(NE) and TYPE(NE) are reset. If the first character of the element name is V or I, the element is active requiring that GENER(NE) be set. If it is V, the element is a voltage source and is immediately required
to be in the tree, therefore \texttt{TYPE(NE)} is set. Finally, before transferring back to step 2 to read the next card, \texttt{NNODES} and \texttt{INODE} (the maximum and minimum node numbers appearing so far) are set.

6. (The error return). A diagnostic is printed, \texttt{ERR} is set and control is returned to the calling program.

7. Before building the tree, an array \texttt{N} is set up which initially contains the number of elements connected to each node \texttt{N(I)}. When \texttt{N(I)} is 0, node \texttt{I} has been connected to the tree. When \texttt{N(I)} is negative, node \texttt{I} is currently being considered for entry into the tree.

8. The next free node having the highest number of elements connected to it is selected for insertion into the tree. Its \texttt{N} entry is reset to 0. Then, all the nodes connected to this one via voltage sources are put under consideration, i.e., \texttt{N(I)} is made negative (DO 23). As long as \texttt{M} is 1 additional nodes have to be considered, consequently step 8 is repeated until \texttt{M} is 0.

9. Each passive element connected to this node is entered into the tree when the other node to which it is connected is not yet under consideration. At the same time, all the nodes connected to this new node via voltage sources are given consideration. (DO 26 and DO 31).

10. The \texttt{N} array is searched for the least value. If this is 0, all possible nodes have been entered into the tree, control returns to the calling program. Otherwise the node is tagged as being processed by subtracting 1000 from its \texttt{N} entry. Then control passes to step 8.

Subroutine \texttt{NASAP} does not perform any checks on the circuit described or the tree it builds (i.e., to see if all nodes are connected to the same tree). If the circuit supplied is valid, then the tree constructed from it will be valid also. If the circuit is invalid, the resulting tree is meaningless. All checking on both program and user constructed trees is performed by Subroutine \texttt{CALC} while solving the current equations. If any invalidity is found, Subroutine \texttt{CALC} prints the appropriate diagnostics.
In general, the tree constructed by Subroutine NASAP produces the minimum number of First Order Loops, and therefore produces a transfer function in minimum computation time. This tree may be described briefly as the "bushest" tree. For instance, for the circuit shown, two trees are given (solid lines represent the tree) both of which are valid. However, tree 2 is the "bushest" and would probably result in fewest First Order Loops.

![Circuit Diagram]

**Figure 4.2**

**Subroutine READ and Subroutine FINE**

In response to reading a heading card beginning with either the word CIRCUIT or the word TREE, Subroutine READ is called to analyze Circuit Description Data. If the heading card was a CIRCUIT card, Subroutine FINE is called to build a tree which results in optimum accuracy at the frequency shown on the CIRCUIT card. If the heading card was a TREE card, Subroutine FINE need not be called because it is assumed that the user has supplied the tree. The format of the circuit description data accepted by Subroutine READ is considerably different from that accepted by Subroutine NASAP. This is because Subroutine READ is designed for a user who has some knowledge of flowgraph theory while Subroutine NASAP is designed for the user interested primarily in the Transfer Function rather than the method of analysis.
CIRCUIT cards have the form:

CIRCUIT (Frequency)

CIRCUIT and TREE circuit description cards have the form

NAME/DEPENDENCY (ORIGIN-TARGET) = VALUE UNITS

(note that DEPENDENCY and UNITS are optional quantities)

Circuit Description Data is described in detail in Sec. 4.2.

1. The first step in Subroutine READ is to reset a number of control variables. Then if this is a CIRCUIT card (TREE=1), the default frequency is set to 1.0, and Subroutines ASCAN and NUMBER are called to scan the CIRCUIT card for the frequency enclosed in the parentheses, if the frequency cannot be found, the appropriate diagnostic is printed.

2. The next card is read and Subroutine SHIFT is called to eliminate blanks and commas. If the card is completely blank or if it starts with the letters PL, the appropriate diagnostic is printed and step 2 is performed again. If the card starts with END, control returns to the calling program. If there are more than 50 elements, the appropriate diagnostic is printed. The TYPE and GENER entries for this element are reset to 0 and the CARD and DEP entries are filled with blanks.

3. The following tests are performed on the first 2 characters in the card buffer (Common block A)
   a. If the first character is E or J, an active source is assumed. Its GENER entry is set to 1. If the first character is E, its TYPE entry is set to 1 also to indicate that it is part of the tree.
   b. If the first character is R, L, C or D, and if the second letter is E, the TYPE entry is set to 1. If the first letter is D, the GENER entry is set to 1 (to show this is a dependent source). Unless TREE is 1 (i.e., unless no user tree is supplied) and if the second letter is not E or J (branch or link) a diagnostic is printed and the second letter is set to J.
   c. If the first letter is V or I, it is assumed that because the user omitted the END card from the circuit description the first Output Request
was read by mistake. Thus, TAG is set to 1 to show that the first Output Request is already in the buffer. A diagnostic is printed and control returns to the calling program.

d. If the first letter is P, it is assumed that a PLOT card has mistakenly been placed in the circuit description. Therefore, a diagnostic is printed and control passes to step 2 to read a new card.

If none of these tests is true, the first letter is set to R and processing proceeds as if test 2 were true.

4. Subroutine ASCAN is called to find the element name. If it is more than 12 characters long, a diagnostic is printed. In the case of an element whose first letter is not D, if the first character after the name is not a left parenthesis, a diagnostic is printed and step 2 gains control to read a new card. In the case of an element having D as the first letter, a diagnostic is printed if a slash is not found after the element name. The element name is then entered into the CARD array. A check is performed of this new name against all the previous names in the CARD list (DO 17). If a match is found, a diagnostic is printed and the program attempts to replace the latest name with another one based on the value of the counter NR. Up to 10 duplications of a name are allowed. If more than 10 have occurred, the ERR flag is set.

5. If this element is not a dependent element (i.e., the first character is not D), step 5 is not performed. Otherwise Subroutine ASCAN is called to extract the Dependency Name. If the character following the Dependency Name is not a left parenthesis, a diagnostic is printed and control passes to step 2 where a new card is read. If the first letter of the Dependency Name is not V or I, a default is assigned and a diagnostic is printed. The Dependency Name is then entered into the DEP array.

6. Subroutine ASCAN is called once to extract the Origin number which is then entered into the ORIGIN array and then again to obtain the Target number which is entered into the TARGET array. In either case, if an
error is detected (FLAG = 1) or if there are more than two digits in the Origin or Target fields, a diagnostic is printed and step 2 gains control to read a new card. If the Origin or Target number is 0, a diagnostic is printed and the number is changed to 99. If the appropriate characters are not found after the Origin or Target nodes, diagnostics are printed.

7. Having reached this point an element is now entered permanently into the list of elements by incrementing NE, the number of elements. NNODES and INODE, the maximum and minimum node numbers, respectively, are set. Subroutine BSCAN and NUMBER are then called to obtain the element value. The characters following the Value field are checked to determine if a Units field is present. If it is not the one (that is, if the next character is blank), then the value in VPATH is not modified. Otherwise the value is multiplied according to the following units

\[
\text{PF} = 10^{-12} \quad \text{K} = 10^3 \quad \text{MF} = 10^{-6} \\
\text{M} = 10^6 \quad \text{MH} = 10^{-3} \quad \text{MMF} = 10^{-12} \\
\text{MMH} = 10^{-6}
\]

Subroutine UNITS is called to write out the units detected. Then control is transferred to step 2 to read another card.

In general, Subroutine READ is fairly tolerant of mistakes in circuit description data. Diagnostics are printed whenever reasonable and defaults are supplied whenever possible.

After Subroutine READ returns to the Main program, Subroutine FINE is called to build a tree, if the heading card was a CIRCUIT card (TREE = 1). Essentially, the logic of building this tree is to take the user supplied frequency (written on the CIRCUIT card) and to evaluate the impedance of inductive and capacitive elements according to,

\[
X_c = \frac{1}{j\omega C} \quad X_L = j\omega L
\]
All elements are then ordered by their impedance magnitudes and the tree is built from elements having the lowest impedance, since these elements have the closest approximation to the impedance of a voltage source (i.e., 0 ohms). The value $9.9 \times 10^{-30}$ is used to represent $\infty$ (i.e., the impedance of a current source).

1. The first step in Subroutine FINE is to evaluate the impedance of each element (DO 1) and to store it in the array $Z$. The elements are then reordered by increasing values of $Z$ (DO 4). The number of nodes in the circuit is found, taking into account the possibility that they may not be numbered consecutively (DO 40).

2. All the TAGs are initially reset to 0 (to exclude all elements from the tree). The first element is then entered into the tree immediately. Then the elements are added to the tree one by one, each time checking that the added branches do not conform to closed loops (i.e., that it always remains a tree). As soon as all the nodes are connected, the ordered list of elements is printed and control returns to the calling program.

In this fashion, as many low impedance elements as possible are included in the tree according to the operating frequency defined by the user. This tree is more likely to result in a larger computation time and a greater number of First Order Loops in the Flowgraph when the Transfer Function is calculated. This is offset, however, by increased accuracy in the Transfer Function.

4.2.3 The Transfer Function

Evaluation of the Transfer Function involves calculation of the current equations for the circuit described employing the tree which has been supplied either by the user or derived by the program. From the current equations calculated by Subroutine CALC, Subroutine GRAPH builds the Flowgraph except for the closing transmittance. Each time a Transfer Function Request appears, Subroutine WHAT is called to obtain the closing
transmittance and Subroutine LOOPS is called to evaluate the Transfer Function from the loops in the flowgraph according to the Shannon-Happ formula. Finally, Subroutine ANSWER is called to normalize the Transfer Function and to print it.

The process of evaluating the Transfer Function involves the manipulation of individual bits in a word. The bit manipulation words are stored in an array of 3000 words in Common block BITS. In addition, these words are handled in blocks of varying size depending on the current value of NTIMES. For instance, if NTIMES is three, the blocks consist of three words each. Furthermore, the various routines involved in calculating the Transfer Function address the array in BITS differently. In order to facilitate the addressing and manipulation of these words, a set of six Bit Manipulation Utilities are provided.

1. Subroutine EQUAL (I, J, N, NTIMES) performs operation N (see LOR, LOX, LSTOR) on the blocks of bits identified by I and J and puts the result into block I. The size of the blocks is given by NTIMES (the number of words per block) while different addressing techniques are used depending on the signs of I, J and NTIMES
   a. If NTIMES is positive and I, J are positive, then they refer to the Ith and Jth blocks in the BITS array.
   b. If NTIMES is positive and I, J are negative, then they refer to the I + 100th and J + 100th blocks.
   c. If NTIMES is negative and I, J are positive, then they refer to the Ith and Jth blocks from the high end of the BITS array.
   d. If NTIMES is negative and I, J are negative, then they refer to the Ith and Jth blocks in the BITS array as in case a.

2. Function LOR(I, J) performs a full-word logical OR on I and J and puts the result in I.

3. Function LOX (I, J) performs a full word logical AND on I and J and subtracts the result from both I and J.
4. Function LSTOR (I, J) sets I equal to J.

5. Subroutine UNPAK(I, J, NN) takes the block of bits identified by I (according to the same scheme as Subroutine EQUAL) and searches them starting at bit 1 and proceeding as far as bit NN. When the first 1 bit is found, Function LOX is used to reset it to 0 and the position of this bit is returned in J. If no 1 bits are found, J gets the value 0.

6. Subroutine INBIT(I, J, NTIMES) takes the block of bits identified by I (according to the same scheme as Subroutine EQUAL) and sets the bit in position J to 1. If J is 0, all the bits in block I are reset to 0.

All the Bit Manipulation Utilities use only the low order 30 bits of a word. Thus on the IBM 360, the settings of the two high order bits are ignored throughout the bit manipulations. Subroutine EQUAL uses Functions LOR, LOX and LSTOR to perform certain operations. For further information on Functions LOR and LOX see Sec. 4.4.

Subroutine CALC is called by the Main program after the Circuit Description Data has been successfully analyzed. CALC calculates the current equations using Kirchhoff’s equations. At the same time the validity of the tree is checked. If the tree should prove to be invalid, a diagnostic is printed, the ERR flag is set, and control returns to the Main program.

1. Upon entry to Subroutine CALC a page is skipped and NTIMES is set according to the number of elements in the circuit (NE). NTIMES is increased by 1 for every 30 elements, i.e., each bit represents 1 element. The arrays NEL (Number of elements at node I), NBR (number of branches at node I) and the LINKS array (the Bit manipulation array in Common block BITS) are reset to 0. Then the NEL array is filled with the number of elements at each node, the NBR array is filled with the number of (tree) branches at each node, NE gets the number of branches in the tree, and by means of Subroutine INBIT, the LINKS array is set up as follows.
(DO 1) Each block in the LINKS array represents a node. Each bit in the block represents an element not in the tree (i.e., a link). Blocks in the lower half of the array represent links leaving the node corresponding to that block. Blocks in the upper half of the LINKS array represent links arriving at the node corresponding to that block. Thus, each node has two entries in the LINKS array, one entry in the lower half of the array containing links directed away from the node, and one entry in the upper half of the array containing links directed towards the node. For example, if node 2 of a circuit has elements 1 and 2 directed away, element 1 being a voltage source (i.e., part of the tree), and element 3 directed towards, then block 2 of the LINKS array has bit 2 set while block (2+100=102) has bit 3 set.

2. The next step is to set up the NS and NQ pointers for the BRANCH list while checking the validity of the tree (DO 2). The BRANCH list contains the branches connected to each node, positive if the branch is directed towards, negative if the branch is directed away. NQ(I) points to the beginning of the list of branches for node I. For example, if node 1 has three branches and node 2 has two branches, then NQ(1) = 1, NQ(2) = 4, NQ(3) = 6. The number of nodes, NN, is also counted at this time. If any node has no elements connected to it, the node numbering was not sequential so a warning is printed. If any node has only one element connected to it, the ERR flag is set.

3. The number of branches, NB, is checked against NN, the number of nodes. For a legal tree NB must be exactly equal to NN-1. If this is not true, an appropriate diagnostic is printed and the ERR flag is set. At this point, a test of the ERR flag is performed, if it has been set, control returns to the calling program. Otherwise, the BRANCH list is filled (DO 7) as described in step 2, using NS as a set of temporary pointers.

4. This step performs the actual solution of the current equations which are now contained in the BRANCH and LINKS arrays. Each node
in the circuit has associated with it a current equation. The object is to express the current in each branch in terms of the current in the circuit links. Since there is one less branch than the number of nodes, there is an independent equation for each node except one. Thus, the equations of nodes with more than one branch are gradually reduced until each equation has only one branch. The solution is then complete.

The first step is to find a node with one branch (i.e., the first cut set) and the first node with more than one branch.

If none can be found, all the equations that could be reduced have already been reduced. If this is not every equation, the ERR flag is set, a diagnostic listing the nodes remaining to be reduced is printed, and control returns to the calling program. Otherwise, the remaining multi-branch nodes are checked against the single branch node just found and Subroutine EQUAL is called to either add or subtract the relevant equations (DO 26). The branch is removed from the list of branches at the multi-branch node and when all reductions have been performed, the single node associated with this branch is reset (i.e., NBR is reset to 0) to show that all possible reductions with this branch have been performed. Step 4 is repeated until every equation has been reduced (NBR(I) are all less than or equal to 1).

5. The current equations are printed by searching the BRANCH list for non-empty entries (i.e., where NQ(I) ≠ NQ(I+1)). When one is found, the branch is printed out along with the words from the LINKS array which constitute the current equation. For instance, the equation:

\[ I_3 = I_1 - I_4 \]

would be printed as

3 2 16

This list is essentially for debugging purposes. After the current equations are printed, control is returned to the calling program.
The next step in Transfer Function evaluation is the construction of the Flowgraph. This is performed by Subroutine GRAPH which stores the Flowgraph in Common Block PATHS.

a. On receiving control, Subroutine GRAPH initially resets NPATH, the number of paths (or transmittances) in the flowgraph, to 0.

b. A Flowgraph transmittance is inserted for each element which is not an independent source (DO 100). If the element is passive, then the transmittance represents an impedance (if the element is a branch) or an admittance (if the element is a link). NPATH is incremented, the S entry is reset and LPATH is assigned. LPATH(I, 1) is the origin node of transmittance I, LPATH(I, 2) is its target node. Nodes with a number less than or equal to NE are the current nodes, nodes between NE+1 and 2xNE are voltages nodes. Thus if element 3 is an impedance, in a 10 element circuit its transmittance goes from node 3 to node 13 (i.e., the voltage node depends on the current node since \( V = IR \)) and there are 20 nodes in the Flowgraph. Admittances go from voltage to current nodes. A series of tests is performed on the element:

a. If it is a resistor branch, its VPATH value is unchanged, and its S value is 0 (Since it is not frequency dependent).

b. If the element is a resistor link, its admittance is \( \frac{1}{\text{VPATH}} \).

c. If it is an inductor branch or capacitor link, its S value is 1 and its VPATH value is unchanged since \( X_c = sL \) and \( Y_c = sC \).

d. If it is an inductor link or capacitor branch, its S value is -1 and its VPATH value is inverted since \( Y_L = \frac{1}{sL} \) and \( X_c = \frac{1}{sC} \).

3. If the element is a dependent source, a search of the list of element names in CARD is performed (DO 17) to find the name of the controlling element in DEP. If the element is not found, a diagnostic is printed and the element is treated as an independent source. Otherwise a transmittance is inserted from the voltage or current node of the controlling element (according to whether voltage or current dependence has been requested) to the voltage or current node of the dependent source (according to whether it is a voltage or current source).
4. Having completed the transmittances due to the elements, step 4 (DO 1) inserts the transmittances due to current and voltage equations. Although only the current relationships have been calculated, the voltage relationships may be easily obtained from them by a simple rule. If there is a current transmittance between two current nodes there is a corresponding voltage transmittance between the two corresponding voltage nodes. The direction of the voltage transmittance is opposite to that of the current transmittance. If it connects the nodes of two passive elements or two sources, its sign is opposite to that of the current transmittance.

![Flowgraph (Figure 4.3)](image)

*Figure 4.3*

For example, given the current relationships of Flowgraph (Figure 4.3) the voltage relationships may be easily determined as shown in (b). These Flowgraphs represent the current equations

\[ I_1 = I_2 \quad I_3 = -I_2 \]

This method is implemented by searching the BRANCH list for non-empty entries. For each non-empty entry, which represents a branch, Subroutine UNPAK is used to search the corresponding LINKS (alias LBITS) entries for 1 bits. The lower half is searched first for positive links, and when UNPAK returns 0 indicating there are no more 1 bits in the word, the search is switched to the upper half of LINKS which contains negative links.
The transmittances are inserted two at a time (i.e., both current and voltage transmittances are added simultaneously). The $S$ value of these relationships is 0 since they are obviously not frequency dependent. The $VPATH$ values are either $+1$ or $-1$ determined as described earlier.

5. Having completed the Flowgraph (except for the unknown transmittance) control returns to the calling program.

The Flowgraph resides in Common block PATHS until a Transfer Function Request is read. Subroutine WHAT is called by the Main program to obtain the closing (unknown) transmittance by analyzing the Transfer Function Request which is in the form

```
TYPE NAME 1 / TYPE NAME 2
```

Subroutine WHAT makes use of the Card Scanning Utilities described in Sec. 4.2.2.

1. Upon receiving control, Subroutine WHAT copies the Flowgraph from its permanent storage in Common block PATHS into an array in Common block BITS (DO 18). Subroutine ASCAN is then called to find the slash which divides the Output field from the Input field. If none is found, the ERR flag is set, a diagnostic is printed and control returns to the calling program. Otherwise the CARD array is searched (DO 2) for the name in the Output field of the Transfer Function Request. If it is not found, a diagnostic is printed, the ERR flag is set, and control returns to the calling program.

2. If the first letter in the Output field (TYPE NAME 1) is not V or I, a diagnostic is printed and defaults are assumed if the element is a branch the default is I (since a branch has independent current), for a link, $V$ is assumed. The unknown transmittance is connected from the voltage or current node (according to the V or I) of the element in the Output field.

3. In a procedure similar to steps 1 and 2, Subroutine ASCAN is called to find the blank at the end of the Input field. If the blank cannot be

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found, the error return is taken. Otherwise a search is made for the
element name (DO 10), defaults are used for V or I, if necessary, and the
transmittance is connected to the voltage or current node of the element in
TYPE NAME 2. Subroutine WHAT then returns control to the calling pro-
gram.

Subroutine WHAT makes no check on the validity of the Transfer
Function Request. Only syntax and the legality of the element names are
checked. For example,

VR2/VV7 could be a valid request but
VR2/IV7 is not, because the voltage across V7 is an independent
variable but the current is not. The Transfer Function resulting from the
second example will be 0 or meaningless.

After Subroutine WHAT has returned control and the Main program
has inserted the Flowgraph in bit representation in Common block BITS
using Subroutine INBIT (DO 18), Subroutine LOOPS\textsuperscript{6} gains control to
perform the actual calculation of the Transfer Function from the flowgraph
according to the Shannon-Happ formula:

\[1 - \sum L_1 + \sum L_2 - \sum L_3 + \ldots = 0\]

where the \(L_i\) represent the sums of the values of the loops of order \(i\). A
loop of order 1 (First Order Loop) is a Simple Directed Loop defined as a
closed path consisting of a sequence of transmittances taken in the direction
of the arrow. The sequence must be taken such that no node is traversed
more than once in the closed path. The value of the directed loop is the
product of the transmittances forming the directed loop. An \(N\)th order
loop is composed of \(N\) disjoint First Order Loops, that is, none of which
have any nodes in common. The value of an \(N\)th order loop is the product
of the \(N\) First-Order Loop values comprising the \(N\)th order loop.

In order to illustrate the operation of Subroutine LOOPS the example
Flowgraph shown in Figure 4.4 is employed.
Note that the transmittances joining nodes 1 and 2, and nodes 6 and 7 have the same sign. This flowgraph is represented in the LPATH, VPATH and S arrays of Common block BITS, as shown.

<table>
<thead>
<tr>
<th>I</th>
<th>LPATH(I, 1)</th>
<th>LPATH(I, 2)</th>
<th>VPATH(I)</th>
<th>S(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>7</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>3</td>
<td>0, 1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>9</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>6</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>8</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
<td>6</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td>1000</td>
</tr>
</tbody>
</table>

NPATH = 13
In addition, the information stored in the LPATH array is also stored in Common block BITS (array LOOP) in a different form.

\[
\text{I} \quad \text{LOOP(I)}
\]

\[
\begin{array}{ll}
3000 & 2^2 + 2^7 = 132 \\
2999 & 2^8 + 2^3 = 264 \\
2998 & 2^7 + 2^9 = 640 \\
2997 & 2^5 + 2^{10} = 1056 \\
2996 & 2^1 + 2^2 = 6 \\
2995 & 2^7 + 2^6 = 192 \\
2994 & 2^3 + 2^2 = 12 \\
2993 & 2^7 + 2^8 = 384 \\
2992 & 2^3 + 2^4 = 24 \\
2991 & 2^9 + 2^8 = 768 \\
2990 & 2^1 + 2^5 = 34 \\
2989 & 2^{10} + 2^6 = 1088 \\
2988 & 2^6 + 2^1 = 66
\end{array}
\]

(Since NTIMES = 1, each transmittance and each loop is contained in only 1 word.)

Subroutine LOOPS receives these data as input and using the Shannon-Happ formula, the Transfer Function is calculated and stored in the VN array in Common block CIRCUIT. VN(I, 1) is the value of the coefficient of the \((I - 51^{th})\) power of S in the denominator. VN(I, 2) is the negative of the value of the coefficient of the \((I - 51^{th})\) power of S in the numerator. SMAX(J) and SMIN(J) are the highest and lowest powers of S in VN(I, J). For example, a Transfer Function such as \(\frac{1}{1+2S}\) would be stored as

\[
\begin{array}{llll}
\text{SMAX}(1) = 1 & \text{SMIN}(1) = 0 & \text{VN}(51, 1) = 1 & \text{VN}(52, 1) = 2 \\
\text{SMAX}(2) = 0 & \text{SMIN}(2) = 0 & \text{VN}(51, 2) = -1
\end{array}
\]

The LOOP array is used in two ways: the low end is used to store First Order Loops and Higher Order Loops during evaluation; the high end is used to store the Flowgraph Transmittances. Thus, as data are
removed from the high end and transformed, it is reinserted into the low end. Other important variables used in Subroutine LOOPS are the arrays V and LS which contain the values and powers of S of flowgraph loops. These arrays are in Common block SPEED which is used elsewhere as workspace. Subroutine CLEAR is used to remove transmittances which have been marked deleted (i.e., LPATH(I, 1) = 0) from the list of paths.

1. The first step in Subroutine LOOPS performs initialization by resetting important program variables to 0. NN, the number of flowgraph nodes is set to 2 x NE (the number of elements) since each element has 2 nodes (voltage and current) in the flowgraph. NLOOP, the number of loops is reset to 0. VN(51, 1) is set to 1; this is one 1 of the Shannon-Happ formula. The NODE(J) and COUNT(J) arrays (which contain the number of transmittances arriving at and leaving node J) are set up (DO 1).

2. The first step in the algorithm is the elimination of all nodes having only one transmittance directed away (i.e., COUNT = 1) since every transmittance entering this node must ultimately exit through the one leaving transmittance. Thus transmittance is attached to the end of each entering transmittance (DO 3) by changing the terminating node (LPATH(I, 2)) and calling Subroutine EQUAL to 'OR' in the bits common to both paths. The leaving transmittance is then deleted (LPATH(I, 1) = 0). At this point the data for the example flowgraph would appear as follows

<table>
<thead>
<tr>
<th>I</th>
<th>LPATH(I, 1)</th>
<th>LPATH(I, 2)</th>
<th>VPATH(I)</th>
<th>S(I)</th>
<th>LOOP(3001-I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>7</td>
<td>10</td>
<td>0</td>
<td>$2^2 + 2^7$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0.1</td>
<td>0</td>
<td>$2^3 + 2^8$</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>$2^3 + 2^7 + 2^8 + 2^9$</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>$2^5 + 2^{10}$</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>7</td>
<td>10</td>
<td>0</td>
<td>$2^1 + 2^2 + 2^7$</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1000</td>
<td>$2^1 + 2^6 + 2^7$</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>7</td>
<td>10</td>
<td>0</td>
<td>$2^2 + 2^3 + 2^7$</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>3</td>
<td>-0.1</td>
<td>0</td>
<td>$2^3 + 2^7 + 2^8$</td>
</tr>
</tbody>
</table>
I LPATH(I, 1) LPATH(I, 2) VPATH(I) S(I) LOOP(3000-I)

9 3 4 1 0 $2^3 + 2^4$
10 0 3 0.1 0 $2^3 + 2^8 + 2^9$
11 1 1 10 1001 $2^1 + 2^5 + 2^6 + 2^{10}$
12 0 6 1 0 $2^6 + 2^{10}$
13 0 1 1 1000 $2^1 + 2^6$

NPATH = 13 NLOOP = 0.

3. A check is now performed (DO 6) for First Order Loops that may have been created. These are recognized by having identical LPATH entries (i.e., LPATH(I, 1) = LPATH(I, 2), e.g., entry 11 above). Each time one is found, it is stored in the lower half of the LOOP array by means of Subroutine EQUAL and its value is stored in V and LS. NLOOP is incremented. The LPATH entry is marked deleted and the loop is printed, (as a debugging aid). The DO 11 then marks all nodes which have only leaving or only arriving transmittances as deleted since they obviously cannot be contained in any loops. (Entry 9 in the example). Subroutine CLEAR is called to remove deleted entries. Now the data looks like this:

I LPATH(I, 1) LPATH(I, 2) VPATH(I) S(I) LOOP(3001-I)

1 7 3 1 0 $2^3 + 2^7 + 2^8 + 2^9$
2 1 7 10 0 $2^1 + 2^2 + 2^7$
3 7 1 1 1000 $2^1 + 2^6 + 2^7$
4 3 7 10 0 $2^2 + 2^3 + 2^7$
5 7 3 -0.1 0 $2^3 + 2^7 + 2^8$

I LOOP(I) V (I) LS(I)
1 $2^{1} + 2^{5} + 2^{6} + 2^{10}$ 10 1001

NPATH = 5 NLOOP = 1

4. If the number of paths remaining (NPATH) is 0, this step is not performed. Otherwise this step combines the remaining paths to generate more First Order Loops. The method is to combine path 1 with path 2 if possible. If this combination is a legal loop, it is stored in the low end of
LOOP. If it is a legal path, it is combined with path 3 and testing continues. If it is not a legal path, the combination 1 and 3 is tested. After the combination of 1 and NPATH has been tested, the procedure begins again with 2 and 3, 2' and 4 and so on until NPATH - 1 and NPATH is reached. During this process all paths are kept in LPATH and the high end of LOOP ORDER(1) is the number of the current transmittance which is being tested against ORDER(2). The ORDER(1) contains the numbers of all the paths from 1 to I being tested. The testing consists of the following:

a. The beginning node of the first path is checked against the ending node of the second. If they are not the same, they cannot be combined (e.g., entries 1 and 3 in the example), so the test fails.

b. The two blocks in LOOP are ANDed and Subroutine UNPAK is called to find the nodes that are common to both.

c. If the ending node of the first path is not the same as the beginning node of the second, this cannot be a loop but it might be a new legal path so test is performed.

d. If N3 is non-zero, there are more than two nodes in common so this cannot be a legal combination - the test fails.

e. If the nodes in common (N1, N2) are the beginning and ending nodes of the two paths, this is a new First Order Loop. It is inserted by incrementing NLOOP and calling Subroutine EQUAL.

f. If more than one node is in common (N2, N3 ≠ 0), this cannot be a new legal path so the test fails. Otherwise Subroutine EQUAL is called to insert the new path and I is incremented so that testing will continue with this latest path.

This step ends when ORDER(1), the pointer to the lowest level path, is pointing to NPATH, the last path.

In the example the following results are obtained from applying these tests.

a. 1 and 2 from a new legal path. This cannot be combined with 3 because node 7 is traversed twice. 1 and 4 however produce a new First Order Loop.
b. 2 and 3 form a new First Order Loop.
c. 3 and 4 form a new path. This new path cannot be combined with 5 because node 7 is traversed twice.
d. 4 and 5 form a new First Order Loop.

Now the data has been changed to First Order Loops.

<table>
<thead>
<tr>
<th>I</th>
<th>LOOP(I)</th>
<th>V(I)</th>
<th>LS(I)</th>
<th>NLOOP = 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2^1+2^5+2^6+2^10</td>
<td>10</td>
<td>1001</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2^2+2^3+2^7+2^8+2^9</td>
<td>10</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2^1+2^6+2^7</td>
<td>10</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2^2+2^3+2^7+2^8</td>
<td>-1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

These First Order Loops may be easily verified by examining the Flowgraph. Notice that the order of the nodes in the loops is irrelevant for the purposes of the program.

5. The values of the First Order Loops are now entered (DO 25) into the Transfer Function array VN according to the Shannon-Happ formula. Tagged values (LS > 500) have the tag of 1000 subtracted and are then entered into the numerator VN(I, 2) instead of the denominator VN(I, 1). The number of First Order Loops is then printed and the calculation of Higher Order Loops is ready to begin.

6. The procedure for the generation of Higher Order Loops is essentially the same as that for generating First Order Loops described in step 4; that is, loop 1 is compared with loop 2. If this creates a new Higher Order Loop, then the value of the new loop is entered into the VN array and it is checked against loop 3 for the possibility of a still higher order loop. When all combinations with loops 1 and 2 have been tried, combinations of 1 and 3 are tried, then 1 and 4 and so on until 1 and NLOOP. Processing then continues with 2 and 3, 2 and 4 and so on. As before, ORDER(1) points to the lowest level loop so that each time it is incremented it is written out, thus serving as a guide to how much
processing remains to be done. (Since this step is often the most time consuming part of the entire NASAP program, this information is very useful). As soon as ORDER(1) is equal to NLOOP, processing is complete and control returns to the calling program with the Transfer Function now in array VN. In the example, Higher Order Loop evaluation would proceed as follows

a. 1 and 2 form a Second Order Loop, its value is entered ($100S^{1001}$) and it is checked against 3 (failure, i.e., $M_1 \neq 0$ because nodes 1, 2, 6, 7 are common to both) and 4 (failure).

Then 1 is checked against 3 (failure) and 4 (success, value $-10S^{1001}$).

b. 2 and 3 fails, 2 and 4 fails.

c. 3 and 4 fails.

In several places, instead of manipulating entries in LOOP by means of Subroutine EQUAL, the manipulations are performed directly in Subroutine LOOPS by means of the Equivalence array LOGIC (See Sec. 4.4). This is because in frequently executed statements the time required for execution of the subroutine linkage becomes significant. This is especially true in the ANDing of Higher Order Loops which can increase rapidly with the number of First Order Loops.

With the Transfer Function now in array VN, Subroutine ANSWER is called to format the raw form in VN, normalize it and print it out.

1. Upon entry Subroutine ANSWER writes the page heading on the output. Then VM, the array containing the Function after normalization, is created (DO 2).

2. The arrays NEXP (containing powers of $S$), AS and ASIGN (containing arithmetic signs) are created (DO 40).

3. The arrays are written out (except for zero coefficients) and the line dividing numerator and denominator is printed to the proper length.
4. Finally the factor after normalization is printed. (Also, as a debugging aid, the original VN array is printed). Control then returns to the calling program. This completes the description of the basic NASAP-70 Transfer Function algorithm. The routines described may be modified by the addition of other options (particularly the Sensitivity and Worst Case option). Nevertheless the basic algorithm remains the same.

4.2.4 Sensitivity and Worst Case

The Sensitivity and Worst Case option involves additions to the basic algorithm for finding the Transfer Function. The basic formulas used for evaluation of the Sensitivity Function, Worst Case Tolerance and Pole Sensitivity are:

**FORMULAS USED**

**SENSITIVITY FUNCTION**

\[
S_P^P = \frac{d(LnP)}{d(LnQ)} = \frac{H(P', \bar{Q})}{H(P')} - \frac{H(P, \bar{Q})}{H(P)}
\]

\[
= \frac{H(P)H(P', \bar{Q}) - (H(P')H(P, \bar{Q}))}{H(P')H(P)}
\]

**WORST CASE TOLERANCE**

\[
T_P = \left[ \left( \frac{\partial P}{\partial Q_1} Q_1 \right)^2 + \cdots + \left( \frac{\partial P}{\partial Q_n} Q_n \right)^2 \right]^{1/2}
\]

Q = circuit element value

or

\[
TP/P = \left[ \sum_{1=1}^{n} \left( \frac{S_P}{Q_1} \frac{dQ_1}{Q_1} \right)^2 \right]^{1/2}
\]

P = dummy transmittance
POLE SENSITIVITY

\[
\frac{dS_i}{dQ} = \frac{-KD(S)}{\frac{\partial}{\partial S} [C(S) + KD(S)]} \quad S=S_i
\]

where Transfer \( F = \frac{A(S)+KB(S)}{C(S)+KD(S)} \), \( K = \) circuit element value, and \( S = \) a pole

\[
= \frac{-Q H(F, Q')}{\frac{\partial}{\partial S} [H(P)]} \quad S=S_i
\]

In response to reading a card following the Circuit Description and before the first Output Requests section, beginning with the letters SENS, Subroutine SENSIT is called. If the card begins with WORS Subroutine WORST is called. Subroutine SENSIT and WORST make use of the Card Scanning Utilities described in Sec. 1.2.2.

Subroutine SENSIT processes Sensitivity Request cards which have the form:

\[ \text{SENSITIVITY} = \text{Element Name} \]

1. Upon entry Subroutine SENSIT calls Subroutine ASCAN to find the equals sign. If one is not found, a diagnostic is printed and step 5 gains control to read a new card.

2. A search of the CARD array is performed (DO 4) in order to find the Element Name. If it is not found, a diagnostic is printed and step 5 gains control.

3. Otherwise the element is rejected with a diagnostic if it is an independent source, if more than 20 Sensitivity Requests have been made, or if it is another Sensitivity Request for the same element, and step 5 gains control.

4. Having passed all these tests the element is inserted in the list of Sensitivity Requests by incrementing NSEN, the number of Sensitivity
Requests and by assigning a TAG value to the SENS entry for this element.
NSEN, SENS and TAG are in Common block GAG. SENS(1) contains the
value of the sensitivity tag assigned to element I from the list of 20 tags,
TAG. These tag values are used later to identify various loops during the
evaluation of Higher Order Loops in Subroutine LOOPS, and Subroutine
REDUCE.

5. A new card is read and Subroutine SHIFT is called. If it is not a
Sensitivity Request card control returns to the calling program. Otherwise
the card is printed and step 1 regains control to continue processing.

If Subroutine WORST is called, Sensitivity Requests are inserted
for each valid request. Thus, if more than 20 Sensitivity Requests results
NFLAG is set and the Worst Case Request is ignored.

1. Initially Sensitivity Requests are inserted for all valid elements
(i.e., not independent sources) in the DO 1. This is done by inserting a
TAG value in SENS(I) for element I.

2. If the number of Sensitivity Requests resulting is greater than 20,
NFLAG, an error flag internal to Subroutine WORST, is set and a diag­
nostic is printed. Otherwise, NWORST, the flag which indicates the Worst
Case option has been requested, is set, and the TOL(I) array which contains
the Tolerance value for element I is initialized to 0.1.

3. This step looks for cards of the form

TOL = Element Name = Value.

A new card is read and Subroutine SHIFT is called. If the card begins
with TOL and NFLAG ≠ 1 (which would indicate that Worst Case analysis
has been aborted) then Subroutine ASCAN is called to find the element
name which is checked against the list in CARD. If there is no matching
element name a diagnostic is printed and step 3 is repeated. Otherwise
Subroutine ASCAN and NUMBER are called to determine the Tolerance
Value which is inserted in TOL(I) for element I. Then step 3 is repeated.
If NFLAG is 1, the Tolerance Cards are read in step 3 but no other action is taken.

4. If step 3 encounters a card not beginning with TOL and NFLAG is not 1, the table of Tolerance Values is printed. Control then returns to the calling program.

Once the Sensitivity Tags have been inserted in the SENS list then, as the Flowgraph is built by Subroutine GRAPH, the tags are inserted in the S array for each Flowgraph transmittance. Then, in order to write out the correct power of S for each Flowgraph transmittance, these tags must be temporarily removed. This is done by calling Subroutine REDUCE for each transmittance before it is printed by the Main program.

Subroutine REDUCE (I, J, K) removes the tags from the S or LS array. I is the entry in the S or LS array. J is the true power of S returned by Subroutine REDUCE after all the tags have been removed. K is set to 1 if the entry does not contain the dummy transmittance and to 2 if it does.

1. Upon entering Subroutine REDUCE, K is set to 1 and J is set to I. If no Sensitivity Requests were made (NSEN = 0) and step 3 gains control.

2. If Sensitivity Requests were made, these tags are removed in the DO 1 loop. Since the Sensitivity Tags start from 2000 and go up, and since it is necessary to remove the largest tags first, the DO I loop is executed from L = 21 - NSEN to 20 and 21-L is used as the index of the TAG array. For example, if two elements are tagged M=21-2=19 then L goes from 19 to 20, i.e., 21-L goes from 2 ro 1. An entry contains a tag if the value (with all higher tags removed) is greater than the tag less 500. If it is greater, the tag is subtracted and the search continues.

3. J is checked for the presence of the unknown transmittance tag (1000). Thus if J is greater than 500, 1000 is subtracted from J and K is set to 2.
Processing continues as normal until the steps in Subroutine LOOPS which insert values of First and Higher Order Loops into various arrays. The method of inserting values into VN, the Transfer Function array, has already been described (Sec. 4.2.3). The Sensitivity Functions now involve three additional arrays: VN00, VN01 and VN10 which represent $-H(\bar{P}, \bar{Q})$, $H(P, Q)$ and $-H(\bar{P}, Q)$ in the formulas described previously in this section. The insertion of these values is performed by DO 979 and DO 799 in Subroutine LOOPS. Subroutine REDUCE is called to extract the pertinent tags and the values are inserted in the correct Sensitivity Function arrays based on these tag values. Thus, when Subroutine LOOPS returns control, not only has the Transfer Function been inserted in VN, but also the Sensitivity Functions have been entered into VN00, VN01 and VN10.

After Subroutine LOOPS has returned and Subroutine ANSWER has printed out the Transfer Function, if NSEN is non-zero (indicating the presence of Sensitivity Functions) then Subroutine SENSC is called.

Subroutine SENSC forms the Sensitivity Functions from polynomials produced by Subroutine LOOPS. The Sensitivity Function is equal to

$$\frac{H(P)H(P, Q) - H(P)H(\bar{P}, \bar{Q})}{H(P)H(\bar{P})}$$

where the $H$ functions are stored as follows

- $H(P)$. VN(L, 1)
- $H(P, Q)$. VN01(L, J)
- $-H(\bar{P}, \bar{Q})$. VN00(L, J)

$J$ is the element whose sensitivity is being found.

In many cases, $H(P, Q)$ (VN01) is 0 in which case the Sensitivity Function reduces to

$$\frac{-H(\bar{P}, \bar{Q})}{H(P)}$$

1. Upon entry to Subroutine SENSC, the DO 305 loop is executed for each circuit element checking to see if it was tagged for sensitivity.
(SENS(I)!=0). If it was tagged the following steps are performed, otherwise the succeeding element is checked. When all the elements have been checked control returns to the calling program.

2. The DO 306 loop determines the sensitivity number of the element (II). Then the DO 701 loop checks the VN01 array. If it is completely 0, the simplified formula above may be used so VNSEN, the array containing the Sensitivity Function is filled with the appropriate coefficients (DO 703) and Subroutine ANSWER is called to print out VNSEN.

3. If VN01 is not completely 0, then the standard formula must be used to compute VNSEN. Thus Subroutine MULT is called once to multiply VN(I, 1) and VN01(I, II) and again to multiply VN(I, 2) and VN00(I, II) and the results are added, (DO 702) to form the Sensitivity Function numerator. Then Subroutine MULT is called again to multiply VN(I, 1) and VN(I, 2) to form the denominator and then Subroutine ANSWER is called to print VNSEN.

Thus, upon termination of Subroutine SENSC, the information in VN, VN00, VN01 and VN10 has been converted to a set of Sensitivity Functions stored in VNSEN and VN00, VN01 and VN10 are no longer needed. Subroutine SENSC (and also Subroutine WORSTC below) make use of Subroutine MULT(A, B, C, MINA, MAXA, MINB, MAXB). This Subroutine multiplies the two polynomials A, B and puts the result in C. MINA, MAXA and MINB, MAXB are the minimum and maximum powers in polynomials A and B. A, B, C are arrays of length 101 and the index is 51 plus the power of the term. Array C is reset to 0 before multiplication occurs.

After Subroutine SENSC returns control to the Main program, the information in VNSEN is copied from Common block BITS into Common block POLY. This is to release the area in BITS for use as a workspace for use in later routines (e.g., the Plotter). If NWORST is non-zero, a Worst Case has been requested so the Main program calls Subroutine WORSTC.
Subroutine WORSTC computes the square of the Worst Case Tolerance function from the Sensitivity Functions and Tolerances for the elements. This function becomes

\[ \frac{T_{P/P}}{P} = \left[ \sum_{i=1}^{n} \left( \frac{S_{Q_1}^P dQ_1}{Q_1} \right) \right]^{1/2} \]

The Sensitivity Function for an element can be in one of two forms,

\[ S_{Q_1}^P = \frac{A_i(s)}{H(P)} \quad \text{or} \quad S_{Q_1}^P = \frac{B_i(s)}{H(P)} \]

where \( A(s) \) and \( B(s) \) are polynomials in \( S \). Therefore two separate sums are kept, one of \( \left( A_i(s) \frac{dQ_1}{Q_1} \right)^2 \) and one of \( \left( B_i(s) \frac{dQ_1}{Q_1} \right)^2 \) and these are combined and put with the proper denominator to produce the square of the function.

1. Upon entry Subroutine WORSTC checks each element to see if a Sensitivity Function exists for that element (DO 10). If a Sensitivity Function exists \( \text{SENS}(I) \neq 0 \), then the Tolerance for that element \( \text{TOL} \) is squared and Subroutine MULT is called to square the Sensitivity Function numerator of that element \( \text{VNSEN}(I, 2, J) \).

2. The denominator of the Sensitivity Function is now checked (DO 20) to see if it is the same as the Transfer Function denominator. If it is, the squared tolerance \( \text{TOL}^1 \) and the squared Sensitivity Function numerator \( \text{VWORKN} \) need only be multiplied and added to VW1. If it is not, NDEM is set to 1 and the result of the product is put in VW2.

3. If NDEM is 0, the simplified formula:

\[ \frac{VW1}{VN(I, I)^2} \]

may be used, so VW1 is put into the numerator of VW(DO 40) and Subroutine MULT is called to square VN(I, 1) and enter it in the denominator,
VW(I, 1). If NDEM is non-zero, the standard formula
\[
\frac{VW2 + VW1 \times VN(I, 2)^2}{VN(I, 2)^2 \times VN(I, 1)^2}
\]
must be used. Thus Subroutine MULT is called once to square VN(I, 2) into VWORKN and again to multiply VWORKN and VW1 into the numerator of the Worst Case Function VW(I, 2). Then VW2 is added into the numerator (DO 31). Finally Subroutine MULT is called to multiply VN(I, 1) and VN(I, 2) into VWOKRN and again to square VWORKN into VW(I, 1), the Worst Case Function denominator.

4. The maximum and minimum powers of S in the Worst Case Functions are determined and control then returns to the calling program.

When Subroutine WORSTC returns control, the Main program calls Subroutine ANSWER to print out the Worst Case Function.

The last subprogram of the Sensitivity and Worst Case option is Subroutine POLSEN. This subroutine evaluates the sensitivities of the Poles of the Transfer Function (determined by Subroutine ROOTS described in Sec. 4.2.6) to variations in a circuit parameter. Subroutine POLSEN is called by the Main program when a card of the form

**ROOTS, POLES**

is read. Subroutine POLSEN then analyzes the roots found by the preceding call to Subroutine ROOTS.

1. If the Poles have not yet been found (NPOLES=0) or there is no Sensitivity Request (NSEN=0), Subroutine POLSEN prints a diagnostic and returns to the calling program.

2. The derivative of the denominator of the Transfer Function is found (DO 5) and stored in VDERIV. This is evaluated at the Real and Imaginary parts of the Poles and is stored in C(Real) and D(Imaginary).
3. For each element, tagged for Sensitivity Analysis, the numerator of the Root Sensitivity Function, \(-QH(\bar{F}, Q)\) (VN10) is evaluated at each Pole and then Real and Imaginary points are stored in X and Y. The Real and Imaginary parts of the Pole Sensitivity \(X/C(L)\) and \(Y/D(L)\) are evaluated and printed.

4. Subroutine Polsen then returns control to the calling program.

Two other routines, Subroutines PLOT and INVERT, of the Plotter also contain some code in connection with the Sensitivity and Worst Case option. These subprograms are described in the following Section 4.2.5.

4.2.5 The Plotter

NASAP-70 is equipped with extensive plotting capabilities for analysis of the Transfer Function and Sensitivity Functions. When a card beginning PLOT is encountered among the Output Requests, the Main program calls Subroutine PLOT to analyze this card and providing that the analysis of this card was successful (ERR \(\neq 0\)), Subroutine INVERT is called to initiate the plotting. If the plot card TYPE option is FREQ or REAL, the calculation of the points to be plotted is handled entirely within Subroutine INVERT. Any other TYPE option constitutes a call to the Fast Fourier Transform routines. After the points have been calculated, Subroutine PRTPLT writes out the plotted points. (BMOD and AMOD below are fixed and floating point names for the internal plotter option list).

1. Subroutine PLOT initially sets the BMOD list (the internal list of options) to \(-1\) which indicates that the option did not appear on the PLOT card. Subroutine ASCAN is called to find the Left Parenthesis of the PLOT card which should be of the form:

\[
PLOT(\text{Option} = \text{Value}/\text{Option} = \text{Value}/\text{Option} = \text{Value}...)\]

If a Left Parenthesis is not found Subroutine MSG is called to print a diagnostic. Subroutine ASCAN is called repeatedly until a Left Parenthesis or a Slash is found. If a Blank is found step 6 gains control to fill in
options which are required by the Plotter but were not specified by the user.

2. Subroutine ASCAN is called to find the equal sign. If an equal sign is not found, Subroutine MSG is called to print a diagnostic. If a Blank or a Right Parenthesis is found, step 6 gains control. If a Slash is detected, step 2 is repeated. At this point, the Option field has been found.

3. Subroutine ASCAN is called to find the Value field. If the first 2 letters in the Option field are TY then BMOD(3) (known elsewhere as NTYPE), the internal code which tells the plotter which type of plot has been requested, is set according to the first 2 letters in the Value field:

<table>
<thead>
<tr>
<th>IM</th>
<th>ST</th>
<th>EX</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

If this is the end of the PLOT card (B is a Blank or a Right Parenthesis), then step 6 gains control. Otherwise step 2 regains control to get the next Option.

4. If the first 2 letters of the Option field are EL, this option is connected with the Sensitivity and Worst Case Option. Thus, the CARD and SENS arrays are searched (DO 31 and DO 37) to match the element name in the Value field and obtain the Sensitivity Tag associated with it. If such a match cannot be obtained, a diagnostic is printed, the ERR flag is set and control returns to the calling program. Otherwise, if this is the end of the PLOT card then step 6 gains control, else step 2 regains control.

5. If this step is reached, the first 2 letters of the Option field are not TY or EL so the Value field contains a number. Hence, Subroutine NUMBER is called to find the number in the Value field. This number is inserted into the correct variable according to the first 2 letters in the Option field.
ST  STEP (AMOD(1), the interval between successive plot points)
TI  TOTEE (AMOD(2), the interval between the first and last points plotted)
AM : AMP1 (AMOD(4), the positive portion of a pulse train)
BI  AMP2 (AMOD(5), the negative portion of a pulse train)
CO  FREQ1 (AMOD(6), a in e^at)
CY  FREQ1 (AMOD(6), f in Sin 2\pi ft)
FR  FREQ1 (AMOD(6), starting point for frequency and real plots)
TO  FREQ2 (AMOD(7), ending point for frequency and real plots)
WI  FREQ2 (AMOD(7), pulse width for a pulse train)
DE  NPLOT (BMOD(8), number of calculated points per printed point)

Then, if the end of the PLOT card has not been reached control returns to step 2.

6. This step completes user options which were not specified, with default values. If an option has not been specified, BMOD is still -1. If BMOD(3) is more than 5 (i.e., not a Time Response) then these defaults are used:

\[
\begin{align*}
FREQ1 (AMOD(6)) & : 1 \\
FREQ2 (AMOD(7)) & : 10^{-6} \\
STEP (AMOD(1)) & : \frac{FREQ2}{FREQ1}
\end{align*}
\]

If BMOD(3) (NTYPE) is less than 6 and then
If \text{STEP} and \text{TOTEE} (AMOD(1) and AMOD(2)) are both unspecified,
\[
\text{STEP} : 0.01 \quad \text{TOTEE} : 1.0
\]
\[
\text{STEP} (AMOD(1)) \quad \text{TOTEE}/100 \\
\text{TOTEE} (AMOD(2)) \quad \text{STEP} \times 100 \\
\text{NTYPE} (BMOD(3)) : 0 \text{ (Impulse Response)}.
\]
\[
\text{AMP1} (AMOD(4)) : 1.0
\]
If AMP2 (AMOD(5)) was specified, AMP1 is biased accordingly.
\[
FREQ1 (AMOD(6)) : 1.0
\]
If \text{FREQ2} (AMOD(7)) was specified, NTYPE is set to 5 to indicate a Pulse Train.
7. In all cases, if DEN (BMOD(8)) was unspecified, it is set to 1.

1. If BMOD(3) is 7 (Sensitivity Plot), the arrays containing the numerator (A1) and denominator (B1) of the function to be plotted are filled with the correct Sensitivity Function (DO 50) and a heading is printed. If BMOD(3) is 8 (Worst Case Plot), the arrays are filled with the Worst Case Function and a heading is printed. For all other values of BMOD(3), the arrays A1 and B1 are filled with the Transfer Function. Subroutine PLOT then returns control to the calling program.

Assuming the analysis of the PLOT card was successful (ERR ≠ 1), Subroutine INVERT is called to initiate the plotting process.

1. Upon entry, Subroutine INVERT resets NFLAG (the remainder indicator) to 0, sets STEP to 1 if it was negative, and evaluates NUMTI, the number of points to be plotted. Then, if a Time Response has been requested (NTYPE less than 6), Subroutine INPUT is called to evaluate the transform of the response. Then, in the case of a Time Response, the function to be plotted in A and B is checked. If it is too simple, a diagnostic is printed and the plot is aborted. If it is not rational, the numerator is divided by the denominator and the remainder of this division is used as the function to be plotted. A message to this effect is printed and NFLAG is set to 1.

2. The function in A and B is printed and if NTYPE is less than 6 (a Time Response), the plot axes (ABSC and ORD) are marked 'TIME' and 'MAG' and Subroutine SCALE, ROUTH, SAMPLE, FLIP and ADJUST are called to perform the Fast Fourier Transform. Control then returns to the calling program.

3. In cases where a Time Response has not been requested (NTYPE greater than 5) a further test is made. If NTYPE is not 9 (a REAL plot), NUMTI is calculated for a logarithmic plot instead of a linear plot. Then the points are calculated (DO 4) and entered into the TEE, FCTN (and PH when NTYPE is not 9) arrays. For a REAL plot, the real part of Z,
(i.e., \( \sigma \)) is incremented in linear steps. Otherwise, the imaginary part of \( Z \) (i.e., \( jw \)) is incremented in logarithmic steps).

4. After the points have been calculated, ABSC and ORD are labelled 'FREQ' and 'MAG,' and Subroutine PRTPLT is called to output the points. In the case of a REAL plot, the Phase must always be 0 so if NTYPE is 9, Subroutine INVERT returns control here. Otherwise, ORD is labelled 'PHA', FCTN is filled with the points from PH and Subroutine PRTPLT is called again before control returns to the calling program.

In the case of Time Response plots (NTYPE less than 6) Subroutine INPUT is called by Subroutine INVERT to evaluate the transform of the response:

1. Upon entry, Subroutine INPUT prints out the quantities associated with each type of plot according to NTYPE.

2. The Transform of the response is calculated as follows:

   NTYPE = 0 **Impulse Response.** No change is required since \( F(jw) = 1 \).

   1 **Step Response.** \( F(jw) = \frac{1}{jw} \) so B, the denominator, is multiplied by \( jw \).

   2 **Exponential.** \( F(jw) = \frac{1}{jw - FREQ1} \) so B is multiplied by \( jw - FREQ1 \).

   3 **Sine Wave.** \( F(jw) = \frac{2\pi x FREQ1}{(jw)^2 + (2\pi x FREQ1)^2} \) so B is multiplied by \( (jw)^2 + (2\pi x FREQ1)^2 \) and SCMAG is multiplied by \( (2\pi x FREQ1) \).

   4 **Single Pulse.** \( F(jw) = \frac{1}{jw} (1 - e^{-jw FREQ2}) \) so B is multiplied by \( jw \) and the tags ISN and NTAY are set to indicate that the factor \( (1 - e^{-jw FREQ2}) \) is to be included.

   5 **Pulse Train.** \( F(jw) = \frac{1}{jw} (1 - e^{-jw FREQ2}) \) \( (e^{-jw FREQ1}) \) \( (1 - e^{-jw FREQ1}) \) so B is multiplied by \( 1/jw \) and the tags NTAY and ISN are set to show that the additional factors must be included later.

3. After the correct transform has been calculated, Subroutine INPUT returns control to the calling program.
Later on, Subroutine INVERT begins the Fast Fourier Transform, by calling Subroutine SCALE:

Subroutine SCALE simply readjusts the values of the Fourier Transform coefficients (in A and B) to avoid Floating Point Overflow. Control then returns to the calling program.

The next step in the Fast Fourier Transform is to call Subroutine ROUTH. Subroutine ROUTH uses Subroutine CALCR to find a path along which the integral

\[ \frac{1}{2\pi} \int_{0}^{2\pi} F(\sigma + j\omega) e^{(\sigma+j\omega)t} \, d\omega \]

is to be evaluated. This path must lie to the right of any poles in the complex plane. As shown in Figure 4.5, Path 1 is not acceptable while Path 2 is acceptable. This is due to the fact that the Real Part of \( S(=\sigma) \) must be negative in \( e^{(\sigma+j\omega)t} \)

in order for the integral to converge. The upper limit of \( 2\pi \) for the integral is sufficient because after Subroutine SCALE has readjusted the Transform coefficients, all the significant information has been pushed into this range.

Figure 4.5
1. Subroutine ROUTH uses an initial SIGMA value of 0.0 and calls Subroutine CALCR(LOGI) to see if all the poles lie to the left of the SIGMA value. Subroutine CALCR returns a LOG1 value of True if all the poles lie to the left of SIGMA, otherwise, it returns False. Subroutine ROUTH increments the value of SIGMA until Subroutine CALCR returns True. Having found an acceptable value of SIGMA, control returns to the calling program.

2. Subroutine CALCR (LOG1) uses the Routh Stability Criterion to determine whether all poles lie to the left of the current value of SIGMA. If they do, the value returned in logical variable LOG1 is True, otherwise it is False. Upon entry, D(I,J), the Routh Table, is reset to 0(DO 242).

3. The Routh Table is then computed, and the first column (D(1,J)) is checked (DO 245). If any zero or negative values are found, LOG1 gets a value of False and control returns to the calling program.

4. Otherwise LOG1 gets the value True, and control returns to the calling program.

Having found an acceptable SIGMA value, Subroutine INVERT calls Subroutring SAMPLE.

1. Subroutine SAMPLE computes the quantities $F(a + jw)$ and $e^{(a+jw)}$ which are stored in RSPNS(I) and EXCMP(I), respectively, (DO 130). As each point is evaluated, the flag ISN is tested to see if the transform requires any modification. (ISN was set by Subroutine INPUT as the Fourier Transform was calculated). Any modification required is performed by means of complex variable ZZ.

2. Subroutine SAMPLE then returns control to the calling program.

With the sample points now in RSPNS and EXCMP, Subroutine INVERT calls Subroutine FLIP, the heart of the Fast Fourier Transform.

1. Upon entry to Subroutine FLIP, the coefficients in the RSPNS array are reordered as prescribed by the Fast Fourier Transform technique (DO 106).
The integral
\[
\int_{-\infty}^{\infty} F(\sigma + j\omega) e^{j\omega t} \, d\omega
\]
is computed (DO 110 and DO 108) thus producing the output response samples in RSPNS.

Subroutine ADJUST is called to re-evaluate the first 5 sample points by means of a Taylor Series. The Taylor Series coefficients are computed by Subroutine TAYLOR and entered into the TERM array.

1. Upon entry Subroutine ADJUST enters the Time points into the TEE array and the output sample points into the FCTN array (DO 150).

2. If SIGMA is non-zero, each of the sample points in FCTN is multiplied by the \( e^{\sigma t} \) factor. (DO 153).

3. Subroutine TAYLOR is called to enter the Taylor Series coefficients into the TERM array.

4. If NTAY is non-zero, the Taylor Series coefficients are used to enter the first 5 output points into the FCTN array. If the series fails to converge at any one of the points (FNP(I) greater than 1000) the remaining points of the original 5 are not altered.

5. Subroutine PRTPLT is called to print and plot the data points. Control then returns to the calling program.

Subroutine TAYLOR uses the Transfer Function coefficients \( A(I) \) \( B(I) \) to obtain a Taylor Series.

1. The Taylor Series is computed term by term and entered into the TERM and POW array. (DO 214). If any term becomes too large (greater than \( 10^{60} \)), the Taylor Series is halted and NTAY is reset to zero.

2. Control returns to the calling program.
Subroutine PRTPLT prints and plots the points in the TEE and FCTN arrays.

1. Upon entry Subroutine PRTPLT writes out the points in TEE and FCTN in three columns. If NPLLOT, the number of points to be plotted from the total number computed (the plot density), is zero, control returns to the calling program.

2. The maximum and minimum plot points are found (DHI, DLO). The points are plotted into the P array and printed out one at a time (DO 182) along with axis labelling for the TEE axis. Control then returns to the calling program.

4.2.6 Rootfinding

The Poles and Zeroes of the Transfer Function are evaluated by means of Subroutine ROOTS. This routine is called by the Main Program in response to reading an Output Request Card containing the word ROOTS.

Subroutine ROOTS is essentially a modified version of the Svoboda Polynomial Rootfinder. In this algorithm, the complex plane is searched for zeroes using a five point test. As a root is detected, the search step size is repeatedly decreased to 1/16 of its previous value until the five points in the five point test do not yield significantly different results. Thus, the root is found to the maximum resolution available from the computer. The original polynomial is used for the final test while the reduced polynomial, having previously found roots divided out, is used for the coarse testing. This technique combines the ability to handle multiple roots while retaining the accuracy of the original unreduced polynomial. The scan is performed initially within the unit circle to obtain roots less than 1.0. The polynomial is then inverted to cause roots which were greater than 1.0 to fall within the unit circle. The five point test used by the algorithm is neither necessary nor sufficient to find all the roots of the polynomial, yet in practice, the algorithm has yielded remarkable results despite its non-rigorous mathematical foundation. The roots produced by this algorithm represent not only the root values themselves but also the
accuracy to which the roots were found, since every non-zero digit in the root is guaranteed correct within the accuracy of the computer. This information is of considerable value when high order polynomials are being evaluated.

Figure 4.6 Flow of Control in Svoboda Algorithm
The flow of control among the various logical routines of the algorithm is depicted in Figure 4.6. After obtaining the input data, the Scanning Routine systematically steps over the Unit Circle evaluating the reduced polynomial (i.e., one having previously found roots divided out) at five points on each step. When a criterion for the possible existence of a root at any step is fulfilled, a transfer is made to the Home-in-Routine. Mathematically, this criterion is neither necessary nor sufficient for the existence of a root. The Home-in-Routine approximates the root as closely as possible and then transfers to the Root Examination Routine. Using the Round-off Routine, the Root Examination Routine either rejects the root or refines it (by means of the Home-in-Routine again) and outputs it. Since refinement always uses the original unreduced polynomial, and since it proceeds by successive significant digits, every non-zero digit printed is guaranteed correct within the accuracy of the computing system. Control then passes back to the Scanning Routine which either continues scanning or stops because the required number of roots has been obtained. When a scan is completed, if the maximum number of scans has not yet been reached, the Inversion Routine gains control to "invert" the polynomial, before returning to the Scanning Routine which continues to scan. A detailed discussion of each element of the algorithm follows.

1. **The Scanning Routine**

The main routine in the Algorithm is the Scanning Routine which moves across the Unit Circle as shown in Figure 4.7. The real and imaginary axes between the ranges (-1, 0), (1, 0) and (0, -1), (0, 1) are divided into sixteenths. The Scanning Routine uses the Polynomial Evaluation Routine to find five points at each step in the scan, the central point and four points one sixteenth above, below, to the left and to the right of the central point. A test is then performed to see if this point is near a root. The criteria for transferring to the Home-in-Routine to examine a possible root more closely are.
1. The value at the central point must be less than the value of any of the four surrounding points.

2. The five points must not be equal in value.

Note that the criteria are mathematically insufficient to determine the existence of a root.

If these criteria are not met, the scan is incremented by one sixteenth and the scanning process is resumed. Scanning is performed from left to right and from bottom to top.

When a scan has been completed, that is, when the point (1, 0) has been evaluated, a check is performed to see if the number of scans has exceeded an upper limit. If not, a transfer is made to the Inversion Routine (described below) which performs the inversion of the polynomial and then returns control to the Scanning Routine.

The maximum number of scans allowable is twice the number of roots in the polynomial. Since at least one root must be obtained after each pass of both the "real" polynomial and the "inverted" polynomial (requiring a total of two scans), a number of scans no more than twice the
number of roots not yet found should be required for the algorithm to work properly. (Usually, considerably fewer scans are required because several roots may be found on one pass). If this number is exceeded, however, the routine stops automatically.

The problem of evaluating the circumference of the Unit Circle twice (once on a "real" scan and once on an "inverted" scan) is solved by taking two precautions. Firstly, all points evaluated in a "real" scan must be within the Unit Circle, while an "inverted" scan is permitted to violate the boundary of the circumference slightly. This precaution alone, however, is not sufficient to avoid a duplication of roots which lie close to the boundary, therefore, in the Root Examination Routine a check is performed to see if the root under consideration has appeared previously in another scan. This second precaution prevents roots which have been found once by a "real" scan and once by an "inverted" scan from appearing twice.

2. Polynomial Calculation

The Polynomial Calculation Routine uses Horner's Technique to evaluate the polynomial complex value from the coefficients. Basically, Horner's Technique is the iterative evaluation of the expression

\[ F_{i+1} = (F_i + a_i) \cdot x \quad i \text{ goes from } 1 \text{ to } n \]

with \( F_1 = (0, 0) \) and \( F_{n+1} = F_n + a_{n+1} \) the final value. \( a_i \) is the \( i \)th coefficient in the polynomial.

\[ P(x) = a_1 x^n + a_2 x^{n-1} + \cdots + a_n x + a_{n+1}. \]

Thus the final value is cumulatively built up in \( F \). If necessary, the complex value \( F \) is divided by previously found roots to form a reduced polynomial value

\[ F = \frac{P(x)}{(R_1 - x) (R_2 - x) \cdots (R_m - x)} \]

where \( m \) is the number of roots found previously. In order to avoid overflow, the absolute value of any of the factors \((R_i - x)\) is not allowed to be
less than $10^{-60}$. The final step is to obtain the residual (the complex absolute value) of $F$.

$$H = \sqrt{([\text{Re}(F)]^2 + [\text{Im}(F)]^2}$$

The residual is computed for four or five points (the Home-in-Routine does not require the central point to be evaluated each time) on each entry to the Calculation Routine. It is these four or five values ($H$) which are used by the Scanning and Home-in-Routines as the polynomial values at the test points.

3. **Polynomial Inversion**

In order to obtain all the roots of the polynomial

$$P(x) = a_1 x^n + a_2 x^{n-1} + \cdots + a_n x + a_{n+1}$$

by scanning the complex plane within the Unit Circle, at some point a new polynomial is formed from the original one by reversing the order of the coefficients. The roots of this new polynomial are the reciprocals of the roots of the original polynomial, thus effectively bringing inside the Unit Circle all the roots which were previously outside. The Inverted Polynomial is

$$P'(y) = a_{n+1} y^n + a_n y^{n-1} + \cdots + a_2 y + a_1.$$ 

If $P(r) = 0$, it is easy to show that

$$P(r) = 1/r^n P(r) = P'(1/r)$$

Therefore, $y = 1/r$ is a root of the new polynomial $p'$.

Thus, in order to obtain all the roots of a polynomial, the program must deal effectively with two kinds of roots, "real" and "inverted," and must obtain the reciprocal of "inverted" roots before writing them on the output. The polynomial Inversion routine, simply reverses the order of the coefficients, sets a program variable to point to either the "real" or "inverted" techniques, and returns control to the main program.
4. **Home-ing In**

Once five points have been obtained which fulfill the criterion for root examination, the homing-in procedure subdivides the distance between the central point and one of the outside points into sixteenths and, using the central points as a starting value, employs the Polynomial Evaluation Routine to compute four new outside test points. These new four points and the central point are then examined for the one having the smallest residual which becomes the central point for a new five point test. If this new central point is the same as the previous central point, the scale is subdivided into sixteenths as before so that the five point test becomes progressively more refined. At each subdivision, a new level of significance is obtained (each significant digit being a Hexadecimal digit because the scale factor is 16). This process of "home-ing in" is continued until either

1. The required number of digits of accuracy is reached or,
2. The residuals of the five points do not differ by a significant amount.

In case 2, the resolution of the computing method and system has been reached and the remaining significant digits, if any, are filled with zeroes. This represents a Stopping Criterion which is independent of any formula for round-off error, but depends only on the previously mentioned resolution.

Each time a new step is taken in the Home-in-Routine, three checks are made. Firstly, if the central point should happen to be the origin (0, 0), the scale is expanded (subdivided by sixteenths), this allows for roots which may range over large orders of magnitude. Secondly, if more than sixteen steps should be taken in one direction at the same level of significance the level of significance is dropped so that larger (coarser) steps may be taken. Finally, a check is performed to ensure that the routine does not stray too far out of the Unit Circle. This safeguards against the possibility that the original location presented to the Home-in-Routine was not in the vicinity
of a root, in which case it could easily wander outside the Unit Circle. If this condition should be detected, the Home-in is aborted and control is returned to the Scanning Routine.

If either case 1 or case 2 occurs, the Home-in-Routine has reached a successful completion and transfers control to the Root Examination Routine.

5. Root Examination Procedures

The Root Examination Routine first checks to see if the root just found came from the original polynomial coefficients or from a reduced polynomial. If the polynomial was a reduced one, the value of the root can be regarded merely as an approximation. The Home-In-Routine is therefore called again to repeat the latter part of the home-in procedure this time using the original polynomial and using the approximate root as a starting value. This technique ensures that every root is found from the original polynomial and that its accuracy does not depend on the accuracy with which previous roots were found.

After the final root value is obtained, a second check is made, this time on its residual. If the residual is greater than a certain value, the root is considered unreliable and is discarded. If this should occur, control is transferred back to the Scanning Routine. The maximum value of the residual is chosen arbitrarily to be one half the value of $a_{n+1}$, the constant coefficient in the polynomial.

Having passed these tests, the root value is rounded-off in the Round-off Routine (which is not discussed here because it has no bearing on the actual rootfinding algorithm). If the root is "inverted" its reciprocal is found using floating point division, and this value, after being rounded-off again, becomes the root value. A third check is then performed on the root to see if it has been found on a previous pass. (This check was mentioned previously in connection with the Unit Circle Boundary). If both real and imaginary parts fall within one significant digit of a root found on the other.
type of pass ("real") it is rejected as a root but is nevertheless entered, in the same way as acceptable roots, in the list of roots used to form a reduced polynomial. (This prevents its being found again). If the root is not rejected, it is converted from its internal hexadecimal representation to decimal, rounded-off again, and is written on the output.

A final check is made to see if the required number of roots has been obtained. If not, control is returned to the Scanning Routine, otherwise the algorithm terminates.

Because the algorithm lacks a rigorous mathematical foundation, it cannot be guaranteed to find all the roots. However, every root detected is guaranteed accurate within the accuracy of the computing system, it is independent of the technique used to find the roots.

4.2.7 The Automatic Scaler

The Main program always calls the Automatic Scaler, Subroutine SCALER, before the Flowgraph is constructed. Subroutine SCALER examines the element values in the VPATH list and if the range of exponents of Inductors and Capacitors is too large, the values are multiplied by $10^\text{FACTOR}$ where FACTOR is an integer which is determined so as to minimize the range of exponents. If no such FACTOR can be found, a warning is printed.

Since the element values are modified after scaling, the 'S' symbol which appears in the Transfer Function must be reinterpreted. For example, if FACTOR is determined to be 3, a capacitor of value $(10^{-3} s)^{-1}$ becomes

$$(10^{-3} s \times 10^3)^{-1} = (s)^{-1}$$

thus the new s is $10^{-3}$ times the true s. Therefore, wherever 's' appears in the Transfer Function $10^3 s$ must be substituted. Similarly, all the plots and roots obtained by operating on this scaled transfer function must be modified.
1. Upon entry to Subroutine SCALER, all elements containing $s$ (i.e., inductors and capacitors) are checked (DO 1). The sum of their exponents is entered into $D$. At the same time, the sum of their exponents scaled by $10^{-1}$ is entered into $DL$ and the sum of their exponents scaled by $10$ is entered into $DR$.

2. If $D$ is less than 60 and FACTOR is 0, no scaling need be done so Subroutine SCALER returns. Otherwise, $D$, $DL$, and $DR$ are compared to see whether FACTOR should be incremented or decremented for minimum $D$. If $D$ is not already minimum, FACTOR is adjusted and then control passes back to step 1 for another iteration. If $D$ is already minimum, FACTOR is checked to see if it is still 0. If it is, no scaling could be performed so a warning is printed and control returns to the calling program.

3. If FACTOR is non-zero, all the inductors and capacitors are multiplied by $10^{FACTOR}$ (DO 5). Control then returns to the calling program.

4. 3 Modular Organization

NASAP-70 has been designed in order to facilitate easy insertion of additional routines and removal of supplied routines. Each module is called from the main routine. In general, three modifications are required:

1. The insertion or deletion of a Fortran CALL statement which transfers to the routines to be inserted or deleted.

2. The addition or removal of the routines themselves.

3. Using the Dictionary of Variables, conflicts in variable names may be eliminated in the case of insertions, and Common blocks and variables no longer required may be removed in the case of deletions.

If these steps are followed, users having a working knowledge of Fortran should have little difficulty adding new capabilities to their versions of NASAP-70.
4.3.1 Removal of Supplied Routines

Under certain circumstances it may be desirable to remove some of the routines supplied with NASAP-70 (e.g., in order to run in less than 32K words). For proper operation NASAP-70 requires only one of the circuit description analysis routines and the Transfer Function routines. Thus, the following modules may be removed:

- Either Subroutine NASAP or Subroutine READ.
- Subroutine FINE.
- Sensitivities and Worst Case option.
- Plotting package.
- Rootfinder.
- Automatic Scaler.

For instance, if the Sensitivities and Worst Case option is to be omitted, all the references to Subroutines SENSC, WORSTC, MULT, SENSIT, WORST, and POLSEN should be deleted, as well as those routines themselves. Finally, Common blocks POLY and WORST1 and references to their variables should be removed.

4.3.2 Addition of User Routines

A user who is familiar with the operation of NASAP-70 may desire to add some of his own options to the supplied program, e.g., for further analysis of the Transfer Function. If any scanning of card images is to be performed, it is wise to become acquainted with the card scanning utilities ASCAN, BSCAN, CSCAN, SHIFT, NUMBER, etc. If bit manipulation is to be performed the utilities LOR, LOX, UNPAK, etc., are available. Finally, if operations are to be performed on the Transfer or Sensitivity Functions, the method of storage of these data in the 'VN' arrays should be examined (4.2.3 and 4.2.4).

If NASAP-70 is used with the Overlay structure, all user-written routines should be called by the main program only. This will eliminate troubles due to calling routines not in core. In general, workspace is
available in the following Common blocks:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BITS</td>
<td>4095</td>
<td>Words</td>
</tr>
<tr>
<td>SPEED</td>
<td>2048</td>
<td>Words</td>
</tr>
</tbody>
</table>

This may not be true at all times, however, so the user should consult the Dictionary of Variables to ensure that he does not erase any useful data.
REFERENCES


CHAPTER 5
SYSTEM REQUIREMENTS

5.0 Computer Requirements

NASAP-70 requires a computer with no less than a 32K word memory to run, using the Overlay Structure in Section 5.3. For some computers having unusually large System Monitors the supplied program may be too large anyway. If this should be the case, some of the supplied options may have to be removed or restricted, e.g., the Sensitivity option could be reduced to handling fewer than 20 elements. This would decrease the size of Common block POLY. On computers with more than 32K words, the Overlay Structure may be neglected entirely. This would not only simplify the loading procedure but also decrease running times.

NASAP-70 needs no additional scratch units other than a card reader and line printer.

5.1 Running a NASAP Problem from the Source Deck

NASAP-70 is distributed as a Fortran source deck. The program must be compiled and loaded in order to run any problems on it. If no changes are to be made, this process may be performed directly. In the case of a machine with a smaller memory, the user may wish to use the Overlay Structure described in Section 5.3. When a user possesses a machine with a very limited memory, some modifications to the source deck may be necessary (e.g., Removal of some supplied routines, reduction of COMMON sizes). Guidelines for these changes are given in Section 4.3.2.

If a user possesses a machine which has a Fortran compiler which uses "backwarding addressing", (e.g., IBM 7094) he should ensure that all COMMON blocks are adjusted to the correct lengths as described in Section 5.5. Further, care should be taken to correct any problems with the Fortran AND function (Section 5.4).
Having made any necessary changes in the source deck, the program may be compiled and loaded. If the machine on which the program is to be run, is not IBM 360 compatible, it is strongly suggested that the sample problems be run and verified with the solutions given before any large-size user problems are attempted.

Here is the IBM/360 control card deck for running NASAP from the source deck 13, 14.

// NASAP JOB (Installation dependent data).
// STEP1 EXEC FORTHCLG, PARM. LKED='XREF, LIST, OVLY'
// FORT, SYSIN DD *
Fortran Source Decks go here.

/*
// LKED, SYSIN DD *
INSERT MAIN
OVERLAY ONE
INSERT ASCAN, BSCAN, CSCAN, ISORT, MSG, NUMBER, SHIFT, SORT
OVERLAY TWO
INSERT NASAP, SENSIT, WORST
OVERLAY TWO
INSERT READ, UNITS
OVERLAY TWO
INSERT WHAT, PLOT
OVERLAY ONE
INSERT FINE, SCALER, POLSEN
OVERLAY ONE
INSERT EQUAL, LOR, LOX, LSTOP, UNPAK
OVERLAY THREE
INSERT CALC, INBIT, GRAPH
OVERLAY THREE
INSERT LOOPS, CLEAR, REDUCE
OVERLAY ONE
INSERT MULT, SENS, ANSWER, WORSTC.
OVERLAY ONE
INSERT INVERT
OVERLAY FOUR
INSERT INPUT, SAMPLE, FLIP
OVERLAY FOUR
INSERT ADJUST, TAYLOR, PRTPLT
OVERLAY FOUR
INSERT SCALE, ROUTH, CALCR
OVERLAY ONE

5-2
5.2 **NASAP-70 Input Data**

The input data consists of three sections

1. Title Cards (Optional)
2. Circuit Description
3. Sensitivity and Worst Case Section (Optional)
4. Output Requests.

1. Up to 10 Title Cards are allowed. They are printed in the output listing exactly as they are read.

2. The Circuit Description section may be in one of three forms depending on the format of the first card

   a. NASAP
   b. TREE
   c. CIRCUIT (Operating Frequency)

   a. For compatibility with other versions of NASAP, this heading card will cause the program to accept the circuit description in the form described in the previous NASAP User's Guide. This data format corresponds to the following conventions.

   Each card contains one circuit element. The first letter describes the element and must be one of the following

   V Voltage Source
   I Current Source
   C Capacitor
   L Inductor
   R Resistor.
Each of these letters may be followed by up to 11 alphanumeric characters to bring the total number of characters in the element name to not more than 12.

The card format is as follows.

NAME ORIGIN TARGET VALUE UNITS (optional) DEPENDENCY (optional)

NAME refers to the previously described element name. ORIGIN and TARGET refer to the origin and target node numbers of the element. VALUE is the element value in any format. UNITS is optional and must be one of the following:

UF
PF
MH
UH
K
M

If UNITS is not specified, MKS units are assumed. DEPENDENCY is also optional and represents the name of some other element appearing in the circuit description, preceded by the letter V or I to denote dependency on voltage or current.

At least one blank must appear between each of the data fields on the card, otherwise the data is freefield. The last card in the circuit description must contain either the word OUTPUT or the word END.

This form of circuit description relieves the user of the need to organize the tree. Instead, the program automatically builds a tree which results in minimum computation time.

b. For a user-defined tree, a different input format is used. Following the TREE card are the circuit description cards. The last card in this section must be a card with the word END. The first 1 or 2 letters on each circuit description card must be one of the following:
E Independent Voltage Source
J Independent Current Source
CE Capacitor Branch
CJ Capacitor Link
LE Inductor Branch
LJ Inductor Link
RE Resistor Branch
RJ Resistor Link
DE Dependent Voltage Source
DJ Dependent Current Source

Each of these may be followed by up to 10 or 11 alphanumeric characters to bring the total to not more than 12.

The data card format is as follows
NAME (ORIGIN - TARGET) = VALUE UNITS (Optional)
or
NAME/DEPENDENCY (Optional) (ORIGIN - TARGET) = VALUE UNITS (Optional)

NAME refers to the element name described above. DEPENDENCY is one of the letters V or I to denote voltage or current dependence, followed by the name of the controlling element. ORIGIN and TARGET are the origin and target node numbers. VALUE is the element value. The optional UNITS field must be one of the following

MF
MMF
PF
MH
MMH
K
M

If the units are not specified, MKS units are assumed. All input cards are free-field. Blanks and/or commas may be used freely and are
ignored by the program. All other punctuation must appear exactly as shown.

c. For a tree constructed for optimum accuracy at a specific frequency, the CIRCUIT card is used in conjunction with the operating frequency in cps enclosed in parentheses. The input data format is identical with that used after a TREE card except for the format of Capacitor, Resistor and Inductor names where it is no longer possible to differentiate between branches and links

C Capacitor
R Resistor
L Inductor.

If no operating frequency is specified, a default of 1 cps is supplied.

3. SENSITIVITY INPUT REQUESTS

SENSITIVITY FUNCTION

To obtain the sensitivity of the transfer function to a particular circuit element, a sensitivity request card is required. These cards must immediately follow the 'END' or 'OUTPUT' cards terminating the circuit description. The format of the sensitivity request card is as follows:

SEN SIVITY = 'ELEMENT NAME',
or
SENS = 'ELEMENT NAME'

where 'ELEMENT NAME' is the name of a circuit element.

Sensitivity request for independent voltage and current sources are ignored. Also, a maximum of twenty valid sensitivity requests may be processed for each circuit.

The sensitivity function (in terms of S) is printed in the same format as the transfer function.
WORST CASE ANALYSIS:

A worst case analysis can be provided for circuits of twenty elements or less (not counting independent voltage or current sources). To obtain this analysis, a card must be provided immediately after the 'END' or 'OUTPUT' cards terminating the input description in the following format:

```
WORST
```

To obtain a worst case analysis, the tolerance of each element must be known. These values may be provided by 'TOLERANCE' cards which have the following format:

```
TOL = 'ELEMENT NAME' = 'VALUE'
```

where 'ELEMENT NAME' is the name of a circuit element, and 'VALUE' is the relative tolerance \( \frac{\Delta Q}{Q} \) for this element. If no 'TOLERANCE' card is provided for an element, a default value of .1 (10%) is assumed for the tolerance.

As well as a function of S giving the square of the worst case tolerance, sensitivity functions for all the elements are also printed. Thus no 'SENSITIVITY' cards may be present when a 'WORST' card follows the circuit description.

4. The Output Requests section may contain:
   a. Transfer Function requests
   b. Plot requests. (optional)
   c. Roots Requests. (optional).

Any number of Transfer Function requests may appear and any number of Plot requests may be included following a single Transfer Function request. Only one Roots request may appear after each Transfer Function request. The last card in the Output Requests section must be a card containing either the word END or the word EXECUTE.
a. The Transfer Function requests have the following format

TYPE NAME 1 / TYPE NAME 2

where TYPE NAME is the name of an element which has appeared in the Circuit Description, preceded by the letter V or I to denote whether Voltage or Current is desired. TYPE NAME 2 must be an Independent Source.

b. The plot request is a single card of the following form:

PLOT (Option = Value / Option = Value....)

The following options are available

1. TYPE = IMPULSE for impulse response
   STEP for a step function
   SINE for a sine wave input
   EXPONENTIAL for an exponential input
   PULSE for a pulse or pulse train
   FREQUENCY for a frequency response
   SENS for a sensitivity function plot
   WORST for a worst case function plot
   REAL for a transfer function plot with \( \sigma \) as the independent variable

2. AMPLITUDE = a number
   represents the magnitude of any of the waveforms.

3. BIAS = a number
   may be used only with PULSE to obtain a train of positive and negative pulses. It is combined with AMPLITUDE. e.g.,
   AMPLITUDE = 10
   BIAS = -2
4. CONSTANT = a number
may be used only with EXPONENTIAL. It represents \( a \) in \( Ke^{at} \).

5. FREQUENCY = a number (in Hz/s.)
may be used only with SINE to specify the frequency of the sine wave.

6. DENSITY = a number
to specify the number of calculated points per plotted point.

7. TIME = a number (in Secs.)
should always appear with a time response. It specifies the duration of the plot.

8. WIDTH = a number (in Secs.)
may be used only with PULSE to specify the duration of a pulse.

9. CYCLE = a number (in Secs.)
may be used only with PULSE to specify the time of 1 cycle.

\[ \text{WIDTH} = 10 \]
\[ \text{CYCLE} = 15 \]
gives:

- Diagram showing the pulse with specified parameters.
10. **STEP** = a number (in Secs.)

specifies the time between individual calculated points. It may be used with any **TYPE** option.

11. **FROM** = a number, **TO** = a number

specifies the beginning and ending points of a frequency response (= w/2\pi), sensitivity, worst case or real plot. (= o).

12. **ELEMENT** = an element name for which a sensitivity function has been requested may be used only with **SENS** to identify the sensitivity function to be plotted.

Only the first 2 letters of each word are used, therefore, AM may be used as an abbreviation for **AMPLITUDE**, IM for **IMPULSE**, etc.

Since continuation cards are not allowed, all the options for any one plot request must appear on one card. Not all the options are required since defaults are provided, e.g.:

**PLOT**(TIME = 1) produces an **IMPULSE** response of 100 steps and of duration 1 sec.

Defaults

```
TYPE = IMPULSE
TIME = 1 sec.
STEP = .01
AMPLITUDE = 1
DENSITY = 1
CONST = 1
FREQ = 1
```

The options may appear in any order on the Plot card. Inconsistent requests will be ignored, e.g., **TYPE** = IMPULSE, **FREQ** = 2 yields an Impulse response.
c. To obtain the roots of the numerator and denominator of the Transfer Function, a card with the word ROOTS must appear after the Transfer Function request.

The sensitivity of the poles of the transfer function may be obtained by adding the word 'POLES' to a 'ROOTS' card

ROOTS, POLES

The sensitivity of the Poles are produced for all elements for which a sensitivity request had been issued (or all elements if a 'WORST' card was included).

Several complete problems may run at one time. To terminate the execution of NASAP, a card containing the word STOP is used.

NASAP-70 can handle.
- Up to 50 elements
- Up to 50 circuit nodes
- Up to 20 sensitivity requests

The circuit nodes should be numbered consecutively starting with 1 for best efficiency. This is not required, however. When more than 30 circuit elements are to be analyzed, the time required for the computation in Subroutine LOOPS begins to increase sharply. This effect is due to the presence of more than 2 words per block in Common Block BITS.

5.3 Overlay Organization

The recommended Overlay Structure is shown in Figure 5.1. This is not required for running NASAP but when included, it decreases the overall program size. However, the Overlay Structure is required to allow the program to fit into a computer with only a 32K word memory.
OVERLAY STRUCTURE FOR NASAP-70

<table>
<thead>
<tr>
<th>ASCAN</th>
<th>FINE</th>
<th>EQUAL</th>
<th>MULT</th>
<th>INVERT</th>
<th>ROOTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESCAN</td>
<td>SCALER</td>
<td>LOR</td>
<td>SENSEC</td>
<td>INPUT</td>
<td>ADJUST</td>
</tr>
<tr>
<td>CSCAN</td>
<td>POLSEN</td>
<td>LOX</td>
<td>ANSWER</td>
<td>SAMPLE</td>
<td>TAYLOR</td>
</tr>
<tr>
<td>ISORT</td>
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<td>LSTOR</td>
<td>WORSTC</td>
<td>FLIP</td>
<td>PRTPLT</td>
</tr>
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<td>MSG</td>
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<td>UNPAK</td>
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<td></td>
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<td></td>
<td>INBIT</td>
<td>CLEAR</td>
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<td>GRAPH</td>
<td></td>
<td>REDUCE</td>
</tr>
<tr>
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<td>READ</td>
<td>WHAT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>UNITS</td>
<td>PLCT</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>WORST</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.1
5.4 The Fortran AND and OR Functions

NASAP-70 requires the ability to perform a full word AND and OR on fixed point word variables in Fortran. This has been accomplished on the IBM 360 by means of the Fortran Logical .AND. and .OR. functions. The fixed point variables are given Logical type aliases and the AND or OR is performed on these logical type names. For example

```fortran
LOGICAL A, B, C
EQUIVALENCE (A, I) (B, J), (C, K)
I = 12
J = 20
C = A .AND. B
```

would yield a value of 4 in K. On many other compilers a Logical type .AND. and .OR. does not operate on all the bits in the word. If NASAP-70 is compiled on such a system it will give incorrect results.

On systems which do not have the full word Logical .AND. and .OR., often another function is available for the same task. If no such facility is provided, the user must write his own AND and OR functions in Assembler Language. In either case statements of the type

```fortran
C = A .AND. B
```

must be replaced by statements of the type

```fortran
K = IAND (I, J)
```

This logical .AND. and .OR. is used in the following subprograms

Subroutine LOOPS

Function LOR

Function LOX

These are the only routines which are affected by the logical type .AND. and .OR., but the user must ensure that these changes have been made before he attempts to run any NASAP-70 problems on a machine which is not IBM 360 compatible.
5.5 **Compatibility Among Various Computers**

Apart from the Fortran Logical type, AND, and OR, functions described in the previous section, there are other facts about the IBM 360 Fortran compilers which could be a source of trouble on other computers.

The origins of Common Blocks on the IBM 360 are computed from the first variable in the block. On some compilers, however, the origin is computed from the last variable in the block, (e.g., IBM 7094). This allows occurrences of Common Blocks with the same name to have different lengths on the IBM 360. On compilers which compute the origin from the last variable (i.e., "backward addressing") all the occurrences of the same Common Block must be adjusted to the same length (with dummy variables if necessary) before compilation.

The test of the index in a DO loop is performed at the bottom of the DO. Thus in the following group of statements, the DO is executed once.

```
N1 = 3
N2 = 2
DO 1 I = N1, N2
```

Further, in the case of the abnormal termination of a DO loop, the index variable retains its most recent value. NASAP has been programmed to avoid these problems with DO statements but they are mentioned here nevertheless to illustrate the way in which the IBM Fortran compilers handle special DO conditions.

Finally, a zero value for the index of a Fortran Computed GO TO is not treated as an error. Instead, execution proceeds with the statement following the GO TO. For example

```
N = 0
GO TO (1, 2), N
N = 2
1  N = 1 - N
```
\[ N = N + 7 \]

would yield \( N = 6 \).

NASAP-70 is designed for IBM 360 compatible computers therefore some modification will be required if it is to be run on computers which are not IBM 360 compatible.
APPENDIX A

A.1 PROGRAM LISTING

```
! BLOCK DATA
H,F,KREN T  UCLA 1967  UCLA 10
INTEGER GAG  UCLA 20
COMMON/GAG/GAG(20), NSEN,SENS(50)  UCLA 30
COMMON/POLY/VNO(101,20), VNO(101,20), MAXO1(20),
+SMINO1(20), SMAO0(20), SMI00(20), SMA10(20), SHIN10(20)  UCLA 50
 COMMON/DATA/A(32)  UCLA 60
 COMMON/SPEED/FN6D(3648)  UCLA 70
 COMMON/BITS/FIT(450)  UCLA 80
 COMMON/X/8(10)  UCLA 90
 DATA  D  UCLA 100
 DATA  G/000,4000,6000,8000,16000,32000,64000,128000,256000,512000,  UCLA 110
+1024000,2048000,4096000,8192000,16384000,32768000,65536000,  UCLA 120
 DATA  D  UCLA 130
 DATA  A,B/C/I,11,161,L1,161,11,L1,11,D1/I,11,J1,V1,F1,C1,  UCLA 140
 DATA  A,B/C/I,11,161,L1,161,11,L1,11,D1/I,11,J1,V1,F1,C1,  UCLA 150
 DATA  A,B/C/I,11,161,L1,161,11,L1,11,D1/I,11,J1,V1,F1,C1,  UCLA 160
 END
 INTEGER SMIN,SMAX,MIN1,MAX1,MINO1,MAXO1,SMINO1,SMAX01,SMINO0,SMAXO0,SMINO0  UCLA 170
 INTEGER FACTER,SENS,GAG,SMAX2,SMIN2  UCLA 180
 INTEGER GENER,TYP,ORIG,TARGET, ER, OUTPUT  UCLA 190
 DIMENSION VN(101,2)  UCLA 200
 DIMENSION SFIN(2),SP2X(2)  UCLA 210
 COMMON/NXST1/NXST2/VN(101,2),TN(50),MAX2,SMAX1,  UCLA 220
 COMMON/GAG/GAG(20), NSEN,SENS(50)  UCLA 230
 DIMENSION VNSEN(101,2,20), MAX1(20), MIN1(20)  UCLA 240
 COMMON/TREE/TREE  UCLA 250
 COMMON/TAG/TAG  UCLA 260
 COMMON/KA/A(50)  UCLA 270
 COMMON/DATA/CAX,CLJ,AL8,AJD,JMD(2),AV,F,AT,8,PARef  UCLA 280
 1, BMD(11), AAX, KBMA(2)  UCLA 290
 COMMON/ERR/ERR, FACTOR  UCLA 300
 COMMON/SPEED/VS(1000), LS(1000), NL(100)  UCLA 310
 COMMON/NPATH/CMPATH(300,2), VPATH(300), ST(300), CNPATH  UCLA 320
 COMMON/CIRCUIT/CARD(50,12), TYPE(50), GENER(50), ORIG(50), TARGET(5)  UCLA 330
 COMMON/NTIMES/NTIMES  UCLA 340
 COMMON/MPATH(1,1), BPS(100), BPS(300), BPS001)  UCLA 350
 COMMON/DEP(50,11), CNPATH(300,2)  UCLA 360
 COMMON/MPATH/MPATH(300,2), SMAX01(20), SM2O00(100)  UCLA 370
 COMMON/EQUIVALENT (VSNEN(11,1), BPS(100), BPS(300),  UCLA 380
 1, CM(11), BPS(100), BPS(300), DEP(11,1), BIT(300),  UCLA 390
 2, MINUS(BITS(362)), (MPATH(11,1), BPS(300))  UCLA 400
 COMMON/S-NPAH(NTIMES)  UCLA 410
 COMMON/NTM/NTIMES  UCLA 420
 DATA  D  UCLA 430
 DATA  N  UCLA 440
 DATA  E  UCLA 450
 DATA  N  UCLA 460
 DATA  E  UCLA 470
 DATA  N  UCLA 480
 DATA  E  UCLA 490
 DATA  N  UCLA 500
```

NOT REPRODUCIBLE
CALL CALC
IF(ERF.EQ.1)GO TO 9
CALL SCALE
IF(FACTOR.NE.0)WRITE(6,'(6,40F9.1))
109 FORMAT(10X,'**AS A RESULT OF AUTOMATIC SCALING THE TRUE S***
110 10 TO THE 1,4,1 POWER TIMES THE PROGRAM DEFINED S.
111 IF(TAG.EQ.1)GO TO 301
READ(5,100)A
301 CALL SHIFT(A)
300 GO TO 390
CALL SENSIT
GO TO 300
300 CALL GRAPH
250 FORMAT(1PE18.8)
UCLA1290
251 FORMAT(1X,13,E20.8)
UCLA1290
-205 FORMAT(1X,130ZPE20.8)
UCLA1370
-20 IF(FACTOR.NE.0)WRITE(6,205)A
19 IF(TAG.EQ.1)GO TO 301
READ(5,100)A
10 WRITE(6,205)A
205 FORMAT(1T12,60A1)
19 IF(TAG.EQ.0)CALL SHIFT(A)
TAG=0
19 IF(TAG.EQ.0)CALL INVERT
A-3
1.(ERR.EQ.O))CALL ROOTS UCLAI560
CALL SHIFT(A) UCLAI580
-- IF A(I)PTAb__.(_
*AND.(ERR.EQ.0))CALL POLSEN UCLA1580
*GO TO 610
WRITE(6,302) UCLA1600
302 FORMAT(/IOX,** SENSITIVITY OR WORST CASE REQUESTS MUST IMMEDIATELY FOLLOW THE CIRCUIT DESCRIPTION REQUEST IGNORED**)
GO TO 610
WRITE(6,302)
GO TO 14
WRITE(6,210)
210 FORMAT(/10X,*** MISSING END OF PROBLEM CARD SIMULATED BY PROGRAM**)
WRITE(6,206)
GO TO 14
WRITE(6,206)
GO TO 14
WRITE(6,207)NTIMES
A-4
207 FOR J=1 TO NTIMES
  CALL WHAT
  IF (ERR.EQ.1) GO TO 17
  DM1(J)=1
  CALL J9IT(1,0,-1,NTIMES)
  CALL J9IT(1,JPATH(1,1),-NTIMES)
  CALL LMPS
  DO 23 J=1,40
  J9IT(J)=0
  SMAX(J)=0
  199 S91(J)=0
  MX1A(J)=0
  VMX1=VMX1(J)
  VMX2=VMX2(J)
  CALL A'EP(VN0,SMX1,NSM[J,05])
  IF (S91.EQ.1.G0) GO TO 14
  CALL SENV
  DO 22 J=1,40
  PLY,J=PLTS(J)
  21 S91,J=0
  SMAX,J=0
  SMJ,J=SMJ,J
  22 IF (NIOT.EQ.0) GO TO 14
  CALL VARSTC
  CALL ANSER(VHJ,SMAX,2,SMJ1,1)
  GO TO 14
  CALL RANC
  SUBROUTINE ASCAN (J1,J)

  REAL LEFT,MNUS
  C0M=MNUS/ATA/A A(7),SLASH,LEFT,BM0S(8),BLANK,PLUS,MNUS,RIGHT,FOU
  C0M=MNUS/A(90)
  SMJ,J=150
  JC=1
  A=AK(J)
  IF (A(K).EQ.LEFT)RETURN
  IF (A(K).EQ.SLASH)RETURN
  IF (A(K).EQ.MINUS)RETURN
  IF (A(K).EQ.MNUS)RETURN
  IF (A(K).EQ.PATRFTJ0)RETURN
  IF (A(K).EQ.EQ)RETURN
  1 IF (A(K).EQ.BLANK)RETURN
  RETURN
  END
  SUBROUTINE PSCAN (J1,J)

  REAL LEF7,MNUS
  COM=MNUS/ATA/A A(7),SLASH,LEFT,BM0S(8),BLANK,PLUS,MNUS,RIGHT,FOU
  COM=MNUS/A(90)
  SMJ,J=150
  JC=1
  A=AK(J)
  IF (A(K).EQ.LEFT)RETURN
  IF (A(K).EQ.SLASH)RETURN
  IF (A(K).EQ.MINUS)RETURN
  IF (A(K).EQ.MNUS)RETURN
  IF (A(K).EQ.PATRFTJ0)RETURN
  IF (A(K).EQ.EQ)RETURN
  IF (A(K).EQ.BLANK)RETURN
  RETURN
  END

  A-5

  NOT REPRODUCIBLE
SUBROUTINE CSCAN(B,I,J)
C     H.F.9KRENT  U+C*AL+*  1967
C   COMMON/A/A(80)
REAL LEFT,MINUS
C   COMMON/DATA/C,A1,A4D(2),E,E4D(8),E,E4D(2),PNT,BLANK,PLUS,_MINUS
DB1K,1,J,80
J=K-1
B=A(K)
IF(A(K).EQ.PNT)RETURN
IF(A(K).EQ.E)RETURN
IF(A(K).EQ.PLUS)RETURN
IF(A(K).EQ.MINUS)RETURN
IF(A(K).EQ.BLANK)RETURN
RETURN
END
SUBROUTINE CSORT1(AL,IB)
C     H.F.9KRENT  U-C*L+A+
INTEGER FLAG
C   COMMON/FLAG/FLAG  1967
C   COMMON/FLAG/FLAG
RETURN
END
SUBROUTINE MESSAGE(AI)
C     H,F.9KRENT  U=C*L+*
WRITE(6,200)I,A
RETURN
FND
SUBROUTINE NUMBER(N1,N2)
C     H.F.9KRENT  U=C*L+A+
C   COMMON/A/A(80)
C   COMMON/DATA/A4D(4),E,E4D(11),PNT,BLANK,PLUS,_MINUS,RIGHT,EQU
C   REAL MINUS
C   COMMON/FLAG/FLAG
C   COMMON/PATH/PATH(300),VPATH(300),S(0),NPATH
C   COMMON/PATH/PATH(300),VPATH(300),S(0),NPATH
RETURN
FND
END
4 IF(VPATH(E) LT I.E-30) VPATH(NE) = .0
IF(TAG.EQ.0) VPATH(E) = VPATH(NE)
WRITE(6,200) K, VPATH(K)
FORMAT(10X, '**** VALUE CANNOT BE COMPLETELY DETERMINED
DUE TO AN ERROR IN CHARACTER, 13/10x, **** VALUE ASSUMED TO
BE E16+8')
RETURN
C CHECK FOR OR SIGNS
IF(A(I).EQ.MINUS) TAG = -
IF((A(I).EQ.MINUS) .AND. (A(I+1).NE.PLUS)) J = J+1
CALL CSCAN(B, I, J)
IF(J.GT.N2) J = N2
IF(J.LT.I) GO TO 2
DO 7 : I = J+1
VPATH(E) = VPATH(E) + (SORT(A(K))*(10**(I-K)))
IF(FLAG.EQ.1) GO TO 4
7 CONTINUE
C CHECK FOR THE END OF THE NUMBER FIELD
IF(J.GT.N2) GO TO 5
C HANDLE NUMBERS LESS THAN 1.0
IF(FNE.PNT) GO TO 6
I = J+1
CALL CSCAN(B, I, J)
IF(J.GT.N2) J = N2
IF(J.LT.I) GO TO 7
DO 8: I = J+1
VPATH(E) = VPATH(E) + (SORT(A(K))*(10**(I-K))))
IF(FLAG.EQ.1) GO TO 4
8 CONTINUE
C HANDLE NUMBERS GREATER THAN 1.0
DO 9: I = J+1
VPATH(E) = VPATH(E) + (SORT(A(K))*(10**(I-K))))
IF(FLAG.EQ.1) GO TO 4
9 CONTINUE
C CHECK FOR THE END OF THE NUMBER FIELD
IF(J.GT.N2) GO TO 5
C HANDLE NUMBERS LESS THAN 1.0
IF(FNE.PNT) GO TO 6
I = J+1
CALL CSCAN(B, I, J)
IF(J.GT.N2) J = N2
IF(J.LT.I) GO TO 7
DO 8: I = J+1
VPATH(E) = VPATH(E) + (SORT(A(K))*(10**(I-K))))
IF(FLAG.EQ.1) GO TO 4
8 CONTINUE
C EVALUATE THE EXPONENT
EXP = 0
IF(A(I).EQ.MINUS) EXP = 1
IF((A(J+1).EQ.PLUS) .AND. (A(J+1).EQ.MINUS)) J = J-1
I = J+2
CALL BSCAN(B, I, K)
IF(K.GT.2) K = N2
IF(K.LE.10) GO TO 7
WRITE(6,200)
20 FORMAT(10X, '**** EXPONENTS WITH MORE THAN 2 DIGITS ARE NOT ALLOWED')
1. THE LAST 2 WILL BE USED.!
IF(K.GT.2) K = N2
IF(K.LE.10) GO TO 7
WRITE(6,200)
20 FORMAT(10X, '**** EXPONENTS WITH MORE THAN 2 DIGITS ARE NOT ALLOWED')
1. THE LAST 2 WILL BE USED.!
IF(K.GT.2) K = N2
IF(K.LE.10) GO TO 7
WRITE(6,200)
SUBROUTINE SHIFT(A)  
C  
FUNCTION SORT(A)  U+C.L+A*  1967  
C  
SUBROUTINE ASAP  
C  
INTEGER TYPE, GENER  
INTEGER FLAG, ERR, A, I, J, TARGET  
COMMON/YDATA/A(300), S(300), T(300), FREG  
COMMON/PATH/LPATH(300, 2), VPATH(300), S(300), FREG  
COMMON/CLF/CARD(50, 12), TYPE(50), GENER(50), IGIN(50), TARGET(50)  
COMMON/CLT/CARD(50, 12), TYPE(50), GENER(50), IGIN(50), TARGET(50)  
COMMON/YDATA/A(300), S(300), T(300), FREG  
COMMON/PATH/LPATH(300, 2), VPATH(300), S(300), FREG  
COMMON/SORT/SORT(A)  U+C.L+A*  1969  
C  
CALL ASCAN(3, 1)  
IF(I*CT+10)GT 10  
I=I+2  
IF(I*CT+10)LE 6  
STOP  
A-8
1 IF(A(I))EQ.5)GO TO 17
IF(A(I))EQ.3)GO TO 17
NE=NE+1
I=I+1
L=I+K=1
CARO(NE,K)=A(L)
IF(L.GT.J(1)AND(CARO(NE,K).LT.BLANK)
CONTINUE
I=J+2
4 CALL ASCAN(P,J,J)
IF(J-NE-1)G0 TO 5
I=J+2
IF(I.GT.72)GO TO 6
5 TARGET(J 1)TARGET(NE)=TARGET(NE)+ISORT(A(J))
IF(FLAG.EQ.1)G0 TO 6
IF(J.GT.71)TARGET(NE)=TARGET(NE)+ISORT(A(J))
I=J+3
6 CALL ASCAN(B,J,J)
IF(J-NE-1-1)G0 TO 7
I=J+2
IF(I.GT.72)GO TO 6
7 TARGET(NE)=TARGET(NE)+ISORT(A(J))
IF(FLAG.EQ.1)G0 TO 6
IF(J.GT.71)TARGET(NE)=TARGET(NE)+ISORT(A(J))
I=J+4
8 CALL BSCAN(B,J,J)
IF(J-NE-1)G0 TO 9
I=J+2
9 G0 TO 10
10 CALL NUMBER(I,J)
IF(I.GT.72)G0 TO 11
11 I=J+3
12 IF(I.GT.72)
13 CALL ASCAN(B,J,J)
14 IF(I.GT.72)G0 TO 15
15 I=J+4
16 CALL BSCAN(B,J,J)
17 I=J+5
18 IF(I.GT.72)
19 GO TO 20
20 IF(I.GT.72)G0 TO 11
GO TO 10
L=I+J
DEP(E1)=A(L)
IF(L.GT.K)DEP(NE1)=BLANK
15 CONTINUE
GENE(NE1)=0
TYPE(NE1)=0
IF(.NOT.ARD(NE1).OR.(CARD(NE1).GT.AI))GENE(NE1)=1
IF(CARD(NE1).GT.AI)TYPE(NE1)=1
MINDE=MIN(INDCF,ARGET(NE1),ORIGIN(NE1))
GO TO 10
17 DB32I=INDE,NNDF
18 CONTINUE
32 N(I),0
DB19I=1*,NE
J=ORIGIN(I)
N(J)=N(J)+1
J=TARGET(I)
19 N(J)=N(J)+1
J=0
DB52I=INDE,NNDF
20 J=TARGET(I)
28 DB21I=INDE,NNDF
21 CONTINUE
22 N(I),0
J=0
DB23J=1*,NE
IF (GENER(J)*TYPE(J).EQ.O)GO TO 22
K=ORIGIN(J)
L=TARGET(J)
IF(N(K).GT.0)GO TO 36
IF(N(L).GT.AI)M=1
N(L)=ABS(N(L))
36 IF(N(K).GT.0)GO TO 26
IF(N(K).GT.0)M=1
N(K)=ABS(N(K))
23 CONTINUE
24 IF(N(E1).GT.0)GO TO 22
DB26J=I*,NE
IF(GENER(J)*TYPE(J).EQ.O)GO TO 26
K=ORIGIN(J)
L=TARGET(J)
IF(K.NE.I)GO TO 27
IF(N(L).LE.0)GO TO 27
N(L)=ABS(N(L))
27 IF(N(L).LE.0)GO TO 26
IF(N(K).LE.0)GO TO 26
N(K)=N(K)
28 N=0
DB32J=1*,NE
IF(TYPE(J)=1)GO TO 31
A-10
A-11
SUBROUTINE WORST

CALL ASCAN(B,I,J)
IF (B.EQ.0) GO TO 3
WRITE(*,102)
102 FORMAT (/10X,'**** EQUAIS SIGN NOT FOUND--REQUEST IGNORED.')
GO TO 2
C FIND CIRCUIT ELEMENT
3 J=J+2
L=K+11
K=I-1,NE
D5=5
I=L+K,L
I2=I1-J-1
IF (A(J).NE.CARD(I,I2)) GO TO 4
C 5 CONTINUE
C CHECK FOR INVALID ELEMENT (INDEPENDENT SOURCE)
IF (GENE(I).EQ.0) GO TO 9
IF (DEP(I).NE.0) GO TO 9
WRITE(*,105)
105 FORMAT (/10X,'**** INVALID ELEMENT TYPE--REQUEST IGNORED.')
GO TO 2
C CHECK FOR TOOH MANY REQUESTS
9 NE1=NE1+1
IF (NE1.LE.LIMIT) GO TO 10
WRITE(*,106)
106 FORMAT (/10X,'**** TOO MANY SENSITIVITY REQUESTS--REQUEST IGNORED.')
GO TO 2
C CHECK FOR DUPLICATE REQUESTS
10 IF (SENS(I).EQ.0) GO TO 11
WRITE(*,104)
104 FORMAT (/10X,'**** DUPLICATE REQUEST--REQUEST IGNORED.')
GO TO 2
C INSERT SENSITIVITY TAGS
11 NSEN=NSFN+1
SENS(I)=TAG(NSN)
GO TO 2
C ELEMENT NOT FOUND IN CIRCUIT
4 CONTINUE
C S* GRANDI U.C.L.A. 1969
C PROCESSES WORST CASE REQUESTS
C
INTEGER TAG,SENS
DIMENSION SMIN(2),SMAX(2)
COMMON/AA(80)
COMMON/CIRCUIT/CARD(50,12),TYPE(50),GENER(50),ORIGIN(50),
TARGET(50),INPUT,OUTPUT,NE
COMMON/GAC/TAG(20),NSEN,SENS(50)

END

SUBROUTINE WORST
C

COMM/N/RITS/LBITS(3000),DEP(50;13)
COMM/N/MOST/LMO/ST,VM(101,2),TSL(50)
COMM/N/DATA/MGOD(2),RSA/LE,SMOD(6),S,T,S,CMOD,XAN,FMOD,FLAG
COMM/N/PATHS/LPATH(600),VPATH(300)
DATA LIMIT/20/

C
INITIALIZE
NFLAG=0
WRITE(6,100)

100 FORMAT('1j8OAl)
C
INSERT SENSITIVITY TAGS FOR ALL VALID ELEMENTS
1  I=1,NE
IF(GENER(I)=.EQ.0)GO TO 2
IF(DEP(I,1)=.NE.BLK)GO TO 2
GO TO 1
2 NSEN=NSEN+1
IF(NSEN+GT.LIMIT)GO TO 3
SENS(I)=TAG(NSEN)
1 CONTINUE
NWRST=1
GO TO 11
C
TOO MANY ELEMENTS
3 NSEN=NSEN-1
WRITE(6,101)
101 FORMAT(10X,'**** TOO MANY ELEMENTS FOR A WORST CASE ANALYSIS--REQUEST IGNORED')
NFLAG=1
GO TO 10
C
SET ALL TOLERANCES TO .1 DEFAULT
4 TOL(I)=.1
10 READ(S,103)
103 FORMAT(80A1)
104 FORMAT(80A1)
CALL SHT7T(A)
IF CARD NOT TOLERANCE, RETURN
IF((A(1),NE.T),OR,(A(2),NE.E),OR,(A(3),NE.AL))GO TO 12
WRITE(6,113)
113 FORMAT(1,102)
IF(NFLAG.EQ.1)GO TO 10
C
CHECK FOR EQUALS SIGN
CALL ASCAN(B,J)
IF(B.EQ.'EQ')GO TO 7
C
BAD CARD
7 WRITE(6,102)
102 FORMAT(10X,'**** ERROR IN TOLERANCE CARD--REQUEST IGNORED')
GO TO 10
5 K=J+2
C
اءEATAIN CIRCUIT ELEMENT
CALL ASCAN(B,K,J)
IF(J.EQ.K=1)GO TO 7
IF(B.EQ.'EQ')GO TO 7
6 L=J+1
A-13
IF(L.GT.t?)L=2
   NE=NE+1
   M=J+2
   CALL ASCAL(B,Y,M)
   CALL NUMBER(M,4)
   TOL(I)=VPA(T(NE))
   NE=NE+1
   GO TO 8
C CONTINUE
C WRITE TOLERANCE TABLE
   IF(FLAG.GE.1)RETURN
   WRITE((6,120)
   120 FORMAT(//' ELEMENT NAME',10X,'TOLERANCE'/)
   DO 13 I=1,NE
      \IF(SENS(I).EQ.0)GO TO 13
      WRITE(A,21)(CAD(TJ),J=1,12),TOL(I)
   121 FORMAT(1X,12A1,1X,F7.4)
   13 CONTINUE
   RETURN
END

SUBROUTINE READ
C
C H-F.OKPENT
C ANALYSIS FREE FIELD CIRCUIT DESCRIPTION CARDS
C
COMMON/TREE/TREE
INTEGER TPEE
COMMON TYPE, GENER
COMMON ORIGIN, TARGET
COMMON TAG, OUTPUT
COMMON DATA/CAIRALE/JS/TS/PA/PM/PT/BA,COMMA
COMMON/A/A(80)
COMMON/TAG/TAG
COMMON ERR/ERR
COMMON Y/X/AC(10)
COMMON FLAG/FLAG
COMMON BITS/LABP(300), DEP(50,13), NNODES, INODE
COMMON/CIRCUIT/CARD(50,12), TYPE(50), GENER(50), ORIGIN(50), TARGET(5)
COMMON/PATHS/LPATH(300,2), VPA(TH(300), S(300), FREG
NE=0
MR=0
ERR=0
INPUT=0
OUTPLT=0

A-14
TA3 = 0
48 IF (TREE.EQ.0) GO TO 2
C EXTRACT CIRCUIT FREQUENCY
49 CALL ASCAN(B,I,I)
50 IF (B.EQ.5) GO TO 2
51 IF (I.EQ.5) GO TO 49
CALL "SYS.LEFT(I+1)
52 CALL ASCAN(I,1,I)
224 FOR AT(10X)***** FREQUENCY ASSUMED TO BE 1.E16*8)
30 T 2
49 I = I+1
CALL ASCAN(B)***J
51 IF (B.EQ.15)***A**(B-NE+MINUS) GO TO 52
CALL ASCAN(S,J)***J
50 T(J) = 1
51 IF (B.EQ.2) CALL HSS(RIGHT,J+1)
**E = 1
CALL NUMBER(I,J)
FREQ = PATH(**E)
2 **E = 3
C BEGIN CIRCUIT DATA ANALYSIS
11 READ (5,100)A
100 WRITE (6,200)A
200 FOR AT(SOA1)
218 WRITE (**E,218)
44 IF ((/1).NE.0.1) GO TO 44
WRITE (**E,218)
217 FOR AT(10X)***** PLOT CARD IGNORED!!!
30 T 11
50 IF (M.F.LE.40) GO TO 53
WRITE (**E,221)
221 FOR AT(10X)***** MORE THAN 50 ELEMENTS NOT ALLOWED, ONLY THE FIRST
10 WILL BE USED!!!
23 DEP (E+1,1) = BLANK
33 TYPE (A +1) = 0
44 IF (E.EQ.1) GO TO 45
DEP (E+1,1) = BLANK
45 IF (A.EQ.1)***A**(A(1).EQ.AJ))GO TO 4
48 IF (((1).EQ.E) OR (A(1).EQ.AJ)) GO TO 4
49 IF (A.EQ.1.EQ.1) OR (A(1).EQ.AJ)) GO TO 4
C END FIRST LETTER FOR ELEMENT TYPE
48 IF (A(1).EQ.1) OR (A(1).EQ.AJ)) GO TO 4
49 IF (A(1).EQ.1.EQ.1) OR (A(1).EQ.AJ)) GO TO 4
C
IF(A(1).EQ.P) GO TO 53
WRITE(6,220)
220 FORMAT(10X,'****** ELEMENT TYPE (FIRST CHARACTER) CANNOT BE IDENTIFIED.'
1RD. DEFAULT VALUE IS R.')
A(1)=R
GO TO 5
UCLA7920
6 WRITE(6,203)
203 FORMAT(10X,'****** ELEMENT TYPE CANNOT BE IDENTIFIED. END OF DATA.')
1! CARD ASSUMED TO BE MISSING.'/14X,'ABOVE CARD BECOMES FIRST OUTPUT.
TAG=1
RETURN
UCLA7990
204 WPITE(6,204)
204 FORMAT(1CXI**** ELEMENT TYPE CANNOT BE IDENTIFIED AS BRANCH BR.
A(2)=AJ
GO TO 7
UCLA8040
7 CALL ASCAN(B,1,J)
IF(I.GT.12)WRITE(6,205)(A(N),N=11)
WRITE(6,206)
206 FORMAT(10X,'****** ELEMENT HAS ILLEGAL DEPENDENCY. ASSUMED TO BE SEL.')
1F DEPENDENT*)
DEP(NE+1,1)=PNT
C INSERT NAME IN LIST AND PAD WITH BLANKS
10 IF(I.GT.12)I=12
UCLA8300
9 DEP(NE+1,1)=LEFT
IF(B.EQ.SLASH)GO TO 10
IF(B.EQ.LEFT)GO TO 12
CALL MSG(SLASH+I+1)
GO TO 11
UCLA8340
12 WRITE(6,206)
206 FORMAT(10X,'****** ELEMENT HAS ILLEGAL DEPENDENCY. ASSUMED TO BE SEL.')
1F DEPENDENT*)
DEP(NE+1,1)=PNT
C INSERT NAME IN LIST AND PAD WITH BLANKS
10 IF(I.GT.12)I=12
UCLA8390
9 DEP(NE+1,1)=LEFT
IF(B.EQ.SLASH)GO TO 10
IF(B.EQ.LEFT)GO TO 12
CALL MSG(SLASH+I+1)
GO TO 11
UCLA8340
12 WRITE(6,206)
206 FORMAT(10X,'****** ELEMENT HAS ILLEGAL DEPENDENCY. ASSUMED TO BE SEL.')
1F DEPENDENT*)
DEP(NE+1,1)=PNT
C INSERT NAME IN LIST AND PAD WITH BLANKS
14 IF(NE.EQ.0)GO TO 16
15 DB17=I-NE
16 DB18=J+1
17 IF(CARD(J,K).NE.CARD(NE+1,K))GO TO 17
18 CONTINUE
19 IF(NE.GT.10)EPR=1
20 DB19=3+11
21 IF(NE.EQ.12)GOTO 219
22 WRITE(6,PO7)(CARD(N,E+1,K),K=1,12)IF(NR.GT.A)
23 1NE 7,12A1/IOX,**** WARNING-RESULTS ARE UNRELIABLE.
24 Go TO 16
25 CONTINUE
26 IF(A11+NE.D)GO TO 20
27 IF(DEP(NE+1,1).EQ.PNT)GO TO 20
28 INSERT DEPENDENCY NAME
29 CALL ASCAN(B,X,C)
30 IF(J-.EQ.LEFT)GO TO 31
31 CALL MSG(LEFT,J+1)
32 IF(A11.EQ.A1)GO TO 15
33 IF(A11.EQ.AJ)DEP(A11,1)=AI
34 WRITE(6,RI9)DEP(NE+1,A1)
35 FORMAT(IOX,'**** DEPENDENCY TYPE (FIRST LETTER OF DEPENDENCY NAME, A1)
36 1 IS ILLEGAL-PROGRAM ASSIGNS ','AI)
37 M=2
38 IF(J+M.GT.13)J=13+1-M
39 DB2X=J+1
40 IF(LEFT.J+1)GO TO 31
41 IF(J+.LT.M)A(K)
42 I=J
43 IF(J1=I+2)
44 CALL ASCAN(B,J+1)
45 IF(J+LT+1)J=I
46 ETRACT ORIGIN NODE
47 IF(J=LF+1)GO TO 26
48 WRITE(6,208)
49 FORMAT(10X,**** MORE THAN 99 NODES NOT ALLOWED-CARD IGNORED)
50 66 TO 11
51 ORIGIN(NE+1)=ISORT(A(J))
52 IF(FLAG.EQ.1)GOTO 29
53 IF(J+NE.EQ.AJ)ORIGIN(NE+1)=ORIGIN(NE+1)+10*ISORT(A(J))
54 IF(FLAG.EQ.0)66 TO 28
55 WRITE(6,209)
56 FORMAT(10X,**** ILLEGAL CHARACTER IN ORIGIN NUMBER- CARD IGNORED)
57 1) GO TO 11
58 IF(ORIGIN(NE+1).NE.0)GO TO 46

A-17
C TRACT TARGET NODE

25 I=J+2
CALL ASCAN(9,1,J)
IF(J.LT.I+1)J=I
IF(J.EQ.I+2)GO TO 27
TARGET(N+1)=ISORT(A(J))
IF(FLAG.EQ.1)99 TO 30
IF(J+1)TARGET(N+1)=TARGET(N+1)+(10*ISORT(A(I)))
IF(FLAG.EQ.0)GO TO 31
WRITE(6,211)
211 FORMAT(10X,** ILLEGAL CHARACTER IN TARGET NUMBER, CARD IGNORED**)
36 IF((B .NE. BLANK) .AND. (B .NE. AI) .AND. (B .NE. E)) GO TO 32
K = 6
CALL UNIT'S(MH')
38 T0 33
32 IF(B.NE.H) GO TO 37
IF(E.F.G) G6 T0 38
K = 12
CALL UNIT'S(MMMF')
37 IF(B .NE. AI) GO TO 33
V = A(J) + 1
IF(B .NE. K) GO TO 33
V = A(J) + 1
CALL UNIT'S(IM')
33 VPATH(NE) = VPATH(NE) * (10. * K)
GR T9 11
END
SUBROUTINE UNIT'S(A)
16 F. SKRENT 1967
WRITE(6,A0O) A
200 FORMAT(1X,1SSSS UNITS ARE f, A))
RETURN
END
SUBROUTINE WHAT
16 F. SKRENT 1967
COMMON/UNIT'S/ A
18 COMMON/OUTPUT REQUESTS/ 1967
16 COMMON/TAG, ERR/ 1967
16 COMMON/TAKE, ERR/ 1967
16 COMMON/ERR/ 1967
16 COMMON/LPATH(J), SAVE(J)
18 COMMON/VPATH(I), VN(B2), NE
16 REAL LFFT
16 COMMON/DATA, AV, AL, BLANK
16 COMMON/NTIME, DTIMES
16 COMMON/BITS, LRITS(3000), LPATH(300, 2), VPATH(300), S(300), NPATH
16 COMMON/DIM, TYPE(50)
16 DIMENSION ISAVE(1201), ISAVE(1201)
18 EQUIVALENCE (LPATH(J), SAVE(J))
16 DIMENSION ISAVE(1201), ISAVE(1201)
16 DIMENSION ISAVE(1201), ISAVE(1201)
16 DIMENSION ISAVE(1201), ISAVE(1201)
16 DIMENSION ISAVE(1201), ISAVE(1201)
16 DIMENSION ISAVE(1201), ISAVE(1201)
16 DIMENSION ISAVE(1201), ISAVE(1201)
18 SET START 1,6 PINTER
18 SET START 1, 6 PINTER
I = 2
J = 1
IF((B .EQ. R) .OR. (B .EQ. C) .OR. (B .EQ. AT) .OR. (B .EQ. E) .OR. (B .EQ. A) .OR. (B .EQ. D)) I = 1
18 FUNCTION FOR THE SLASH
CALL ASCAN(B, I, J)

A-19
IF((B.EQ.SLASH).AND.(J.GE.I))GO TO 1
WRITE(*,20C)
200
IF(J.EQ.11)J=11
C2=X+1
N=F
A=I
M=L/I
IF(A(L).NE.CARD(K,'I'))GO TO 2
4 CONTINUE
GO TO 6
2 CONTINUE
WRITE((201)(A(K)/N,I,J)
201 FORMAT(1Gx,'**** ILLEGAL NAME IN OUTPUT FIELD, CARD IGNORED.*')
GO TO 7
5 IF(I.EQ.2)GO TO 6
6 IF(A(1).EQ.AV)LPATH(NPATH,1)=N
IF(A(1).EQ.AI)LPATH(NPATH,1)=N
GO TO 8
7 I=I+3
A=I(I)
1A=I(I)
CALL ASCAN(B,I,J)
WRITE((204)(B.EQ.BLANK).AND.(J.GE.I))GO TO 9
204 FORMAT(1Gx,'**** ILLEGAL NAME IN INPUT FIELD, CARD IGNORED.*')
GO TO 3
9 IF(J.EQ.11)J=11
N=X+1
A=I
M=L/I
IF(A(L).NE.CARD(K,'I'))GO TO 10
11 CONTINUE
GO TO 12
10 CONTINUE
GO TO 13
12 IF(I.EQ.11)GO TO 14
16 LPATH(NPATH+2)=A+(I*E+TYPE(N))
B=AV

A-20

NOT REPRODUCIBLE
IF (TYPEF(N) .EQ. 0) B = 1
WRITE(6, 205) B
205 FORMAT(10X, '***** INPUT ELEMENT HAS ILLEGAL DEPENDENCY TYPE, PROGRAM')
IM ASSIGN 1, A1, A, A1)
GO TO 15
14 IF (A(I-1) .EQ. AV) LPATH(NPATH, 2) = N + NE
IF (A(I-1) .EQ. A1) LPATH(NPATH, 2) = N
IF (LPATH(NPATH, 2) .EQ. 0) GO TO 16
RETURN
END
SUBROUTINE PLPT
C H.F. OKRENT U.C.L.A.
INTEGER INDEX, ERR-
REAL TMINUS
DIMENSION SMIN(2), SMAX(2)
COMMON/CIRCUIT/CARD(50, 12), VN(101, 2), NSMAX, SMIN
COMMON/PATH/PATH(600), VPATH(300), S(300), NPATH
COMMON/PLVS/NSEN(101, 20), VNOS(20), SMAX(20), SMIN(20)
COMMON/BITS/F1(4, 96)
COMMON/CIR/CARD(50), VXFR, AI(50), NXT1, AMBD(8)
COMMON/ITS/F1(4, 96)
COMMON/NPNT/NUMTINF(11), NR(1), NUMMTAY, ISN, SCYAG, SCFREG, SIGMA
COMMON/PS/PNUM, NINF(11), NR(1), NUMMTAY, ISN, SCYAG, SCFREG, SIGMA,
COMMON/IN/IBLAJKPLSYUSRIGHTEQUAMHAKCOMMAtYAAX, JABW
COMMON/POLY/VNSEN(101, 2), VNOS(20), SMAX(20), SMIN(20)
COMMON/ERR/ERR
F tuition (AMBD(I), BMOD(I))
I = 0
DO = 0
NE = NE
NE = PATH
DBL = 1, 8
1 BMOD(I) = 1
IF (NE .EQ. LEFT) CALL ASCAN(B, I)
4 IF (NE .EQ. LEFT) CALL ASCAN(B, I + 1)
IF (NE .EQ. LEFT) GO TO 2
IF (B .EQ. BLANK) GO TO 3
CALL ASCAN(B, I + 1)
IF (B .EQ. BLANK) GO TO 3
CALL ASCAN(B, I + 2)
GO TO 4
3 CALL ASCAN(B, I + 2)
IF (NE .EQ. LEFT) CALL ASCAN(B, J + 1)
IF (B .EQ. BLANK) GO TO 2
IF (B .EQ. BLANK) GO TO 12
K = J + 2
IF (NE .EQ. LEFT) GO TO 7
CALL ASCAN(B, K, L)
CALL ASCAN(B, K, L)
K=2
6
GO TO 5
7
IF(A(I+2).NE.T) GO TO 8

8
IF((A(I+2).EQ.A1) .AND. (A(I+3).EQ.).AM) .AND. (A(I+4).EQ.) .AND. (A(I+5).EQ.T) BMOD(3) = 0

9
IF((A(I+2).EQ.E) .AND. (A(I+3).EQ.).AM) .AND. (A(I+4).EQ.) .AND. (A(I+5).EQ.T) BMOD(3) = 1

10
IF((A(I+2).EQ.E) .AND. (A(I+3).EQ.).AM) .AND. (A(I+4).EQ.) .AND. (A(I+5).EQ.T) BMOD(3) = 2

11

12
IF((A(I+2).EQ.E) .AND. (A(I+3).EQ.).AM) .AND. (A(I+4).EQ.) .AND. (A(I+5).EQ.T) BMOD(3) = 4

13

14
IF((A(I+2).EQ.E) .AND. (A(I+3).EQ.).AM) .AND. (A(I+4).EQ.) .AND. (A(I+5).EQ.T) BMOD(3) = 6

15

16
IF((A(I+2).EQ.E) .AND. (A(I+3).EQ.).AM) .AND. (A(I+4).EQ.) .AND. (A(I+5).EQ.T) BMOD(3) = 8

17

18
GO TO 9

19
IF ((A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) GO TO 20

20
CALL NUMBER(J+2,L)

21
IF (A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) AMOD(3) = 0

22
IF (A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) AMOD(3) = 1

23
IF (A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) AMOD(3) = 2

24
IF (A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) AMOD(3) = 3

25
IF (A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) AMOD(3) = 4

26
IF (A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) AMOD(3) = 5

27
IF (A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) AMOD(3) = 6

28
IF (A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) AMOD(3) = 7

29
IF (A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) AMOD(3) = 8

30
IF (A(I).EQ.E) .AND. (A(I+1).EQ.E) .AND. (A(I+2).EQ.E) .AND. (A(I+3).EQ.E)) AMOD(3) = 9

31
GO TO 15
A-23
END

SUBROUTINE FINE
C
DAVID PALETZ  U.C.L.A.  1967
INTEGER ORIGIN, TARGET, ORIGINOTARGT, DUM, GENER
INTEGER TAGERR, GENER
INTEGER BLANK
COMMON ERR/ERR
COMMON CIRCUIT/CARD(50,12), TAG(50), GENER(50), ORIGIN(50), TARGET(50)
COMMON PATHS/CARD(50,12), VPATH(300), Z(100), BZ(100), ORIGIN(50),
TARGET(50), W
COMMON BITS/LB(3000), DPL(50,13), NNODES, NODELINE(132), INDIC(50)
COMMON PATHS/CARD(50,12), VPATH(300), Z(100), BZ(100), ORIGIN(50),
TARGET(50), W
COMMON DATA/C, AIJ, AL, SLASHLEFT, AV, F, AS, T, A, P, AN, PNT, BLANK
WRITE(6,99) W
99 FORMAT(//2Xs-'='pE12.4)
C CALCULATING THE RESISTANCE, IN OHMS, OF THE ELEMENTS.
C 9.9*10**30 STAYS FOR INFINITY.
J=1
DO 1 I=1,NE
IF(CARD(I,J).EQ.E) Z(I)=D.
IF(CARD(I,J)'EQ.A) Z(I)=9.9E30
IF(CARD(I,J).EQ.C) Z(I)=1./(VPATH(I)*W)
IF(CARD(I,J).EQ.AJ) Z(I)=VPATH(I)*W
IF(CARD(I,J).EQ.R) Z(I)=VPATH(I)
IF(CARD(I,J).EQ.D) GO TO 2
GO TO 1
1 CONTINUE.
C ARRANGING THE ELEMENTS IN A SEQUENCE OF INCREASING RESISTANCE
DO 4 I=1,NE
IF(Z(I)-Z(J))3P3,4
3 DUMMY=Z(J)
Z(J)=Z(I)
DUM=ORIGIN(J)
TARGET(J)=TARGET(I)
TARGET(I)=DUM
ORIGIN(J)=ORIGIN(I)
GO TO 2
4 CONTINUE
C
A-24
DETERMINING HOW MANY NODES THERE ARE IN THE CIRCUIT.

C DETERMINING THE ELEMENTS THAT FORM TREE, I.E. HAVING TAG 1

C
13 \( L = 3 \)
15 \( I = 2 \)
16 \( J = 1 \)
17 IF (\( \text{ORIGIN}(I) \times \text{INDIC}(J) \)) GO TO 10
18 IF (\( \text{TARGT}(I) \times \text{INDIC}(J) \)) GO TO 11
19 \( J = J + 1 \)
20 \( I = I + 1 \)
21 \( \text{GO TO 16} \)
22 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
23 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
24 \( J = J + 1 \)
25 \( \text{GO TO 16} \)
26 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
27 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
28 \( J = J + 1 \)
29 \( \text{GO TO 16} \)
30 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
31 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
32 \( J = J + 1 \)
33 \( \text{GO TO 16} \)
34 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
35 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
36 \( J = J + 1 \)
37 \( \text{GO TO 16} \)
38 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
39 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
40 \( J = J + 1 \)
41 \( \text{GO TO 16} \)
42 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
43 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
44 \( J = J + 1 \)
45 \( \text{GO TO 16} \)
46 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
47 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
48 \( J = J + 1 \)
49 \( \text{GO TO 16} \)
50 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
51 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
52 \( J = J + 1 \)
53 \( \text{GO TO 16} \)
54 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
55 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
56 \( J = J + 1 \)
57 \( \text{GO TO 16} \)
58 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
59 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
60 \( J = J + 1 \)
61 \( \text{GO TO 16} \)
62 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
63 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
64 \( J = J + 1 \)
65 \( \text{GO TO 16} \)
66 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
67 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
68 \( J = J + 1 \)
69 \( \text{GO TO 16} \)
70 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
71 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
72 \( J = J + 1 \)
73 \( \text{GO TO 16} \)
74 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
75 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
76 \( J = J + 1 \)
77 \( \text{GO TO 16} \)
78 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
79 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
80 \( J = J + 1 \)
81 \( \text{GO TO 16} \)
82 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
83 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
84 \( J = J + 1 \)
85 \( \text{GO TO 16} \)
86 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
87 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
88 \( J = J + 1 \)
89 \( \text{GO TO 16} \)
90 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
91 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
92 \( J = J + 1 \)
93 \( \text{GO TO 16} \)
94 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
95 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
96 \( J = J + 1 \)
97 \( \text{GO TO 16} \)
98 \( \text{IF} (\text{ORIGIN}(I).E.\text{INDIC}(J)) \text{GO TO} 10 \)
99 \( \text{IF} (\text{TARGT}(I).E.\text{INDIC}(J)) \text{GO TO} 11 \)
100 \( J = J + 1 \)
101 \( \text{GO TO 16} \)

\( \text{WRITE}(6,100) \)
102 \text{THE TREE IS FORMED BY THE ELEMENTS THAT HAVE TAU} \)
103 \text{AND THEIR TAGS.} \)
104 \text{WRITE}(6,101)
105 \text{FORMAT('ELEMENT NUMBER',5X,'ELEMENT NAME',5X,'ORIGIN NODE',5X,'TARGET}
106 \text{NODE',9X,'VALUE (OHMS)',13X,'TAG',12X,'GENER'})
107 \text{DB 7 I=1,132}
108 \text{LINE(I)=BLANK}
109 \text{DB 2 I=1,120}
110 \text{LINE(I)=MINUS}
111 \text{WRITE(6,104)}(\text{LINE(I),I=1,120})
112 \text{FORMAT('7X,J2',12X,'INDEX',5X,'TARGET',10X,'TAU')}
113 \text{CONTINUE}
114 \text{RETURN}
115 \text{END}
116 \text{SUBROUTINE SCALER}
117 \text{INTEGER FACTOR}
118 \text{COMMON/ERR/ERRFACTOR}
119 \text{COMMON/CIRC/CID(150,12),BM5D(202),NE}
120 \text{COMMON/NP/NP(400),NP(300),S(300),NPATH}
121 \text{COMMON/DATA/AC,AM5D(2),AL}

\text{A-26}
FACTER=0

8 DO 0,

DL=0.

DF=0.

DF=DF+1.

IF(CARD(IJ,1).NE.AC).AND.(CARD(IJ,1).NE.AL).GO TO 1

IF(VPATH(1)+EQ.0).GO TO 1

A=AL*G0((ADIV(VPATH(I)))

DF=DF+1.

IF(AL*ABS(A+FLOAT(FACTER)).GO TO 1

IF(AL*A3S(A*FLOAT(FACTER)).

DF=DF+1.

IF(DL-FACTER.AND. (CARD(IJ,1).NE.AC).AND.(CARD(IJ,1).NE.AL)).GO TO 1

CONTINUE

IF(DL.LT.D)GO TO 3

IF(DR.LT.D)GO TO 4

IF(FACTER.EQ.0).GO TO 6

DO 1=1,10

IF(CARD(IJ,1).NE.AC).AND.(CARD(IJ,1).NE.AL).GO TO 5

VPATH(I)+VPATH I+10**FACTER

CONTINUE

7 RETURN

6 FORMAT(6,200)

100 FORMAT(10X,'*** THE RANGE OF ELEMENT VALUES IS TOO LARGE TO BE SCLE.'**** ERRONEOUS RESULTS DUE TO OVERFLOW MAY OCCUR.)

3 D=DL

FACTER=FACTER-1

IF(FACTER.LT.INDEX).GO TO 8

END

SUBROUTINE POLSEN

C

S. GRANDI U.C.L.A. 1969

C COMPUTE THE SENSITIVITIES OF THE POLES OF THE TRANSFER FUNCTION

INTEGER SENS,GAG

INTEGER SMAX1,SMAX2,SMAX3,SMAX4,SMAX5,SMAX6,SMAX7,SMAX8,SMAX9,SMAX10

SMAX10

COMPLEX POLE

COMMON/VLY/VN01(V101-20),VN02(V101-20),VN10(V101-20),SMAX10,SMAX1,SMAX2,SMAX3,SMAX4,SMAX5,SMAX6,SMAX7,SMAX8,SMAX9,SMAX10

COMMON/SPEED/POLE(50),NP0LE

COMMON/PCIRCL/CARD(50),NP0LE

COMMON/GAG/GAG(2),NSEN,SENS(50)

DIMENSION SMAX1(2),SMAX2(2)

RETURN IF ROOTS OR SENSITIVITY FCN NOT PREVIOUSLY FOUND

IF(FACTER.NE.0).AND.(SENS.NE.0).GO TO 1

'WRITE(6,100)

100 FORMAT(10X,'*** NO TS AND/OR SENSITIVITY REQUEST NOT PREVIOUSLY

*** REQUEST NOT PREVIOUSLY REQUESTED. ')
RETURN UCL14260

TAKE DERIV. OF DENOMINATOR OF TRANSFER FUNCTION UCL14270

1 I1 = MIN(I) + S1
2 I2 = MAX(I) + S1
3 T = I1, I2
5 VDERIV(I-1) = (I-51) * VN(I, 1)

EVALUATE IT AT THE POLES UCL14300

D0 7 K = 1, 50
8 C(K) = 0.0
9 D0 6 L = 1, NPOLES
10 A(L) = REAL(P(L))
11 B(L) = IMG(P(L))
12 D0 6 K = 1, 52
13 C(K) = VDERIV(K-1) * A(L)**(K-52) + C(L)
14 IF(A(L) EQ 0.0) GO TO 60
15 B(L) = - VDERIV(K-1) * B(L)**(K-52) + C(L)
16 CONTINUE UCL14340

FIND SENSITIVITY FCNS FOR ALL SPECIFIED ELEMENTS UCL14350

D0 2 J = 1, N
12 IF(SENS(J) EQ 0.0) GO TO 2
13 D0 3 J = 1, NSEN
14 IF(SENS(J) EQ 0.0) GO TO 4
15 CONTINUE UCL14370
16 WRITE(6, 101)(CARD(I), K, 12)
17 101 FORMAT(I5, IPE16.4, 3X, 1E16.4, 6X, IPE16.4, 3X, IPE16.4)

EVALUATE NUMERATOR OF ROOT SENSITIVITY FCN AT THE POLES UCL14380

D0 2 L = 1, NPOLES
12 X = 0
13 Y = 0
14 I = SHIN10(J) + S1
15 I2 = SHAX10(J) + S1
16 D0 11 K = 1, 52
17 IF(A(L) EQ 0.0) GO TO 22
18 X = X + VN10(KJ) * A(L)**(K-52)
19 22 IF(B(L) EQ 0.0) GO TO 23
20 Y = Y + VN10(KJ) * B(L)**(K-52)
21 11 CONTINUE UCL14390
22 OTAIN ANSWER (PREVENTING ZERODEVIDE) UCL14400
23 IF(C(L) NE 0.0) GO TO 12
24 P = X/C(L)
25 IF(P EQ 0.0) GO TO 13
26 Q = Y/P
27 WRITE(6, 103)(CARD(I), K, 12)
28 103 FORMAT(I5, IPE16.4, 3X, IPE16.4, 6X, IPE16.4, 3X, IPE16.4)

A-28
CONTINUE
RETURN
END

SUBROUTINE EQUAL(I,J,N,NTIMES)
COMMON/BITS/K(3000)
IF(NTIMES.GT.0)GO TO 2
IF(I.LT.0)I=ABS(I+1)*ABS(NTIMES)
IF(J.LT.0)J=ABS(J+1)*ABS(NTIMES)
IF(I.GT.0)I1=300-+(NTIMES*I)
IF(J.GT.0)J1=3000+(NTIMES*J)
GO TO 3

2 I2=-1
J2=-1
IF(I.LT.0)I2=99
IF(J.LT.0)J2=99
I=NTIMES*(ABS(I)+1)
J=NTIMES*(ABS(J)+1)
M=ABS(NTIMES)
RETURN
END

FUNCTION LRX(I,J)
LOGICAL K1, L1
EQUIVALENCE (K1,K),(L1,L)
LRX=0
K=I
L=J
K1=K1.OR.L1
I=K
RETURN
END

FUNCTION LSTBR(I,J)
LOGICAL K1, L1, M1
EQUIVALENCE (K1,K),(L1,L),(M1,M)
LSTBR=0
K=I
L=J
M=J1.AND.L1
J=M
I=J
RETURN
END

FUNCTION LSTBR(I,J)
LOGICAL K1, L1
EQUIVALENCE (K1,K),(L1,L)
LSTBR=0
I=J
RETURN
SUBROUTINE UNP(I, J, NN)
  COMMON/BITS/L(-L-)
  COMMON/NTIMES/TIMES
  K=1
  IF(I*L+J)*K*99
  I=NTIMES*(IABS(I+1)+K)
  D83M1,NTIMES
  N1=N+M
  IF(L(N1)*NE.0)G0 TO -2
  CONTINUE
  RETURN
  N1=1
  J=O
  RETURN
  N1=1
  IF(N.GT.NN)GO TO 4
  IF(N.LE.30)GO TO 5
  M=M+1
  N=N1-30
  J=I+N1
  K=LOX(L(N1)+J)
  IF(J*EG*O)GO TO 1
  M=M1+1
  G0 TO 6
  J=I+(30*H+1)
  RETURN
END

SUBROUTINE CALC
  C EVALUATES CURRENT EQUATIONS BY BIT MANIPULATION
  INTEGER TARGET,ORIGIN,TYPE,BRANCH
  INTEGER ERR...
  COMMON/CIRCI,TI,ARD(50;12),TYPE(50),GENR(50),ORIGIN(50),TARGET(5
  10),INPUT,OUTPUT,MEN
  COMMON/BITS/LINKS(500,BRANCH(200),NQ(100),N0(100),NBR(100),NS(10
  10),AMEND(1500),DEP(50;13),NUMDES
  WRITE(6,199)
  NTIMES=(NE+1)/30+1
  INITIALIZE
  NQ(INDE)=1
  NS(INDE)=1
  N0=0
  D83O=INDE=NUMDES
  NEL(I)=0
NBR(I)=0
CALL INBIT(1,0,TIMES)
30 CALL INBIT(*1,0,TIMES)
C
FORM EQUATIONS
DO1=1,NE
J=IPRED(I)
K=TARGET(I)
NFL(J)=NEL(J)+1
NEL(K)=VEL(K)+1
IF(TYPE(1)=0 THEN 29
CALL INBIT(J,1,TIMES)
CALL INBIT(K,1,TIMES)
GO TO 1
29 NBR(J)=NBR(J)+1
NBR(K)=NBR(K)+1
GO TO 1
CONTINUE
300 FORMAT(1X,10I10)
C
CHECK TREE LEGALITY AND ENTER BRANCHES
DO1=INBNODES
NS(I+1)=NS(I)+NBR(I)
NQ(I+1)=NQ(I)+1
IF(VEL(I),NEIK)GO TO 3
WRITE(6,202)I
202 FORMAT(1X,'**ERROR** NODE',I3,' IS ISOLATED DUE TO NON-CONSECUTIVE NUMBERING--PROGRAM INEFFICIENCY WILL RESULT."
GO TO 2
3 NN=NN+1
WRITE(6,203)I
203 FORMAT(1X,'**ERROR** NODE',I3,' IS CONNECTED TO ONLY ONE ELEMENT, SOLUTION IS IMPOSSIBLE.*)
IF(NBR(I),NE.0) GO TO 4
WRITE(6,204)I
204 FORMAT(1X,'**ERROR** NO BRANCH HAS BEEN ENTERED, THE TREE IS ILLEGAL, SOLUTION IS IMPOSSIBLE.*)
4 CONTINUE
IF(NR.GT.TIMES) WRITE(6,205)
205 FORMAT(1X,'**ERROR** THE TREE IS OVER-DEFINED (THERE ARE TOO MANY BRANCHES), SOLUTION IS IMPOSSIBLE.*)
IF(NB.LT.NN-1) WRITE(6,206)
206 FORMAT(1X,'**ERROR** THE TREE IS UNDER-DEFINED (THERE ARE TOO FEW BRANCHES), SOLUTION IS IMPOSSIBLE.*)
5 IF(ERR.EQ.1) RETURN
DO1=1,NE
IF(TYPE(I),EQ.0.0) THEN 7
J=IPRED(I)
K=TARGET(I)
L=NS(J)
A-31
BRANCH(L) = -1
L = NS(K)
BRANCH(L) = 1
NS(J) = NS(J) + 1
NS(K) = NS(K) + 1
CONTINUE
JNODE = INODE + 1
25 K = 0
J = 0
C SEARCH FOR THE FIRST CUT-SET AND EQUATION
D22I = JNODE*NODE
IF((K.EQ.0).AND.(NSR(I).GT.1)) K = I
IF((K.NE.0).AND.(J.NE.0)) GO TO 24
CONTINUE
C IF NONE IS FOUND, SOLUTION IS COMPLETE
IF(J.EQ.0) GO TO 23
ERR = 1
WRITE(6,207)
207 FORMAT(10X, '**** SOLUTION IS IMPOSSIBLE DUE TO A LOOP CONCERNING THE FOLLOWING NODES = ') RETURN
24 N3 = NO(J)
D026I = K*NODES
IF(NBR(I).LE.1) GO TO 26
L = NSR(I)
NS = NO(I) + L - 1
D038I = N - 1
N4 = N(I) + M - 1
IF((ABS(BRANCH(N3)).NE. ABS(BRANCH(N4)))) GO TO 8
N1 = 1
N2 = 1
IF((BRANCH(N3)*BRANCH(N4)).LE.0) GO TO 13
N1 = 1
N2 = 1
13 CALL EQUAL(I, J + N1, LOR, NTIMES)
CALL EQUAL(-I, J + N2, LOR, NTIMES)
CALL EQUAL(I, J, LOR, NTIMES)
BRANCH(N4) = BRANCH(N5)
NSR(I) = NSR(I) + 1
GO TO 26
8 CONTINUE
26 CONTINUE
NSR(J) = 0
GO TO 25
23 D0101 = JNODE*NODES
IF(N(I).EQ.NO(I + 1)) GO TO 10
J = NO(I)
K = NTIMES*(I + 1)
N = NTIMES*(I + 99)
CONTINUE
SUBROUTINE INBIT(I,N,NTIMES)
   COMMON/BITS/K(3000)
   N=I
   L=J
   IF(I.LT.0) N=99
   M=NTIMES*(ABS(I)+1)+1
   IF(NTIMES.LT.0) M=1001*(ABS(NTIMES)+1)
   IF(J.EQ.0) GO TO 3
   L=L-30
   M=M+1
   GO TO 2
1 K(M)=K(M)+(2**L)
   RETURN
2 N=ABS(NTIMES)
   DO I,N
      5 K(M+N)=0
   GO TO 5
   END

RETURN
   NPATH=0
   DO 10 I=1,NE
      TYP(I)=TYPE(I)
      S(I)=S(I)+1
   GO TO 10
C 10 PRINT PATHS DUE TO IMPEDANCES
   NPATH=1
   LPATH(NPATH)=1
   IF(TYP(I).EQ.1) G0 TO 12
   NPATH=NPATH+1
   IF(DP(I).EQ.1) G0 TO 12
   NPATH=NPATH+1
   NPATH=NPATH+1
   IF(TYP(I).EQ.1) G0 TO 12
LPATH(NPATH+1) = I+NE
LPATH(NPATH+2) = I

12 IF (CARD(I,1) .NE. R) GO TO 13
IF (TYPE(I) .EQ. 1) GO TO 10
GO TO 14

13 S(NPATH) = 1
IF (CARD(I,1) .NE. AL) GO TO 15
IF (TYPE(I) .EQ. 1) GO TO 10
GO TO 16

15 IF (TYPE(I) .EQ. 0) GO TO 10
GO TO 17

16 S(NPATH) = -S(NPATH)
GO TO 10

14 VPATH(NPATH) = VPATH(NPATH)
GO TO 10

C INSERT PATHS DUE TO DEPENDENT ELEMENTS

11 IF (DEP(J,1) .EQ. PNT) GO TO 10
D817J = 1, NE
L = J
D818K = 1, 12
IF (CARD(J, K) .NE. DEP(I, K+1)) GO TO 17
CONTINUE
GO TO 19

17 CONTINUE
WRITE(6, 200)(CARD(J, I), J = 1, 2)
200 FORMAT(10X, '*** REL DEP ENDS***: DEPENDEUC1)
INCY IS IGNORED. ...
GO TO 10

19 NPATH = NPATH + 1
LPATH(NPATH+1) = L
LPATH(NPATH+2) = I
IF (TYPE(I) .EQ. 1) LPATH(NPATH, 1) = I+NE
IF (TYPE(I) .EQ. 1) LPATH(NPATH, 2) = I+NE
GO TO 10

10 IF (SENS(I) .EQ. 0) GO TO 100
S(NPATH) = S(NPATH) + SENS(I)
CONTINUE

C INSERT CURRENT AND VOLTAGE RELATIONSHIPS

JNODE = INBDE + 1
D8111 = T JNODE, NNODES
M = 0
N = 1
X = 1.
IF (ADDR(I) .EQ. ADDR(I+1)) GO TO 1
L = ADDR(I)
IF (BRANCH(L) .LT. 0) GO TO 1
K = IABS(BRANCH(L))
M = M + 1
GO TO 1

6 M = M + 1
IF (M .GE. 3) GO TO 1
CALL UNPAK (I*NJNE)

3 NPATH = NPATH + 2
LPATH(NPATH, 1) = K
LPATH(NPATH, 1) = K+NE
LPATH(NPATH, 1) = J
VAPATH(NPATH) = X

A-34
LPATH(NPATH,2)=J4NR
VPATH(NPATH)=X
IF (GENER(X) .EQ. GENER(J)) VPATH(NPATH)=X
S(NPATH-1)=0
S(NPATH)=0
GA TO 4
X=-1
*  TO 6
CONTINUE
RETURN
END

SUBROUTINE LOOPs

C H.F. KREKT \* J+C+L+A+ 1967
C OBTAINS THE SUM OF EACH ORDER OF LOOPS

EXTERNAL L9RLSTOR
C\*MN/NAG/GAG/GAG(2n),VSE/VSENS(Sn)
CALL POLY/VM01(120),VM10(120),SMAX1(20),
-SMIN1(20),SMAX0(20),SMIN0(20),SMAX0(20),
-SMIN0(20),SMAX1(20),SMIN1(20),SMAX0(20),SMIN0(20)
CALL NAG/SENSE(VNO1(20),VNO0(20),VN10(20),VNO(20),
-V00(20),V01(20),V0(20),V(20),VN(20),VN1(20),VN0(20)
CALL NAG/NODES/VA(20),LPATH(NPATH,2),VPATH(NPATH,2)

C DIMENSION S(2),SMAX(2)
C DIMENSION VM01(2020),VM10(2020)
C EQUIVALENCE (VM01(1),VM01(1))
C EQUIVALENCE (VM10(1),VM10(1))
C EQUIVALENCE (LM01(1),LM10(1),LM01(1))
C EQUIVALENCE (ORDER(1),COUNT(1))

500 WRITE(6,300)LPATH(NPATH,1),LPATH(NPATH,2)
300 FORMAT(I6)
C THE UNKNOWN TRANSMITTANCE GOES FROM NODE1,13 TO 1,13

I INITIALISE
N=2*NE
M01=1,Nn
M0D(1)=0
COUNT(1)=0
M01=1,202
VM(1)=0
V=99 I=1,20
VM0(I)=0
VM0(I)=0
VM0(I)=0
99 I=1,20
SMAX(1)=0
SMAX(1)=0
SMAX(1)=0

A-35
FIND HOW MANY TRANSMITTANCES LEAVE NODE J

DO 11, I = 1, 2
  M1 = 0
  M2 = 0
  NL0P = 0
  DO 9 J = 1, 20
    VM0O(5, J) = -1.
    VM(5, J) = 1.
    SMAX(1) = 0
    SMAX(2) = 0
    SMIN(1) = 0
    SMIN(2) = 0
  9 CONTINUE
  CALL ECUAL(J, 1, 2, 1, NTIMES)
  VPATH(J) = VPATH(1) * VPATH(J)
  S(J) = S(I) + S(J)
  LPAT(J, 2) = LPAT(1, 2)
  CONTINUE

C STORE ANY LOOPS THAT MAY HAVE BEEN FORMED

DO 6 J = 1, 20
  IF(LPATH(J, 2) .NE. LPATH(J, 1)) GO TO 6
  NL0P = NL0P + 1
  CALL ECUAL(J, 1, 2, 1, NTIMES)
  V(NL0P) = VPATH(J)
  LS(NL0P) = S(J)
  JJ = NTIMES * NL0P - 1
  WRITE (*, 999)(LS(NL0P - JJ + II), II = INTINES), LS(NL0P)
  999 FORMAT (1X, 2120/I4, 20)

  CONTINUE

  DO 11, NPATH
    J = LPATH(1, 1)
    K = LPATH(1, 2)
    IF(J .EQ. 0) GO TO 13
    A = 36

A-36
IF(NODE(J).EQ.0) LPATH(I,1)=0
IF(K.EQ.0) GO TO 11
IF(COUNT(K).EQ.0) LPATH(I,1)=0
CONTINUE
CALL CLEAR
IF(NPATH.EQ.0) GO TO 27
CONTINUE
CALL CLEAR
19 I=1
ORDER(I)=1
ORDER(I+1)=ORDER(I)
IF(I.GE.NPATH) GO TO 27
ORDER(I+1)=ORDER(I)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I+1
GO TO 9
8 I=I+1
IF(NPATH.EQ.0) GO TO 27
ORDER(I)=ORDER(I+1)
ORDER(I+1)=ORDER(I)
IF(I.EQ.0) GO TO 7
ORDER(I+1)=ORDER(I+1)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I-1
GO TO 9
7 IF(NPATH.EQ.0) GO TO 27
ORDER(I)=ORDER(I+1)
ORDER(I+1)=ORDER(I)
IF(I.GE.NPATH) GO TO 27
ORDER(I+1)=ORDER(I)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I+1
GO TO 9
CONTINUE
CALL CLEAR
IF(NPATH.EQ.0) GO TO 27
ORDER(I)=ORDER(I+1)
ORDER(I+1)=ORDER(I)
IF(I.EQ.0) GO TO 7
ORDER(I+1)=ORDER(I+1)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I-1
GO TO 9
7 IF(NPATH.EQ.0) GO TO 27
ORDER(I)=ORDER(I+1)
ORDER(I+1)=ORDER(I)
IF(I.GE.NPATH) GO TO 27
ORDER(I+1)=ORDER(I)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I+1
GO TO 9
CONTINUE
CALL CLEAR
IF(NPATH.EQ.0) GO TO 27
ORDER(I)=ORDER(I+1)
ORDER(I+1)=ORDER(I)
IF(I.EQ.0) GO TO 7
ORDER(I+1)=ORDER(I+1)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I-1
GO TO 9
7 IF(NPATH.EQ.0) GO TO 27
ORDER(I)=ORDER(I+1)
ORDER(I+1)=ORDER(I)
IF(I.GE.NPATH) GO TO 27
ORDER(I+1)=ORDER(I)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I+1
GO TO 9
CONTINUE
CALL CLEAR
IF(NPATH.EQ.0) GO TO 27
ORDER(I)=ORDER(I+1)
ORDER(I+1)=ORDER(I)
IF(I.EQ.0) GO TO 7
ORDER(I+1)=ORDER(I+1)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I-1
GO TO 9
7 IF(NPATH.EQ.0) GO TO 27
ORDER(I)=ORDER(I+1)
ORDER(I+1)=ORDER(I)
IF(I.GE.NPATH) GO TO 27
ORDER(I+1)=ORDER(I)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I+1
GO TO 9
CONTINUE
CALL CLEAR
IF(NPATH.EQ.0) GO TO 27
ORDER(I)=ORDER(I+1)
ORDER(I+1)=ORDER(I)
IF(I.EQ.0) GO TO 7
ORDER(I+1)=ORDER(I+1)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I-1
GO TO 9
7 IF(NPATH.EQ.0) GO TO 27
ORDER(I)=ORDER(I+1)
ORDER(I+1)=ORDER(I)
IF(I.GE.NPATH) GO TO 27
ORDER(I+1)=ORDER(I)+1
IF(ORDER(I+1).LE.NPATH) GO TO 8
I=I+1
GO TO 9
IF (NSEN .EQ. 0) GO TO 980
J = LS(I)
K8 = 21 - NSEN
DO 979 K9 = K8, 20
LOC = 21 - K9
IF (J .GT. GAG(LOC) - 500) GO TO 998
CALL REDUCE(J, <, K9)
IF (K2 .EQ. 2) GO TO 830
VNO(K3 + 51, LOC) = VNO(K3 + 51, LOC) + V(I)
SMAX(LOC) = MAX(SMAX(LOC), K3)
SMIN(LOC) = MIN(SMIN(LOC), K3)
GO TO 979
998 J = GAG(L OC)
CALL REDUCE(J, K9, K2)
IF (K2 .EQ. 2) GO TO 979
VNO(K3 + 51, LOC) = VNO(K3 + 51, LOC) + V(I)
SMAX(LOC) = MAX(SMAX(LOC), K3)
SMIN(LOC) = MIN(SMIN(LOC), K3)
GO TO 979
CONTINUE
280 J = LG(I)
CALL REDUCE(J, K9, K)
SMAX(K) = MAX(SMAX(K), K9)
SMIN(K) = MIN(SMIN(K), K9)
VNO(K3 + 51, K9) = VNO(K9 + 51, K9) + V(I)
CONTINUE
C OBTAIN HIGHER ORDER LOOP VALUES
C S=T LOOP ORDER POINTER
14 I = 1
WRITE(6, 990) NLOOP
990 FORMAT(' NO. OF FIRST ORDER = ', I3)
ORDER(I+1) = ORDER(I)
IF (ORDER(I).LE. NLOOP) GO TO 18
I = I + 1
17 ORDER(I+1) = ORDER(I)
C CHECK FOR MORE FIRST ORDER LOOPS
IF (I .EQ. 1) WRITE(6, 999) ORDER(I)
IF (ORDER(I) .GT. NLOOP) RETURN
16 ORDER(I+1) = ORDER(I+1) + 1
IF (ORDER(I+1) .LE. NLOOP) GO TO 18
I = I + 1
GO TO 16
18 IF (I .EQ. 6) STOP
N = ORDER(I)
M = ORDER(I+1)
L = NLOOP + 1
IF (I .EQ. 1) N = L
I1 = TIMES(I, L - 1)
J1 = TIMES(M - 1)
K1 = TIMES(K - 1)
D0(I) = TIMES(I1, K1)
L\text{OGIC}(1) = \text{L\text{OGIC}}(J+\text{MM}) \cdot \text{AND} \cdot \text{L\text{OGIC}}(K1+\text{MM})

\text{IF}(\text{L\text{OGIC}}(1) \cdot \text{EQ} \cdot 0) \text{GO TO 14}

C \text{E} \text{ TE} \text{R} \text{ THE } \text{L\text{OOP}} \text{ OF } \text{ARDER } I+1

701 \text{L\text{OGIC}}(11+\text{MM}) = \text{L\text{OGIC}}(J1+\text{MM}) \cdot \text{OR} \cdot \text{L\text{OGIC}}(K1+\text{MM})

L(L) = L(N) + L(M)

\text{IF}(\text{L\text{OGIC}}(11+\text{MM}) = \text{L\text{OGIC}}(J1+\text{MM}) \cdot \text{OR} \cdot \text{L\text{OGIC}}(K1+\text{MM})) \text{GO TO 281}

J = L(S)

K8 = 21 + \text{SEN}

G9 799 K9 = K8, 20

L6 = 21 + \text{SEN}

\text{IF}(J \cdot \text{GT} \cdot \text{GA}(S\text{LC}) \cdot -500) \text{GO TO 798}

\text{CALL} R\text{REDUCE}(J, \cdot 3, K2)

\text{IF}(\text{R} \cdot \text{EQ} \cdot 2) \text{GO TO 850}

V\text{\text{3O}}(K3 + 51, L\text{OC}) = V\text{\text{LO}}(K3 + 51, L\text{OC}) \cdot (V(L) \cdot \text{((-1)**(I+1)))}

S\text{MAX}(1)(S\text{LC}) = \text{MAX}(S\text{MAX}(1)(L\text{OC}), K3)

S\text{MIN}(1)(L\text{OC}) = \text{MIN}(S\text{MIN}(1)(L\text{OC}), K3)

G6 TO 799

850 V\text{\text{3O}}(K3 + 51, L\text{OC}) = V\text{\text{LO}}(K3 + 51, L\text{OC}) \cdot (V(L) \cdot \text{((-1)**(I+1)))}

S\text{MAX}(1)(L\text{OC}) = \text{MAX}(S\text{MAX}(1)(L\text{OC}), K3)

S\text{MIN}(1)(L\text{OC}) = \text{MIN}(S\text{MIN}(1)(L\text{OC}), K3)

G6 TO 799

798 J = L(S)

\text{CALL} R\text{REDUCE}(J, K3, K2)

\text{IF}(K2 \cdot \text{EQ} \cdot 2) \text{GO TO 799}

V\text{\text{1O}}(K3 + 51, L\text{OC}) = V\text{\text{LO}}(K3 + 51, L\text{OC}) \cdot (V(L) \cdot \text{((-1)**(I+1)))}

S\text{MAX}(1)(L\text{OC}) = \text{MAX}(S\text{MAX}(1)(L\text{OC}), K3)

S\text{MIN}(1)(L\text{OC}) = \text{MIN}(S\text{MIN}(1)(L\text{OC}), K3)

G6 TO 799

799 \text{CONTINUE}

281 J = L(S)

\text{CALL} R\text{REDUCE}(J, K3, K)

S\text{MAX}(K) = \text{MAX}(S\text{MAX}(V), K9)

S\text{MIN}(K) = \text{MIN}(S\text{MIN}(V), K9)

V\text{\text{N}}(K3 + 51, K) = V\text{\text{N}}(K3 + 51, K) \cdot (V(L) \cdot \text{((-1)**(I+1)))}

24 I = I + 1

G6 TO 17

E29

\text{SUBROUTINE CLEAR}

\text{U} \cdot \text{C} \cdot \text{L} \cdot \text{A} \cdot \text{.}

1967

\text{INTEGER}

\text{C} \cdot \text{H} \cdot \text{MN} \cdot \text{31} \cdot \text{30} \cdot \text{3} \cdot \text{0} \cdot \text{0}, \text{L}\text{PATH}(300, 2), \text{V}\text{PATH}(300), S(300), N\text{PATH}

\text{EXTERNAL LS} \text{T} \text{R}

\text{CD} \cdot \text{IN} \cdot \text{MN} \cdot \text{NT} \cdot \text{IMES} / \text{NT} \text{IMES}

N = 0

G6 I = 1, N\text{PATH}

\text{IF}(\text{L}\text{PATH}(I, 1) \cdot \text{EQ} \cdot 0) \text{GO TO 1}

N = N + 1

L\text{PATH}(N, 1) = \text{L}\text{PATH}(I, 1)

L\text{PATH}(N, 2) = \text{L}\text{PATH}(I, 2)

\text{CALL} \text{EU} \text{QUAL}(N, I, L\text{T} \text{AR}, \cdot \text{NT} \text{IMES})

V\text{PATH}(I) = V\text{PATH}(I)

S(V) = S(I)

\text{CONTINUE}

1

\text{C} \cdot \text{H} \cdot \text{MN} \cdot \text{31} \cdot \text{30} \cdot \text{3} \cdot \text{0} \cdot \text{0}

\text{U} \cdot \text{C} \cdot \text{L} \cdot \text{A} \cdot \text{.}

1967

\text{INTEGER}

\text{C} \cdot \text{H} \cdot \text{MN} \cdot \text{31} \cdot \text{3} \cdot \text{0} \cdot \text{0}, \text{L}\text{PATH}(300, 2), \text{V}\text{PATH}(300), S(300), N\text{PATH}

\text{EXTERNAL LS} \text{T} \text{R}

\text{CD} \cdot \text{IN} \cdot \text{MN} \cdot \text{NT} \cdot \text{IMES} / \text{NT} \text{IMES}

N = 0

G6 I = 1, N\text{PATH}

\text{IF}(\text{L}\text{PATH}(I, 1) \cdot \text{EQ} \cdot 0) \text{GO TO 1}

N = N + 1

L\text{PATH}(N, 1) = \text{L}\text{PATH}(I, 1)

L\text{PATH}(N, 2) = \text{L}\text{PATH}(I, 2)

\text{CALL} \text{EU} \text{QUAL}(N, I, L\text{T} \text{AR}, \cdot \text{NT} \text{IMES})

V\text{PATH}(I) = V\text{PATH}(I)

S(V) = S(I)

\text{CONTINUE}

1
SUBROUTINE REDUCE(I,J,K) U.C.L.A. 1969
INTEGER TAG
C=MINA/GAG/TAG(20),NSEN,SENS(50)
K=1
J=1
IF(NSEN.EQ.0)GO TO 2
M=21-ASEN
DB 1 L=20
DO 1 1=21-L TO 500 J=J+TAG(21-L)
1 CONTINUE
2 IF(J.LT.500)RETURN
J=J-100
K=2
RETURN
END

SU3ReUTINE MULT(A,B,C) U.C.L.A. 1969
MULTYPLIES THE Polynomials
DIMENSION A(101),B(101),C(101)
ZERO ANSER
DE 1 I=1,101
C LIMITS OF MULTIPLICATION
IMINA=MINA+51
IMAXA=MAXA+51
IMINB=MINB+51
IMAXB=MAXB+51
C MULTIPLY
DB 2 I=IMINB,IMAXB
DE 2 J=IMINB,IMAXB
2 C(I+J-51)=C(I+J-51)+A(I)*B(J)
RETURN
END

SU3ReUTINE SENSC
GRANDI U.C.L.A. 1969
FORMS THE SENSITIVITY FUNCTIONS
INTEGRAL SENS
INTEGRAL SMAX,SMIN(2),SMAX1,SMIN1,SMAX0,SMIN0,SMAX00,SMIN00,SMAX10,SMIN10,
DIMESION G(101),B(101)
DIMENSION (101),SMAX(20),SMIN(20),SMAX0(20),SMIN0(20),SMAX00(20),SMIN00(20),SMAX10(20),SMIN10(20),
DIMENSION (50,12),V(101,2),NE,SMAX,SMIN
DA 3-5 II=1,505
IF(SENS(I1).EQ.0)GO TO 305
DB 3-5 II=1,NSEN
A-40
IF(SEI="Slfi)E0.GAGC(TI )OT

637

VCL21150

306 CONTINUE

UCL21160

C CHECK FOR ZERO VN01

UCL21170

307 DO 701 I=I,101

UCL21180

IF(VNO1(I,II).NE.OO)GO TO 710

UCL21190

701 CONTINUE

UCL21200

G0 TO 720

UCL21210

C ZERO VN01

UCL21220

710 CALL MULT(VN(I,2),VN01(I,II),SMIN(I),SMAX(I),SMNO1(II),

UCL21230

*SMAX00(I))

UCL21240

CALL MULT(VN(I,2),VN00(I,II),SMIN(2),SMAX(2),SMNO1(II),

UCL21250

*SMAX00(I))

UCL21260

DO 702 I=I,101

UCL21270

702 VNSEN(I,2(I))=E(I)+B(I)

UCL21280

CALL MULT(VN(I,1),VN(I,2),VNSEN(I,II),SMIN(2),SMAX(2),SMNO1(II),

UCL21290

*SMAX00(I))

UCL21300

SMIN(I) =MIN(SMIN(I)+SMIN(2),SMIN(I)+SMNO1(II)+SMIN(2)+

UCL21310

*SMINO0(II))

UCL21320

SMAX(I) =MAX(SMAX(I)+SMAX(2),SMAX(I)+SMAX00(II)+SMAX(2)+

UCL21330

*SMAX00(II))

UCL21340

GO TO 800

UCL21350

720 CONTINUE

UCL21360

RETURN

UCL21370

END

UCL21380

SUBROUTINE ANSWER(VN,SMAX,SMIN,ITAG)

UCL21390

DAVID PALETZ U.C.L.A. 1967

UCL21400

DIMENSION VN(101,2)

UCL21410

COMPON/CIPCIT/CARD(50,12)

UCL21420

CRHmBN/SPEED/NEXPS(100,2),AS(100,2),ASIGN(100,2),LINE(132),NUM(50)

UCL21430

13),JUNK(19)

UCL21440

INTEGER BLANK,SMAX,SMIN,ASIGNPLUSMINUS,AS,LINE

UCL21450

COMM/LN/DATA/AMD(11),NSBMBD(5L)BLANK,PLUSMINUS

UCL21460

COMM5N/OITS/F(4096),V(101,2)

UCL21470

DOIIJ1,tOO

UCL21480

AS(I,1)=NS

UCL21490

UCL21500

AS(I,2)=NS

UCL21510

L=51-SMIN

UCL21520

K=SMAX-SMIN+1

UCL21530

C SKIP A PAGE AND WRITE HEADING

UCL21540

IF(ITAG.EQ.O)WRITE(6,201)

UCL21550

201 FORMAT(I1,'TRANSFER FUNCTION//')

UCL21560

IF(ITAG.EQ.-1)WRITE(6,220)

UCL21570

220 FORMAT(I1,' SQUARE OF WORST CASE TOLERANCE//')

UCL21580

IF(ITAG.GT.O)WRITE(6,210)(CARD(ITAG,J)+J-1,12)

UCL21590

A-41
210 FORMAT(11, 'SENSITIVITY TO ', 12A1, '//')
C SETTING THE NUMERATOR IF J=2 AND THE DENOMINATOR WHEN J=1
J=2
C FAN IS THE NUMERATOR FACTOR, FAD IS THE DENOMINATOR FACTOR
11 KK=5J+5MAY
3 IF(VN(KK,J).NE.0)GO TO 7
  K<=K+1
  G6 TO 3
7 IF(J.EQ.2)FAN=VN(KK,J)
  IF(J.EQ.1)FAD=VN(KK,J)
  DP(I,J)=1K
  ASIGN(I,J)=PLUS
  VMEXP(I,J)=I-1
  VM(I,J)=VM(L,J)
  IF(J.EQ.2.AND.VM(I,J).NE.0.VM(I,J)/FAN
  IF(J.EQ.2.AND.JTAG.NE.0.AND.SEM(I,J).NE.0).VM(I,J)/FAN
  IF(J.EQ.1).VM(I,J)=VM(I,J)/FAD
  IF(VM(I,J).NE.0).VM(I,J)=VM(I,J)/FAN
  VM(I,J)=VM(I,J)
4 ASIGN(I,J)=MINUS
  G6 TO 5
6 VMEXP(I,J)=0
  ASIGN(I,J)=BLANK
5 L=L+1
2 CONTINUE
  IF(ASIGN(I,J).EQ.PLUS).ASIGN(I,J)=BLANK
  AS(IN(I,J)=BLANK
  G6 TO 43
43 NL=1K
  IF(NEXPS(N,J).GE.10)GO TO 41
  LEXP=NEXPS(N,J),1
  NUM(N,J)=IDEC(LEXP)
  IF(LEXPS.EQ.1.AND.LEXPS.FQ.2)NUM(N,J)=BLANK
  NUM(N,J)=BLANK
  NUM(N,J)=BLANK
  G6 TO 43
41 IF(NEXPS(N,J).GE.100)GO TO 42
  IARG=NEXPS(N,J)/10
  LEXP=NEXPS(N,J)-10*IARG
  NUM(N,J)=IDEC(LEXP)
  NUM(N,J)=IDEC(IARG+1)
  NUM(N,J)=BLANK
  G6 TO 40
42 LEXP=NEXPS(N,J)/103
  LEXP=NEXPS(N,J)-103*IARG
  LEXP=LEXP/10
  LEXP=LEXP/10
  LEXP=LEXP+1
  NUM(N,J)=IDEC(LEXP)
  NUM(N,J)=IDEC(IARG+1)
  NUM(N,J)=IDEC(1A+1)
40 CONTINUE
HBE31
8 MEND=NEPG+7
  IF(M.NE.0.GE.K)GO TO 9
  G7 TO 10
WRITE(6,202)((VNUM(-,I),I=1,3),M=NBEG,NEND) UCL22210
202 FORMAT(1H0,B8(11X,3A1)) UCL22220
WRITE(6,204)(ASIGV(I,J),VM(I,J),AS(I,J)),I=NBEG,NEND) UCL22230
204 FORMAT(1H8,A1) UCL22240
IF(J.EQ.1)GO TO 10 UCL22250
9 TO 10
10 IF(K.EQ.8)GO TO 13 UCL22260
13 LEND=k UCL22270
14 LTOTAL=LEND*14 UCL22280
15 LINE(I)=BLANK UCL22290
16 LINE(I)=MINUS UCL22300
17 WRITE(6,203)(LINE(I),I=1,LTOTAL) UCL22310
203 FORMAT(132A1/) UCL22320
204 FACT=FACTOR UCL22330
FACT=FAN/FAD UCL22340
WRITE(6,205)FACT UCL22350
205 FORMAT(6,20A5) UCL22360
FACT=FACTOR =',3X,1PE10,3///) UCL22370
RETURN UCL22380
END UCL22390
SUBROUTINE WRSCTC UCL22400
C S. GRANDI U.C.L.A. 1969 UCL22410
C CALCULATES WORST CASE TOLERANCE UCL22420
C INTEGER S$EVS,S'MAX2,SMAX1,SMIN1,SMIN2,MAX SMAX1,SMAX2,SMAX3,SMAX4,SMAX5,SMAX6,SMAX7,SMAX8,SMAX9,SMAX10
C MAIN $A, $A,TW(101,2),TOL(50),S'MAX2,SMIN2
C $A, $A,GAG(20),N$EEN,GENS(50)
C $A, $A,BITS/VM$E(101,2,20),S'MAX1(20),S'MIN1(20)
C $A, $A,CIRCUIT/CARD(50,12),VM(101,2),N$E,SMAX,SMIN
C D$E$ESION,VM$R($N,111),VM1(101),VM2(101),S'MIN(2),S'MAX(2)
C INITIALIZE
C I=5$'IV(1)5 I=5$'MAX(1)5 I=5$'NC$'X=0
C 'MAX1=0
C 'MIN1=0
C 'MAX2=0
C 'MIN2=0
C A-43
DO I=1,101
    VK1(I)=0.0
    VW2(I)=0.0
    VK(I,1)=0.0
    VW(I,1)=0.0
END IF

C OBTAIN SENSITIVITY FCNS FOR ALL VALID ELEMENTS
NSEni=0
DR 10 K=1,N
IF(SENS(K).EQ.0)GO TO 10
NSEni=NSEni+1
C SQUARE THE TOLERANCE
TOL1=TOL(K)*TOL(K)
SQUARE SENSITIVITY FUNCTION
CALL MULT(VNSEN(1,1,NSEN1),VNSEN(1,2,NSEN1),VWRKN,
  *SMIN1(NSEN1),SMAX1(NSEN1),SMIN1(NSEN1),SMAX1(NSEN1))
VN=MIN1(NSEN1)+SMAX1(NSEN1)
VN=SMAX1(NSEN1)+SMAX1(NSEN1)
L=SMIN1(NSEN1)+SMAX1(NSEN1)
C FIND TYPE OF DENOM
J1=MSO(0,NSEN1)*SI1(1)
J2=MSO(0,NSEN1)*SI1(1)
DO 20 J=J1,J2
C DENOM SAME AS TRANSFER FUNCTION
TOL=J1,J2
DO 10 J=J1,J2
IF(VN(J,2).NE.VNSE(JUJNSEN1))GO TO 21
C DENOM NOT SAME AS TRANSFER FCN
21 IF(NDEM.EQ.0)GO TO 30
DO 10 J=J1,J2
10 CONTINUE
GET FUNCTION
IF(NDEM.EQ.0)GO TO 30
C BOTH TYPES PRESENT
CALL MULT(VN(1,2),VN(1,2),VWRKN,SMIN(2),SMAX(2),SMAX(2),SMAX(2),SMAX(2))
N1=SMIN(2)+SMIN(2)+SMIN(2)
V2=SMAX(2)+SMAX(2)
CALL MULT(VW1,VW2,VWRKN,VW1,VNSEN2,1,1,NSEN1,NSEN1)
DO 31 J=1,101
31 VW(1,2)=VW1+VW2+VW(1,2)
CALL MULT(VW(1,1),VW1,VW2,VWRKN,SMIN(1),SMAX(1),SMAX(1),SMAX(1))
SIN1=SMIN(1)+SMAX(1)
SMAX2=SMAX(2)+SMAX(2)
SMAX2=SMAX2+SMAX2
C
C
C
C
G' TO
100
UCL23270
FIRST TYPE ONLY uCL23280
30 99 4# I=1,101
40 VW(I,2)=VW(I,1)
UCL23300
CALL MULT(VK(I,1),VH(I,1),SMIN(I,1),SMAX(I,1),SMIN(I,1),SMAX(I,1))UCL23310
SMIN2=SMIN(1)+SMN(I)
UCL23320
SMAX2=SMAX(1)+SMAX(I)
UCL23330
C
C
FIND MIN AND MAX POWERS OF VW
100 DO 50 I=1,101
IF(V(I,2).NE.0.0) GO TO 51
UCL23350
50 CONTINUE
UCL23360
51 L=1-51
UCL23390
SMIN2=SMN(I
UCL23400
DO 52 J=1,11
UCL23410
IF(V(I*2).NE.0.0) GO TO 53
UCL23430
52 CONTINUE
UCL23440
53 L=1-51
UCL23450
SMAX2=SMAX(I)
UCL23460
55 RETURN
UCL23470
END UCL23480
SUBROUTINE INVERT
UCL23490
A. R. TYRILL, UCLA, 6/21/68
UCL23500
COMPLEX ZCA(50),PCn(SO)J,1,G
UCL23510
DIMENSION FCTN(512),TEE(512),PH(512)
UCL23520
COMMON/SPEED/F2(COf8)
UCL23530
COMMON/9ITS/F1 (496)oB(50),C(50),NXFRoA(SO),NXTISTEPTOTEE,
UCL23540
ANTY0EFAMPIAMP2,FREQI,FRE02,NPLOT,
UCL23550
1NUlFRNUMTISNF(II),NR(II),MOR*I1ORNJMJNTAYISN;SCAGSCFREQSIGMA,
UCL23560
2T1 ,T?,T3,DMOD(6)JABSC,9ORD
UCL23570
EGIVALLNCE (F2(j),FCTN()),(F2(513),TEE(1)),(F2(1025),CA(1)),
UCL23580
(F2(ll2S CB(1)),(F2(ll25),PH())
UCL23590
DATA FREQAMAGPHATIM/tFREll,.MAG tIPHA IITIMEI/ UCL23600
112 FORMAT (?3X, 12, 3X, IP2E20,5) UCL23610
12 FORMAT('0',22XI+ '.IP2E20.5) UCL23620
14 FORMAT(///IOXI***
UCL23630
THE PLOT IS OF THE NON-CONSTANT REMAINDER TERM UCL23640
NFLAG=0 UCL23650
IF (.STEP .LE. 0.0) STEP = 1.0 UCL23660
SCFREQ = STEP UCL23670
NF(1) = 1 UCL23680
DO 116 I= 2, 11 UCL23690
116 NF(I) = I*SF(I-1)
UCL23700
INTS = TOTTEE/STEP
UCL23710
IF (INTS .LT. 10) INTS = 10 UCL23720
G# 117 I = 1, 10 UCL23730
117 IF (INTS .LT. 10) INTS = 10 UCL23740
UCL23750
118 CONTINUE
UCL23760
120 FNRAT (;;;; NOT RATIONAL, CANNOT INVERT*)
UCL23660
125 FORMAT(///IOXI***
UCL23670
THE TRANSFORM OF THE RESPONSE IS ---
UCL23680
2'EXP OF SI, 6X, NUMBER COEFFS, 1, 6X, DENOM, COEFFS / 20X, 3!----------, 6X, "-----------" / 6X, "---------")
UCL23690
121 FORMAT (P3X, I2, 3X, IP2E20.5)
UCL23660
122 FORMAT('0',22XI+ '.IP2E20.5)
UCL23670
**ONLY**
UCL23680
NFLAG=0
UCL23690
IF (.STEP .LE. 0.0) STEP = 1.0
UCL23700
SCFREQ = STEP
UCL23710
NF(1) = 1
UCL23720
DO 116 I= 2, 11
UCL23730
116 NF(I) = I*SF(I-1)
UCL23740
INTS = TOTTEE/STEP
UCL23750
IF (INTS .LT. 10) INTS = 10
UCL23760
G# 117 I = 1, 10
UCL23770
117 IF (INTS .LT. 10) INTS = 10
UCL23780
118 CONTINUE
UCL23790
A-45

NOT REPRODUCIBLE
117 CONTINUE
I = 10
118 NXTI = I - 1
NXFR = I + 1
DO 119 I = 1, NXTF
119 NUMFR = 2*NR(1)
NUMTI = NR(2)
IF (NTYPE.LT.6) CALL INPUT
DO 122 I = 1, 50
IF (B(I+1)) 123, 122, 123
122 CONTINUE
123 MBR = 51 - I
DO 124 I = 1, 50
124 CONTINUE
125 MRNUM = 51 - I
MRNUM = MBR NUM + 1
DO 11 I = 1, MRNUM
11 A(I) = A(I) - B(I)
A(MBR) = 0
NFLAG = 1
111 WRITE (6, 120)
DO 126 I = 1, MBRAX
J = I - 1
126 WRITE (6, 121) J, A(I), B(I)
WRITE (6, 122) NFLAG
WRITE (6, 123)
123 IF (MR = 2) GO TO 127
127 RETURN
128 IF (NTYPE = 8) GOTO 129
129 RETURN
1969
A-46
6  NUMTI=Abs10(Abs(FREQ02/FREQ01))/Abs10(Abs(STEP))
7  Z*CMPLX(X.E0,6.32*FREQ01)
8  IF(NPMTI.GT.512)NUMTI=512
9  IF(IJMTI.LE.01)NUMTI=101
10  DE2J=1*MRMAX
11  KE=MRMAX-J+1
12  CA(J)=CMPLX(A(J),X.E0)
13  G1=(C.E0,0.*E0)
14  G2=(C.E0,0.*E0)
15  IF(NUMTI.E.1)J=1
16  IF(NTYPE.E.9)I=0
17  TEE(I)=REAL(Z)
18  FCN(I)=SORT((REAL(G1)**2)+(IMAG(G1)**2))
19  IF(NUMTI.E.9)RETURN
20  P(N)=P(0)
21  RETURN
22  END
2 = 1, IPE12.5, 1 SEC.0
322 FREQ=AT (20X, I'PULSE TRAIN, WAVELENGTH = 1, IPE12.5, 1 SEC., 5X, UCL24770
2 PULSE DURATION = 1, IPE12.5, 1 SEC/33X, 1SHS1AL MAG. = 1, IPE12. UCL24780
35, I. X., [BACKGROUNDF = 1, IPE12.5] UCL24790
WRITE(6, 310)
GO TO (311, 312, 313, 314, 315), NTAYPE
WRITE (6, 316) AMP1
GO TO 320
311 WRITE (6, 317) AMP1
GO TO 320
312 WRITE (6, 318) AMP1, FREQ1
GO TO 320
313 WRITE (6, 319) AMP1, FREQ1
GO TO 320
314 WRITE (6, 321) AMP1, FREQ1
GO TO 320
315 WRITE (6, 322) FREQ1, FREQ2, AMP1, AMP2
320 ISN = 1
NTAYPE = 1
SC'AG = AMP1
GO TO (305, 301, 303, 305, 305), NTAYPE
300 RETURN
301 OR 302 I = 1, 48
302 B(50-I) = B(49-I) - B(50-I)*FREQ1
B(1) = -5(1)*FREQ1
RETURN
303 IF (FREQ1 .LE. 0.0) FREQ1 = 1.0
MEGA = FREQ1*6.2831853
MGSO = MEGA**2
SCMAG = SCMAG*OMEGA
DO 304 I = 1, 43
304 B(51-I) = B(49-I) + B(51-I)*MGSO
B(1) = B(1)*MGSO
B(2) = B(2)*MGSO
RETURN
305 OR 306 I = 1, 48
306 R(50-I) = B(49-I)
B(1) = 0.0
 IF (FREQ1 .LE. 0.0) FREQ1 = 1.0
 T1 = FREQ1
 IF (NTAYPE=4) 308, 307, 309
307 ISN = 2
IF (T1 .LE. 5*STEP) NTAY = 0
308 RETURN
309 ISN = 3
IF (T2 .LE. 5*STEP) NTAY = 0
RETURN
END
SUBROUTINE SAMPLE
C R. TYRRILL, UCLA, 6/21/68
C\texttt{OMPLEX} *6 RSPN(2048), EXCMP(1024), SPW(50), S, SUMNM, SUMDN UCL25290
C\texttt{OMPLEX} *6 ZAWIC, Z, ZI UCL25300
D\texttt{ouble} PRECISION X, Y UCL25310
COMMON/SITG/RSPNS, B(50), C(50), NXFR, A(50),NXTI,STEP, T6TEU, UCL25320
ANTYPL, AMP1, AMP2, FREQ1, FREQ2, NPLB, UCL25330
1NUMF, NUMT1, INF(11), NR(11), MBR, MBN, NTA, ISN, SCHA, SCFREQ, SIGMA UCL25340
2T1, T2, T3, DM50(6), AESC, 6RD UCL25350
C\texttt{OMMON/SPEED/EXCMP} UCL25360
X = A*283185307179586D + 00/FLAT(NUMFR) UCL25370
Y = 0*23 + 00 UCL25380
SPW(J) = (1.00,0.00) UCL25390
00 130 I = 1, NUMFR UCL25400
S = \texttt{C\texttt{OMPLEX}}(SIGMA, SGVL(Y)) UCL25410
IF (I = NR(1)) 134, 134, 133
134 76IE = CMPLX(0.0,0.0) UCL25420
EXCP(X) = CEXP(26*IE) UCL25430
133 Y = X + Y UCL25440
SUMNM(0.0,0.0) UCL25450
SUMDN = (0.0,0.0) UCL25460
09 131 J = 2, MBR UCL25470
131 SPW(J) = SPW(J-1)*S UCL25480
09 132 J = 1, MBR UCL25490
SUMNM = A(J)*SPW(J) + SUMNM UCL25500
132 SUMDN = B(J)*SPW(J) + SUMDN UCL25510
IF (ISN-2) 135, 136, 137
135 ZZ = (1.00,0.00) UCL25520
GO TO 130 UCL25530
136 ZZ = 1.0 - CEXP(T1*S/SCFREQ) UCL25540
130 RSPNS(I) = SUMNM/Z/SUMDN UCL25550
136 RSPNS(I) = RSPNS(I)/2.0 UCL25560
RETURN UCL25570
END UCL25580
SUB\texttt{ROUTINE} FLIP UCL25590
C A. F. YPRAILL, UCLA, 6/21/68
C\texttt{OMPLEX} RSPNS(2048), EXCMP(1024), Z UCL25600
D\texttt{ouble} PRECISION X, Y UCL25610
C\texttt{OMMON/SITG/RSPNS, B(50), C(50), NXFR, A(50), NFTI, STEP, T6TEU, UCL25620
ANTYPL, AMP1, AMP2, FREQ1, FREQ2, NPLB, UCL25630
1NUMF, NUMT1, INF(11), NR(11), MBR, MBN, NTA, ISN, SCHA, SCFREQ, SIGMA UCL25640
2T1, T2, T3, DM50(6), AESC, 6RD UCL25650
C\texttt{OMMON/SPEED/EXCMP UCL25660
136 FORMAT /// 20X, *SIGMA = \texttt{4}, 1PE12+5) UCL25670
S15CT = SIGMA/SCFREQ UCL25680
WRITE (12, 136) SIGACT UCL25690
102 \texttt{NXH} = \texttt{NFR}/2 UCL25700
06 106 L = 1, NXH UCL25710
NFR = NF(L) UCL25720
NDIF = NR(L) - NFR UCL25730
\texttt{NXH} = \texttt{Y}(L + 1) UCL25740
06 106 \texttt{X} = 1, HFX UCL25750
A-49
JUMP = (K-1)*2*NRF(L)

105 DO 106 J = NF8, NDIF, N2F8
   JI = J + JUMP
   JF = JI + NDIF
   DO 106 I = 1, NRF(L)
   JJI = JI + I
   JF = JF + I
   Z = 6SPNS(JJI)
   RSPNS(JJI) = RSPNS(JF)
106 RSPNS(JF) = Z

DO 110 L = 1, NXTI
   NF8 = NF(L)
   NRF(L) = D0 110

DO 110 J = 1, NFO
   JF = JF + J
   JF = JF + J
   Z = 6SPNS(JF)*EXCM((J-1)*NRF + 1)
   RSPNS(JF) = RSPNS(JJI) = Z
110 RETURN

END

SUBROUTINE ADJUST


COMPLEX RSPNS(2048)

DIMENSION FNP(4)

COMMON/BITS/RSPSFACTL(50),TERM(50),NXFR,P5W(50),NXTSTEP,
BTOF,NTYPE+AMP1,AMP2,FREQ,FREQ2,NPLO,D,
NUMFR,NXNT,RFIR(11),NR(11),NM0,MNRMUM,NTERM,ISN,SCMAG,SCFREQ,SIGMA,
T11,T2,T3,D,M0,D0(50),ABC,5

COMMON/SPEED/FCTN(512),TEE(512)

DLW = 2.0*SCMAG/SCFREQ

DO 150 I = 1, NUTI
   TEE(I) = (FLBAT(I-1))*SCFREQ
150 FCTN(I) = DLW*(REAL(RSPNS(I))

IF (SIGMA) 151, 153, 151 -
151 SIGQ = SIGMA/SCFREQ

DO 152 I = 1, 2, NUMT

FCTN(I) = FCTN(I)*EXP(SIGQ*TEE(I))
152 CALL TAYLOR

DLW = SCMAG/SCFREQ

FCTN(I) = TERM(2)*DLW

"IF (NTAY) '156', 155, 159' -

A-50
FACTL(2) = 1*0
DO 1,4 I = 3, 50
FACTL(I) = FACTL(I-1) * (I-2) * 0 + 25
DO 155 I = 2, 50
TERM(I) = TERM(I) / FACTL(I)
DO 157 I = 1, 4
FNP(I) = 0.0
P64(I) = 1.0
DO 158 J = 2, 50
FNP(I) = FNP(I) + TERM(J) * P64(J)
IF (FNP(I) .GT. 1.0E+03) GO TO 156
PEk(J+1) = P64(I) * 1.0E+25
157 FCTN(I+1) = FNP(I) * DLY
156 CALL PRPLT
RETURN END
SUBROUTINE TAYLOR
CALL PRPLT
RETURN END
SUBROUTINE SCALE
C A. R. TAYLOR, UCLA, 6/21/68
COMMON/BITS/F1(4096),B(50),C(50),NXFR,A(50),AXTI,STEP,T0TEE,
ANSTYPE,AMPI,AMP2,PSEP0,PSEP2,PSEP3,PSEP4
IF (I .LE. 132) GOTO 172
P(1) = SYMBOL(5)
P(KZERO+11) = SYMBOL(2)
P(KZERO-11) = SYMBOL(2)
P(132-11) = SYMBSL(2)
P(132) = SYMbSL(5)
P(KZERO) = SYMeUL(2)
WRITE (5, 183) (SYMBOL(2),J=11,132)
RETURN
END

183 FORMAT (10X, 22A1)
191 FORMAT (4(1PE16.3, 1PE16.5))
194 FORMAT (10X, A4, 11X, A4, 3X)/
WRITE (6, 194) (ASC.ERR, I=1, NF)
J = NFO + I
JJ = NF9 + J
190 WRITE (6, 191) TEE(I), FCTN(I), TEE(J), FCTN(J), TEE(JJ), FCTN(JJ)
2, TEE(NFO+JJ), FCTN(NFO+JJ)
IF (NPLB + LE + 0) RETURN
DHI = 0.0
DL0 = DHI
D0 = 176 I = 1, NUMTI
IF (FCTN(I) *GT, DHI) DHI = FCTN(I)
IF (FCTN(I) *LT, DL0) DL0 = FCTN(I)
176 CONTINUE
DG = (DHI - DL0)/115.0
KZERO = 14.5 = (DL0/DG)
IF (KZERO=11) 177, 177, 178
178 IF (132-KZERO) 177, 177, 178
173 IF (KZERO = 11) 177, 177, 178
177 KZERO = 1
170 DO 120 I = 11, 132
180 P(I) = SYMBSL(2)
WRITE (6, 181) DHI, DL0, DG
LL = C
DO 182 I = 1, NUMTI, NPLB
K = (FCTN(I) - DL0)/DG) + 14.5
182 P(K) = SYMBOL(3)
IF (LL) 171, 171, 170
170 WRITE (6, 183) (P(J), J = 11, 132)
LL = LL - 1
G0 TO 172
171 WRITE (6, 175) TEE(I), (P(J), J = 11, 132)
LL = LL - 1
172 DO 184 J = 10, 132
184 P(J) = SYMBOL(1)
IF (LL) 185, 185, 183
185 DO 144 I = 1, 3
P(I+11) = SYMBE(2)
P(KZERO+11) = SYMBE(2)
P(KZERO-11) = SYMBE(2)
P(132-11) = SYMBE(2)
P(132) = SYMBE(5)
P(KZERO) = SYMBE(2)
188 P(11) = SYMBOL(5)
WRITE (6, 183) (SYMBE(2), I=11,132)
RETURN
END

C A. R. TAYLOR, UCLA, 6/21/68
COMMON/BITS/F1(4096),B(50),C(50),NXFR,A(50),AXTI,STEP,T0TEE,
ANSTYPE,AMPI,AMP2,PSEP0,PSEP2,PSEP3,PSEP4
IF (I .LE. 132) GOTO 172
P(1) = SYMBOL(5)
P(KZERO) = SYMBOL(2)
WRITE (5, 183) (SYMBOL(2),I=11,132)
RETURN
END

A - 52
** A. R. TYRILL, UCLA, 6/21/68

** INUMFR, NUMTI, NF(11), NR(11), MOR, MORNUM, NTAY, ISN, SCMAG, SCFREQ, SIGMA,

2T1, T2, T3, DMD(6), ASYC, BRD

MRG = MR + 1

IF (SCFREQ = 1.0) 231, 232, 231

DB 231 I = 1, M, M0

DB 233 J = 1, I

A(MRG-I) = A(MRG-I)*SCFREQ

233 B(MRG-I) = B(MRG-I)*SCFREQ

SCMAG = 1.0/B(MOR)

DB 234 I = 1, M, M0

SCMG = SCMAG*A(MOR)

DO 235 I = 1, M0

SIGTRY = 0.005*NF(13-NXFR)

SIGMA = SIGMA + SIGTRY

END

SUBROUTINE CALCNR (LOG1)

LOGICAL LOG1

COMMON/BITS/MIN(50,50), D(26,50), AMOD(296), B(50), C(50), NXFRA(50)

A, 53
SUBROUTINE ROOTS

DIMENSION SMIN(2), SMAX(2)
INTEGER SMAX, SMIN

COMPLEX D(50,2)
REAL A(50), C(50,2), SMAX, SMIN

DIMENSION N1(5), NRT(50,3,2), IN(2), JN(2)

COMPLEX POLE

COMMON/A/CHAR(80)

CRMMN/SPEED/POLE(NP), NPOLES

COMPLEX P(50), C(50), SMAX, SMIN

REAL A(50), C(50), SMAX, SMIN

A - 54
EQUIVALENCE (G,N(1)),(F,V(1)),(S,N(1))

3005N9=1,2
3N6-MAX(N9)-MIN(N9)+1
N6=MIN(N9)+1
N7=MAX(N9)+1
DBN0=I=4,7
IF(VN(1,N9)+NE.0.E0)G0 TO 1

40 CONTINUE
G0 TO 25
1 N6=1
DBS?IP=NS,N7
J=NS+N6+1
IF(VN(J,N9)+NE.0.E0)G0 TO 53

52 CONTINUE
G0 TO 25
1 N7=J
N=J+N6+1
IF(N.LT.1)G0 TO 25
M=N-1
WRITE(6,203)M

203 FORMAT(11I4,E15.10)//STANDARD POLYNOMIAL ROOTFINDER ***",32X","F",60X/UI
1RE'IT'/116X,'JAN. 1969'//10X,'IPOLYNOMIAL OF DEGREE',14,"/',")

JN(1)=0
JN(2)=0
N=0
IN(1)=0
IN(2)=0
NPASS=0
J=I/6+1
K=0
DO991J=1,N

991 FORMAT(400I,5)
WRITE(6,991)N2,K

204 FORMAT(4X,'ACCURACY REQUESTED -- 6 SIGNIFICANT FIGURES//45X,'REAUC3500
1L PART -- IMAGINARY PART EXPONENT//')

WRITE(6,205)45

205 FORMAT(42X,*1))
C=0.E0
DB2I=1
V
J=NS+1
A(1)=VN(J,N9)
B(I)=CMPLX(A(1),0.E0)

45 L=L+1

C*********THE SCANNING ROUTINE...........................................

31 X*1=V-1.E0
Y*1=SQR(ABS(1.E0+(XMIN**2)))-6.25E+2
NR=6-JN(3-L)
THE CALCULATION ROUTINE-- USING HORNER'S TECHNIQUE...........

DO261=N4+5

V(I)=(GEOOE3)
P:B(N)
DO31,M
T.3(I)
V(K)=(V(K)*J(K)
DO271=N4+5

V(I)=V(I)+E(N)
IF(NTAG.EC.O)GO TO 27

De47,rl=TAG
T:W(I)-D(KL}
IF(CABS(T).LE.1.E-,)T=(t.E-60,E-60)
P:P/T
47 V(I)=V(1)/T

END CALCULATION ROUTINE-- RETURN TO THE PROPER POINT.

THE CRITERION FOR FINDING A ROOT--
THE RESIDUAL AT THE CENTRAL POINT MUST BE LESS THAN THAT OF
THE FOUR SURROUNDING POINTS.

CONTINUE

HOWEVER, IF ALL 5 POINTS ARE EQUAL, THIS POINT MUST BE REJECTED.

THE HOME-IN ROUTINE..................A-56
SS = CMPLX( FLOAT(Nq)*C, FLOAT(NINX)*C) UCL29450
SH = CMPLX( FLOAT(NR-NX)*C, FLOAT(NI)*C) UCL29460
SH = CMPLX( FLOAT(NR+NX)*C, FLOAT(NI)*C) UCL29470
C... BRANCH TO THE CALCULATION ROUTINE.
UCL29480
Nq = 2
GO TO 33 UCL29490
302 FORMAT(1X,4E20.8) UCL29500
10 F=AN*H(1),H(2),H(3),H(4),H(5)
D911I=I,5
IF(E,E0,H(I))GO TO 12
11 CONTINUE
WRITE(6,303)
UCL29510
99 FORMAT(IX,4ERO,8) UCL29520
10 R:APIN1 H(1),H(2),(3),HC4),H(5))
OllIzlS UCL29530
IF(EE0,H(I))GO
TO 12
It
CONTINUE 
WRITE(6,303)
UCL29540
303 FORMAT(' ERO0') UCL29550
303 FORMAT(' ERO0') UCL29560
1P GO TO (13,17,20,22,23,1)
C... IF THE DESIRED ACCURACY HAS BEEN REACHED, EXIT THE HOME-Routine.
C... ROUTINE.
15 IF(NJ.GE.6)GO TO 15
J=J+1
GO TO 16 UCL29570
17 N1=NI+N X
GO TO 21 UCL29580
GO TO 21
18 N1=NI+N X
GO TO 28 UCL29590
21 IF((J.NE.1).AND.(MOD(NR+NX,16),EQ.0))J=J+1
GO TO 14 UCL29600
22 NR=NR-NX
GO TO 28 UCL29610
GO TO 28
23 NR=NR+N X
GO TO 28 UCL29620
28 IF((J.NE.2).AND.(MOD(NR-NX,16),EQ.0))J=J-1
GO TO 14 UCL29630
14 S=NEW(I)
G=H(I)
IF( CABS(S)GT.2.E0)GO TO 46
GO TO 32 UCL29640
GO TO 32
C... ROOT EXAMINATION ROUTINE
C... CHECK THE LAST FEW STEPS, BUT THIS TIME WITHOUT DIVIDING OUT
C... THE ROOTS.
15 IF(NTAG.EQ.0)GO TO 43 UCL29740
15 IF(NTAG.EQ.0)GO TO 43 UCL29740
15 IF(NTAG.EQ.0)GO TO 43 UCL29740
15 IF(NTAG.EQ.0)GO TO 43 UCL29740
15 IF(NTAG.EQ.0)GO TO 43 UCL29740
15 IF(NTAG.EQ.0)GO TO 43 UCL29740
15 NTAG=0
F=(G*E10+0.0) UCL29750
DB50=1=M
UCL29760
UCL29770
UCL29780
50 F=F*B(I)+S
F=F+B(N)
G=CABS(F)
UCL29790
UCL29800
UCL29810
UCL29820
UCL29830
UCL29840
UCL29850
UCL29860
43 NTAG=1=L
UCL29870
UCL29880
UCL29890
UCL29900
UCL29910
UCL29920
UCL29930
UCL29940
UCL29950
UCL29960
UCL29970
UCL29980
UCL29990
UCL29000
UCL29010
UCL29020
UCL29030
UCL29040
UCL29050
UCL29060
UCL29070
UCL29080
UCL29090
UCL29100
UCL29110
UCL29120
UCL29130
UCL29140
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UCL29330
UCL29340
UCL29350
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UCL29380
UCL29390
UCL29400
UCL29410
UCL29420
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UCL29650
UCL29660
UCL29670
UCL29680
UCL29690
UCL29700
UCL29710
UCL29720
UCL29730
UCL29740
UCL29750
UCL29760
UCL29770
UCL29780
UCL29790
UCL29800
UCL29810
UCL29820
UCL29830
UCL29840
UCL29850
UCL29860
UCL29870
UCL29880
UCL29890
UCL29900
UCL29910
A-57
IF(MOD(NR,N2).LE.(-N2/2))NR=NR-N2 UCL29930
NI=NI/N2 UCL29950
NEXP=NEXP+1 UCL29960
GO TO 29 UCL29970

34 IF(K.EQ.1)GO TO 35 UCL29980
C=(FLOAT(NR)**2)+(FLOAT(NI)**2) UCL29990
E=(FLOAT(NR)/C)*2.72057594037927936E17 UCL30000
C=(FLOAT(NI)/C)*2.72057594037927936E17 UCL30010
NEXP=NEXP+1 UCL30020
GO TO 29 UCL30030

35 IF(J.GE.7)GO TO 24 UCL30111
K=N2**(7-J) UCL30120
IF(M3D(NR,K).GE.E*K/2)NR=NR+K UCL30130
IF(M3D(NR,K).LE.(-K/2))NR=NR-K UCL30140
K=N2**(7-J) UCL30150
IF(M6D(NI,K).GE.E*K/2)NI=NI+K UCL30160
IF(M6D(NI,K).LE.(-K/2))NI=NI-K UCL30170
NR=NR-MOD(NR,K) UCL30180
NI=NI-MOD(NI,K) UCL30190
CONTINUE UCL30200

C...RETURN TO THE PROPER POINT. UCL30210
IF(J.LT.0)GO TOO 37 UCL30220
K=J+1 UCL30230
38 DO391=1,NROOT UCL30240
K1=ABS(NR-NRT(I,1,K))/(16**(7-J)) UCL30250
K2=ABS(NI-NRT(I,2,K))/(16**(7-J)) UCL30260
IF((K1.LT.2).AND.(K2.LT.2))GO TO 5 UCL30270
CONTINUE UCL30280

39 CONTINUE UCL30290

NRT(I,3,K)=NR UCL30300
NRT(I,2,K)=NI UCL30310
NRT(I,1,K)=NEXP UCL30320
C...PERFORM THE CONVERSION FROM HEX TO DECIMAL. UCL30330
N3=N1 UCL30340
C=FLOAT(NR)*(16**((NEXP-7))) UCL30350
E=FLOAT(NI)*(16**((NEXP-7))) UCL30360
NEXP=ALOG10(16**((NEXP-7))) UCL30370
NR=C*(10**((7-NEXP))) UCL30380
NI=E*(10**((7-NEXP))) UCL30390
C=0 UCL30400
N2=10 UCL30410
C***  BRANCH TO THE ROUND-OFF ROUTINE AGAIN. 
37  NY=M 
Q=DCPLX(DFLOAT(NR)*1.*D-6,DFLOAT(NI)*1.*D-6) 
K=IEP-1 
WRITE(*,200)Q,K 
200  FORMAT(40X,2F15.9,E11) 
C  INSERT POLES IN COMMON BLOCK 
IF(NP**1)GO TO 5 
NPoles=NPoles+1 
POLE(NPOLES)=Q*(10.**K) 
5  IF(J1(I)+Jn(2).LT.4)GO TO 44 
36  WRITE(*,205) 
GO TO 25 
44  IN(L)=IN(L)+1 
J=IN(L) 
30  CONTINUE 
IF(YMIN.GE.YMAX)GO TO 6 
K=K;41 
Ym=K;*625E-2 
IF(L.EQ.1)GO 
31  TO 7 
IF(YMIN.LT.YMAX)GO TO 7 
KP=KAP+ 
XMI4=KP*6.25E-2 
Y=0.54AT(Abs(1.E0+(XMIN**2)))*6.25E-2 
IF(XMIN.LE.1.EQ)GO TO 8 
36  PRINT 
RETURN 
STOP* C
A. 2.1 Dictionary of Variables

A(I) In Common A. An array of 80 elements containing the 80 characters of the most recently read data card.

A(I) In Common BITS. An alias for A1(I).

A(I) In Subroutine ROOTS. The coefficients of the polynomial being evaluated.

A(I) In Subroutine POLSEN. The real part of the I'th pole.

ABSC In Common BITS. The abscissa label for Subroutine PRTPLT.

ADDR(I) In Common BITS. An alias for NQ(I) used in Subroutine GRAPH.

AMOD(I) In Common BITS. The list of plot control variables STEP to NPLT.

AMP1 In Common BITS. The positive portion of a pulse train.

AMP2 In Common BITS. The negative portion of a pulse train.

AS(I, J) In Subroutine ANSWER. Alphanumeric array of S's used in printing Transfer and Sensitivity Functions.

ASIGN (I, J) In Subroutine ANSWER. Alphanumeric array of signs used in printing Transfer and Sensitivity Functions.

A1(I) In Common BITS. Numerator of function to be plotted. The coefficient of S^{I-1}.

B(I) In Subroutine POLSEN. The imaginary part of the I'th pole.

B(I) In Common BITS An alias of B1(I).

B(I) In Subroutine ROOTS. A Complex type array of the polynomial coefficients.

BITS(I) In Common BITS. Array of words used in logical bit manipulations.

BINO(I) In Common BITS. A list of Binomial Coefficients used in Subroutines ROUTH and CALCR.

B MOD(I) In Subroutine PLOT. An integer type alias for AMOD(I).

B RANCH(I) In Common BITS. The list of branches connected to each circuit node. Used in Subroutines CALC and GRAPH.

B 1(I) In Common BITS. Denominator of function to be plotted.

The coefficient of S^{I-1}.

C(I) In Subroutine POLSEN. The derivative of the Transfer Function Denominator evaluated at the real part of the I'th pole.

C(I) In Common BITS. An alias for POW(I).

CA(I) In Subroutine INVERT. A Complex type alias for A1(J) with CA(I) the coefficient of the highest power of S.

CB(I) In Subroutine INVERT. A Complex type alias for B1(J) with CB(I) the coefficient of the highest power of S.

CARD(I, J) In Common CIRCIT. Array containing the J characters of the I'th element name.

CONST In Subroutine INVERT. The quotient resulting when the numerator of the transform is divided by the denominator.

COUNT(I) In Subroutine LOOPS. The number of transmittances leaving flowgraph node I.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(I)</td>
<td>In Subroutine POLSEN. The derivative of the Transfer Function Denominator evaluated at the imaginary part of the I'th pole.</td>
</tr>
<tr>
<td>D(I, J)</td>
<td>In Common BITS. The Routh Table built by Subroutine CALCR.</td>
</tr>
<tr>
<td>D(I, J)</td>
<td>In Subroutine ROOTS. List of roots used for forming the reduced Polynomial.</td>
</tr>
<tr>
<td>D</td>
<td>In Subroutine SCALER. The sum of the element value exponents scaled by FACTOR.</td>
</tr>
<tr>
<td>DEP(I, J)</td>
<td>In Common BITS. Array containing the J characters of the name of the element controlling the I'th element.</td>
</tr>
<tr>
<td>DGP</td>
<td>In Subroutine PRTPLT. The ordinate interval.</td>
</tr>
<tr>
<td>DHI</td>
<td>In Subroutine PRTPLT. The maximum ordinate value.</td>
</tr>
<tr>
<td>DL</td>
<td>In Subroutine SCALER. The sum of the element value exponents scaled by FACTOR-1.</td>
</tr>
<tr>
<td>DLO</td>
<td>In Subroutine PRTPLT. The minimum ordinate value.</td>
</tr>
<tr>
<td>DR</td>
<td>In Subroutine SCALER. The sum of the element value exponents scaled by FACTOR+1.</td>
</tr>
<tr>
<td>ERR</td>
<td>In Common ERR. = 1 when a serious error is detected, = 0 otherwise.</td>
</tr>
<tr>
<td>EXCMP(I)</td>
<td>In Common SPEED. Contains the $e^{(\sigma+j\omega)}$ points calculated by Subroutine SAMPLE.</td>
</tr>
<tr>
<td>EXPO</td>
<td>In Subroutine NUMBER. = 1 when the exponent is negative, = 0 otherwise.</td>
</tr>
<tr>
<td>FACT</td>
<td>In Subroutine ANSWER. The normalizing factor of the Transfer or Sensitivity Function.</td>
</tr>
<tr>
<td>FACT(I)</td>
<td>In Common BITS. Used in computing Taylor Series coefficients.</td>
</tr>
<tr>
<td>FACTOR</td>
<td>In Common ERR. Contains the Scaling Factor determined by Subroutine SCALER.</td>
</tr>
<tr>
<td>FAD</td>
<td>In Subroutine ANSWER. The normalizing factor of the function denominator.</td>
</tr>
<tr>
<td>FCTN(I)</td>
<td>In Common SPEED. The ordinate points for Subroutine PRTPLT.</td>
</tr>
<tr>
<td>FAN</td>
<td>In Subroutine ANSWER. The normalizing factor of the function numerator.</td>
</tr>
<tr>
<td>F, FE, FN, FS, FW</td>
<td>In Subroutine ROOTS. The function values at the five points of the five point test</td>
</tr>
<tr>
<td>FLAG</td>
<td>In Common FLAG. = 1 when Function ISORT fails to convert a numeric character its value, = 0 otherwise.</td>
</tr>
<tr>
<td>FNP(I)</td>
<td>In Subroutine ADJUST. Used in computing the Taylor Series corrections to the first five plot points.</td>
</tr>
<tr>
<td>FREQ</td>
<td>In Common PATHS. The frequency used by Subroutine FINE to build a circuit tree.</td>
</tr>
<tr>
<td>FREQ1</td>
<td>In Common BITS. $a in 3at, f in Sin 2\pi ft$, starting point for frequency plots.</td>
</tr>
</tbody>
</table>
FREQ2 In Common BITS. Pulse width in a pulse train, ending point for frequency plots.
GAG(I) In Common GAG. Contains the list of values to be used as Sensitivity Tags.
GENER(I) In Common CIRCUIT. = 0 if the I' th element is passive. = 1 if the I' th element is active.
INDIC(I) In Subroutine FINE. Used during circuit tree building.
IN(I) In Subroutine ROOTS. Number of discontinuities found on a type I pass.
INODE In Common BITS. The lowest node number in the circuit.
INP In Main Program. = 1 when a Transfer Function Request has been read. = 0 otherwise
ISN In Common BITS. = 2 for a pulse response. = 3 for a pulse train response. = 1 otherwise.
ITAG In Subroutine ANSWER. = -1 for a Worst Case Function. = 0 for a Transfer Function. Else, Sensitivity Function for element number ITAG.
ITREE In Common TREE. = 1 when Subroutine FINE is to be called to build a tree. = 0 otherwise.
JN(I) In Subroutine ROOTS. Number of roots found on a type I pass.
KI In Subroutine ROOTS. Counter for the Imaginary axis.
KR In Subroutine ROOTS. Counter for the Real axis.
KZERO In Subroutine PRTPLT. The location of the zero axis on the print line.
LIMIT In Subroutine SENSIT, WORST. The maximum number of Sensitivity Requests that can be handled.
LINE(I) In Subroutine FINE. Used for output formatting.
LINE(I) In Subroutine ANSWER. Used for printing the dividing line.
LINKS(I) In Common BITS. Area for logical bit manipulations during evaluation of current equations in Subroutine CALC.
LOGIC(I) In Common BITS. A Logical Type alias for LOOP(I). Used in Subroutine LOOPS.
LOGIC1 In Subroutine LOOPS. A Logical type alias for M1.
LOG1 In Subroutines ROUTH and CALCR. = TRUE if the current SIGMA value lies to the right of all poles in the complex plane.
= FALSE otherwise.
LOOP(I) In Common BITS. Area for logical bit manipulations during flowgraph loop evaluation.
LPATH(I, J) In Common BITS, PATHS. LPATH(I, 1) is the origin node of the I' th flowgraph transmittance. LPATH(I, 2) is the target node of the I' th flowgraph transmittance.
LS(I) In Common SPEED. Contains the S value and tags of the I' th loop in the flowgraph.
MOR In Common BITS. Number of coefficients in the transform denominator.
MORNUM In Common BITS. Number of coefficients in the Transform numerator.
MPATH(I, J) In the Main Program. An alias for LPATH(I, J).
MRMAX In Subroutine INVERT. Number of coefficients in the transform.
M1 In Subroutine LOOPS. Used during Higher Order Loop evaluation.
N(I) In Subroutine NASAP. Used during circuit tree building.
NB In Subroutine CALC. Number of branches in the circuit tree.
NBR(I) In Subroutine CALC. Number of branches at circuit node I.
NDEM In Subroutine WORST. = 0 if the simplified formula can be

used. = 1 for the standard formula.
NE In Common CIRCUIT. Number of elements in the circuit.
NEL(I) In Subroutine CALC. Number of elements at circuit node I.
NEXP In Subroutine ROOTS. The magnification factor for homing-in.
NEXPS(I, J) In Subroutine ANSWER. Array containing powers of S.
NFLAG In Subroutine WORST. = 1 when Worst Case analysis has been
aborted. = 0 otherwise.
NFLAG In Subroutine INVERT. = 1 when the transform is not rational.
NI In Subroutine ROOTS. The hexadecimal imaginary part of the
root.
NINDIC(I) In Subroutine FINE. Used during circuit tree building.
NLOOP In Common SPEED. Number of loops in the flowgraph.
NN In Subroutine LOOPS. Number of nodes in the circuit.
NN In Subroutine CALC. Number of nodes in the circuit.
NNODES In Common BITS. The highest node number in the circuit.
NODE(I) In Subroutine LOOPS. The number of flowgraph transmittances
arriving at flowgraph node I.
NPATH In Common PATHS. Number of transmittances in the flowgraph.
NPILOT In Common BITS. Number of calculated points per printed point.
NPOLES In Common SPEED. Number of poles in the Transfer Function.
NQ(I) In Common BITS. The beginning of the list of branches for node
I in the BRANCH array. Used in Subroutine CALC.
NR In Subroutine ROOTS. The hexadecimal real part of the root.
NR In Subroutine READ. Number of duplicate elements names.
NRT(I, J, K) In Subroutine ROOTS. The hexadecimal list of roots.
NS(I) In Subroutine CALC. Initially the same as NQ(I). Used during
the calculation of the current equations.
NSEN In Common GAG. Number of elements tagged for Sensitivity
Analysis.
NTAY In Common BITS. = 1 if a Taylor Series is to be used to compute
the first five plot points. = 0 otherwise.
NTIMES In Common NTIMES. Number of words per block to be used in
logical bit manipulation in Common BITS.
NUM(I, J) In Subroutine ANSWER. Alphanumeric array of S exponents.
NUMB(I) In Subroutine FINE. Used during tree building.
NUMNOD In Subroutine FINE. Number of circuit nodes.
NUMFR In Common BITS. Number of points along the w axis.
NUMTI In Common BITS. Number of calculated points in the plot.
NWORST In Common WORST1. = 1 if a Worst Case analysis is to be
performed. = 0 otherwise.
NX
In Subroutine ROOTS. The step size of the Home-in routine.

N1
In Subroutine LOOPS. The first node in a Higher Order Path. Detected by Subroutine UNPAK.

N2
In Subroutine LOOPS. The second node in a Higher Order Path. Detected by Subroutine UNPAK.

N3
In Subroutine LOOPS. The third node in a Higher Order Path. Detected by Subroutine UNPAK.

OCARD(I,J)
In Subroutine FINE. The ordered CARD array.

OGENER(I)
In Subroutine FINE. The ordered GENER array.

OORIGIN(I)
In Subroutine FINE. The ordered ORIGIN array.

ORD
In Common BITS. The ordinate label for Subroutine PRTPLT.

ORDER(I)
In Subroutine LOOPS. A pointer to the location of the I'th order loop or transmittance in the LOOP area.

ORIGIN(I)
In Common CIRCIT. Origin circuit node of the I'th element.

OTARGT(I)
In Subroutine FINE. The ordered TARGET array.

OVPATH(I)
In Subroutine FINE. The ordered VPATH array.

OZ(I)
In Subroutine FINE. The ordered Z array.

P(I)
In Subroutine FINE. The ordered VPATH array. Used to format the print line during plotting.

P
In Subroutine POLSEN. The Real part of the Pole Sensitivity.

PH(I)
In Subroutine INVERT. Array of phase points in a frequency plot.

POLE(I)
In Common SPEED. The I'th pole of the Transfer Function, a Complex number.

POW
In Subroutine NUMBER. Used to hold the exponent value.

POW(I)
In Common BITS. Part of the Taylor Series computed by Subroutine TAYLOR.

Q
In Subroutine POLSEN. The Imaginary part of the Pole Sensitivity.

RSPNS(I)
In Common BITS. The points F(α+jω) computed by Subroutine SAMPLE. The work array for the Fast Fourier Transform in Subroutine FLIP.

S, SE, SN, SS, SW
In Subroutine ROOTS. The five points of the five point test.

S(I)
In Common BITS, PATHS. Contains the S value and tags of the I'th flowgraph transmittance.

SCFREQ
In Common BITS. The frequency scale factor.

SCMAG
In Common BITS. The amplitude scale factor.

SENS(I)
In Common GAG. Numerical Sensitivity Tag for the I'th element.

SIGMA
In Common BITS. The real part of S, the complex frequency.

SIGPOW(I)
In Subroutine CALCR. An array of powers of SIGMA σ^I.
SMAX(I)  In Common CIRClT.  SMAX(1). Highest s power in Transfer function Denominator, VN(I, 1).  SMAX(2) Highest s power in Transfer Function Numerator, VN(I, 2).

SMAX00(J)  In Common POLy. Highest s power in \(-H(\bar{P}, Q)\), VN00(I, J), for the J\(^{th}\) element.

SMAX01(J)  In Common POLy. Highest s power in \(H(P', Q)\) VN01(I, J), for the J\(^{th}\) element.

SMAX1(K)  In Common BITS, POLY. Highest s power in Sensitivity Function for K\(^{th}\) element, VNSEN(I, J, K).

SMAX10(J)  In Common POLy. Highest s power in \(-H(\bar{P}, Q')\), VN10(I, J), for the J\(^{th}\) element.

SMAX2  In Common WORST1. Highest s power in Worst Case Function, VW(I, J).

SMIN(I)  In Common CIRClT. SMIN(1) Lowest s power in Transfer Function Denominator, VN(I, 1).  SMIN(2) Lowest s power in Transfer Function Numerator, VN(I, 2).

SMIN00(J)  In Common POLy. Lowest s power in \(-H(\bar{P}, Q)\), VN00(I, J), for the J\(^{th}\) element.

SMIN01(J)  In Common POLy. Lowest s power in \(H(P', Q)\) VN01(I, J), for the J\(^{th}\) element.

SMIN1(K)  In Common BITS, POLy. Lowest s power in Sensitivity Function for K\(^{th}\) element, VNSEN(I, J, K).

SMIN10(J)  In Common POLy. Lowest s power in \(-H(\bar{P}, Q')\), VN10(I, J), for the J\(^{th}\) element.

SMIN2  In Common WORST1. Lowest s power in Worst Case Function, VW(I, J).

STEP  In Common BITS. The interval between successive plot points.

SPOW(I)  In Subroutine SAMPLE. The value of SI-I.

TAG  In Common TAG. A utility flag used by the Main Program.

TAG  In Subroutine NUMBER. = 1 when the number is negative. = 0 otherwise.

TARGET(I)  In Common CIRClT. Target circuit node of the I\(^{th}\) element.

TAG(I)  In Common GAG. An alias for GAG(I).

TAG(I)  In Subroutine FINE. An alias for the TYPE array.

TEE(I)  In Common SPEED. The abscissa points for Subroutine PRTPLT.

TERM(I)  In Common BITS. The coefficients of the Taylor Series computed by Subroutine TAYLOR.

TOL(I)  In Common WORST1. Tolerance value for the I\(^{th}\) element.

TOTEE  In Common BITS. The interval between the first and last points plotted.

TREE  In Common TREE. = 1 when Subroutine FINE is to be called to build a circuit tree. = 0 otherwise.

TYP(I)  In Subroutine GRAPH. An alias for TYPE(I).

TYPE(I)  In Common CIRClT. = 0 if the I\(^{th}\) element is a Current Source (Link). = 1 if the I\(^{th}\) element is a Voltage Source (Branch)
T1, T2, T3  In Common BITS. Coefficients for the pulse response Transforms.
V(I)  In Common SPEED. The value of the I'th loop in the flowgraph.
VDERIV(I)  In Subroutine POLSEN. The symbolic derivative of the Transfer Function Denominator. I=51+ power of s.
VM(I, J)  In Subroutine ANSWER The Function after normalization.
VN(I, J)  In Common CIRCIIT. VN(I, 1) Transfer Function Denominator. VN(I, 2) Negative Transfer Function Numerator. I=51+ power of s.
VPATH(I)  In Common BITS, PATHS. Value of the I'th flowgraph transmittance.
VN00(I, J)  In Common POLY. -H(P, Q) for the J'th element. I=51+ power of s.
VN01(I, J)  In Common POLY. H(P, Q) for the J'th element. I=51+ power of S.
VN10(I, J)  In Common POLY. -H(P, Q) for the J'th element. I=51+ power of S.
VPATH(I)  In Common PATHS. Value of the I'th flowgraph transmittance.
W  In Subroutine FINE. An alias for FREQ.
X  In Subroutine POLSEN. The Numerator of the Real part of the Pole Sensitivity Function, -QH(P, Q) or VN10(I, J) evaluated at a pole.
Y  In Subroutine POLSEN. The Numerator of the Imaginary part of the Pole Sensitivity Function, -QH(P, Q) or VN10(I, J) evaluated at a pole.
Z(I)  In Subroutine FINE. The impedance of the I'th element.
<table>
<thead>
<tr>
<th>Subprogram</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADJUST</td>
<td>In the Plotter. Re-evaluates the first 5 sample points via a Taylor Series.</td>
</tr>
<tr>
<td>ANSWER</td>
<td>In the Transfer Function package. Prints Transfer and Sensitivity Functions normalized and formatted.</td>
</tr>
<tr>
<td>BLOCK DATA</td>
<td>Part of the Main Program. Initializes Common Blocks DATA, X and GAG.</td>
</tr>
<tr>
<td>CALC</td>
<td>In the Transfer Function Package. Evaluates current equations from the circuit tree.</td>
</tr>
<tr>
<td>CALCR</td>
<td>In the Plotter. Uses the Routh Stability Criterion to determine if the current SIGMA value is acceptable.</td>
</tr>
<tr>
<td>CLEAR</td>
<td>In the Transfer Function package. Removes transmittances in the Flowgraph which have been marked deleted.</td>
</tr>
<tr>
<td>EQUAL</td>
<td>A Bit Manipulation Utility. Performs various operations on blocks of word in Common Block BITS.</td>
</tr>
<tr>
<td>FINE</td>
<td>A Circuit Description Analysis routine. Builds a circuit tree for a user-specified frequency.</td>
</tr>
<tr>
<td>FLIP</td>
<td>In the Plotter. Computes the Fast Fourier Transform coefficients.</td>
</tr>
<tr>
<td>GRAPH</td>
<td>In the Transfer Function package. Builds the Flowgraph except for the unknown transmittance.</td>
</tr>
<tr>
<td>INBIT</td>
<td>A Bit Manipulation Utility. Sets bits in blocks of words in Common Block BITS.</td>
</tr>
<tr>
<td>INPUT</td>
<td>In the Plotter. Evaluates the transform of the response.</td>
</tr>
<tr>
<td>INVERT</td>
<td>In the Plotter. Controls the execution of the Plot Request.</td>
</tr>
<tr>
<td>ISORT</td>
<td>A Card Scanning Utility. Converts numeric characters to fixed binary values.</td>
</tr>
<tr>
<td>LOOPS</td>
<td>In the Transfer Function package. Computes Transfer and Sensitivity Functions from the Flowgraph, via the Shannon-Happ formula.</td>
</tr>
<tr>
<td>LOR</td>
<td>A Bit Manipulation Utility. Performs 'OR'ing.</td>
</tr>
<tr>
<td>LOX</td>
<td>A Bit Manipulation Utility. Performs 'AND'ing and subtracts the result from the arguments.</td>
</tr>
</tbody>
</table>
LSTOR  A Bit Manipulation Utility. Copies one word into another.
MAIN   The Main Program. Controls execution of NASAP-70.
MULT   In the Sensitivities and Worst Case package. Multiplies polynomials.
NASAP  A Circuit Description Analysis Routine. Interprets the standard form of circuit description data and builds a circuit tree for minimum computation time.
NUMBER A Card Scanning Utility. Converts alphanumeric representation of numbers into floating point values.
PLOT   In the Plotter. Interprets Plot Request Cards.
POLSEN In the Sensitivities and Worst Case package. Computes Pole sensitivities.
PRTPLT In the Plotter. Prints and plots the calculated response points.
READ  A Circuit Description Analysis routine. Interprets the special form of circuit description data.
REDUCE In the Sensitivities and Worst Case package. Decodes tags from the S or LS arrays.
ROOTS  The Rootfinder. Finds poles and zeroes of the Transfer Function.
ROUTH  In the Plotter. Finds an acceptable SIGMA value.
SAMPLE In the Plotter. Computes the initial Fast Fourier Transform points.
SCALE  In the Plotter. Scales the Fast Fourier Transform coefficients.
SCALER The Automatic Scaler. Re-adjusts, if necessary, circuit data values to avoid floating overflow.
SENSC  In the Sensitivities and Worst Case package. Computes Sensitivity Functions.
SENSIT In the Sensitivities and Worst Case package. Interprets Sensitivity Request Cards.
SORT   A Card Scanning Utility. Converts numeric characters to floating binary values.
TAYLOR In the Plotter. Computes Taylor Series coefficients.
UNITS  A Circuit Description Analysis routine. Prints a message.
<table>
<thead>
<tr>
<th>UNPAK</th>
<th>A Bit Manipulation Utility. Removes bits from blocks in Common block BITS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHAT</td>
<td>In the Transfer Function package. Interprets Transfer Function Request cards.</td>
</tr>
<tr>
<td>WORST</td>
<td>In the Sensitivities and Worst Case package. Interprets Tolerance Cards.</td>
</tr>
<tr>
<td>WORSTC</td>
<td>In the Sensitivities and Worst Case Package. Computes the Worst Case function.</td>
</tr>
</tbody>
</table>
A. 2. 3    Dictionary of Common Blocks

A    The Card Buffer. Contains the last card read.

BITS    The area for bit manipulations. Also used to hold the Fast Fourier Transform coefficients.

CIRCUIT    Contains data compiled from the circuit description.

DATA    Contains alphabetic characters.

ERR    Contains the Error flag and scaling factor.

FLAG    Contains a utility flag.

GAG    Contains Sensitivity Tags.

NTIMES    Contains the number of words per block in BITS.

PATHS    Contains the Flowgraph paths.

POLY    Contains polynomials used to compute Sensitivity and Worst Case Functions.

SPEED    Contains Flowgraph loops. Also used by the plotter.

TAG    Contains a utility flag.

TREE    Contains the switch for building a tree for user-supplied frequency.

WORST1    Contains data for Worst Case Analysis.

X    Contains numeric characters.

In the interest of saving space, some Common Blocks (especially BITS) are used for various purposes at different times.
APPENDIX B
MODELS FOR COMPUTER AIDED CIRCUIT DESIGN/ANALYSIS PROGRAMS:
PART I. COMMON TRANSISTOR MODELS, A SURVEY

By Donnamae E. Meyerhoff†

INTRODUCTION

The analysis of circuits by computer depends upon the ability of the analyst to appropriately simulate device performance by a model consisting of the recognized parameters of the CAD program being utilized. The analyst must work with a lumped model of the device in question if he is to remain within the limits of a CAD program, and he must also select appropriate approximations to be made in the representation of the device behavior. These approximations must be such that they simplify analysis while maintaining an acceptable level of validity in the results.1, 2

A model is a mathematical entity with precise definitions of its variables and their relationships. It is never completely equivalent to the physical device, rather, the behavior of the model approximates that of the physical device.2 The development of a semiconductor model requires:
(1) formulation of the ideal voltage-current equations and definition of the topology of the model, (2) modification for actual device performance, (3) invention of techniques for measurement from which model parameters may be extracted, (4) the extraction of those parameters.3

An ideal model will (1) incorporate parameters either measurable or derivable, as from a manufacturer's data sheet,* (2) involve parameters acceptable to the given CAD program (facilitating analysis), (3) be sufficiently simplified to be comprehensive, to promote invention and design, and to be economical, (4) be complex enough to assure a tolerable degree of accuracy in the simulation of device performance over the operating

†Northrop Corporate Laboratories, this work was prepared while the author was with TRW Systems Group, California

* Used with discretion

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range desired.\textsuperscript{1, 2, 4, 5} The less complicated the model, the more restricted its range of application.

The primary concern of the circuit analyst is with the characterization of the external behavior of the device (functional modeling) without detailed simulation of internal processes (physical modeling) although an understanding of the internal processes must be assumed.\textsuperscript{2}

The selection of an appropriate model and its parameter values to correspond to given device operating conditions (temperature, biasing, load, etc.) for the circuit under consideration is the critical step in analysis, with or without computer assistance as the model finally selected will be the limiting factor in the degree of accuracy of the results.\textsuperscript{5, 6}

The following discussion is concerned with transistor models and their representation in present general purpose CAD programs. Diodes are more easily represented and are omitted here for brevity.

Transistors were selected to demonstrate CAD program modeling because the majority of circuit analysis is still primarily concerned with them, and because their models are presently the primary building block of Integrated Circuit modeling. It should be emphasized that there is no single transistor model capable of simulating all regions of operation for all applications, a model this capable would be prohibitively complex.

This description of modeling is divided into two sections: (1) small signal (linear, incremental) models, and (2) large signal (nonlinear) models. The models are not derived here, the reader is referred to the appropriate references for the derivations.

SMALL SIGNAL MODELS

A small signal is defined as an AC signal significantly smaller in peak to peak amplitude than the DC bias upon which it is superimposed. Small signal transistor models are intended to simulate the behavior of a transistor at a specific operating point in the linear region of operation.
The transistor model is constructed of parameters that remain relatively constant over the voltage and current swings encountered. These parameters are then assumed constant for the analysis.\(^7\)

The small signal models are not versatile, large signal swings may not be accurately analyzed (due to the lack of parameter variation and the linearity of the model), saturation and cut off are not represented. The model is valid only in the active region.\(^8\) Although it is limited in its application, the small signal model provides a straightforward method for simulating transistor performance when the operating restrictions have been satisfied.

A family of small signal models composed of \(h, y, z,\) and \(r\) parameters (see for examples References 7 to 10) exists for the user and the most commonly applied models are given here. The input formats for the models for the CAD programs which accept them are also presented. The common emitter configuration is used in most cases to facilitate comparison.

**Low Frequency Models.** The two commonly used configurations are the Hybrid and the Tee using \(h\) and \(r\) parameters respectively.

![Figure B 1 Hybrid Model](image-url)
The Hybrid Model is considered the best model for small signal representation because (1) the $h$ parameters are real numbers at low frequencies, (2) the parameters may be easily obtained by measurement when required or from the device static characteristic curves, (3) if the $h$ parameter of one configuration is available, the conversion to another configuration is relatively simple. The Hybrid Model is valid for any configuration at low frequencies, for a device operating in the active region.

![Figure B.2](image)

**Figure B.2** Tee Model Equivalent Alternate of the Hybrid Model

**Program Models.** SCEPTRE has a prestored hybrid model for small signal analysis. The program accepts the voltage generator (EA) described as a function of the voltage across $h_0$ (R2 in the diagram below) and the current generator (JB) described as a function of the current through $h_n$ (R1 below).

![Figure B.3](image)

**Figure B.3** SCEPTRE Representation — Hybrid Model (Prestored)
If the Tee model is preferred, SCEPTRE will accept a user-description for that model without requiring modifications in the representation. ECAP, however, will not accept a nonlinear dependency and requires the conversion of the hybrid model voltage generator into a DC bias and some resistance such that the branch\(^*\) resulting is a linear approximation of the performance of the original generator. The current source is dependent linearly on the current through R1 and it is not modified.\(^{12}\)

\[^{12}\text{branch} - \text{one impedance with or without a source between two nodes, ECAP requires a "dummy" impedance in parallel with an I source, and in series with a V source, 1K is used.}\]

Figure B 4 ECAP Representation - Hybrid Model
High Frequency Models \[ F << \frac{2D_b}{w} \] The two most commonly used configurations are the Hybrid-Pi (Figure B-5) and the Modified-Tee (Figure B-6). Their parameters are not frequency dependent and most manufacturers provide data for one of them.

![Analytical Hybrid Pi](image)

![Reduced Hybrid Pi](image)

**Figure B 5 Hybrid Pi**

This circuit is known to give results in excellent agreement with experiment in the range dc to limiting frequency of the device, that frequency where the gain is significantly reduced and operation is no longer validly assumed linear.

The reduced version of the circuit is justified when source or load impedances or other factors or uncertainties swamp the effects of various parameters. Parameters \( r_{b'c} \) and \( r_{ce} \) are considered approximate opens in Figure B-5b, \( C_{b'e} \), \( C_{b'c} \) are lumped and include \( C_T \).

The Modified Model is generally used for common base circuits, and is limited in transient response analysis in range of operating biases and bandwidth. The Simplified Tee uses one base resistance, and \( r_c \) is an approximate open.
Program Models

ECAP will accept the Hybrid-Π in either form, although the reduced version is the most commonly used. The current dependency is linear and the elements must be single valued.
SCEPTRE has no pre-stored Hybrid-Pi but the user may enter a model which describes the current generator as a function of $I_{rb'}e'$, and which is not restricted to single valued elements.

There are numerous other small signal models, the ones presented above are the most commonly applied to small signal analysis. There are more complex circuits for device simulation at higher operating frequencies and for noise analysis.

**LARGE SIGNAL MODELS**

A large signal is defined as an AC signal with a peak to peak amplitude that exceeds the DC bias upon which it is superimposed. Large signal transistor models are intended to simulate the behavior of a transistor when its operation encompasses more than one region of operation, or when its operation enters the nonlinear portion of the device characteristics.

There are four regions of operation for a transistor (See References 13 - 17.) They are.

I. **Cut-off Region** Collector current cut-off or collector voltage saturation, both junctions are reverse biased, only small reverse saturation currents flow across the junctions

$$I_e < 0 \quad V_{EB} << -\frac{kT}{q} \quad V_{CB} << -\frac{kT}{q}$$

The transistor behaves as an open (nonconducting) switch.

II. **Normal Active Region** Emitter junction forward biased, collector junction reverse biased, $0 < I_e < -\frac{I_C}{\alpha}$

$$V_{CB} << -\frac{kT}{q}$$

III. **Saturation Region** Collector current saturation or collector voltage cut off, both junctions carry a forward bias, $I_e < -\frac{I_C}{\alpha}$
the voltages across the junctions are in the millivolt range. The transistor behaves as a closed (conducting) switch.

IV. **Inverse Active Region.** Emitter reverse biased, collector forward biased, similar to normal active with emitter and collector interchanged, low reverse current gain.

Large signal operation for transistors includes power applications and switching (an extreme case where the device goes rapidly from Region III to Region I and vice versa, and generally includes the first three regions of operation.14

Small signal models dealt only with Region II. The parameters were assumed to remain constant and operation was approximately linear. Large signal modeling is complicated by the variation of parameter values with changes in voltage and current, the thermal and power limitations that must be accounted for, and the nonlinear behavior of the device.7,9

There are three primary models used for large signal analysis: (1) the Beaufoy-Sparkes Charge Control model; (2) the Ebers-Moll model, (3) the Linvill-Lumped model.

In their paper "Comparison of Large Signal Models for Junction Transistors,"4 Hamilton et al, had the following conclusions about the three models.

First, the three models are all described by two first order ordinary differential equations. The main difference in the equations is in the dependent variables. The same four measurements provide the values for parameters for Ebers-Moll and the Beaufoy-Sparkes models and determine the characteristics equation of the Lumped model. (Table B-I shows parameter conversion for #1 and #2, and Figure B-14 demonstrates equation similarity for #2 and #3.)

Second, although each model is derived by means of approximations made at different stages of the theoretical development, the final overall
degree of approximation is the same. The models have the same natural frequencies and give the same results for transient problems. Therefore, as far as numerical results are concerned, the three models are equivalent.

Last, the Charge Control model is considered more cumbersome in application that the Ebers-Moll model, the Lumped model is considered the most general in development approach.

The Ebers-Moll Model. The well-known Ebers-Moll equations for device operation are given below. They are valid for any transistor in low level injection, regardless of shape, which has negligible voltage drop everywhere but the junctions. They are also valid for a graded base region device.

The Ebers-Moll model for Regions I, and II is based on these equations of ideal device operation. To more closely approximate actual device performance resistances $r_b$, $r_e$, $r_c$ must be added. The model is completed for high frequency by adding $C_{be}$, $C_{bc}$.

Program Models: Two CAD programs have prestored versions of the Ebers-Moll model for the first three regions of operation, NET-1, and SCEPTRE. The Ebers-Moll based model is the only model available with NET-1 for circuit analysis, and it requires all of its parameters be pre-stored for each device prior to its use in analysis, a requirement that has been found to be too restrictive.

SCEPTRE uses a more flexible prestored Ebers-Moll model. The user must have access to $I_{CO}$, $I_{EO}$, $\theta_N$, $\theta_I$ to describe $J_1$ and $J_2$ (current generators) or may enter tables of laboratory measurement data. $R_{bb}$ and $R_{cc}$ may be omitted from separate representation when measurements are used since they are included in the values for $J_1$ and $J_2$. If $\alpha_1 \sim 0$, $J_A$ may be omitted.
a) IDEALIZED EQUATIONS

\[ I_E = \frac{I_{EO}}{1 - \alpha_N I} \left( e^{\frac{\lambda V_{EB}}{N}} - 1 \right) + \frac{\alpha I_{CO}}{1 - \alpha_N I} \left( e^{\frac{\lambda V_{CB}}{N}} - 1 \right) \]

\[ I_C = \frac{\alpha_N I_{EO}}{1 - \alpha_N I} \left( e^{\frac{\lambda V_{EB}}{N}} - 1 \right) - \frac{I_{CO}}{1 - \alpha_N I} \left( e^{\frac{\lambda V_{CB}}{N}} - 1 \right) \]

\[ I_B = -I_E - I_C \]

\[ \alpha_N I_{EO} = \alpha I_{CO} \quad \text{reciprocity requirement} \]

\[ \lambda = \frac{q}{\eta KT} \quad \eta = 1 \quad \text{valid when the transition region has no effect} \]

\[ \eta \sim 1 \quad \text{for germanium, } \eta \sim 2 \quad \text{for silicon, } 1 \leq \eta \leq 3 \]

b) IDEALIZED MODELS

TERMINAL CURRENT CONTROL

TERMINAL VOLTAGE CONTROL

\[ I_{CS} = \frac{I_{CO}}{1 - \alpha_N I} \]

\[ I_{ES} = \frac{I_{EO}}{1 - \alpha_N I} \]

\[ I_F = I_{ES} \left( e^{\frac{qV_{EB}}{KT}} - 1 \right) \]

\[ I_R = I_{CS} \left( e^{\frac{qV_{CB}}{KT}} - 1 \right) \]

Figure B 8  Ebers–Moll Equations and Idealized Models (PNP)
Figure B 9  Ebers—Moll Model for Regions I, II, High Frequency

\[ I_{E0} = \frac{\lambda V_{EB}}{1 - \alpha N \alpha I} \]

\[ I_{B'} = \frac{\alpha N I_E}{1 - \alpha N \alpha I} \]

\[ I_{C'} = \frac{\lambda V_{EB}}{1 - \alpha N \alpha I} \]

\[ I_{C} = F(I_{C}) \]

\[ I_{1} = I_{ef} - \alpha I_{ef} \]

\[ I_{2} = I_{cf} - \alpha N I_{ef} \]

\[ I_{ef} = \frac{I_{cs}}{1 - \alpha N \alpha I} \left( e^{\frac{\lambda V_{EB}}{m_e}} - 1 \right) \]

\[ I_{cf} = \frac{I_{cs}}{1 - \alpha N \alpha I} \left( e^{\frac{\lambda V_{CB}}{m_c}} - 1 \right) \]

Figure B 10  NET—1 Transistor Model

B-12
**Figure B.11** SCEPTRE Prestored Model

**Charge Control Model.** The concepts of charge control may be briefly summarized as (1) the base charge \((q_B)\) may be defined uniquely by the past behavior of the base current, (2) the collector current is proportional to the base charge, is controlled by the base charge.\(^{18}\) The active region model and its equations are given in Figure B.12.\(^{17,20,21}\)

The similarity of the charge control model and more familiar parameters is seen by the relations

\[
\tau_{BF} \approx \frac{h_{fe}}{\omega_T} = \frac{1}{\omega_\beta}, \quad h_{fe} \approx \frac{\tau_{BF}}{\tau_F} \quad \text{(Forward Injection)}
\]
The similarity of the charge control model and more familiar parameters is seen by the relations

\[ \tau_{BF} \approx \frac{q_B}{I_b + I_{CO}} \]

\[ \tau_F \approx \frac{q_B}{I_c - I_{CO}} \]

\[ \beta \approx \frac{\tau_{BF}}{\tau_F} \]

The program equations are

\[ \lambda_b = \frac{q_B}{\tau_{BF}} + \dot{q}_B - C_{bc} \frac{dV_e}{dt} - C_{bc} \frac{dV_c}{dt} - I_{CO} \]

\[ \lambda_c = \frac{q_B}{\tau_F} + C_{bc} \frac{dV_c}{dt} + I_{CO} \]

\[ \lambda_e = q_B \left( \frac{1}{\tau_F} + \frac{1}{\tau_{BF}} \right) + q_B + C_{bc} \frac{dV_e}{dt} \]

**Figure B.12 Charge Control Model and Equations (NPN Device)**

**Program Models:** CIRCUS includes a radiation-pulse current generator in its prestored charge control model. CIRCUS requires that the user define 13 single valued parameters and 4 parameters that are single valued or tabled. The program equations are
\[ C_{be} = \frac{\alpha_I}{(\theta_1 - V_{be}) N_1} + \theta_N T_{CN} \left( I_N + I_{es} \right) \]

\[ C_{bc} = \frac{\alpha_N}{(\theta_2 - V_{bc}) N_2} + \theta_I T_{CI} \left( I_I + I_{CS} \right) \]

\[ I_{be} = \left( \frac{1}{\beta N + 1} \right) I_N - I_I \quad I_{bc} = - I_N + \left( \frac{1}{\beta I} + 1 \right) I_I \]

\[ I_N = I_{es} \left( e^{\theta_N V_{be}} - 1 \right) \quad I_I = I_{CS} \left( e^{\theta_I V_{bc}} - 1 \right) \]

\[ \beta_N, \quad T_{CN} = \gamma \left( I_N \right) \quad \beta_I, \quad T_{CI} = \gamma \left( I_I \right) \]

\( N_1, \quad N_2 \) are proportionality constants

These parameters may be converted to Ebers-Moll parameters

**TABLE B-1**

**CHARGE CONTROL TO EBERS-MOLL CONVERSION RELATIONS**

<table>
<thead>
<tr>
<th>Charge-Control Ebers-Moll</th>
<th>Charge-Control Ebers-Moll</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{es} )</td>
<td>( \frac{\alpha_N I_{es}}{1 - \alpha_N \alpha_I} )</td>
</tr>
<tr>
<td>( I_{cs} )</td>
<td>( \frac{\alpha_I I_{cs}}{1 - \alpha_N \alpha_I} )</td>
</tr>
<tr>
<td>( T_{CN} )</td>
<td>( \frac{10^{-9}}{2\pi \alpha_N F N} )</td>
</tr>
</tbody>
</table>

Other parameters correspond directly.
The Linvill Lumped Model  The Linvill model uses lumped elements to represent paths through which charge will flow in a transistor, the rate and amount of this charge-flow being governed by hole and electron concentrations and voltage. The lumped elements are given in terms of length dimensions and electrical constants. A reduced lumped diffusion model for a transistor is given in Figure B-14. 

Figure B 13  CIRCUS Prestored Charge Control Model — NPN

Figure B 14  Linvill's Two Lump Transistor Model
Equations Showing Parallel to Ebers-Moll Model:

\[
I_e = \frac{-I_{EO}}{1 - \alpha_N \alpha_I} \left( e^{\frac{V_e}{M_e} - 1} \right) - T_N \frac{d}{dt} \left[ \frac{I_{EO}}{1 - \alpha_N \alpha_I} \left( e^{\frac{V_e}{M_e} - 1} \right) \right]
\]

\[
I_e = \frac{\alpha_N I_{CO}}{1 - \alpha_N \alpha_I} \left( e^{\frac{V_c}{M_C} - 1} \right) + \frac{d}{dt} \left( C_{je} V_e \right)
\]

\[
I_c = \frac{-I_{EO}}{1 - \alpha_N \alpha_I} \left( e^{\frac{V_c}{M_C} - 1} \right) - T_I \frac{d}{dt} \left[ \frac{I_{CO}}{1 - \alpha_N \alpha_I} \left( e^{\frac{V_c}{M_C} - 1} \right) \right]
\]

\[
I_c = \frac{\alpha_N I_{EO}}{1 - \alpha_N \alpha_I} \left( e^{\frac{V_e}{M_e} - 1} \right) + \frac{d}{dt} \left( C_{jc} V_c \right)
\]

where:

\[
I_{EO} = \frac{-p_n \left( G_{r1} + \alpha_1 G_{r2} \right)}{G_d + G_{r1}} \quad I_{CO} = \frac{-p_n \left( G_{r2} + \alpha_N G_{r1} \right)}{G_d + G_{r2}}
\]

\[
T_N = \frac{C_{ho}}{G_d + G_{r1}} \quad T_I = \frac{C_{ho}}{G_d + G_{r2}} \quad \alpha_N = \frac{G_d}{G_{r1} + G_d} \quad \alpha_I = \frac{G_d}{G_{r2} + G_d}
\]

Program Models A version of the Linvill model has been developed for use as the prestored model for the TRAC program. The model and its parameters are shown in Figure B-15. The model is dependent on past values of \( V_{cb} \) and \( V_{eb} \) for the \( j \)th step.
\[ R_C = \frac{m \theta (1 - \alpha_N \alpha_R)}{V_c^i / m \theta} \quad I_{co} (e^{V_c^i / m \theta}) \]

\[ R_E = \frac{m \theta (1 - \alpha_N \alpha_R)}{I_{co} (e^{V_E^i / m \theta})} \]

\[ I_C = \frac{(e^{V_c^i / m \theta} - 1) I_{CO}}{1 - \alpha_N \alpha_R} \]

\[ I_E = \frac{I_{EB}}{1 - \alpha_N \alpha_R} \left( e^{V_E^i / m \theta} - 1 \right) \]

\[ I_{ppe}(t), I_{ppc}(t) = \text{radiation induced pulse currents} \]

Figure B 15  TRAC Model – Prestored Lumped Model–NPN
SUMMARY

The most commonly used small signal models, the Modified Tee and the Hybrid-Pi, have been presented with a description of the CAD programs that accept them. The three large signal models have also been briefly presented with a discussion of the CAD programs that have incorporated them.

The Hybrid-Pi is suitable for AC and small signal transient analysis and is the most effectively used model for ECAP

Large signal analysis requires a degree of complexity ECAP cannot accept without a loss of efficiency and accuracy. NET-1 attempted analysis with only a complex Ebers-Moll model with extensive data requirements and this has been found severely restrictive. TRAC has attempted analysis with only a complex version of the Linvill model and has met the same restrictions. CIRCUS attempts analysis with a charge-controlled model with less stringent requirements, is more effective but is also restricted. Some piece-wise linear modeling may be effected but this is generally cumbersome, especially without a dependent current source

SCEPTRE is the first major program to combine the features of the prestored models and the flexibility of the user-derived models. SCEPTRE is capable of both small and large signal analysis with its prestored models

It should be reemphasized that there is no single model capable of all analysis since such a model would be cumbersome and overly complex for any given analysis just as there is no ideal CAD program to perform analysis. The selections of the model and the program are both determined from considerations of the application of the device, the availability of parameter data and the accuracy requirements of the solution among others.

Table B-II presents a summary of some major CAD programs and the models included in this paper, Table B-III is a summary of symbols applied throughout the text.
<table>
<thead>
<tr>
<th>Model:</th>
<th>NASAP</th>
<th>ECAP</th>
<th>SCEPTRE</th>
<th>CIRCUS</th>
<th>TRAC</th>
<th>NET-1</th>
<th>PREDICT</th>
</tr>
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<tbody>
<tr>
<td>Small Signal</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Low Frequency</td>
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<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td>E</td>
<td>E</td>
<td>P</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>E</td>
</tr>
<tr>
<td>Tee</td>
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<td>E</td>
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<td>N</td>
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<td>E</td>
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<td>High Frequency</td>
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<td></td>
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</tr>
<tr>
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<td>N</td>
<td>N</td>
<td>N</td>
<td>E</td>
</tr>
<tr>
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<td>E</td>
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<td>N</td>
<td>N</td>
<td>E</td>
</tr>
<tr>
<td>Large Signal</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge Control</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>P</td>
<td>N</td>
<td>N</td>
<td>E</td>
</tr>
<tr>
<td>Ebers-Moll</td>
<td>D</td>
<td>D</td>
<td>P</td>
<td>D</td>
<td>N</td>
<td>P</td>
<td>E</td>
</tr>
<tr>
<td>Linvill Lumped</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>D</td>
<td>P</td>
<td>N</td>
<td>E</td>
</tr>
</tbody>
</table>

**Key**
- E Engineer Derived
- P Prestored Model
- D Inefficient, difficult
- N Not acceptable
A manufacturer's data sheet typically contains information on $I_{co}$, $V_{CE(sat)}$, $V_{BE(sat)}$, $h_FE$ (Beta), $C_{ob}$ and $f_T$, as well as stress limits for the device. Many also include the small signal parameters $h_{re}$, $h_{le}$, $h_{oe}$, $h_{fe}$ (AC amplification). Based on this information and the knowledge of what load current is desired (small signal operating point or large signal – maximum stress on the device) the designer/analyst must derive the parameter values (or functions of values) for the selected device.

The following is a tabulation of the symbols used in this paper and their definitions. Those parameters necessary for analysis include the generally applied approximation for their computation.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B, B'$; $b, b'$</td>
<td>Base terminal, suffix-parameter related to base characteristics</td>
</tr>
<tr>
<td>$C, C', c, c'$</td>
<td>Collector terminal, suffix-parameter related to collector characteristics</td>
</tr>
<tr>
<td>$C_{b'c}$</td>
<td>Capacity from base internal point to collector, generally labeled $C_{ob}$ on data sheet</td>
</tr>
<tr>
<td>$C_{b'e}$</td>
<td>Capacity from base internal point to emitter</td>
</tr>
<tr>
<td>$C_{c'}, C_e$</td>
<td>Collector, emitter capacity - large signal symbol</td>
</tr>
<tr>
<td>$C_{ge}$ or $C_{de}$</td>
<td>Diffusion capacity of emitter, collector, corresponds to $C_{b'e}$, $C_{b'c}$</td>
</tr>
<tr>
<td>$C_T$</td>
<td>Transition capacity, $C_T \ll C_{b'e}$ and '. generally omitted</td>
</tr>
<tr>
<td>$E, E', e, e'$</td>
<td>Emitter terminal, suffix-parameter related to base characteristics</td>
</tr>
<tr>
<td>$f_\alpha$</td>
<td>Alpha cut off frequency, $f_\alpha \approx \beta_0 f_\beta \approx f_T$</td>
</tr>
<tr>
<td>$f_\beta$</td>
<td>Beta cut off frequency</td>
</tr>
<tr>
<td>$f_T$</td>
<td>Current gain - bandwidth product</td>
</tr>
</tbody>
</table>
$g_m$ Transconductance, $g_m = \frac{\alpha_N}{r_e}$, $g_m = \frac{h_{fe}}{1 + h_{fe}}$, for germanium, room temp. $h_{fe} >> I_E$ in ma, $g_m \approx \frac{I_e}{26}$ ma.

$h_l$ Input impedance, small signal, $\approx \frac{\Delta V_{in}}{\Delta I_{1n}} | \Delta V_{out} = 0$

$h_r$ Feedback voltage ratio, small signal, $\frac{\Delta V_{in}}{\Delta V_{out}} | \Delta I_{1n} = 0$

$h_i$ Current transfer ratio, small signal, $\frac{\Delta I_{out}}{\Delta I_{1n}} | V_{out} = 0$

$h_o$ Output admittance, small signal, $\frac{\Delta V_{out}}{\Delta I_{1n}} | \Delta I_{in} = 0$

$I_{co}$ Collector to Base saturation current when $I_E = 0$

$I_{EO}$ Emitter to Base saturation current when $I_c = 0$

$K$ Boltzmann's Constant ($8.63 \times 10^{-5}$ ev/°K)

$M_E, M_c$ Emitter, collector proportionality constants ($1 \leq M_x \leq 3$) (emission constant)

$n$ Electron density

$p$ Hole density

$q$ Electron charge ($1.6 \times 10^{-19}$ coulomb)

$q_B$ Control charge in base region

$r_{bb'}, v_{bb''}, r_b$ Components of $r_{bb'}$, base resistance generally $r_{bb'} \approx 0$ compared to circuit components ($r_{bb'} = h_{ie} - r_{bb' e}$)

$r_b$ Small signal base resistance, Tee configuration, $r_b \approx h_1 - \frac{h_r h_e}{h_o}$
Resistance-base internal point to collector, generally very large, appears as an open to a CAD program. 

\[ r_{b'c} = \frac{1}{h_{re} g_{b'c}} \]

Resistance-base internal point to emitter, \( r_{b'e} \approx (\beta+1)r_e \)

Collector resistance \( r_c, r_{CE} \), also appears as an open, generally omitted

Emitter resistance, \( r_e \approx \frac{1}{h_o} \approx \frac{kT}{qV_e} \) at \( 27^\circ C \), \( kT/q = 26 \text{mv} \)

Base store

Absolute temperature - \( ^\circ \text{Kelvin} \)

Electron-volt equivalent of temperature, \( V_T = \frac{kT}{q} \)

Inverted current gain

Normal current gain

Low frequency \( \alpha_N \)

Inverted Beta \( \approx \frac{\alpha_I}{1-\alpha_I} \)

Normal Beta \( \approx \frac{\alpha_N}{1-\alpha_N} \)

Current gain at edge of saturation

\[ \lambda = \frac{q}{\eta kT} \] symbol for simplification (also \( \theta \)), \( \lambda = \frac{1}{\eta V_T} \)

Parameter accounting for recombination of carriers in the junction transition region, dependent on material

\[ 1 \leq \eta \leq 3 \quad \eta \approx 1 \text{ for germanium} \]

\[ \eta \approx 2 \text{ for silicon} \]

Junction voltages \( V_{b'e'}, V_{b'c} \)

Alpha cut off frequency, radians
\( \omega_T \approx \frac{\alpha}{1.2} = 2\pi \lambda_T \) current gain bandwidth product

\( \tau_{BF} \) Base charge time constant

\( \tau_F \) Collector charge control time constant

\textbf{Typical Values of } h\textbf{ parameters}\(^8\)
\textbf{(common Emitter Configuration)}

\begin{align*}
 h_{ie} & \quad 1,100 \\
 h_{re} & \quad 2.5 \times 10^{-4} \\
 h_{fe} & \quad 50 \\
 1/h_{oe} & \quad 40K
\end{align*}
BIBLIOGRAPHY


ADDITIONAL REFERENCES


PART II. TRANSISTOR MODELS FOR HOSTILE (WEAPON) ENVIRONMENT EFFECTS

INTRODUCTION

The present concern of circuit specialists, both designers and analysts, has been the degradation of systems upon exposure to nuclear radiation, specifically that resulting from the detonation of a weapon.

The inability of system shielding to be effective for all radiations makes it necessary to design and analyze for the generation of radiation-induced transient and permanent effects in semiconductor devices. There is no laboratory procedure capable of providing either the mixture or the intensity of the radiations produced in a real weapon environment, which may consist of any mixture of photons, charged particles or neutrons. As a result, it becomes necessary to turn to the computer. Several computer circuit analysis programs, such as SCEPTRE, CIRCUS, and TRAC, have been developed specifically for the analysis of transient radiation effects on circuits.

The purposes of this paper are (1) to describe the first order radiation effects in semiconductor material in terms of the weapon environment, (2) to describe the physical interactions which produce the altered device behavior, and (3) to discuss the computer program models available for the analysis of an exposed device. The discussion is primarily in terms of bipolar transistors. Because of the practical complexity of a discussion of a weapon or space radiation environment, such a discussion is not attempted here.

THE FIRST ORDER EFFECTS

Radiations consist of high energy photons such as gamma rays and energetic particles such as neutrons, electrons and fission fragments.

The effects initiated by the high energy photons are primarily transient ionization and excitation of the absorbing material. The effects initiated by the energetic particles, specifically neutrons, are primarily localized bulk
displacements, disruptions of the crystal lattice structure along the particle path. Because of the obvious complexity of a simultaneous discussion of each radiation expected in an incident environment, the two classes of radiation will be discussed separately.

IONIZATION

The ionization effects of a pure photon environment result from the interaction of the photons and the atomic electrons of the absorbing material. The photon-atomic electron interaction produces charged particles which in turn produce ionization through further interactions.

The three primary photon-atomic electron interaction processes are 1, 2

1. **The Photoelectric Effect** The inelastic collision of a photon and an atomic electron, the photon energy is absorbed by the electron which is ejected from the atom if the photon energy exceeds the binding energy of the electron. The extent of the photoelectric interaction is dependent on both the photon energy and the atomic number of the absorbing material and is most important at low photon energies for materials of high atomic number.

2. **The Compton Effect** The elastic collision of a photon and an atomic electron of the absorbing material in which part of the photon energy is transferred to the electron, both the electron and a reduced-energy photon are scattered. The Compton effect is most important in an energy range between 100 KeV and 4 MeV and is more significant for materials with a high atomic number.

3. **Pair-Production** The interaction of the electric field of the atomic nucleus (or the field of an atomic electron) and a photon in which the photon energy (when $E > 1.02$ MeV) is absorbed in the formation of an electron-positron pair. The positron is rapidly annihilated by an
electron with the interaction resulting in the production of two lower-energy photons. Pair-production is most important for high photon energies and is especially important for heavy elements. It is the major reaction process for high energies.

The result of each of these three major interaction processes is the production of one or more secondary electrons. The Coulomb interaction of these electrons produces additional ionization and excitation. Successive generation of the interactions ceases when low energy electrons are produced which do not have sufficient energy to continue the production of ionization or excitation. These last-order electrons will lose energy by elastic scatterings until they are either captured or thermalized.

Interactions Produced in a Photon Environment

Ionization is also created by energetic particles. The ionization effects of a primary beam of charged particles (electrons, positrons) are identical to the ionization effects of the secondary electrons produced by photon irradiations. Heavy charged particles (protons, fission fragments) create ionization along the primary particle path of such a high intensity that electron-positron charge recombination occurs rapidly. The net effect of the heavy particles is less than the effect of an equivalent, more uniformly distributed energy deposition.

Neutrons are heavy uncharged particles that produce ionization only through secondary processes. Neutron ionization effects are a function of neutron energy. The important neutron interaction processes are (1) elastic scattering - a collision of a neutron and a nucleus with transfer of...
kinetic energy, and (2) inelastic scattering - a collision of a high energy neutron and a nucleus with conversion of some of the neutron kinetic energy into excitation energy in the struck nucleus. The excited nucleus returns to its stable state by emitting the excess energy as a photon $^{1,2}$

Ionization produces primarily transient effects in the incident material, displacement produces primarily permanent effects

**DISPLACEMENT**

For the typical energetic neutrons produced in nuclear reactions, the production of atomic displacements is the principal interaction process through which neutron energy is dissipated. Displacement effects are the result of defects in the crystal lattice structure that introduce additional energy states in the energy band gap. These defects behave either as additional recombination centers, which can produce a reduction in minority carrier lifetime or they can alter the impurity concentration of the affected material, which can produce alterations in the physical properties of the material. Large defect clusters result from a neutron interaction in which a large amount of the neutron kinetic energy is transferred to a single atom $^{4}$

Ionization and displacement defects can produce significant alterations in the electrical behavior of the affected material.

**MANIFESTATION OF THE EFFECTS**

The most significant result of the three primary photon-interaction processes is the production of free electron-hole pairs. The number of electron-hole pairs created in semiconductor material is proportional to the amount of energy absorbed from the radiation environment. The differences between the exposure and absorbed radiation environments can be a complex function of the equilibrium radiation environment at the specimen. The complex prediction of carrier generation rate may be simplified by considering the energy deposition to be uniform throughout the geometry of the device if the incident particle or photon energy exceeds 200 KeV. For photon or electron irradiation between 1 to 5 MeV, the absorbed dose is essentially identical to the exposure dose $^{3}$
Radiation induced carrier generation in the bulk semiconductor will increase the minority and majority carrier densities.

\[ \Delta n = \Delta p = g_0 \gamma(t) \quad (B-1) \]

The change in majority and minority carriers is seen to be equal and therefore the relative effect on minority carrier density is greater. The minority carrier density increase results in the junction photocurrents and secondary photocurrents in diodes and transistors.

Displacement damage in the bulk semiconductor introduces a number of recombination centers, which is generally assumed to be proportional to the integrated neutron flux. The primary result is the reduction of minority carrier lifetime.\(^4\)

\[ \frac{1}{\tau_F} = \frac{1}{\tau_0} + \frac{\Phi}{K} \quad (B-2) \]

where \( \tau_F \) is the new lifetime

\( \tau_0 \) is the initial lifetime

\( K \) is the lifetime damage constant

\( \Phi \) is the integrated neutron flux

In terms of device performance, the reduction in minority carrier lifetime produces a transient reduction in the forward gain of a transistor that is not completely recovered. The damage value of Beta for a single radiation pulse may be obtained from the Messenger-Spratt Equation.\(^4\)

\[ \frac{1}{\beta_F} = \frac{1}{\beta_0} + \frac{0.194}{\frac{r}{\alpha} K} \quad (B-3) \]

The detailed analysis of displacement damage in transistors is complicated by the variation of the common emitter current gain (\( \beta \)) with the injection level.
THE PHYSICAL DESCRIPTION

In semiconductor material, electrical currents are the result of the motion of either holes or electrons and are associated with two independent mechanisms: (1) Drift motion, the result of charged particles being acted upon by an electric field, and (2) Diffusion, the result of the tendency of carriers to diffuse from regions of high charge concentration to regions of low concentration. The net current density is the sum of the drift and diffusion component currents.5

Carrier density that is greater than the equilibrium carrier density is termed excess carrier density. Excess carriers can be introduced by electrical, optical, thermal or radiation injection mechanisms. Excess carriers are opposed by the recombination process (mutual annihilation) by which holes and electrons are removed from circulation as charge carriers. The net rate of recombination of excess holes and electrons is approximately

\[ \begin{align*}
\text{n-type} & \quad \text{Rate} = \frac{P_n(x) - P_o}{\tau_p} = \frac{P'_n(x)}{\tau_p} \quad \text{(B-4)} \\
\text{p-type} & \quad \text{Rate} = \frac{n_n(x) - n_o}{\tau_n} = \frac{n'_p(x)}{\tau_n} \quad \text{(B-5)}
\end{align*} \]

for one dimensional, conductive, extrinsic, homogeneous material operating with a low injection rate.

The carrier generation rate by external mechanisms, \( g \), has been shown to be \( g = g_0 \gamma(t) \) for ionizing radiation, where \( \gamma(t) \) is the exposure in radians.

The continuity of current requires
\[
\frac{\partial p}{\partial t} = -\frac{1}{qA} \frac{\partial p}{\partial x} - \frac{\left(p_n'(x)\right)}{\tau_p} + g_o \gamma(t) \tag{B-6}
\]

**n-type:**
\[
\frac{\partial n}{\partial t} = \frac{1}{qA} \frac{\partial n}{\partial x} - \frac{\left(p_n'(x)\right)}{\tau_p} + g_o \gamma(t) \tag{B-7}
\]

The equations of current flow are:

\[
J_{\text{holes}} = q \mu_p p(x) E - q D_p \frac{\partial p}{\partial x} \tag{B-8}
\]

**n-type**
\[
J_{\text{electrons}} = q \mu_n n(x) E + q D_n \frac{\partial n}{\partial x} \tag{B-9}
\]

\[
I = A \left(J_{\text{holes}} + J_{\text{electrons}}\right) \tag{B-10}
\]

and the presence of the electric field requires the application of Gauss' Law:

\[
\frac{\partial E}{\partial x} = \rho(x) = \frac{q}{\varepsilon} \left[N_d(x) - N_a(x) + p(x) - n(x)\right] \tag{B-11}
\]

The terminal relationships of a device may be derived from these equations. To demonstrate briefly the relationship of the physical behavior and the transistor models available for computer aided analysis, the equations of an ideal diode and an ideal PNP transistor are included. Because of the complexity of the equations, worst case steady state conditions are primarily discussed.

**AN IDEAL DIODE**

The current appearing at the terminals of this device will be related to the internal redistribution of the carriers upon application of a bias potential. The following analysis is based on an abrupt junction device composed of homogeneous n-type and p-type material with a transition or space charge layer surrounding the junction of width \(W\).
For forward bias, assuming carrier flow by diffusion only

\[ n\text{-type } J_n(o) = \frac{q D_n P_{no}}{L_n} \left( \frac{e^{qV/\text{KT}} - 1}{e^{qV/\text{KT}} - 1} \right) = \frac{q D_n P_{n(o)}}{L_n} \quad (B-12) \]

\[ \text{sine } I = A \left( J_\text{h}(o) + J_e(o) \right), \text{ substituting } L_n = \sqrt{\frac{D_n \tau_n}{e^{qV/\text{KT}} - 1}} \text{ and including similar expressions for the electrons} \]

\[ I_{\text{diode forward}} = Aq \left( \frac{L_n P_{no}}{\tau_n} + \frac{L_P P_{po}}{\tau_p} \right) \left( e^{qV/\text{DT}} - 1 \right) \quad (B-13) \]

\[ = I_s \left( e^{qV/\text{DT}} - 1 \right) \quad (B-14) \]

Adding the effects of the space charge region contribution to reverse current, for reverse bias

\[ I_{\text{diode reverse}} = Aq \left( \frac{L_n P_{no}}{\tau_n} + \frac{L_P P_{po}}{\tau_p} + \frac{W}{\tau_o} \right) \quad (B-15) \]

\[ = I_s \]

In a steady state ionizing radiation environment where the carrier generation is increased by \( g_0 \gamma(t) \) the equation for reverse bias becomes \( (B-16) \)

\[ I_d = Aq \left[ L_n \left( \frac{P_{no}}{\tau_n} + g_0 \gamma(t) \right) + L_p \left( \frac{P_{po}}{\tau_p} + g_0 \gamma(t) \right) + W \left( \frac{n}{\tau_o} + g_0 \gamma(t) \right) \right] \]

The equilibrium diode photocurrent can be seen to be

\[ I_{dp p} = Aq g_0(\gamma) \left[ L_n + L_p + W \right] \quad (B-17) \]

For pulsed transient photoresponse, the complexity of the equation is considerably increased \( (3) \)

A step function response

\[ I_{dp p}(t) = Aq \left[ L_n \text{erf} \left( \frac{t}{\tau_n} \right) + \frac{1}{2} + W u(t) \right] \quad (B-18) \]

Figure B-16 diagrams the minority-carrier concentrations for forward and reverse bias, demonstrating the increase in minority carrier density
Junction

Electron concentration increase due to ionization

\[ n'_p = n_p \left( e^{qV/kt} - 1 \right) \]

Space Charge Region

\[ n'_p (o) = n_{po} \left( e^{qV/kt} - 1 \right) \]

\[ n_{po}, p_{no} = \text{equilibrium concentrations} \]

(a) MINORITY CARRIER CONCENTRATIONS - FORWARD BIAS

Ionization increase

\[ \Delta n_p = g \tau_n \]

\[ \Delta p_n = g \tau_p \]

(b) MINORITY CARRIER CONCENTRATIONS - REVERSE BIAS

High Frequency Diode Model

(d) FIRST ORDER APPROXIMATE MODEL

(c) TYPICAL ALTERATION OF V-I CHARACTERISTIC

Figure B 16  P-N Junction Ideal Diode (1,2,3)
as a result of ionizing radiation absorption. Figure B-16c diagrams the alterations of a diode V-I characteristic. A current generator $i_{dp}(t)$ placed across the junction in parallel with the high frequency model of the device has proven satisfactory as a first-order approximation model.

**THE TRANSISTOR MODELS**

There are three large signal nonlinear models: (1) Ebers-Moll, (2) the Beaufoy-Sparkes Charge Control, and (3) the Linvill Lumped Model, that have been modified for radiation effect computer analysis.

**EBERS-MOLL**

A reversed biased ideal PNP transistor with abrupt junctions, $W_{\text{base}} < L_{\text{base}}$ that is extrinsic and homogeneous in all three regions and that is operating with a low injection level is diagramed in Figure B-17. For the cut-off mode $V_{EB} \ll -\frac{KT}{q}$, $V_{CB} \ll -\frac{KT}{q}$, bias conditions are

\begin{align*}
I_C &= q A_{jc} \left[ \frac{n_{co}}{\tau_{nc}} + \frac{W_b}{2} \frac{p_{bo}}{\tau_{pb}} + \frac{x_c}{c} \frac{n_1}{\tau_{oc}} \right] \\
I_E &= q A_{je} \left[ \frac{n_{eo}}{\tau_{ne}} + \frac{W_b}{2} \frac{p_{bo}}{\tau_{pb}} + \frac{x_e}{e} \frac{n_1}{\tau_{oe}} \right] \\
I_B &= -I_E - I_C \\
&= I_{I_c} + I_{ppc}
\end{align*}

(B-19) (B-20) (B-21)

When ionizing radiation effects are included the equation for equilibrium effects (steady state) are

\begin{align*}
I_C' &= q A_{jc} \left[ \frac{n_{co}}{\tau_{nc}} + g_o(\gamma') \right] + \frac{W_b}{2} \left( \frac{p_{bo}}{\tau_{pb}} + g_o(\gamma') \right) + x_c \left( \frac{n_1}{\tau_{oc}} + g_o(\gamma') \right) \\
&= I_C + I_{ppc} \\
&= I_{I_c} + I_{ppc}
\end{align*}

(B-22)
MINORITY CONCENTRATIONS IN THE CUTOFF MODE - PNP

MINORITY CONCENTRATIONS IN THE ACTIVE MODE - PNP

Figure B 17  PNP Ideal Transistor Minority Carrier Concentrations
Similar to the diode approximation, current generators representing $i_{ppe}$ and $i_{pc}$ placed across the junctions of a transistor high frequency nonlinear model provide a satisfactory first order approximation model.

A nonlinear model (capable of cutoff-active-saturation representation) is necessary because the photocurrents could be sufficient to turn on the device. The photocurrent generators generally replace the leakage current generators in the nonlinear models. The equations for active region operation may be derived by assuming all current is from diffusion and neglecting the space charge layer carrier generation and recombination, then

$$I_E = q A_j e \left[ \frac{d}{dx} P_b'(o) - D n_e'(o) \right]$$

(B-25)

$$I_c = q A_j c \left[ \frac{d}{dx} P_b'(w) - D n_c'(o) \right]$$

(B-26)

Since $P_b'(o)$, $n_e'(o)$, $n_c'(o)$, $P_b'(w)$ are linearly dependent upon $\left(e^{qV_{EB}/KT} - 1\right)$ and $\left(e^{qV_{CB}/KT} - 1\right)$ the form of the classic Ebers-Moll equations is readily verified

$$I_E = I_{ES} \left(e^{qV_{EB}/KT} - 1\right) - \alpha_R I_{CS} \left(e^{qV_{CB}/KT} - 1\right)$$

(B-27)

$$I_C = -\alpha_F I_{ES} \left(e^{qV_{EB}/KT} - 1\right) + I_{CS} \left(e^{qV_{CB}/KT} - 1\right)$$

(B-28)

$$I_B = -I_E - I_C$$

(B-29)
From the cutoff condition

\[ I_{E}^{\prime \text{off}} = - \left( 1 - \alpha_{R} \right) I_{ES} + I_{\text{ppc}} \]  \hspace{1cm} (B-30)

cutoff:

\[ I_{C}^{\prime \text{off}} = - \left( 1 - \alpha_{R} \right) I_{CS} + I_{\text{ppc}} \]  \hspace{1cm} (B-31)

Using the same procedure, the equations for general operation under radiation exposure may be developed

\[ I_{E}(\gamma) = I_{E} + I_{\text{ppc}}(\gamma) \]  \hspace{1cm} (B-32)

\[ I_{C}(\gamma) = I_{C} + I_{\text{ppc}}(\gamma) \]  \hspace{1cm} (B-33)

The photocurrent effects on the device and circuit are compounded by multiplication of the photocurrent. The secondary photocurrent so produced could damage the device if it is sufficiently large.

Figure B-18a diagrams the Ebers-Moll PNP Transistor model and modifications to include the junction capacitance, bulk resistance and the photocurrent generators, B-18b shows the version incorporated in the SCEPTRE program.

**CHARGE CONTROL**

The characterization of the ideal transistor described above is in terms of excess minority carriers. An alternate description is in terms of minority-carrier charge density distribution. Figure B-19 is a diagram of charge density distribution for the active region of operation. The total distribution for the four regions of operation is also shown. This is a direct relationship between this internal charge distribution and the operating region.

Assuming the ideal device for simplicity and recombination processes occur only in the base and are defined by a uniformly constant lifetime \( \tau_{B} \), for steady state conditions the stored excess minority carrier charge \( (+ q_{B}) \) and the equal majority carrier charge \( (- q_{B}) \) are maintained by the base current \( I_{B} \). \( I_{B} \) is defined as a sustaining current which supplies majority electrons at a rate equal to their loss due to recombination in the base. For transient operation, the stored base charge changes with time.
\[ I_F = I_{ES} \left( e^{\frac{qV_{EB}}{KT} - 1} \right) \]
\[ I_R = I_{CS} \left( e^{\frac{qV_{CB}}{KT} - 1} \right) \]

(a) EBERS-MOLL DEVICE MODEL (NPN)  
(TERMNIAL VOLTAGE CONTROL)

NOTE: \( I_{ppc}(t) \gg I_{ppe}(t) \) generally

\[ I_{CO} = (1 - \alpha_R \alpha_F) I_{CS} \]
\[ I_{EO} = (1 - \alpha_R \alpha_F) I_{ES} \]
\[ \theta_N = \frac{q}{\eta KT} \]

(b) SCEPTRE EBERS-MOLL MODEL (PNP)  
(TERMNIAL CURRENT CONTROL)

Figure B.18 The Ebers–Moll First-Order Approximation to \( \gamma \) Effects
(a) MINORITY CARRIER CONCENTRATIONS IN THE BASE FOR THE FOUR REGIONS OF OPERATION

(b) MINORITY CARRIER CONCENTRATIONS IN THE SATURATION REGION

Figure B 19 Excess Minority Carrier Concentrations in the Base Region (PNP)
The stored base charge is composed of forward and reverse components of stored minority carrier charge as shown in Figure 4

\[ q_B = q_F + q_R \]  \hspace{1cm} (B-35)

Therefore

\[ i_B = -\left( \frac{q_F}{\tau_{BF}} + \frac{dq_F}{dt} \right) + \left( \frac{q_R}{\tau_{BR}} + \frac{dq_R}{dt} \right) \]  \hspace{1cm} (B-36)

By assuming that the base charge is limited to relatively slow variations, \( i_c \) and \( i_e \) may be defined. For DC steady state, forward injection only:

\[ i_c = -\frac{\beta_F q_F}{\tau_{BF}} = -\frac{q_F}{\tau_F} \]  \hspace{1cm} (B-37)

For slow variations in \( q_B \), \( i_c \approx i_c \) and

\[ i_e = -i_c - i_b = q_F \left( \frac{1}{\tau_{BF}} - \frac{1}{\tau_F} \right) + \frac{dq_F}{dt} \]  \hspace{1cm} (B-38)

Similar equations can be written for reverse injection \( i_E = -\frac{q_R}{\tau_R} \) and the total expression for terminal currents of an ideal device become

\[ i_c = -\frac{q_F}{\tau_F} + q_R \left( \frac{1}{\tau_R} + \frac{1}{\tau_{ER}} \right) + \frac{dq_R}{dt} \]  \hspace{1cm} (B-39)

\[ i_e = q_F \left( \frac{1}{\tau_F} + \frac{1}{\tau_{BF}} \right) + \frac{dq_F}{dt} - \frac{q_R}{\tau_R} \]  \hspace{1cm} (B-40)

\[ i_B = i_c - i_e \]  \hspace{1cm} (B-41)

(To include saturation, an increase in the base charge is represented by \( \frac{q_{BS}}{\tau_{BS}} \) and \( \frac{dq_{BS}}{dt} \) in parallel with \( \frac{q_F}{\tau_{BS}} \) and \( \frac{dq_F}{dt} \))
Leakage currents $i_{EO}$, $i_{CO}$ are included and space charge layer charge storage is represented by the terms $C_{be} \frac{dV_{eb}}{dt}$ and $C_{ob} \frac{dV_{cb}}{dt}$. In the complete model as shown in Figure B-20 CIRCUS incorporates the charge control model as its radiation model and represents the photocurrents by current generators placed in parallel with $i_{EO}$, $i_{CO}$ exactly as represented in the Ebers-Moll model. The CIRCUS model and its equations are shown in Figure B-21.

THE LUMPED MODEL

The third approach to describing device behavior is the Linvill approach of lumped modeling. The simplest model is the 2-lump model shown in Figure 7. The model is based on a description of excess minority carrier behavior similar to the Ebers-Moll approach. The model shown has parameter definitions that correspond to the charge-control model parameters. Terminal equations for the ideal device are

$$
i_c = -H_D p_{b'}(o) + \left( H_D + H_{CR} \right) p_{b'}(w) + S_R \frac{dp_{b'}(w)}{dt} + C_{VC} \frac{dV_{CB}}{dt} - i_{EO}
$$

$$
i_e = -H_D p_{b'}(w) + \left( H_D + H_{CF} \right) p_{b'}(o) + S_F \frac{dp_{b'}(o)}{dt} + C_{VE} \frac{dV_{EB}}{dt} - i_{CO}
$$

$$
i_b = -i_c - i_e
$$

where the space charge layer charge storage is represented as well as the leakage currents. The radiation version replaces $i_{EO}$, $i_{CO}$ with $i_{ppe}$, $i_{ppc}$ as in the other models. TRAC employs the Linvill model for analysis and the TRAC representation is given in Figure B-22.

CONCLUSIONS

The three program models discussed are first-order approximations for representation of ionizing radiation effects. The three models use identical approaches to the representation of the junction photocurrents $i_{ppe}$, $i_{ppc}$.
\[
q_{BF} = Q_{BF} \left( \frac{qV_e}{e nKT} - 1 \right)
\]
\[
q_{BR} = Q_{BR} \left( \frac{qV_c}{e nKT} - 1 \right)
\]

\[ r_E = 0. \]

\[ V_E = r_b + V_e \]
\[ V_C = r_c - V_c + V_e \]

\[ i_C = \frac{-q_F}{\tau_F} + \frac{qR}{\tau_R} \left( \frac{1}{\tau_R} + \frac{1}{\tau_{BR}} \right) + \frac{dq_R}{dt} + C_{ob} \frac{dV_c}{dt} - i_{CO} \]

\[ i_E = q_F \left( \frac{1}{\tau_{BF}} + \frac{1}{\tau_F} \right) + \frac{dq_F}{dt} - \frac{q_R}{\tau_R} + C_{be} \frac{dV_e}{dt} - i_{EO} \]

\[ i_B = -i_C - i_E \]

Figure B.20  PNP Charge-Control Model for Normal and Inverse Operation

B-46
\[ C_{be} \triangleq \frac{A_1}{\left(\phi_1 - V_e^\prime\right)^n_1} + \theta_N T_{CN} (I_N + I_{es}) \]

\[ C_{bc} \triangleq \frac{A_2}{\left(\phi_2 - V_c^\prime\right)^n_2} + \theta_R T_{CR} (I_R + I_{cs}) \]

\[ I_N = I_{es}\left(\theta_N V_e^\prime - 1\right) \]

\[ I_R = I_{cs}\left(\theta_R V_c^\prime - 1\right) \]

\[ I_{be} \triangleq \left(\frac{1}{\beta_N} + 1\right) I_N - I_R \]

\[ I_{bc} \triangleq -I_N - \left(\frac{1}{\beta_R} + 1\right) I_R \]

\[ \beta_N = F(I_N) \quad \text{Single Valued Parameters} \]

\[ \beta_R = F(I_R) \quad R_b, R_E, R_c, A_1, A_2, n_1, n_2 \]

\[ T_{CN} = F(I_N) \quad \phi_1, \phi_2, I_{es}, I_{cs}, \theta_N, \theta_R \]

\[ T_{CR} = F(I_R) \]

Figure B 21 CIRCUS Model (Charge Control) and Parameters — PNP Device
**Terminal Currents**

\[ i_C (\dot{\gamma}) = -H_D P_b (o) + \left( H_D + H_{CR} \right) P_b (w) + S_R \frac{dP_b (w)}{dt} + C_{VC} \frac{dV_c}{dt} \]

\[ i_E (\dot{\gamma}) = -H_D P_b (w) + \left( H_D + H_{CF} \right) P_b (o) + S_F \frac{dP_b (o)}{dt} + C_{VE} \frac{dV_e}{dt} \]

\[ i_B (\gamma) = -i_C (\gamma) - i_E (\gamma) \]

For analysis without \( i_{ppe} \), \( i_{ppc} \)

Delete the current generators

\[ q_F = S_F P_b (o) \]
\[ q_R = S_R P_b (w) \]
\[ P_b (o) = P_{bo} \left( e^{qV_e/nKT} - 1 \right) \]
\[ P_b (w) = P_{bo} \left( e^{qV_c/nKT} - 1 \right) \]

**Figure B 22  Linvill Two-Lump Model – PNP Including Radiation Pulse Currents**
Figure B 23  TRAC Representation of the Linvill Two-Lump Model — PNP — Including Radiation Photocurrents (prestored)
The variations of Beta with time, injection level and radiation exposure for a given device is complex. A general approach has evolved because most programs require the Beta be either single valued or expressed as a function of current in a simple table. Beta is first computed for the injection level and other 'normal' operating conditions. A degraded Beta for the given flux level is computed from Equation (3) and then degraded by a factor of 2 or 3 to provide a worst-case analysis (The actual transient loss may be this great or greater with a recovery of Beta to its damage value $\beta_F$, dependent upon the device and its exposure.) This approximate analysis is sufficient to indicate the presence of difficulties in the circuit under analysis.

SCEPTRE allows the programming of Beta as a function (equation or tabled expression) and CIRCUS allows a table ($\beta_N = F(I_n)$). The more elaborate expressions for Beta are justified when sufficient laboratory data exists to warrant the increased computer computation time.
**TABLE OF SYMBOLS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{jc}'$, $A_{je}'$, $A_{base}$</td>
<td>Junction area</td>
</tr>
<tr>
<td>$C_{jc}$, $C_{je}$</td>
<td>Incremental capacitance of the junction</td>
</tr>
<tr>
<td>$C_{VC}$, $C_{VE}$</td>
<td>Nonlinear charge store of the junction</td>
</tr>
<tr>
<td>$D$, $D_n$, $D_{pb}$</td>
<td>Charge-carrier diffusion constant (e, p for electrons in p-material, e, b, c for a transistor to denote emitter, base or collector)</td>
</tr>
<tr>
<td>$E$</td>
<td>Electric field</td>
</tr>
<tr>
<td>$g_o$</td>
<td>Carrier generation rate at equilibrium</td>
</tr>
<tr>
<td>$H_{CP}$, $H_{CR}$</td>
<td>Forward and reverse combination parameter of the Linvill model</td>
</tr>
<tr>
<td>$H_D$</td>
<td>Diffusance parameter of the Linvill model</td>
</tr>
<tr>
<td>$I_{co}$, $I_{EO}$</td>
<td>The collector and emitter junction saturation current (opposite junction open)</td>
</tr>
<tr>
<td>$I_{CS}$, $I_{ES}$</td>
<td>The collector and emitter junction saturation current (opposite junction shorted)</td>
</tr>
<tr>
<td>$I_S$</td>
<td>Saturation current of an ideal diode</td>
</tr>
<tr>
<td>$J$</td>
<td>Electric current density</td>
</tr>
<tr>
<td>$K$</td>
<td>Damage constant</td>
</tr>
<tr>
<td>$K_A$, $k$</td>
<td>Boltzmann's Constant</td>
</tr>
<tr>
<td>$L$</td>
<td>Charge carrier diffusion length (see D)</td>
</tr>
<tr>
<td>$N_a$, $N_d$</td>
<td>Acceptor (donor impurity concentration)</td>
</tr>
<tr>
<td>$n(p)$</td>
<td>Electron (hole) concentration</td>
</tr>
<tr>
<td>$n'(p')$</td>
<td>Excess electron (hole) concentration</td>
</tr>
<tr>
<td>$n_i$</td>
<td>Intrinsic carrier concentration</td>
</tr>
<tr>
<td>$q$</td>
<td>Magnitude of the electronic charge</td>
</tr>
<tr>
<td>$q_{B}$</td>
<td>Total excess minority carrier charge stored in the case $q_B = q_F + q_R$ (forward and reverse components)</td>
</tr>
<tr>
<td>$q_{VE}$, $q_{VC}$</td>
<td>Junction space charge layer charge (at $V_g = 0$)</td>
</tr>
<tr>
<td>$r_B$, $r_{E}$, $r_{C}$</td>
<td>Large signal bulk resistances</td>
</tr>
<tr>
<td>$T$</td>
<td>Absolute temperature</td>
</tr>
<tr>
<td>$W$</td>
<td>Width of the base region</td>
</tr>
<tr>
<td>$x$, $x'$, $x''$</td>
<td>Longitudinal coordinate in one dimensional transistor model</td>
</tr>
</tbody>
</table>
\( \alpha_{FR}(\alpha_{R}) \) large signal forward (reverse) injection common base short circuit gain

\( \beta_{FR}(\beta_{R}) \) large signal forward (reverse) injection common emitter short circuit current gain

\( \gamma(t) \) ionizing radiation

neutron flux

\( \varepsilon \) dielectric permittivity

\( \eta \) base width modulation factor

\( \mu \) charge carrier mobility

\( \rho \) space charge concentration

\( \tau \) lifetime of excess charge carriers

\( \theta \) \( \theta = q/\eta kT \)
BIBLIOGRAPHY


APPENDIX C
CURRENT CODING EXAMPLES


Given: The Equivalent Circuit Diagram of a Telemetry Transmitter

![Telemetry Transmitter Circuit]

Figure C.1  Telemetry Transmitter Circuit

![Equivalent Circuit of Telemetry Transmitter for NASAP Analysis]

Figure C.2  Equivalent Circuit of Telemetry Transmitter for NASAP Analysis
Input Codes:

NASAP Input Code

NASAP PROBLEM TELEMETER
I1 1 2 1.0
C1 1 2 100UF
R1 1 2 20K
C2 2 3 2UF
R2 2 3 100
R3 1 3 220
L1 4 1 0.25
C3 2 4 2.0UF
C4 3 1 47UF
C5 3 4 10UF
I2 4 3 0.3 IR2
OUTPUT
WORST CASE
I1/I1
PLOT(TY=FR/FR=80/TO=126)
PLOT(TY=RE/FR=0/TO=100)
ROOTS, POLES
END
PLOT(TY=SE/FR=80/TO=126/EL=DJ1)
PLOT(TY=SE/FR=80/TO=126/EL=CJ3)
PLOT(TY=SE/FR=80/TO=126/EL=LE3)
PLOT(TY=SE/FR=80/TO=126/EL=KE3)
EXECUTE
TREE NASAP PROBLEM TELEMETER
J1(1-2)=1.0
CJ1(1-2)=100MF
RE1(1-2)=20K
CJ2(2-3)=2MF
RJ2(2-3)=100
RE3(1-3)=220
LE1(4-1)=0.25
CJ3(1-4)=LOMF
CE4(3-1)=47MF
CJ5(3-4)=1OMF
DJ2/IRJ2(4-3)=0.3
END
WORST CASE
I1/I1
PLOT(TY=FR/FR=80/TO=126)
PLOT(TY=RE/FR=0/TO=100)
ROOTS, POLES
END
PLOT(TY=SE/FR=80/TO=126/EL=DJ3)
PLOT(TY=SE/FR=80/TO=126/EL=CJ3)
PLOT(TY=SE/FR=80/TO=126/EL=LE3)
PLOT(TY=SE/FR=80/TO=126/EL=KE3)
CIRC(1E6) NASAP PROBLEM TELEMETER
J1(1-2)=1.0
C1(1-2)=100MF
R1(1-2)=20K
C2(2-3)=2MF
R2(2-3)=100
R3(1-3)=220
L1(4-1)=0.25
C3(2-4)=2.0MF
C4(3-1)=47MF
C5(3-4)=10MF
DJ2/IR2(4-3)=0.3
END
WORST CASE
IL1/II1
PLOT(TY=FR/FR=80/TO=126)
PLOT(TY=RE/FR=0/TO=100)
ROOTS, POLES
END
PLOT(TY=SE/FR=80/TO=126/EL=CJ1)
PLOT(TY=SE/FR=80/TO=126/EL=EJ3)
PLOT(TY=SE/FR=80/TO=126/EL=LE1)
PLOT(TY=SE/FR=80/TO=126/EL=KE3)
EXECUTE
STOP
**NASAP**

NETWORK ANALYSIS AND SYSTEMS APPLICATION PROGRAM

THIS VERSION WAS DEVELOPED AT UCLA ENGR. DEPT.

NASAP PROBLEM: TELEMETER

I1 1 2 1.0C
C1 1 2 100
R1 1 2 20K
C2 2 3 2UF
R2 2 3 100
R3 1 3 220
L1 4 1 10e-25
C3 2 4 2.0C
C4 3 1 47UF
C5 3 4 10UF
I2 4 2 0.3 IR2

OUTPUT

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<th>ELEMENT NUMBER</th>
<th>ELEMENT NAME</th>
<th>DEPENDENCY (IF ANY)</th>
<th>ORIGIN NODE</th>
<th>TARGET NODE</th>
<th>VALUE</th>
<th>TAG</th>
<th>GENER</th>
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<td>C4</td>
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2  2  304  10  
3  6  1556  2096  
4  7  2048  1280
WORSTCASE

ELEMENT NAME | TOLERANCE
--- | ---
C1 | 0.1000
R1 | 0.1000
C2 | 0.1000
R2 | 0.1000
R3 | 0.1000
L1 | 0.1000
C3 | 0.1000
C4 | 0.1000
C5 | 0.1000
I2 | 0.1000

FLOWGRAPH
FROM | TO | VALUE
--- | --- | ---
2 | 13 | 1.00000039E-04
14 | 3 | 4.5998878E-05
15 | 4 | 1.599886E-05
16 | 5 | 5.998869E-03
6 | 17 | 2.00CC00E 02
7 | 18 | 2.4998981E-01
19 | 8 | 1.599886E-05
20 | 9 | 4.698665E-05
21 | 10 | 9.599934E-06
5 | 11 | 2.599886E-01
4 | 2 | 1.000000E 00
13 | 15 | 1.000000E 00
5 | 2 | 1.000000E 00
13 | 16 | 1.000000E 00
8 | 2 | 1.000000E 00
13 | 19 | 1.000000E 00
1 | 2 | 1.000000E 00
13 | 12 | 1.000000E 00
3 | 2 | 1.000000E 00
13 | 14 | 1.000000E 00
9 | 6 | 1.000000E 00
17 | 20 | 1.000000E 00
10 | 6 | 1.000000E 00
17 | 21 | 1.000000E 00
4 | 6 | 1.000000E 00
17 | 15 | 1.000000E 00
5 | 6 | 1.000000E 00
17 | 16 | 1.000000E 00
11 | 6 | 1.000000E 00
17 | 22 | 1.000000E 00
8 | 7 | 1.000000E 00
18 | 19 | 1.000000E 00
10 | 7 | 1.000000E 00
18 | 21 | 1.000000E 00
11 | 7 | 1.000000E 00
18 | 22 | 1.000000E 00
\textbf{ILI/III}

\textbf{NTIMES} = 1

\textbf{THE UNKNOWN TRANSMITTANCE COES FROM NODE} 7 TO 1

\textbf{24588} 5999

\begin{align*}
1180224 & \quad 288001 \\
3057108 & \quad 746003 \\
3089892 & \quad 754002 \\
786816 & \quad 192002 \\
3057108 & \quad 146003 \\
3089892 & \quad 754002 \\
3091940 & \quad 1778002 \\
236044 & \quad 576002 \\
2600180 & \quad 1658002 \\
462628 & \quad 1234001 \\
2559200 & \quad 1648002 \\
1626548 & \quad 1274002 \\
239732 & \quad 1662000 \\
2305254 & \quad 1587000 \\
75942 & \quad 1042999 \\
239862 & \quad 1083000 \\
198752 & \quad 1072000 \\
40980 & \quad 10000 \\
237684 & \quad 58000 \\
237684 & \quad 58000 \\
2270422 & \quad 555001 \\
73764 & \quad 17999 \\
2303206 & \quad 563000 \\
532740 & \quad 130000 \\
532870 & \quad 131000 \\
2229312 & \quad 544001 \\
163920 & \quad 40001 \\
196704 & \quad 48000
\end{align*}
NO. OF FIRST ORDER LOOPS = 29
1
2
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6
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8
9
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28
29
TRANSFER FUNCTION

\[ 5 \cdot 88 \times 10^{-4} + 4 \cdot 282 \times 10^{-4} C_s + 1 \cdot 0000 \times 000 + 0 \times 0 + 0 \times 0 \]

\[ 2 \cdot 54 \times 10^{-8} + 1 \cdot 56 \times 10^{-7} C_s + 3 \cdot 65 \times 10^{-7} C_s + 3 \cdot 65 \times 10^{-7} 02s + 1 \cdot 0000 \times 000 \]

THE FACTOR IS: \( -8 \times 78 \times 10^{-4} C_3 \)
SENSITIVITY TC C1

\[
0 \cdot 0 + 1 \cdot 0154E 08 \cdot 3 \cdot 6E2E 05S + 2 \cdot 0069E 02S + 1 \cdot 0000E 00S
\]

-----------------------------

\[
2 \cdot 940E 09 + 1 \cdot 509E 08S + 3 \cdot 54E 05S + 3 \cdot 65E 02S + 1 \cdot 0000E 00S
\]

THE FUNCTION FACTOR = \(-5 \cdot 671E-01\)

| \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) |
| \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) |
| \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) |
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| \(5 \cdot 2176E 00\) | \(1 \cdot 00103E-02\) | \(1 \cdot 00138E-05\) | \(3 \cdot 5773E-08\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(1 \cdot 01930E 02\) |
| \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) |
| \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) |
| \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) |
| \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) |
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| \(0 \cdot 0\) | \(0 \cdot 0\) | \(-3 \cdot 66000E 00\) | \(-1 \cdot 029600E-02\) | \(-6 \cdot 95E 08-06\) | \(-3 \cdot 24399E-08\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) |
| \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) | \(0 \cdot 0\) |
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SENSITIVITY TO A1

\[-1.140E13 \quad -4.0329E10S \quad +6.853E7TS \quad +2.765E05S \quad +2.533E02S \quad +1.0000E00S\]

\[+0.0\]

\[+2.165E05S \quad +2.533E02S \quad +1.0000E00S \quad +0.0\]

\[-2.513E14 \quad -1.504E13S \quad -4.257E10S \quad +5.841E05S \quad +3.422E02S \quad +1.0000E00S\]

THE FUNCTION FACTOR = \[4.636E-01\]

\[0.0\]

\[0.0\]

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\[C.0\]

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SENSITIVITY TC C2

\[ 0 = 0 + 4.905E 11S + 2.154E 10S + 2.656E 09S + 5.740E 08S + 1.000E 07S \]

\[ - 2.513E 14 - 1.804E 13S - 4.250E 10S + 9.575E 07S + 2.084E 05S + 3.042E 03S + 1.000E 01S \]

THE FUNCTION FACTOR = \(-1.817EE-41\)
SENSITIVITY TO R2

\[
2.543E 09 + 7.858E 09 + 1.307E 05 + 4.027E 05 + 3.403E 08 + 1.000E 00 + 0.0
\]

\[
- 2.913E 14 - 1.504E 13 - 4.298E 10 + 9.525E 07 + 2.641E 05 + 3.422E 02 + 1.000E 00
\]

THE FUNCTION FACTOR = 4.033E 02
### Sensitivity to R3

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The function factor = -2.467E+01
## Sensitivity TC Li

\[
Q_0 + C_0 + 9.143E08S - 3.844E07S - 1.006E05S + 3.422E02S + 1.000E05S
\]

\[
- 2.913E14 - 1.004E13S - 4.258E10S + 9.575E07S + 2.041E05S + 3.422E02S + 1.000E05S
\]

The function factor = \(1.000E00\)

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**C-14**

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**SENSITIVITY TO C3**

\[ C_0 + 1.494 \times 10^{-12} S + 6.454 \times 10^{-10} S + 6.464 \times 10^{-8} S + 7.934 \times 10^{-6} S + 1 \times 10^{-4} S \]

\[ - 2.913 \times 10^{-14} - 1.494 \times 10^{-12} S - 4.928 \times 10^{-10} S + 9.575 \times 10^{-8} S + 2.841 \times 10^{-6} S + 3.422 \times 10^{-4} S + 1 \times 10^{-2} S \]

**THE FUNCTION FACTOR =** \[-6.494 \times 10^{-1} \]
SENSITIVITY TC C4

\[ \begin{align*}
0.0 & + 1.698E \times 10^1 S + 4.28E \times 10^1 S + 1.352E \times 10^6 S + 3.272E \times 10^3 S + 1.000E \times 10^0 S \\
\end{align*} \]

\[ \begin{align*}
- 2.913E \times 10^4 S - 1.504E \times 10^3 S - 4.28E \times 10^0 S \\
\end{align*} \]

THE FUNCTION FACTOR = \( 2.489E-01 \)

\[ \begin{align*}
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\end{align*} \]
SENSITIVITY TO C5

\[
0.0 \quad -5.0 \times 10^{-1} \quad 12S \quad 2 \quad -6.536 \times 10^{-3} \quad 00S \quad -7.576 \times 10^{-5} \quad 05S \quad -1.001 \times 10^{-3} \quad 03S \quad +1.000 \times 10^{-6} \quad 00S
\]

\[
-2.913 \times 10^{-1} \quad -1.524 \times 10^{-1} \quad 12S \quad 2 \quad -2.982 \times 10^{-2} \quad 00S \quad +2.841 \times 10^{-4} \quad 02S \quad +3.422 \times 10^{-6} \quad 02S \quad +1.000 \times 10^{-8} \quad 00S
\]

THE FUNCTION FACTOR = \[5.513 \times 10^{-1} \]

\[
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### Sensitivity to I2

\[ 2 \times 926E+11 + 1 \times 594E+05 + 1 \times 877E+08 + 4 \times 53E+05 + 3 \times 9790E+02 + 1 \times 000E+00 + 0 \times 0 \]

\[ - 2 \times 913E+14 - 1 \times 504E+13 - 4 \times 2E+10 + 2 \times 64E+07 + 2 \times 841E+05 + 3 \times 422E+02 + 1 \times 000E+00 \]

The function factor = \( 9 \times 923E+02 \)

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SQUARE CF WORST CASE TOLERANCE

\[ 3.082 \times 10^{28} + 3.406 \times 10^{27} + 2.323 \times 10^{26} + 3.244 \times 10^{25} + 1.376 \times 10^{24} + 3.456 \times 10^{23} + 7.276 \times 10^{22} + 1.000 \times 10^{21} \]

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INTERVAL = 2.95010E-03

0 ≤ x ≤ 10.0

...
*** SVORQCA POLYNOMIAL ROOTFINDER ***

POLYNOMIAL OF DEGREE 4

0.101929927E 03 X 0.5217680531E 01 X 0.1381032541E-01 X 0.1331278280E-04 X 0.3457731168E-07 X

ACCURACY REQUESTED -- 6 SIGNIFICANT FIGURES

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C-27
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PLOT(TY=SE/FR=80/TC=126/EL=C1)

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C-28
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Sensitivity with respect to TC 12

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### NETWORK ANALYSIS AND SYSTEM APPLICATION PROGRAM

THIS VERSION WAS DEVELOPED AT UCLA ENGR CEPT.

**TREE**
- **NASAP PROBLEM TELEMETER**
- **J1(1-2)=1000**
- **CJ1(1-2)=100MF**
- **REL(1-2)=20K**
- **CJ2(2-3)=2MF**
- **RJ2(2-3)=100**
- **LEI(4-1)=1025**
- **CJ3(2-4)=20OMF**
- **REL(1-3)=2200**
- **CJ4(3-1)=57MF**
- **DJ2/IRJ2(4-3)=40**

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   2608376    1660003
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   2559260    1448002
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   2313450    1589001
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C-51
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TRANSFER FUNCTION

\[ 2.881 \times 10^{-2} + 5.681 \times 10^{-4} + 4.2 \times 10^{-2} + 3.948 \times 10^{-4} * C_4 + 5.00 \times 10^{-2} \]

\[ + 0.681 \times 10^{-2} C_5 + 1.50 \times 10^{-2} C_6 + 3.94 \times 10^{-4} C_7 + 3.94 \times 10^{-4} C_8 + 1.00 \times 10^{-2} \]

THE FUNCTION FACTOR = \(-8.78 \times 10^{-2} \)

C-52
SENSITIVITY TO CJ1

\[ \begin{align*}
\text{C}_0 & \quad 1.141E-13 & \quad -4.338E-10 & \quad +6.947E-07 & \quad +2.766E-05 & \quad +2.541E-02 & \quad +1.000E-00 & \quad -2.913E-14 \\
\text{C}_1 & \quad 2.310E-13 & \quad -1.504E-10 & \quad +5.298E-07 & \quad +2.841E-05 & \quad +3.422E-02 & \quad +1.000E-00 & \quad -2.301E-14 \\
\text{C}_2 & \quad 3.671E-13 & \quad -1.504E-10 & \quad +5.298E-07 & \quad +2.841E-05 & \quad +3.422E-02 & \quad +1.000E-00 & \quad -2.301E-14 \\
\text{C}_3 & \quad 4.000E-13 & \quad -1.504E-10 & \quad +5.298E-07 & \quad +2.841E-05 & \quad +3.422E-02 & \quad +1.000E-00 & \quad -2.301E-14 \\
\text{C}_4 & \quad 4.371E-13 & \quad -1.504E-10 & \quad +5.298E-07 & \quad +2.841E-05 & \quad +3.422E-02 & \quad +1.000E-00 & \quad -2.301E-14 \\
\text{C}_5 & \quad 4.700E-13 & \quad -1.504E-10 & \quad +5.298E-07 & \quad +2.841E-05 & \quad +3.422E-02 & \quad +1.000E-00 & \quad -2.301E-14 \\
\text{C}_6 & \quad 5.000E-13 & \quad -1.504E-10 & \quad +5.298E-07 & \quad +2.841E-05 & \quad +3.422E-02 & \quad +1.000E-00 & \quad -2.301E-14 \\
\end{align*} \]

THE FUNCTION FACTOR = 5.671E-13
Sensitivity to REL

\[
1 \times 10^4 E \quad + \quad 3 \times 8.82 E \quad 0.05 \quad + \quad 2 \times 9.69 E \quad 0.02 \quad + \quad 1 \times 10^6 E \quad 0.05 \quad + \quad 0 \times 0.0
\]

\[
2 \times 9.48 E \quad 0.05 \quad + \quad 1 \times 5.09 E \quad 0.08 \quad + \quad 3 \times 5.54 E \quad 0.05 \quad + \quad 3 \times 8.50 E \quad 0.02 \quad + \quad 1 \times 10^6 E \quad 0.05
\]

The function factor = \(-4.636E-01\)

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SENSITIVITY TO CJ2

0 0  + 4.905E 11 5  + 2.154E 10 5  + 2.665E 08 5  + 4.656E 05 5  + 5.740E 02 5  + 1.000E 00 5

- 2.913E 14  - 1.504E 13 5  - 4.268E 10 5  + 9.575E 07 5  + 2.841E 05 5  + 3.422E 02 5  + 1.000E 00 5

THE FUNCTION FACTOR = -1.178E-11
SENSITIVITY TO RJ2

\[ 3.543 \times 10^9 + 7.856 \times 10^8 + 1.3 \times 10^7 + 4.279 \times 10^5 + 3.403 \times 10^3 + 1.000 \times 10^0 + 0.0 \]

\[ - 2.913 \times 10^{-14} - 1.504 \times 10^{-13} - 4.296 \times 10^{-10} + 1.3 \times 10^{-8} + 2.041 \times 10^{-5} + 3.422 \times 10^{-2} + 1.000 \times 10^0 + 0.0 \]

THE FUNCTION FACTOR = \[ 4.332 \times 10^2 \]
SENSITIVITY TO RES

\[ \begin{align*} 
1.6598 \times 10^1 & + 4.828 \times 10^1 & + 1.2357 \times 10^1 & + 1.352 \times 10^1 & + 2.72 \times 10^1 & + 1.0 \times 10^0 & + 0.0 \\
-2.613 \times 10^1 & - 1.064 \times 10^1 & - 4.298 \times 10^1 & - 9.375 \times 10^1 & - 2.841 \times 10^1 & - 3.422 \times 10^1 & + 1.0 \times 10^0 & + 0.0 \\
\end{align*} \]

\[ \text{THE FUNCTION FACTOR} = -2.4 \times 10^1 \]
**SENSITIVITY TO LE1**

\[
0_0 + 0_0 - 3.844E-07S - 3.422E+02S + 1.000E+00S \\
- 2.913E 14 - 3.894E 13S - 4.979E 07S + 2.841E 05S + 3.422E 02S + 1.000E 00S
\]

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**THE FUNCTION FACTOR = 1.000E 00**

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SENSITIVITY TO CJ3

0.0 + 1.0494E 12S + 6.0454E 10S + 3.0640E 08S + 6.0985E 06S + 7.0934E 04S + 1.0000E 02S

- 2.913E 14 - 1.564E 13S - 4.02E 09S + 9.5755E 07S + 2.0841E 05S + 3.0422E 03S + 1.0000E 01S

THE FUNCTION FACTOR = -6.0454E-01
SENSITIVITY TC CJ4

\[ \begin{align*}
0.0 & + 1.0658E 11S + 4.328E 11S + 1.257E 09S + 1.352E 06S + 3.027E 03S + 1.000E 00S \\
- 2.913E 14 & - 1.504E 13S - 4.228E 10S - 9.575E 07S + 2.841E 05S + 3.422E 02S + 1.000E 00S
\end{align*} \]

THE FUNCTION FACTOR = \[ 2.480E-01 \]
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THE FUNCTION FACTOR = 5.51E-C1
SENSITIVITY TO DJ2

\[ 2 \times 526E \ 11 + 1 \times 599E \ 10S + 1 \times 877E \ 08S + 4 \times 53E \ 05S + 4 \times 790E \ 02S + 1 \times 000E \ 00S + 0 \times 0 \]

\[ - 2 \times 513E \ 14 - 1 \times 504E \ 13S - 4 \times 558E \ 10S + 9 \times 575E \ 07S + 2 \times 841E \ 05S + 3 \times 422E \ 02S + 1 \times 000E \ 00S \]

THE FUNCTION FACTOR = 9 \times 923E \ 02
### Square of Worst Case Tolerance

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### The Function Factor = 2.737E-02

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### Calculations

- \(3.082 \times 10^{-28} + 3.406 \times 10^{-27}S + 2.323 \times 10^{-26}S + 3.244 \times 10^{-24}S + 3.197 \times 10^{-22}S + 1.376 \times 10^{-20}S + 3.456 \times 10^{-17}S + 7.276 \times 10^{-14}S\)
- \(1.070 \times 10^{-12}S + 9.990 \times 10^{-08}S + 1.166 \times 10^{-06}S + 5.955 \times 10^{-02}S + 1.000 \times 10^{00}S\)

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The function factor is \(2.737 \times 10^{-02}\)
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Note: The above table represents the frequency, magnitude, and coefficients as per the given context. Each row corresponds to a specific frequency, with columns indicating the magnitude and coefficients for different exponential sections of the response. The calculations are based on the provided coefficients and the exponential terms. The transparency is calculated using these coefficients and the exponential terms for each frequency point.
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ACCURACY REQUESTED -- 6 SIGNIFICANT FIGURES

REAL PART  IMAGINARY PART  EXPONENT
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0.000000000 -6.260100000  2
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POLYNOMIAL OF DEGREE 2 --

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ACCURACY REQUESTED -- 6 SIGNIFICANT FIGURES

REAL PART  IMAGINARY PART  EXPONENT
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C-72
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**NASAPTEMP**

**NETWORK ANALYSIS AND SYSTEMS APPLICATION PROGRAM**

**THIS VERSION WAS DEVELOPED AT UCLA ENGRC DEPT.**

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