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CIRAN B LINEAR CIRCUIT-ANALYSIS PROGRAM--
USER'S MANUAL

G. S. Tool and Joseph E. Katz

April 15, 1968

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Contents

Abstract v
1. Introduction 1
2. Defining the Analysis Problem 2
3. Example Problem 3
4. Scaling of Component Values 9
5. Limitations and Restrictions 10
6. CIRAN B Problem Description Language 10
Acknowledgments 21
References. 21

CIRAN B LINEAR CIRCUIT-ANALYSIS PROGRAM--USER'S MANUAL*

Lawrence Radiation Laboratory
University of California
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Abstract

CIRAN B is a computer program used to perform ac steady-state analysis and transient analysis of linear networks. The circuit schematic and analysis options are described to the program by means of the CIRAN B problem-description language. The problem-description language is a format-free means of describing a circuit-analysis problem in terms familiar to circuit designers. This report is designed to serve as a user's manual for the CIRAN B program.

An example of a typical circuit-analysis problem is presented to illustrate the many conveniences built in to enable the user to rapidly describe his circuit analysis problem to the computer program. A means of obtaining graphical output which can superimpose related curves for variational analysis on the same frame is described and illustrated by the sample problem.

*Work done under auspices of the U. S. Atomic Energy Commission.
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1. Introduction

The mathematical analysis of electronic circuits containing more than a few elements is a tedious task at best when attempted by manual methods. Many simplifications are usually made to reduce the circuit to be analyzed to bare essentials in order to reduce the labor required in the analysis. These simplifications often remove important parts of the circuit, and the circuit being analyzed may have quite different characteristics from those of the actual circuit. This is especially true when one is interested in the fast-pulse response or high-frequency response of the circuit.

The modern digital computer can be utilized to greatly reduce the labor required in circuit analysis. There are now many computer programs that perform some part of the circuit-analysis function. Some of these do only parts of the task, such as matrix inversion, whereas other programs are capable of producing several different types of analysis starting from a simple description of the circuit schematic.

CIRAN B is a general program used to perform steady-state ac analysis and transient analysis of linear networks. The circuit schematic and the analysis options desired are described to the program by means of the CIRAN B problem-description language. The steps an engineer would take to analyze a circuit for which he has a schematic are:

(i) Draw an ac-equivalent circuit for the circuit to be analyzed.
(ii) Number the nodes in the resulting circuit sequentially starting with the number 1.
(iii) Label each component in the circuit; the first letter of the label is determined by the type of component.
(iv) Write a description of the circuit and the problem, using the CIRAN B problem-description language.
(v) Have cards punched containing the problem-description language statements.
(vi) Submit the problem to the computer.
(vii) Review the results obtained from the computer.

As one can deduce from the above procedure, CIRAN B does not create a circuit design nor does it optimize an existing design. However, its analysis capabilities can be used to great advantage in the overall design process.

CIRAN B is a modified version of a linear circuit-analysis program written at the University of Illinois under the direction of D. A. Calahan. This program has received wide-spread use under various names such as CIRAN II and CALAHAN.[1] This CIRAN B version does exactly the same mathematical analyses as the previous versions, with the following features added as conveniences to the user.

(i) An input language which is relatively format-free, more easily remembered, and more mnemonically descriptive of the circuit and problem.
(ii) A "library" of input waveforms for use in transient analysis.
(iii) The capability of changing the analysis options and of altering the values of an arbitrary number of components for variational analysis without redefining the complete problem.

(iv) The capability of adding or deleting components from the circuit for variational analysis without redefining the complete problem.
(v) The writing of a plot tape for use by an additional plotting program, removing restrictions concerned with the actual plotting media from the analysis program. The plotting program can superimpose related curves from variational analysis on the same graph frame.

2. Defining the Analysis Problem

The CIRAN B program provides any or all of the following results relating input and output node pairs, starting with a description of the circuit.
(i) Network function in the form of numerator and denominator polynomials. The network functions available are:

- Open-circuit voltage transfer ratio.
- Open-circuit input impedance.
- Open-circuit transfer impedance.
- Short-circuit input admittance.
- Short-circuit transfer admittance.
- Short-circuit current transfer ratio.

(ii) Poles and zeros of the network function.
(iii) Network function in symbolic form.
(iv) Frequency response of the network function over a given frequency range.
(v) Transient response of the network to a given input waveform for a given duration of time.

Starting with a schematic of the electronic circuit, the engineer must generate a linear ac-equivalent circuit to adequately represent the small-signal behavior of the circuit being analyzed. The component types allowed by the program are:

- resistance,
- capacitance,
- inductance,
- mutual inductance,
- voltage-controlled current source.

Any active components such as transistors or vacuum tubes must be replaced by a combination of the above components.

Once a suitable ac-equivalent circuit has been obtained, the next step is to number all the nodes in the circuit in any convenient order, starting with the integer 1 and proceeding sequentially through the integer value corresponding to the total number of nodes in the circuit.

The next step is to assign a name to each of the circuit components. The name consists of 1 to 7 characters, with the first character designating the element type according to the following table:

Character	Component type
R	Resistance
C	Capacitance
L	Self-inductance
M	Mutual inductance
G	Voltage-controlled current source

After the circuit components are labeled, the problem is described to the computer program by use of the CIRAN B problem-description language.

3. Example Problem

As an example, the analysis of a three-stage differential video amplifier circuit[2] shown in Fig. 1 upper is detailed to illustrate the use of the CIRAN B program. The ac-equivalent circuit of the video amplifier is shown in Fig. 1 lower.

In this example the hybrid-pi model is used to represent the transistor equivalent circuit. The hybrid-pi transistor equivalent circuit model is described by Searle, Boothroyd, et al.[3] This equivalent-circuit model is particularly useful because generally the necessary parameters are available from most transistor specification sheets. The transistor used in this example is assumed to have the following parameters:

$$h_{fe} = 60,$$
$$h_{re} = 1\times10^{-4},$$
$$h_{oe} = 10\times10^{-6} \text{ mhos},$$
$$f_t = 1 \text{ GHz},$$
$$C_{be} = 2 \text{ pF},$$
$$R_{bb} = 30 \text{ ohms}.$$

After the nodes and elements of the ac-equivalent circuit have been labeled, one is ready to describe the problem using, the CIRAN B input language (see Section 6). The values of the ac-equivalent circuit elements should be appropriately scaled (as explained in Section 4).

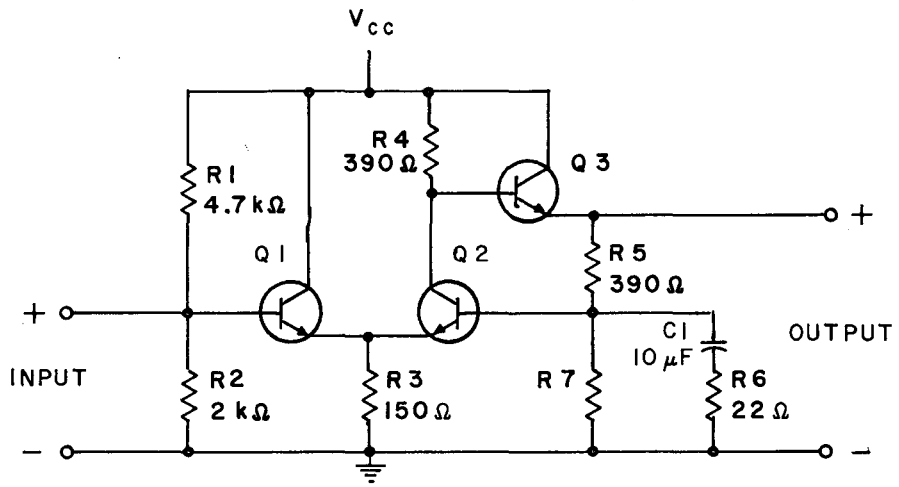
A listing of the CIRAN B problem-description language necessary to analyze the circuit represented in Fig. 1 is shown in Table I.

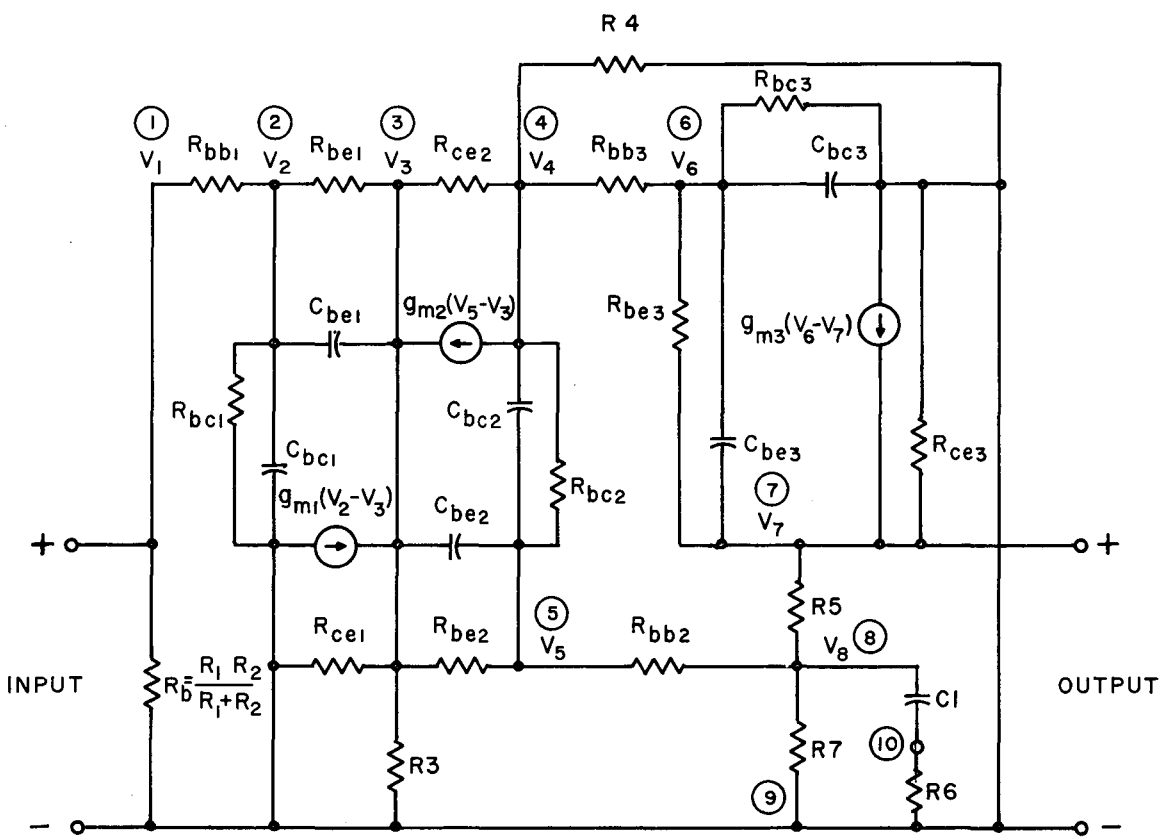
The circuit component values, listed in Table I, have been scaled to a microsecond-kilohm-nanofarad system of units; see Set 3 of Table II.

The CIRAN B program includes, as a portion of its output, plots of the voltage transfer function for four values of R6: 140, 51, 22, and 0 ohms (see Figs. 2 and 3).

The transient response of the video amplifier circuit to a unit step function input is shown in Fig. 4 for each of the four values of R6.

Limitations and restrictions on the number, size, and type of circuit elements that may be handled are discussed in Section 5. Analysis of a circuit of this size and complexity is very efficiently handled by the CIRAN B program. The total Central Processor time required, on a CDC 6600 computer, to do the analysis and plotting for this problem was 91 seconds.



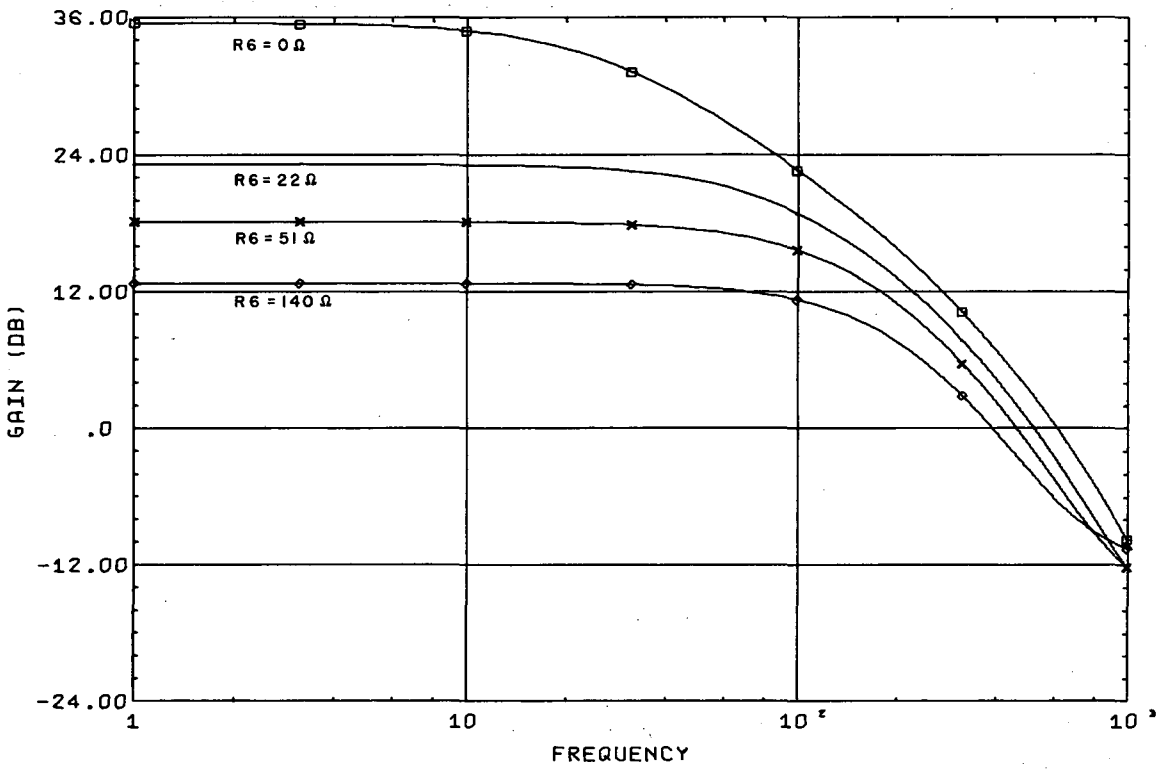


XBL 685-806

Fig. 1 (upper) Video amplifier circuit diagram.
(lower) Video amplifier ac-equivalent circuit.

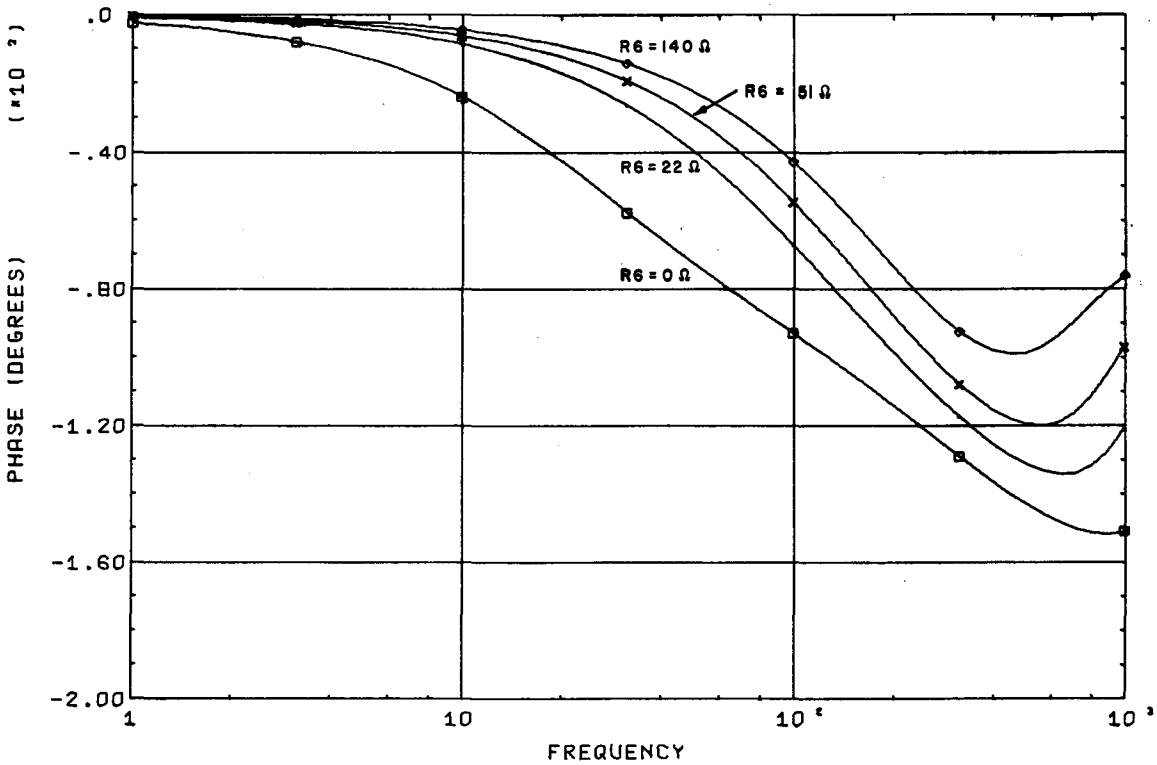
Table I. Listing of CIRAN B input language necessary to define the analysis problem.

```
VIDEO AMPLIFIER FROM PAGE 86 OF THE 7/10/67 ISSUE OF ELECTRONICS
FREQUENCY RESPONSE
  PLOT,GAIN,PHASE
  LOG,1,1000
TRANSIENT RESPONSE
  PLOT,RESPONSE
CONTINUOUS,STEP,1,0.2,0.002
INPUT = 1-9
OUTPUT = 7-9
FUNCTION = VOLTAGE TRANSFER
VARIABLE ELEMENT
  R6 = .051, .022
ELEMENTS
RB, 1-9 = 1.4
RBB1, 1-2 = .03
RBE1, 2-3 = .159
RCE2, 4-3 = 100
CBE1, 2-3 = .061
RBC1, 2-9 = 100
CBC1, 2-9 = .002
GM1, 9-3, 2-3 = 385
RCE1, 9-3 = 100
R3, 9-3 = .15
GM2, 4-3, 5-3 = 385.
CBC2, 4-5 = .002
RBC2, 4-5 = 100
CBE2, 3-5 = .061
RBE2, 3-5 = .159
R4, 4-9 = .39
RBB3, 4-6 = .03
RBE3, 6-7 = .159
CBE3, 6-7 = .061
RBC3, 6-9 = 100
CBC3, 6-9 = .002
GM3, 9-7, 6-7 = 385.
RCE3, 9-7 = 100
R5, 7-8 = .39
RBB2, 5-8 = .03
R7, 8-9 = .36
C1, 8-10 = 10000
R6, 10-9 = .140
ALTER
DELETE, R6, C1
ADD
  C1, 8-9 = 10000
VARIABLE ELEMENT
  NONE
END
END OF JOB
```



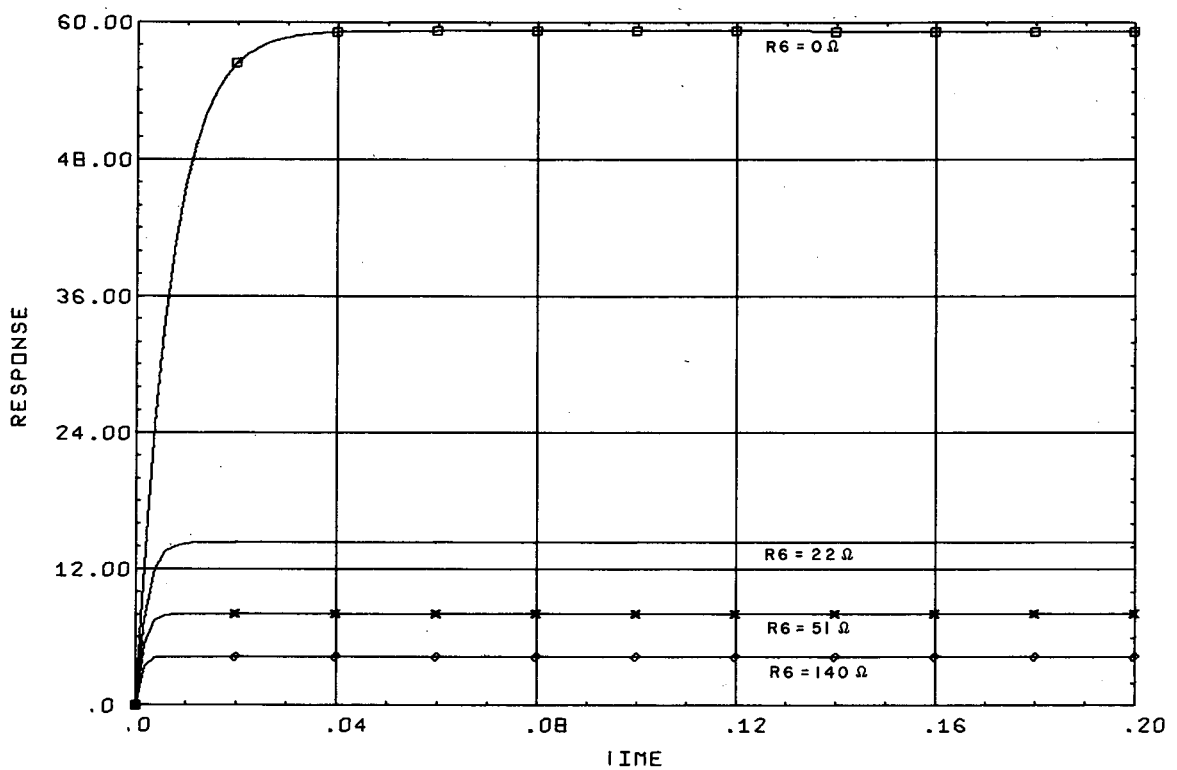
XBL 685-807

Fig. 2. Gain as a function of frequency; voltage transfer function, video amplifier from page 86 of the 7/10/67 issue of Electronics.



XBL 685-808

Fig. 3. Phase as a function of frequency; voltage transfer function, video amplifier from page 86 of the 7/10/67 issue of Electronics.



XBL 685-809

Fig. 4. Response as a function of time; voltage transfer function, video amplifier from page 86 of the 7/10/67 issue of Electronics.

4. Scaling of Component Values

In principle, CIRAN B will conduct the analysis of a circuit whose component values are expressed in any self-consistent set of units. However, the algorithms used to locate the roots of the network polynomials and to perform the numerical integration for arbitrary transient analysis make it highly desirable to scale the component values. A consistent set of units should be chosen that results in circuit values (in particular, time constants) that center about the value 1.0. Exact compliance is not required, but this should be achieved within a few orders of magnitude.

A scaled self-consistent set of units may be obtained from any existing set (i.e., MKS) by satisfying the following relationships:

$$S_T = S_R S_C,$$
$$S_T = \sqrt{S_L S_C},$$
$$S_V = S_I S_R,$$

where S_i is a scaling multiplier, and the subscripts refer to the circuit quantities as follows:

T – time,
R – resistance,
C – capacitance,
L – inductance,
V – voltage,
I – current.

Several self-consistent sets of units are given in Table II. Most electronic circuit problems can be satisfactorily expressed in one of these sets. When the elements have been properly scaled, the majority of the network function polynomial coefficients will be of similar order of magnitude.

Table II. Self-consistent sets of units.

Quantity	Units			
	Set 1	Set 2	Set 3	Set 4
T	sec	millisec	microsec	nanosec
R	ohm	kilohm	kilohm	kilohm
C	farad	microfarad	nanofarad	picofarad
L	henry	henry	millihenry	microhenry
V	volt	volt	volt	volt
I	amp	milliamp	milliamp	milliamp

5. Limitations and Restrictions

The use of CIRAN B is subject to the following limitations and restrictions:

- 50 passive elements.
- 10 active elements.
- 12 or 13 nodes is the practical limit for the number of nodes--above this, the time taken for analysis is prohibitive.
- 20 values for the variable element.
- All nodes must be connected (i.e., a path must exist between any two nodes).
- A zero value of resistance or inductance is not allowed.
- A zero value for a capacitance or current generator is allowed with the restriction that only the last value to be assigned to a variable element may be zero.
- Two or more elements across the same node pair must have their nodes listed in the same order on their respective element cards.
- When a transient analysis is requested, the time step size requested should be smaller than the smallest time constant in the network.
- The results given by computer programs of this type should always be reviewed in the light of common sense and experience to verify that the answers are reasonable.

6. CIRAN B Problem-Description Language

The circuit-analysis problem is described to the program by means of the CIRAN B problem-description language. This language is composed of three types of statements:

(i) word description of problem,
(ii) primary statements,
(iii) secondary statements.

Each problem to be analyzed is described on a set of punched cards referred to as a data set. The organization of the data cards is subject to the following rules.

(i) The first card in each set is a word description to be used as identification on printed and plotted output.
(ii) The last card in each set is an END card.
(iii) A "complete problem description" must precede any ALTER cards.
(iv) An ELEMENTS card may not occur in the same data set after the first ALTER card.
(v) Secondary statements refer to the last preceding primary statement.
(vi) The last data set must be followed by an END OF JOB card. Except as noted above, the order of primary and secondary statements in a data set is immaterial. The statements are punched on the cards in a field-free format, i.e., there is no need to place particular symbols in specific columns of the card; blanks may be used freely for visual clarity and are ignored by CIRAN B. Wherever punctuation such as equal signs (=) and dashes (-) are shown in the statement descriptions that follow, a comma (,) may be substituted if desired. Node numbers are integers; all other values may be expressed in any of the following forms: 100, 100., 100.0, 1.0E2, 1E2.

Word Description Card

As indicated above, each data set begins with a single card on which the program user may punch descriptive information to identify the problem or case. The entire card may be blank, but the card must be present as the first card of each data set.

Primary and Secondary Statements

The primary statements and their associated secondary statements describe the circuit to be analyzed and the analysis options desired. Key words are used in each statement to indicate its purpose. Whenever a key word is required in a primary statement, only the first three letters of the key word are required for recognition by the program. (The single exception to this is the END OF JOB statement.) In a secondary statement only the first two letters are required. The primary statement types are listed below.

* ELEMENTS
VARIABLE ELEMENT
* FUNCTION
* INPUT
* OUTPUT
FREQUENCY
TRANSIENT
SYMBOLIC
\# NUMERATOR
\# DENOMINATOR
ALTER
NEW VALUES
TITLE
DELETE
ADD
END
END OF JOB

A "complete problem description" must include, as a minimum, one of each of the cards indicated by the symbol (*) or, alternatively, one of each of the cards indicated by the symbol (#). Each of the primary statements and its associated secondary statements are described in detail in the following paragraphs. An example of each statement is shown with the essential characters underlined. All other characters in the examples are superfluous and included only for readability.

ELEMENTS Card

This card indicates to the program that a set of secondary cards describing the elements of the circuit is to follow.
Example: ELEMENTS. Each element of the circuit is described on a separate card. Any two elements in parallel must have their terminal node numbers given in the same order.

Passive elements

Resistors, inductors, and capacitors are described by the format
name, node - node 2 = value .

Example: A 2.5-kilohm resistor, R1, connected between nodes 4 and 7 might be described as

R1, 4-7 = 2.5 .

Active elements and mutual inductance

Voltage-controlled current sources are described by the format

name, node 1 - node 2, node 3 - node 4 = value ,

where the direction of current is from node 1 to node 2; node 3 is the positive control node, and node 4 is the negative control node.

Example: A current source, GM1, between nodes 3 and 5 whose value is 340 milliohms times V_{1-2} might be described as

GM1, 3-5, 1-2 = 340 .

Mutual inductances are described by this same format in the following manner. Two inductors having a mutual inductance are represented as indicated in Fig. 5.

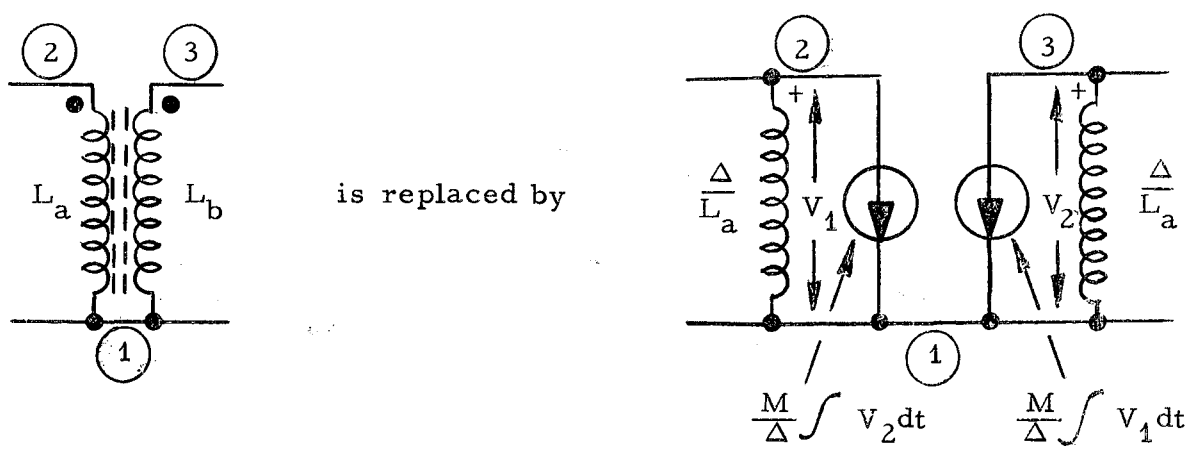


Fig. 5. Representation of a mutual inductance.

The symbols in Fig. 5 are related as follows:

$M = k \sqrt{L_a L_b}$ (k = coupling coefficient),

$\Delta = L_a L_b - M^2$,

M/Δ = value of current source on element description card.

Example: In the above circuit, suppose $L_a = 1\times10^{-3}$, $L_b = 2\times10^{-3}$, k = 0.9; then

$M = 1.273\times10^{-3}$,

$\Delta = 0.38\times10^{-6}$,

$M/\Delta = 3.35\times10^{3}$,

$\Delta/L_a = 0.38\times10^{-3}$,

$\Delta/L_b = 0.19\times10^{-3}$,

The resulting circuit is then described by the four cards

L1, 2-1 = .19E-3 ,
L2, 3-1 = .38E-3 ,
M1, 2-1, 3-1 = 3.35E3 ,
M2, 3-1, 2-1 = 3.35E3 .

VARIABLE ELEMENT Card

This card indicates that the name of the element to be varied and the values to be assigned to it follow on the next card. The complete analysis requested will be performed once for the original value on the element description card plus once for each value on the variable element secondary card which has the format

name = value 1, value 2, ··· , value n .

Example: VARIABLE ELEMENT
C3 = 100, 10., .01, 1E-3, 0

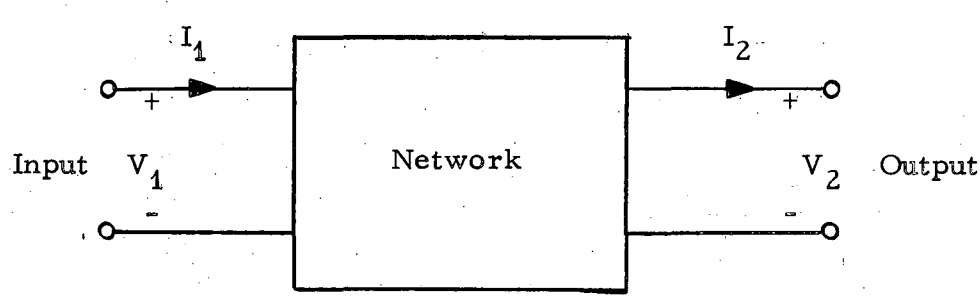
As many as 20 values may be specified, and they may continue onto additional cards as long as successive values are separated by a comma. Only one circuit element may be specified as the variable element. Note: the repeated analysis for different values of the variable element is very efficient, since the network function does not have to be completely reevaluated for each new value. Hence, repeated analysis with one circuit value varied as a parameter may be accomplished with very little added computer time.

FUNCTION Card

The FUNCTION card defines the network function desired in the format

FUNCTION = function name .

If the network is considered as a two-port depicted below,



the function names allowed and their definitions are:

Name	Definition
VOLTAGE TRANSFER	$(V_2/V_1 \mid I_2 = 0)$
Z INPUT	$(V_1/I_1 \mid I_2 = 0)$
Z TRANSFER	$(V_2/I_1 \mid I_2 = 0)$
Y INPUT	$(I_1/V_1 \mid V_2 = 0)$
CURRENT TRANSFER	$(I_2/I_1 \mid V_2 = 0)$

Example: FUNCTION = VOLTAGE

INPUT Node Card

This card defines the input nodes in the format
INPUT = plus node - minus node.

Example: INPUT = 2-1

OUTPUT Node Card

This card defines the output nodes in the format
OUTPUT = plus node - minus node.

Example: OUTPUT = 3-1

FREQUENCY Response Card

This card specifies that the frequency response of the network is desired. Example: FREQUENCY RESPONSE. The frequency range is specified on a secondary card, having the format

LOG, fmin, fmax, np

or

LINEAR, fmin, fmax, np

If LOG is specified, np points per decade are chosen in logarithmic intervals and any curves plotted have a logarithmic frequency axis. Note: for a logarithmic scale, fmin = 0 is not allowed. If LINEAR is chosen, a total of np points is chosen equally spaced, and any curves plotted have a linear frequency axis. If np is not specified, it is assigned the value 20; fmin and fmax must be specified.

Example: LOG, 1, 1000, 50

If plots of the frequency response are desired, a card with the format
PLOT, name 1, ... , name n
is required. The recognized names and the network functions (as defined under FUNCTION Card) for which each is valid are:

Name	Network functions
GAIN	VO, CU
PHASE	all
DELAY	VO, CU
IMPEDANCE	ZI, ZT
ADMITTANCE	YI, YT
NO PLOTS	all

Example: PLOT, GAIN, PHASE

TRANSIENT Response Card

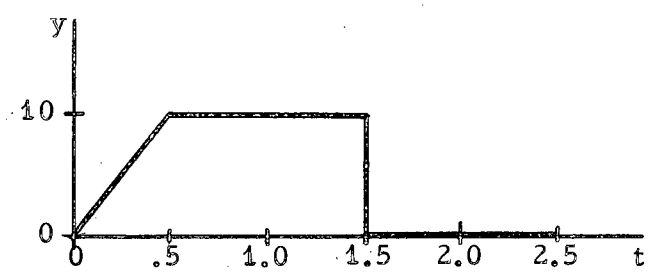
This card specifies that the time response of the circuit to some input waveform is desired. Note: Transient response is meaningful only for the VOLTAGE and CURRENT transfer network functions. Example: TRANSIENT ANALYSIS. The input waveform may be specified by one of several types of secondary statements: TABLE, PULSE, PERIODIC, CONTINUOUS.

The TABLE input is specified by a card containing TABLE followed by one card for each point in the table in the format

time, value, step size .

The input waveform consists of straight line segments connecting the points specified. The size of the time steps taken between the time specified on one card and that specified on the next card is "step size." If "step size" is not specified, the time between successive time values is divided into 100 intervals. The number of straight line segments specified in the table is limited to 21.

Example:



The waveform shown above containing four straight line segments would be specified by the following cards:

```
TABLE
0, 0, .05
.5, 10, .1
1.5, 10
1.5, 0, .1
2.5, 0
```

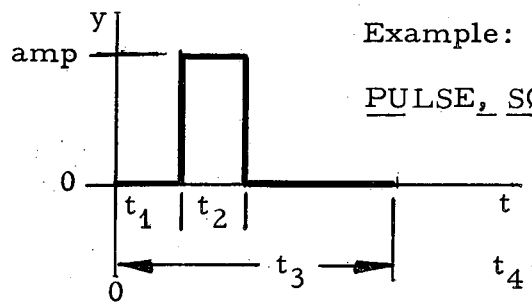
PULSE type input waveforms are described by a single card having the format

PULSE, type, amplitude, t_1, t_2, ··· , t_n

where "type" is a key word describing the form of the pulse, and t_1 to t_n are values of time necessary to define the pulse.

The types available and their definitions are shown below.

SQUARE (rectangular pulse)

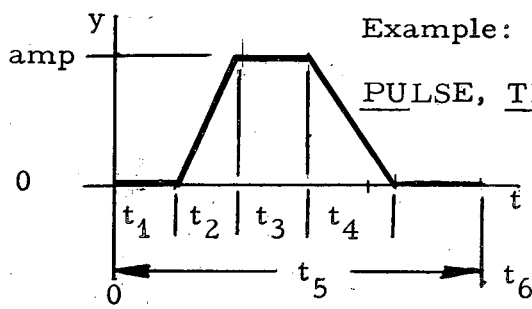


Example:

PULSE, SQUARE, 1, 0, .5, 1, .02

t_4 = step size

TRAPEZOID

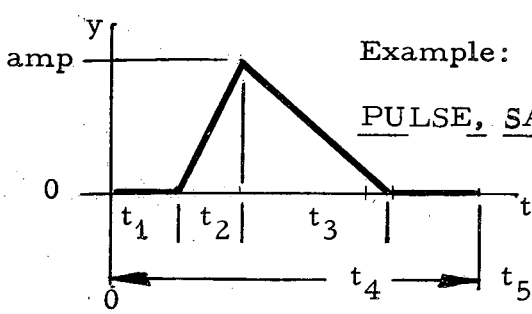


Example:

PULSE, TRAP, 1, .1, .1, .5, .1, 1., .01

t_6 = step size

SAWTOOTH (triangular pulse)

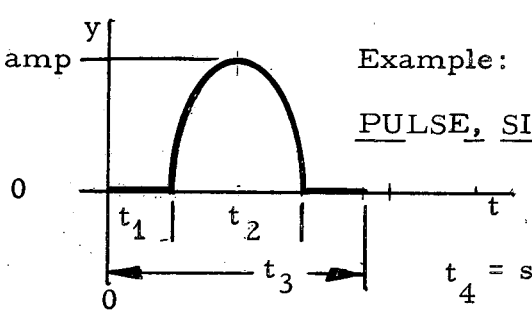


Example:

PULSE, SAWTOOTH, 1, 0, .2, .3, 1.5, .01

t_5 = step size

SINE

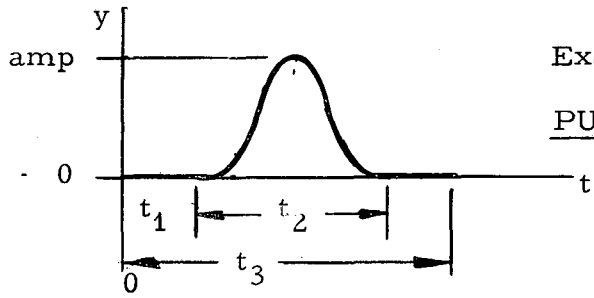


Example:

PULSE, SINE, 1, .1, 1, 2, .025

t_4 = step size

SSQUARE (sine-squared pulse)

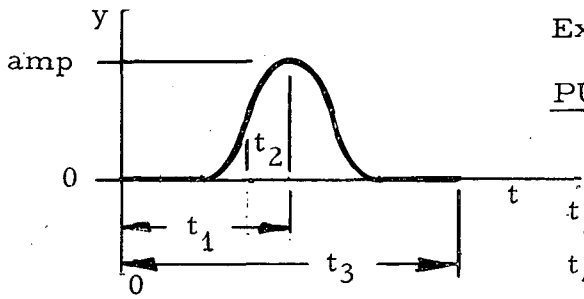


Example:

PULSE, SSQ, 1, 0, .5, 1.1, .01

t_4 = step size

GAUSS (Gaussian pulse)



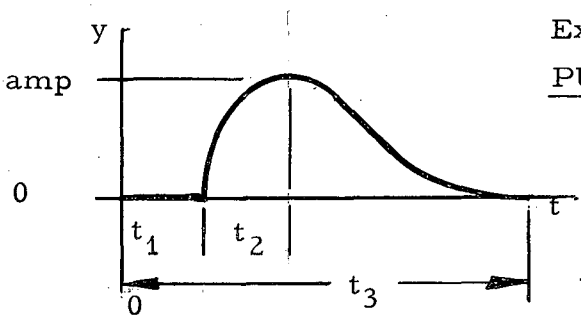
Example:

PULSE, GAUSS, 1, 1, .2, 2.5, .01

t_2 is one standard deviation

t_4 = step size

EXPONENTIAL (critically damped exponential pulse)



Example:

PULSE, EXPON, 1, 0, .1, 1., .01

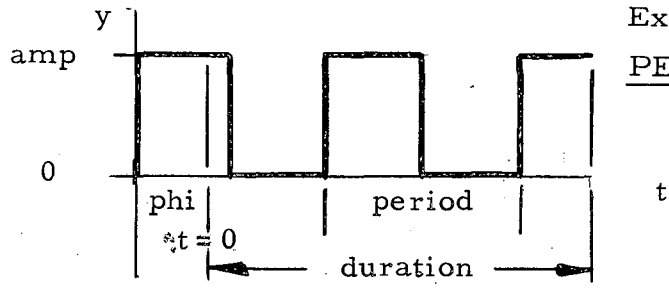
t_4 = step size

PERIODIC input waveforms are described by a single card having the format

PERIODIC, type, amplitude, period, duration, step size, phi .

Phi is expressed in degrees; if phi is not specified, it is set at 0.
A positive value indicates advance, and a negative value indicates delay.
The types available and their definitions are shown below.

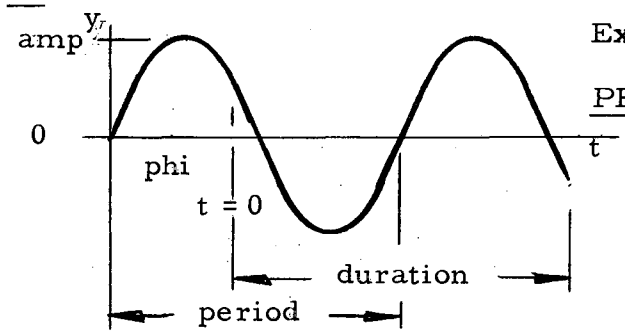
SQUARE WAVE (symmetric rectangular wave)



Example:

PERIOD, SQUARE, 1, 1, 2.5, .01, 30

SINE WAVE



Example:

PERIOD, SINE, .5, 2, 3, .02, 45

HALF WAVE and FULL WAVE

These are half-wave and full-wave rectified sine waves respectively, based on the sine wave shown above.

CONTINUOUS input waveforms are described by a single statement having the format

CONTINUOUS, type, amplitude, t_1, ... , t_n .

The types available and their definitions are given below (A = amplitude) .

STEP

$y(t) = A$, t_1 = duration, t_2 = step size.

RAMP

$y(t) = A \times t$, t_1 = duration, t_2 = step size.

EXPONENTIAL (capacitor charging waveform)

$y(t) = A \times (1 - \exp(-t/t_1))$, t_1 = time constant, t_2 = duration, t_3 = step size.

POWER

$y(t) = A \times t^{t_1}$, t_1 = power of t, t_2 = duration, t_3 = step size.

Example: CONTIN, STEP, 1, 2.5, 2, .01

For the PULSE, PERIODIC, and CONTINUOUS type waveforms, if "step size" is not specified, it is set at 1/100 of the analysis duration.

If plots of the transient response are desired, a card with the format

PLOT, name 1, ... , name n

is required. The recognized names are INPUT, RESPONSE, and NO PLOTS.

SYMBOLIC Output Card

The network function may be requested in symbolic form by including a card SYMBOLIC in the data set. Symbolic output consists of a table relating the physical elements to the topological elements used in the network analysis and a listing of all the trees, 2-trees, and 3-trees of the network.

NUMERATOR, DENOMINATOR coefficients cards

If the network function is known in the form of numerator and denominator

polynomials, the network may be described to the program by listing the numerator and denominator polynomial coefficients in place of providing the element description. Analysis starting with the network function is much faster for large networks than that starting with the element description. The numerator polynomial is specified by supplying a card containing

NUMERATOR

followed by as many cards as necessary to list the coefficients, starting with the constant term. As many coefficients as desired may be placed on one card, with successive values separated by a comma. The denominator polynomial is specified in the same manner with a card containing

DENOMINATOR

followed by cards containing the coefficients. The number of coefficients for each polynomial is limited to 30.

If the network is described in polynomial form, the following primary statements have no meaning: ELEMENTS, VARIABLE ELEMENT, FUNCTION, INPUT, OUTPUT, SYMBOLIC, NEW VALUES, ADD, DELETE.

ALTER Card

The ALTER card defines the end of the primary circuit description and signifies that some variation of the original specifications is to follow. When the program encounters this card, it immediately ceases reading data cards and proceeds with analysis of the circuit as defined by the preceding cards. When the requested analysis has been completed, the program returns to reading cards which redefine parts of the circuit description or the types of analysis desired.

Example: ALTERATIONS

Any primary card except the ELEMENTS card may follow the ALTER card. Elements may be added to or deleted from the circuit by use of ADD and DELETE cards. The input and output nodes may be changed by supplying new INPUT and OUTPUT cards. No computer time is saved by use of this feature as with the VARIABLE ELEMENT feature, but it is often convenient to specify only the changes in the problem rather than a complete new problem.

NEW VALUES Card

The values of previously specified circuit elements may be changed by supplying a

NEW VALUES

card followed by a card for each element value to be changed having the format

name = new value

Example: C9 = .001

TITLE Card

The word description provided on the first card of a data set may be changed by supplying a card

TITLE

followed immediately by a card containing the new word description. The TITLE card also causes subsequent plotted output to appear on separate graphs from that which was produced previous to the alteration in which the TITLE card occurs.

ADD Card

After an ALTER card, elements may be added to the circuit by supplying an

ADD

card followed by an element description card (as described under ELEMENTS card) for each new element.

DELETE Card

After an ALTER card, elements may be removed from the circuit by supplying a card having the format

DELETE, name 1, name 2, ..., name n.

The names of the elements to be deleted may continue onto as many cards as necessary.

Example: DELETE, C1, R10

NOTE: Extreme caution should be exercised in the use of ADD and DELETE cards. The resulting circuit must still meet all the conditions such as containing sequentially numbered nodes from 1 through the highest node number, etc.

END Card

Each problem to be solved must be terminated with an END card.

Example: END (all columns after this must be blank)

Additional complete problems may follow after the END card.

END OF JOB Card

The last card in the data deck following all problem descriptions should be an END OF JOB card.

Example: END OF JOB

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3. C. L. Searle, A. R. Boothroyd, E. J. Angelo, Jr., P. E. Gray, and D. O. Pederson, Elementary Circuit Properties of Transistors (John Wiley and Sons, New York, 1964).

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