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INTERACTIVE FUNCTIONAL MODELLING OF INSTRUMENTS

by

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A Thesis presented for the Degree of

DOCTOR OF PHILOSOPHY

in

SYSTEMS ENGINEERING

of

THE CITY UNIVERSITY

conducted in

THE DEPARTMENT OF SYSTEM SCIENCE

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List of Symbols

Unless otherwise stated, all dimensions are in SI units.

A	Area/Across Variable
A_c	Heat transfer area of junction
a_{ij}	Element of general matrix
A_r	Area of restriction
AA(I)	Across to Across (and Integrate)
AC	Across Variable
AT(I)	Across to Through (and Integrate)
B	Bulk Modulus
C	Capacitance
C_d	Thermal Capacitance
C_{ij}	Discharge Coefficient between sections/ i,j /Capacitance element of the i th row and j th column
c	Annular gap/specific heat of junction
d	Diameter
E	Effort variable/Electrical Domain
F	Force/Flow variable/Fluid domain
f	Frequency
G	General gain
G_{ij}	Conductance element of the i th row and j th column
GY	Gyrator
hc	Coefficient of heat transfer by convection
I	Current
K	Stiffness/specific heat ratio

L	Inductance
L_{ij}	Inductance element of the ith row and jth column
l	Length
M	Mass/Mechanical Translation Domain
M_c	Mass of junction
N	Node
n	Turns ratio
O	Output
P	Parameter/Pressure
p	Small signal pressure
Q	Heat Flow Rate
R	Resistance/Mechanical Rotation Domain
R_{ij}	Resistance element of the ith row and jth column
S	Sensitivity
s	Laplace Transform/Supply
T	Through Variable/Temperature/Thermal Domain
t	Instantaneous time
TA(I)	Through to Across (and Integrate)
TF	Transformer
TH	Through Variable
TT(I)	Through to Through (and Integrate)
U	Input Vector
V	Velocity/Variable
$X, \dot{x}$	State Vector/Displacements
Y	Output Vector
α	Element type/constant
β	Domain type
θ	Angle

ζ	Dynamic Viscosity
ρ	Density
τ	Time Constant
ω	Angular Frequency

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INTERACTIVE FUNCTIONAL MODELLING OF INSTRUMENTS

ABSTRACT

A Computer package has been developed which enables the interactive functional modelling of instrument systems to be undertaken.

Instruments are multi-energy domain systems in general and this creates difficulties for interactive modelling using current established techniques. Consequently the first part of this thesis considers the main functional modelling representations, these being:-

- a) Signal Flow Graphs
- b) Linear Graphs
- c) Bond Graphs

These are examined on a practical basis by the modelling, with results of five instrument systems. This led to a comprehensive review to be made of the benefits and drawbacks that each method allows in representing instrument systems.

In general there are disadvantages to the current graphical representations as the evolved techniques do not take account of modern design concepts which allow computers to be used as design aids. By considering the process on a more global basis a new representation called 'Structure Graphs' is formed. The language is described and formally defined, and shows with examples, the improvement of the following:-

- i) The ease of model construction
- ii) The ease of structural changes,

thereby enhancing the man-machine dialogue essential for good interactive design (uni-directional flow being mainly described).

A package was then developed called MEDIEM (Multi Energy Domain Interactive Element Modelling) to implement this new approach and mounted on a PDP 11/10 computer. This is a small mini computer, but nevertheless the package will allow:-

- a) Linear and Nonlinear representations
- b) Modelling of five energy domains
- c) Multiport representations.

The outputs obtained from the computer must enable the engineer to determine the performance characteristics of an instrument. There are three basic responses:-

- a) Time response
- b) Steady State response
- c) Frequency response.

The developed package will give all these responses (b and c for linear systems only) and provides for four different ways of displaying the results.

Although principally developed for modelling and designing instrument systems, the work should find important use in the more general modelling and design of multi-energy domain systems.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Instrument design on entering the 1980's can be considered still very much an art rather than a science. In many cases 'rule of thumb' and 'pencil and paper' approaches are the basic tools of analysis and design. This is not altogether surprising as instruments are comprised of a wide variety of different sensing elements, transducers, converters etc., interconnected in an almost indefinite number of ways. Under these conditions the instrument engineer may feel that of prime importance is his experience and judgement.

At City University, the Instrument Systems Centre has for many years been successfully analysing and designing instruments. The main approach has been the formulation of mathematical models to be subsequently solved on a computer. The advantages of a computer simulation are well known ⁽¹⁾ and in particular the desirability of altering a program rather than making experimental changes in a laboratory. However, much of this work has been carried out using fairly remote batch processing, with large 'main frame' computers. The need was apparent, therefore, for a research project specifically to examine the ways of incorporating the engineer more directly in the modelling and design, by computer, of instrument systems.

Accordingly, this thesis is concerned with the general 'interactive' modelling of instruments. The aim is to utilise the experience of the engineer, coupled with the problem solving power of the machine. A package has been developed for use on the Department's Digital Equipment Company PDP 11/10 computer - a small machine comparable in power to many mini and/or micro computers. This will allow the interactive analysis and design of a wide variety of instruments to be undertaken. The package uses a new type of language called 'Structure Graphs' which has been specifically developed in this thesis for instrument systems. However the generality of the language is such that it is expected that there are other applications outside of this field. Five instruments have been modelled for this research which enabled not only a basis for the comparison of the established graphical techniques, but also provided some validation of the developed package.

1.2 Area of Modelling Considered

For instrument systems there are two main types of modelling:

- a) Physical Models
- b) Functional Models

For a) the dimensions, length, thickness of an instrument component are specified along with material properties. From this a finite difference, and more

recently finite element models can be constructed. The model may encompass one, two or three dimensions. However due to the complexity of the analysis only a small part of an instrument is normally analysed. For example a pressure to displacement transducer may be very well modelled using finite elements ⁽²⁾. But this may be only part of the 'forward path' of a system that has overall feedback.

In the case of b) the input-output operating characteristics are utilised. For example a spring could be modelled as a capacitive term (inverse of stiffness) and a corresponding mathematical relationship established. The disadvantage of the approach is the lower order accuracy usually obtained, as, very often, many areas of an instrument can only be approximately represented in this manner. However functional relationships can be:-

- i) Easily identifiable for a wide variety of common components.
- ii) Less complicated in theory and in computing needs.⁽³⁾

Because it is the overall modelling and design of instruments systems that are of interest in this thesis (which in general would encompass many energy domains), only functional models of instruments will be considered. Earlier work has established that fruitful results can be obtained.⁽⁴⁾

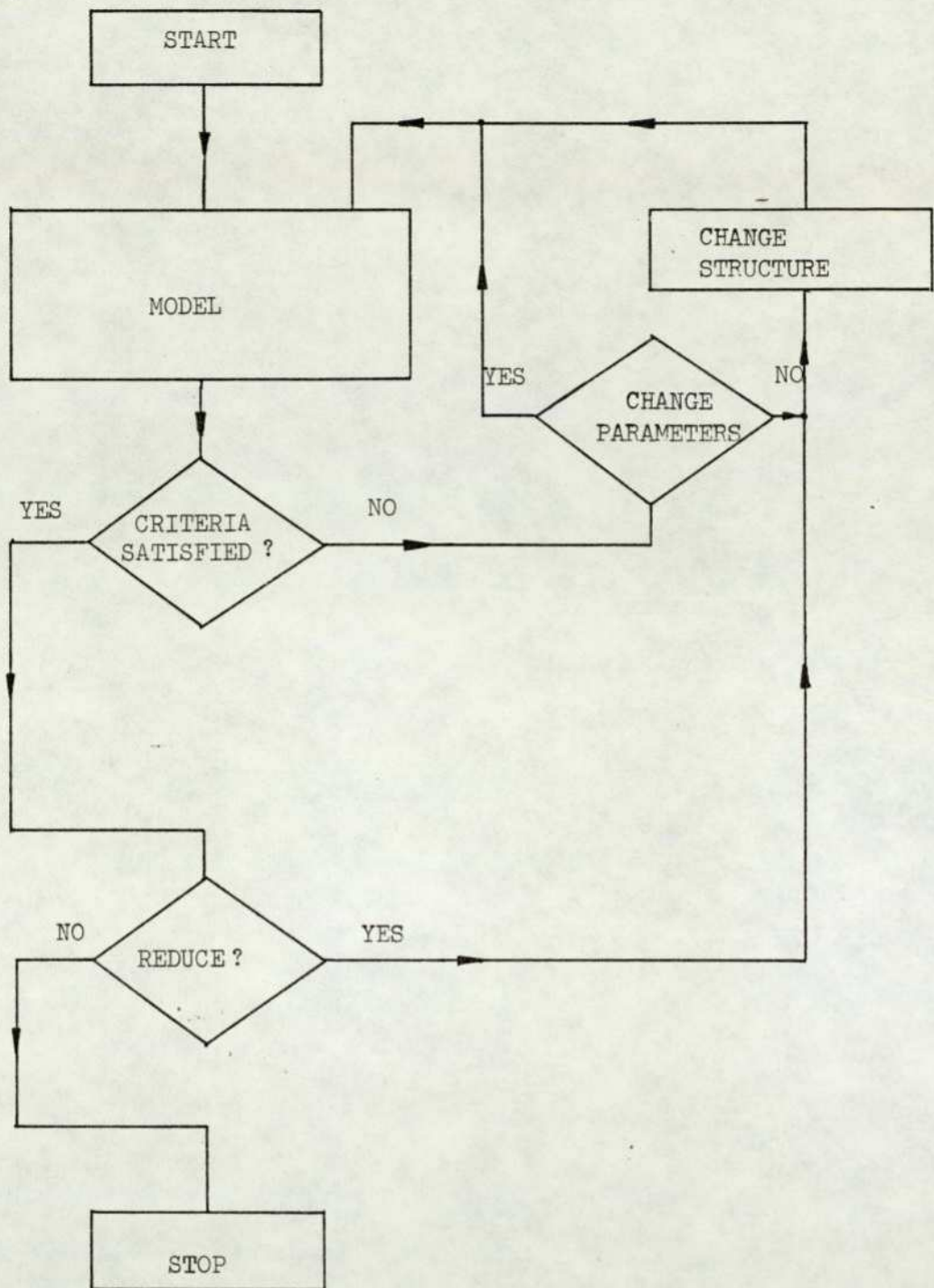
As a subscript to this section it is often the case that both modelling processes can be used in the analysis of an instrument. It may, for instance, be difficult to provide measurement facilities to determine the input-output characteristics of a certain component or sub-system. A physical model could then be employed to obtain this information - perhaps by a finite element program. The results could then be utilised by a functional model for both the linear and nonlinear analysis of a system.

1.3 The Interactive Computer Aided Modelling/Design Approach

The subject of Interactive Computer Aided Modelling Design has received much attention in recent years.⁽⁵⁾ It is ideally suited for instrument systems where many alternative models or designs may be possible. In essence for man-machine interaction

- a) Man generates ideas, innovative concepts, flexibility of thought etc.
- b) The machine performs evaluation of formulae, storing and displaying of results etc.

Fig 1.1 gives a flowchart of how this would work in practice. Initially a model of the physical system is produced and entered into the computer. This is dependent on the engineer's/designer's experience and judgement in selecting the most important features. The computer then



THE INTERACTIVE MODELLING/DESIGN PROCESS.

Figure 1.1

produces graphs, tables etc of the model (for various disturbances) for inspection by the user. If the criteria (i.e. overall functional representation or design specification) has not been satisfied, then manipulation of either the structure or parameter changes (see Chapter 2) will be necessary. Finally, once a model has been found to be acceptable it may on hindsight, be possible to eliminate certain features and hence reduce the size. The level of interaction between the man and machine will depend on:-

- a) Ease of model constructions into a computer.
- b) Ease of model changes - that is both the structural and parameter phases.
- c) Readability and convenience of the computer output produced.

Provided these are satisfactory, the engineer should find the computer a sophisticated modelling or design tool aid, replacing more conventional techniques.

1.4 Outline of Chapters

The chapters of this thesis can be divided into two main groups:

- i) Identify the essential needs for functional interactive instrument modelling and design. Analyse the current available modelling techniques by the use of practical instrument examples.

- ii) Proceed to introduce a new modelling approach.
Develop a new computer package for functional modelling of instrument system and with it model the instrument examples of i).

Chapter 2 gives the requirements of an interactive package for instrument design. This chapter provides an overview of the necessary interaction, computer responses and type of computer facilities needed. It discusses both the software and hardware aspects.

Chapter 3 then proceeds to analyse the current graphical techniques available. These are three techniques of particular interest, these being:-

- a) Signal Flow Graphs.
- b) Linear Graphs.
- c) Bond Graphs.

where the word graph refers to a 'graphical description' of the physical systems. These each have advantages and disadvantages and these are discussed with the aid of five instrument examples. In general, instruments have:⁽⁶⁾

- i) Signal Flow
- ii) Power Flow
- iii) Information Flow

inherent in their structure, and this poses a strain on the interactive modelling efficiency of any one graphical method.

Chapter 4 therefore suggests a new approach based on a computer-aided graph, i.e. a graphical technique relying on a computer interface. Essentially all the current graphical techniques will directly produce state equations - a necessary requirement if there is no computer. (This, in fact, pre-determines the precise form of each graphical display). However, if sufficient information is encoded into the computer then these constraints can be relaxed. The advantage is that a more natural topological formulation is now possible (excepting higher order couplings, ⁽⁷⁾ etc., where there is more than one degree of freedom for the direction of flow). This chapter describes this new approach, formally defines the language, and gives examples.

Chapter 5 describes how state equations can be derived for the new graphical technique described in Chapter 4. Fundamentally, the procedure is to analyse the user's model by making various passes, allowing expansions, (similar to Macro's in computer terminology), to a more convenient fundamental set. This is comparable to the compilation of a high level program to object code. From this a global matrix can be determined which is subsequently reduced to state variable form. For the nonlinear case, linearization around an operating point takes place, which entails entering values into the global matrix at each time step. Flowcharts of the implemented package are described in Appendix E.

Chapter 6 then gives a description of the use of the package, first with a simple example, and then with the modelling of the five instruments described in Chapter 3. The results of the simulations are presented here in order to provide some validity of the package. The ease of model formulation and model changes is established in this chapter.

Chapter 7 discusses some possible further developments. The PDP 11/10 has, unfortunately, been utilised to its full capacity. However the Department has now obtained a Prime 550 mini computer, which has a much larger immediate and backup memory. The main areas of interest are:

- i) Call up models.
- ii) Modelling in the Design variable Space.
- iii) Graphical enhancement of Structural Format.

As well as this some local improvements are also mentioned, i.e. integration routines, etc.

Chapter 8 contains the conclusions. It includes a summary of the facilities of the developed package, with some brief notes on the applicability to other engineering fields and the direction that further work could take.

CHAPTER 2

REQUIREMENTS OF AN INTERACTIVE PACKAGE

FOR INSTRUMENT MODELLING AND DESIGN.

2.1 Introduction

This Chapter examines the features necessary to provide a computer package suitable for the instrument engineer. Instruments can be defined as information machines which are required to maintain a functional relationship between the input and output signals under all likely environmental conditions⁽⁶⁾. Instruments are generally composed of sub-systems which convert energy from one form to another, and they can comprise primary sensing elements, conversion elements, data transmission elements etc⁽⁸⁾. These must be selected by the engineer to meet a desired set of criteria. The purpose of an interactive package is to aid the designer to meet these conditions in an efficient manner.

For simulation work mathematical models are required. The functional modelling approach for instrument systems will not in general be discussed in this chapter, but rather the adequacy of the simulation language in an interactive environment. This should be of a form so as to provide a high degree of convenience to the user⁽⁹⁾, thereby promoting 'interaction' with the system. This is discussed in Section 2.2.

Instrument designs can normally be specified by a set of performance characteristics. These enable a quantitative meaning to be attached to how well an instrument performs.

These characteristics must be made available to the designer and Section 2.3 describes these terms and how they can be found from a simulated model.

With low cost computers becoming prevalent, the type of computer and how useful it will be becomes all the more relevant. A discussion in Section 2.4 is given of the sort of facilities that would be needed. In this context, available packages are also discussed and reasons given in the conclusions why it is in this area that further work is necessary.

2.2 Computer Aided Modelling

2.2.1 Requirements for Model Formulation and Evaluation

The requirements for modelling instrument systems are discussed below. The section is concerned with the procedural language rather than the input-output hardware described later in the Chapter.

i) Feed in a Model Logically and Easily

For instrument systems it is necessary, as they are in general multi - energy devices, to have a clear procedure to follow. A language capable of providing preciseness of modelling with a degree of generality is required. In addition, this should not be difficult to understand or apply as interactive feedback will suffer. As functional models

are used in this thesis there are two stages to model formulation - the structure and parameter input, both of which are now examined.

a) Structure Input

A structure represents the functional input-output blocks and their interconnections. There should be good correspondence between the system being modelled and the necessary encoding into the computer. In general the easier the mapping process the simpler it becomes for the designer to make changes. As an example consider the modelling of the weighing machine shown in Fig 2.1.

The first model, shown in a) only models the spring. The time response gives an indefinite fast rise time. Mathematically:

$$F = kx \quad 2.2.1$$

where F is the force

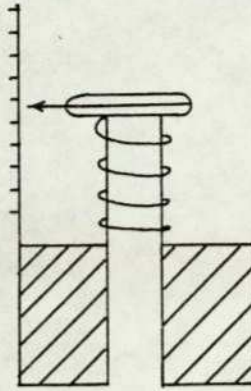
k is the stiffness

x is the displacement.

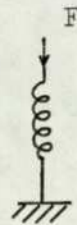
The engineer in seeing the results of a) is not satisfied that the response is realistic. Model b) is then tried with the mass included. This gives:

$$F = M\ddot{x} + kx \quad 2.2.2$$

where M is the mass.



SCHEMATIC

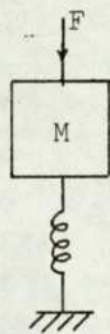
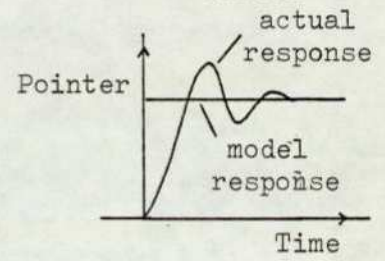


PROGRAM

1) Feed in Spring

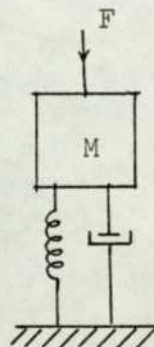
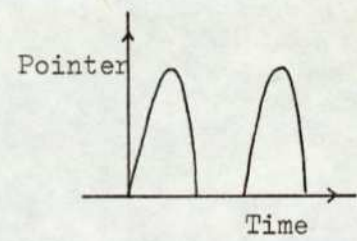
a)

RESULT



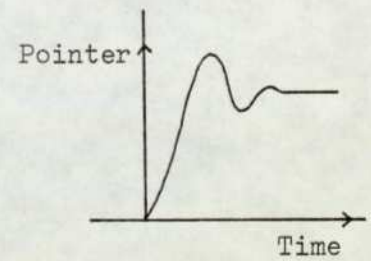
2) Add in Mass in 'SERIES'

b)



3) Add in dashpot in 'PARALEEL' with Spring

c)



EXAMPLE OF INTERACTIVE MODELLING OF A WEIGHING MACHINE

Figure 2.1

Unfortunately the result is an oscillatory response. Adding in the dashpot resistance the third model, model c) results:

$$F = M\ddot{x} + R\dot{x} + kx$$

2.2.3

where R is the total resistance to motion.

b) Parameter Input

Parameters are the numerical values of the elements. For the previous example mass, resistance and capacitance (inverse of stiffness) quantities need to be entered into the computer. Some of the quantities may in general be nonlinear. It should be possible to enter linear or nonlinear parameters without having to change the model structure.

(ii) Logical Program Control

The commands necessary to activate the various sections of a program should be easy to understand. It should be possible to terminate at any stage and return to a central program control. This is especially important at the evaluation state (for example the point by point evaluation of a time response) as it would then become apparent whether the model is giving incorrect results.

The structure and parameter phases should not have restrictions of sequential numbering etc. It should be possible to organize a file so that additions can be made around a local point of interest rather than being appended at one end.

As many commands as possible should be self-explanatory.

(iii) Outputs

It should be possible to examine any part of the generated model. There should be enough outputs available so that various comparisons, important to the design engineer, can be made whilst the program is running.

(iv) Minimisation of Computer Response Delays

It has been noted by several authors⁽⁹⁾ ⁽¹⁰⁾ that delays involved in producing results will have a serious effect on a successful interactive design. Both the necessary internal model formulation and evaluation stage should take as little time as possible.

(v) Error Messages

It is essential to inform the user that a model is incorrect, or a particular control mode has not been activated. (This is however an extremely difficult problem

where great flexibility of user input is possible). Error messages should in general be informative and thereby suggest how to proceed.

2.2.2 Desirable Design Aids

In order to aid the design process, certain other features would be useful. Some of these are listed below.

- a) Sensitivity Analysis.
- b) Worst Case.
- c) Monte Carlo.
- d) Optimization.

a) Sensitivity analysis (not the same as sensitivity of an instrument discussed in Section 2.3) shows the effect of a variation on model performance, i.e.

$$S = \left(\frac{\delta O}{O} \right) / \left(\frac{\delta P}{P} \right) \quad 2.2.4$$

where S is the sensitivity

O is the output

P is the parameter of interest.

b) Worst Case gives the lowest (or alternatively the highest value) in a local region⁽¹¹⁾. For example it may be necessary to know the extreme value due to component variations.

Lowest (O): increase P if $\frac{\delta O}{\delta P} < 0$ 2.2.5 a)

decrease P if $\frac{\delta O}{\delta P} > 0$ 2.2.5 b)

for the parameters of interest.

Highest (O): decrease P if $\frac{\delta O}{\delta P} < 0$ 2.2.6 a)

increase P if $\frac{\delta O}{\delta P} > 0$ 2.2.6 b)

for the parameters of interest.

c) Monte Carlo simulation gives a statistical variation of an output by using random variates for the parameters⁽¹²⁾.

$$O = f(P_1 \dots P_n) \quad 2.2.7$$

where $P_1 \dots P_n$ are the
parameter variations within
specified limits,
O is the output.

The probability density function of the different outputs generated could then be used to give the mean, estimate the variance etc. This is especially useful for realistically estimating the effect of manufacturing variations.

d) Optimization strategies would attempt to improve the performance of an instrument by parameter variation. In general:

Optimize $F(P_1 \dots P_n)$ - Objective Function 2.2.7

Subject to $G_k(P_1 \dots P_n) \leq 0$ - Constraint 2.2.8
 $k=1, m$

A typical objective function could utilise a least squares algorithm. However, various other search methods are also commonly employed⁽¹³⁾.

These design aids are useful for parameter variations. There are no general purpose routines for aiding structural changes.

2.3 Performance Characteristics

The performance characteristics of an instrument attempt to give some indication of how the instrument will 'perform'. Although each instrument is different, and may require special characteristic measures, this section will attempt to give some of the more common characteristics⁽³⁾. In general the performance is downgraded by either influence or inherent errors, which affect either the static or dynamic characteristics.

a) Influence Errors

These are extraneous inputs that affect the outputs of the particular instrument in question. Examples are external vibration, Gaussian noise etc. This category also includes modifying inputs,⁽¹⁴⁾ that is changes of parameter values due to external influences.

b) Inherent Errors

These are errors that are 'inherent' in the basic construction of an instrument. For example scale calibration, mismatching, incorrect filtering etc. These are often of a more serious nature as they involve fundamental design problems.

2.3.1 Static Characteristics

Static characteristics are either slow or stationary phenomenon. A list of the more common characteristics is given below.

- 1) Accuracy
- 2) Repeatability
- 3) Linearity
- 4) Sensitivity (Gain)
- 5) Hysteresis
- 6) Resolution
- 7) Dead Space

2.3.2 Dynamic Characteristics

These are characteristics that measure the instruments ability to respond to changes in signal. Typical terms are:

- 1) Overshoot
- 2) Settling time
- 3) Corner frequency
- 4) Gain margin
- 5) Frequency response
- 6) Phase margin.

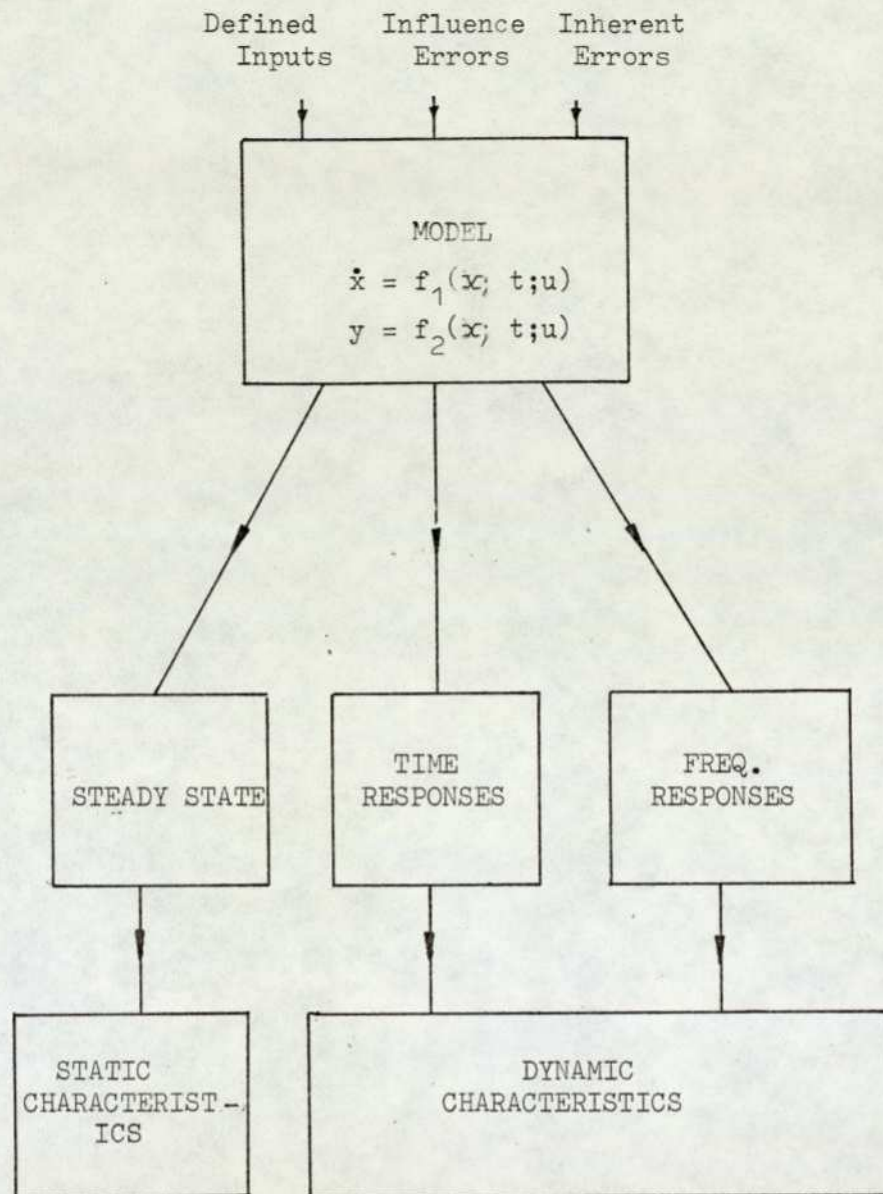
As there are many characteristics of interest, a detailed discussion is left to the references,⁽³⁾ where excellent treatments are found.

2.3.3 Determination of Performance Characteristics With A Computer Package

Fig 2.2 gives a flowchart of the procedure necessary to obtain the relationships in Section 2.3.1 and 2.3.2. The model will, for the following analysis, be represented in state variable form.

$$\dot{x} = f_1(x;t;u) \quad 2.3.1$$

$$Y = f_2(x;t;u) \quad 2.3.2$$



x : STATE VECTOR

t : TIME VARIABLE

u : INPUT VECTOR

y : OUTPUT VECTOR

PROCESS TO OBTAIN INSTRUMENT CHARACTERISTICS

Figure 2.2

The state equations being obtained directly or indirectly from the formulated model.

a) Steady State

For this condition $\dot{x} = 0$

this gives using 2.3.1

$$0 = f_1(x_F; t; u) \quad 2.3.3$$

$$Y = f_2(x_F; t; u) \quad 2.3.4$$

where x_F is the final value of the states (assumed to exist).

If the system is linear then

$$\dot{x} = Ax + Bu \quad 2.3.5$$

$$Y = Cx + Du \quad 2.3.6$$

then if $\dot{x} = 0$

$$x_F = -A^{-1} Bu$$

provided A is nonsingular

giving if substituted in 2.3.6

$$Y = (-CA^{-1}B + D)u \quad 2.3.7$$

b) Time Response

The time response can be found either:

- 1) Numerically
- 2) Directly (for linear systems).

For a numerical solution the simplest approach would be to consider equ. 2.3.1 as a difference equ.

$$x_{n+1} = x_n + \Delta t \cdot f_1(x_n; t_n; u_n) \quad 2.3.8$$

which is the Euler solution of the problem.

Alternatively using Laplace transforms for the linear case and using eq. 2.3.5

$$sx(s) - x(0) = Ax(s) + B \cdot u(s)$$

giving

$$x(s) = (sI - A)^{-1} [x(0) + B \cdot u(s)] \quad 2.3.9$$

substituting into the Laplace transformed version of eqn 2.3.6 gives

$$Y(s) = C(sI - A)^{-1} [x(0) + B \cdot U(s)] + D \cdot U(s) \quad 2.4.0$$

and by inversion of $(sI - A)$ and simple matrix manipulation the time response can be determined.

c) Frequency Response

This is only possible for the linear case. Using equ. 2.4.0 and putting $s=j\omega$

$$Y = C(j\omega - A)^{-1}B + D \quad 2.4.1$$

where the input is an impulse and the initial conditions are defined to be zero.

2.4 Computer Facilities

2.4.1 Types of Machine

The type of machine available affects to a considerable degree the software produced. Large mainframes allow

- 1) Extended high level languages
- 2) High computation speed
- 3) Large memory resources.

These facilities allow greater freedom for the software developer to use a more structural and modular approach⁽¹⁵⁾. However, there are disadvantages, some of these being

- 4) High cost to rent or buy
- 5) Alternatively, high cost for time sharing (telephone, CPU etc)
- 6) Security, loss of files etc., by external personnel.

For the mini or micro system, although 1), 2) and 3) may not be true, they have the following attributes:-

- 7) Low cost to buy
- 8) Low upkeep
- 9) Hardware and special software more readily developed for the machine.

Within the Department of Systems Science at City University, a PDP 11/10 has been available for interactive work and a Prime 550 mini has recently been added to the department. For these reasons the computer facilities will be limited to small (mini and micro) machinery. This should be particularly relevant in the future with the use of micros and personal computers becoming more prevalent.

2.4.2 Peripheral Hardware

This section examines the peripheral (input-output) equipment and its utilisation for interactive analysis. In general there is a two-way process: man-to-machine and machine-to-man communication. There are a wide variety of devices available, and fortunately the size of the machine is not particularly significant.

Table 2.1 shows typical facilities that are available. These are now briefly described (excluding the standard Keyboard).

i) Light Pen

The light pen allows interaction with a V.D.U. screen by a light sensitive cell. It is convenient to use but suffers from quantization errors.

ii) Tablet

The tablet is a pressure sensitive pad suitable for inputting a layout. However it has limitations if changes are to be made to a model.

iii) Joystick/Thumbwheels

The Joystick or Thumbwheels pinpoint positions on a screen by manipulating the X-Y co-ordinates. Because of their accuracy they are common tools of interactive design.

iv) V.D.U's

For inputting data or displaying information, visual display units (V.D.U.) are the most common. This is particularly so for interactive work, as the speed of display allows rapid changes. There are three types:

INPUT	KEYBOARD	LIGHT PEN	TABLET	JOYSTICK/ THUMBWHEELS	TAPE/DISC
STRUCTURE	✓	N.S.	N.S.	N.S.	✓
PARAMETERS	✓	-	-	-	✓
COMMANDS	✓	N.S.	-	N.S.	-

OUTPUTS	V.D.U. LIST	V.D.U. PLOT	LINE PRINTER	GRAPH PLOTTER	TAPE/DISC
MODEL	✓	N.S.	✓	N.S.	✓
RESULTS	✓	N.S.	✓	N.S.	✓



NORMALLY AVAILABLE

N.S.

NON STANDARD USING A HIGH LEVEL LANGUAGE

-

NOT POSSIBLE

UTILISATION OF COMPUTER FACILITIES BY A COMPUTER AIDED MODELLING/DESIGN PACKAGE

TABLE 2.1

a) Storage Tube

The storage tube has the highest resolution as the spot size is usually the smallest. It is particularly useful as core is not the medium of storage. Therefore families of curves can be displayed without undue processing demands.

b) Refresh tube

A refresh tube allows dynamic representations to be made. Because the precise co-ordinates on the screen are stored dynamically, a good resolution but low picture content results. However, the dynamic array facility allows good control of picture modification.

c) Raster Tube

The raster tube has a fairly poor resolution. However, as each picture is effectively re-drawn 25 times a sec., high information content with a low flicker is possible. It is in general the most suitable for micro based systems, primarily due to its low unit cost.

For instrument systems there are four types of display outputs that are useful:-

Schematic,

Tables or Lists,

Plots,

Histograms.

As plots are usually essential in interactive work, a line-printer (with limited resolution) is often used. Histograms are useful for statistical analysis.

Table 2.1 also gives some indication of what is to be expected from a machine independent program, i.e. one designed to operate on a variety of computers. In general the barest minimum would be provided leaving the user to update for specific requirements. The problem is becoming less pronounced though, by the standardization of various input-output routines. One example is GINO/F which, by allowing direct coding in FORTRAN, enables a variety of peripheral equipment to be utilised from a variety of machines.

2.4.3 Programming Languages

The general trend is for packages to be written in high level languages. By far the most common is FORTRAN although BASIC, ALGOL and more recently PASCAL are alternatives. For a high level language it is necessary that it is:-

- (i) Compiled
- (ii) Allows modular construction.
- (iii) Is accepted on a fairly universal basis.

Although no language is distinctly inferior, in a practical environment FORTRAN would seem to be the first choice.

2.4.4 Size and Complexity of Model

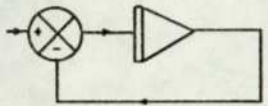
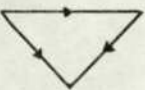
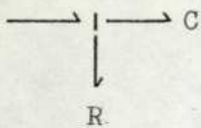
The size of a user defined model is difficult to estimate as many different instrument designs are possible. However it is necessary to choose a realistic limit (for small machines) whilst allowing free expression in model formulation. The package should be able to handle linear and nonlinear systems and have at least 30 element capability. In general square law effects, multipliers saturation elements are all realistic instrument characteristics.

2.4.5 Computer Packages Available

Table 2.2 shows some examples of simulation packages currently available. Of interest, of course, is to meet the requirements outlined in Section 2.2.1. There are three types of representations that are currently in use - and applicable to instrument design. For a simple R-C network the three graphs drawn alongside give an illustration of the different approaches to the problem. These graphical techniques are discussed in detail in Chapter 3. They are mentioned here as they help to identify the area of applicability of a particular package.

(i) Signal Flow Diagram

A Signal Flow Diagram can be used to model most engineering applications that are functional in nature⁽¹⁶⁾.

PACKAGE	INPUT MECHANISM	NONLINEAR	LANGUAGE	OUTPUTS
C.S.M.P.	SIGNAL FLOW DIAGRAMS	YES	FORTRAN	TRANSIENT
SLANG		YES	FORTRAN	TRANSIENT
ECAP	LINEAR GRAPHS	NO	FORTRAN	TRANSIENT, STEADY STATE
SCEPTRE		YES	FORTRAN	TRANSIENT, STEADY STATE
THTSIM	BOND GRAPHS	YES	P.D.P.MACRO	TRANSIENT, FREQUENCY
ENPORT		NO	FORTRAN	TRANSIENT, STEADY STATE FREQUENCY

TYPICAL FUNCTIONAL COMPUTER PACKAGES USEFUL FOR INSTRUMENT MODELLING AND DESIGN

TABLE 2.2

ii) Circuit Diagrams

Circuit diagrams are primarily developed for circuit analysis but other engineering systems such as fluid systems can also be modelled directly⁽¹⁷⁾. They are directly related to Linear graphs, discussed in Chapter 3.

iii) Bond Graphs

Bond graphs can model most engineering applications, but unlike signal flow diagrams consider power transfer⁽¹⁸⁾.

Each of the packages can at least produce a transient response. Theoretically it is possible, although very often inconvenient, to use this to obtain the steady state (as described in Section 2.3.3). The frequency response could also be ascertained from a transient response by taking the Fourier Transform.

Unfortunately some of the packages are for main frame machines (i.e. CSMP, ECAP, SCEPTRE, ENPORT). These would not be possible to directly modify for mini and/or micros.

2.5 Conclusions

This chapter has given an outline of the requirements for an interactive computer package which is specifically dedicated to the functional modelling of instruments. Instruments are multi-energy in nature and thereby pose more stringent requirements for good interactive simulation.

Both the software and hardware aspects have been discussed.

In Section 2 it was mentioned that the encoding process in transferring an instrument model into the computer should be easy and logical to follow. It is essential that structure and parameter changes can be easily made. For interactive work it is also particularly important that all computer response time delays be kept to a minimum.

Section 3 described the necessary performance characteristics and how they may be obtained. In general, three responses are required. These are:-

- i) Steady State
- ii) Time Response
- iii) Frequency Response.

Given these responses, a wide variety of instrument characteristics can be found.

The last section discussed the computer facilities available for use. The type of computer package utilised or developed may well depend on the computing power and memory of the machine. Most of the more sophisticated packages have been developed for large mainframes. An order of magnitude would be 40,000 lines of source code on a mainframe to approximately 4,000 lines on a small mini. Under these circumstances it would not be possible in general to:-

- a) Mount a package from a mainframe to a mini.
- b) Develop techniques and algorithms to the level of sophistication of a large computer.

Given these constraints, the most likely course would be to rebuild a package specifically for interactive instrument design - if a mini or micro computer is to be used. This is the intended course and the next chapter proceeds to review the first stage i.e. to examine the current graphical techniques as applied to instrumentation in order to find the most suitable for implementation.

CHAPTER 3

A COMPARISON OF CURRENT GRAPHICAL MODELLING TECHNIQUES

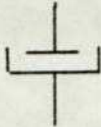
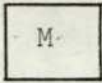
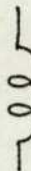
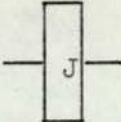
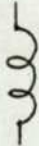
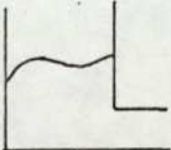
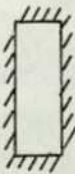
3.2 Introduction

This chapter discusses the currently used graphical modelling techniques with respect to the functional modelling of instruments. In general instruments, in this Chapter, can be viewed as having the following features:-

- i) They are multi-energy domain systems.
- ii) They have Power Transfer and/or
- iii) Signal Transfer
- iv) Instruments are Linear or Nonlinear.

The problem then centres on a method of modelling a system with the above properties in a manner suitable for interactive analysis.

Functional modelling, as defined in the introduction, is a powerful way of describing the physical components of a system. For instance, an electrical capacitance or mechanical mass can not only be identified directly from a physical system but also have well-defined mathematical forms. Fig 3.1 shows some examples of 1 port elements (i.e. one input, one output). As can be seen, a resistance, capacitance and inductance (R-C-L) can represent a wide range of components. (More extensive lists are available in the references⁽⁶⁾ ⁽¹⁸⁾). This approach has the following advantages:

ENERGY DOMAIN	RESISTANCE	INDUCTANCE	CAPACITANCE
MECHANICAL TRANSLATION			
MECHANICAL ROTATION			
ELECTRICAL			
FLUID			
THERMAL		NONE	

EXAMPLE OF SINGLE PORT - FUNCTIONAL ELEMENTS

Figure 3.1

A large number of physical components can be modelled for a small number of functional forms.

The resulting mathematical relationships (i.e. mass=force/d(velocity)/dt) are of a primitive nature, that is no higher than first order. This lends itself to ease of evaluation using for instance integration routines; a general solution from state equations etc.

When the required functional forms have been found, it is then necessary to interconnect them so that a lumped parameter schematic of the system can be formulated. An example of this was the schematic of the weighing machine described in Chapter 2.

Thus for this stage the process is dependent on the experience and judgement of the modeller and will not be discussed further. Of importance at this point however, is the methodology leading to the evaluation of the schematic and hence the determination of the performance characteristics described in the previous chapter.

Unfortunately, a schematic cannot directly be used to obtain the system equations. This means that the information available must be converted. As the schematic is of a pictorial nature it would seem logical to transform this to an established 'graphical' technique.

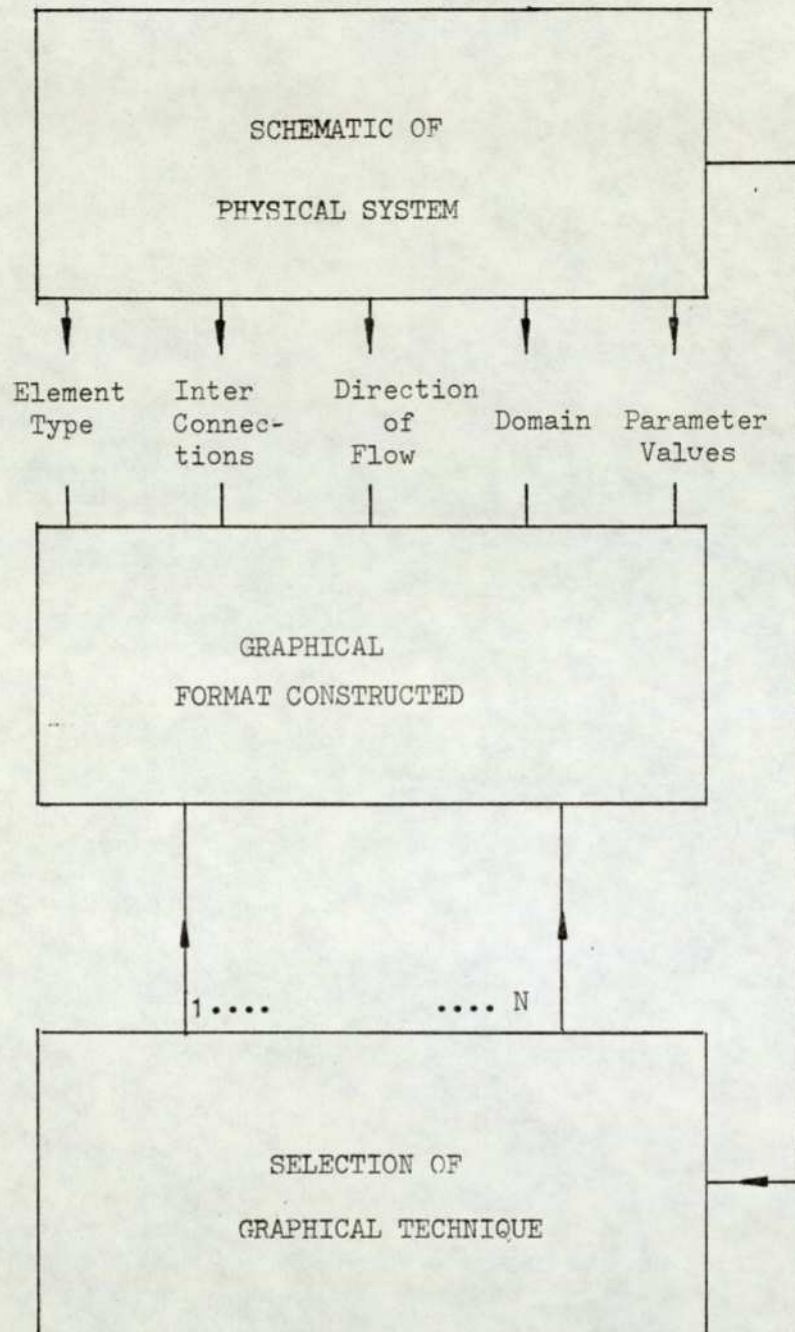
However, the choice of a particular method is by no means apparent. Consider Fig 3.2. In general the information flow from a schematic to any graphical form requires:

- a) The element type
- b) The interconnections
- c) The direction of flow
- d) The relevant energy domain
- e) The parameter value(s) of each functional component.

Clearly the degree of ease or difficulty of carrying out this transformation is of great importance to the modeller. This is especially true in an interactive environment. However, of the variety of different graphical techniques available, none are universal rather all have definite advantages for modelling certain types of systems. These are now explained.

i) Signal Flow Graphs

Because of the general nature of instruments and in particular the general application of available packages⁽¹⁹⁾ signal flow diagrams (henceforth called signal flow graphs for compatibility) is a candidate for further discussion and examination. As it's name implies, it transfers signal from one functional block to another in a direct manner. Signal interactions take place at summers, multipliers etc. It has the following immediate advantages for modelling instrument systems.



FACTORS AFFECTING A GRAPHICAL REPRESENTATION

Figure 3.2

- a) Can model in any domain.
- b) Possible to have signal and indirectly power flow relationships.
- c) Suitable for linear and nonlinear analysis.

One other point that will be made is the ease of computer implementation - as the graph can be made analageous to a sequence of computer code.

Although general in nature, signal flow graphs have been found to be most useful when pure signal transfer is involved. For instrument systems it is often more convenient to consider two variables (variable and co-variable) associated with each element. These are the following approaches:

ii) Circuit Graphs

Circuit graphs have been associated historically with the electrical engineer. There are two methods:

a) Two port networks

Two port networks⁽²⁰⁾ model systems on an elemental two input, two output basis. An example is a transistor modelled using 'h' parameter or a network of resistors modelled using 'y' or 'z' parameters. By manipulation and transformation an overall matrix representing the system equations can be found. However this method has a number of disadvantages these being:-

Many elements are natural one ports. It would, therefore, seem to be an unnecessary complication to transpose these to two port devices.

Conversely multiport elements greater than two would in general be modelled more approximately by fields⁽²¹⁾.

The early matrix manipulation, necessary with this method, will cause problems in efficiency for nonlinear numerical solutions.

Because of these difficulties this approach will not be considered further.

b) Linear Graphs

The Linear Graph⁽¹⁷⁾ of a schematic is obtained by first modelling the interconnections of the system, one for each domain, and then describing the terminal relationships (but not on the graph) of how the through and across variables⁽²²⁾ (variable for co-variable) are defined for each element. By selection of trees and co-trees, the cutset and tie set equation can be found and by this the overall system equations formulated.

It has the advantage of:

Being topological for many energy domains.

Providing a logical procedure to obtain the state equations.

Therefore this approach will be discussed and examined further in this chapter.

iii) Bond Graphs

Bond graphs⁽²³⁾ is a newer technique that has evolved in an attempt to model multi-energy domain system in a more unified manner. It directly models power bonds (analagous to chemical bonds). It interconnects elements (represented on the graph) between junction structures and by developing a set of causal influences the equations of the system can be determined. They use effort and flow variables⁽⁷⁾.

It has the following advantages:-

- a) Being specifically designed to model multi-energy domain systems.
- b) Highly descriptive giving a high content (and unique) visual presentation.
- c) Providing a logical procedure to obtain the state equations.

This is thereby a candidate for further analysis and examination.

Recapping, there are therefore three techniques of particular interest:

- i) Signal Flow Graphs, described in Section 3.2.1
- ii) Linear Graphs, described in Section 3.2.2
- iii) Bond Graphs, described in Section 3.2.3.

Although these graphical techniques are all established methods, it is not clear how they will perform in modelling instruments. Hence Section 3.5 onwards is devoted to modelling five commercially available instruments in order to obtain a better understanding of the advantages and disadvantages that each technique offers. A summary then follows.

3.2 Description of Graphical Techniques

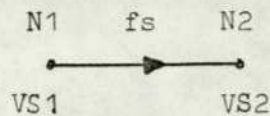
This section will now describe more formally the various techniques of interest that will be used for the modelling of instrument systems. However only a brief exposition is given as the methods are well-established and documented. Series and parallel junctions will be shown and each method illustrated with a simple example.

3.2.1 Signal Flow Graphs

i) Variables in Use

There is no restriction on the type of variables used but for modelling multi-energy systems some combination of through-across and effort flow is usually employed⁽²⁴⁾.

ii) Graphical Description of Function Relationship



$$V_{S2} = f_s (V_{S1}) \quad 3.2.1$$

$$\text{or } V_{S2} = f_s^{-1} (V_{S2}) \quad 3.2.2$$

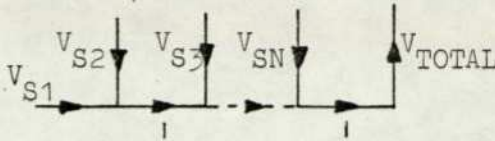
The nodes (N1 and N2) represent the variables V_{S1} and V_{S2} at that point on the graph. The arrow represents the direction of signal flow. f_s can be a gain, integrator etc., and in general would be nonlinear.

iii) Series Junction

$$V_{TOTAL} = \sum_{i=1}^N V_{Si} = \quad 3.2.3.$$

where an optional unit gain is introduced and utilised in the text.

iv) Parallel Junction

$$V_{TOTAL} = \sum_{i=1}^N V_{Si} =$$


3.2.4

where the convention of summing the lower line is employed and used in the text. (The quantity V_{TOTAL} represents a total summation of the variable quantities).

v) Causal Assignments

Already realised.

vi) Method of Construction

Consider the second order system described in Chapter 2. The equation was:

$$F = M\ddot{x} + R\dot{x} + kx$$

3.2.5

Once the equation has been obtained it is then possible to construct a signal flow graph for evaluation (i.e. producing the time response etc) of the system.

There are many ways to model this. A first attempt may lead to a re-arrangement of eqn 3.2.5 to give:

$$F - M\ddot{x} - R\dot{x} = kx$$

giving a flow graph as shown in Fig 3.3.

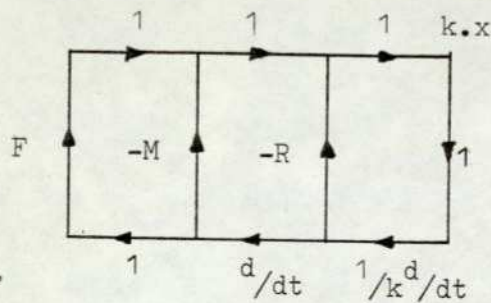


Fig 3.3

where summation of force is considered as a series junction.

This has the disadvantage of having differentiations in the system thereby allowing errors to arise in a solution. It is always preferable to rearrange the equations to avoid this problem as much as possible⁽²⁵⁾.

Using $F - kx - R\dot{x} = M\ddot{x}$ gives the graph shown in Fig 3.4.

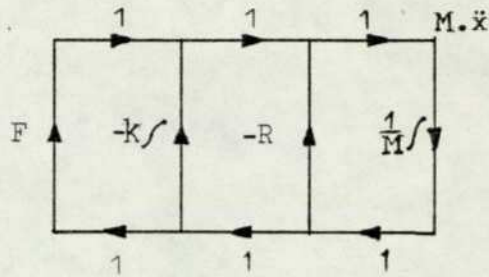


Fig 3.4

allowing the use of standard integration routines. In general modelling applications (C-R-L) Capacitance Resistance & Inductance will be used in order to introduce some conformity into the graphical display. A short table was shown in Fig 3.1.

3.2.2 Linear Graphs

i) Variables in Use

Linear graphs use Through & Across Variables⁽¹⁷⁾ in the modelling of engineering systems. For a single port these can be described as follows:

$$A = \Phi (T \oplus T \oplus \int T) \quad 3.2.6$$

$$T = \Phi (A \oplus A \oplus \int A) \quad 3.2.7$$

where A is the across variable

T is the through variable

$\oplus$ represents an exclusive OR (i.e. only one out of three)

Giving the fundamental forms

$$A = R.T \quad 3.2.8$$

$$A = L.\dot{T} \quad 3.2.9$$

$$A = 1/C \int T \quad 3.2.10$$

where R is the resistance in say the electrical domain,

L is the inductance in say the fluid domain,

C is the capacitance in say the thermal domain.

Table 3.1 shows the associated variables for five energy domains.

<u>Energy Domain</u>	<u>Across</u>	<u>Through</u>
Mechanical Translation	Velocity	Force
Mechanical Rotation	Angular Velocity	Torque
Electrical	Voltage	Current
Fluid	Pressure	Mass Flow Rate
Thermal	Temperature	Heat Flow Rate

Table 3.1

This follows the Firestone analogy⁽²²⁾ and has the following advantages:

- a) 'Equivalent' networks can be established using Tellegen, Kirchoff's laws etc.,
- b) Convenience of measurement (not tied to power flow product) .

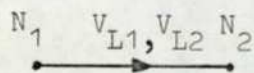
For mechanical systems the dual of effort-flow relationships are taken, i.e.

$$A \neq L \cdot \dot{T} \text{ where } L \text{ is the mass but}$$

$$\dot{A} = 1/L \cdot T$$

3.2.11

ii) Graphical Description of Functional Relationships



where V_{L1} and V_{L2} form a variable pair

giving

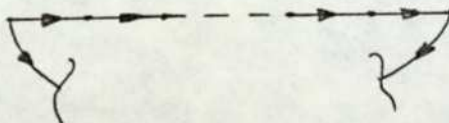
$$V_{L1} = f_L(V_{L2}) \quad 3.2.12$$

$$V_{L2} = f_L^{-1}(V_{L1}) \quad 3.2.13$$

N1 and N2 are defined as endpoints of an element⁽¹⁷⁾. The arrow represents the direction of positive flow into the element represented between N1 and N2. The precise nature of the element is not entered on the graph but defined by terminal relationships⁽⁷⁾. For example a resistance would be defined as $V_{L1} = R.V_{L2}$.

For general modelling of systems, N1 and N2 can be considered as across variable reference points.

iii) Series Junction

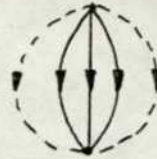
$$A_{TOTAL} = \sum_{i=1}^N A_i =$$


$$3.2.14$$

This effectively represents a circuit of serial elements.

iv) Parallel Junction

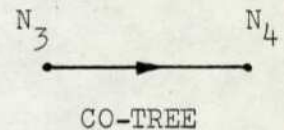
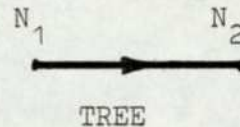
$$T_{TOTAL} = \sum_{i=1}^N T_i =$$



3.2.15

This effectively represents a circuit of parallel elements.

v) Causal Assignment



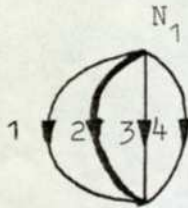
As indicated by eqn(s) 3.2.12 and 3.2.13 there are two ways to precisely define the causal influence of the variables. For equation formulation to proceed, this must be determined for each element, and this is accomplished by the assignment of trees and co-trees. The approach is based on the topological consideration of spanning each node once for each forest⁽⁷⁾ (thick line above). The co-trees (thin line) are then automatically accounted for (but not ignored) as being the rest of the elements.

vi) Method of Construction

The method of construction after equivalent networks have been formed is to represent the system in a topological

fashion. However for mechanical translations and mechanical rotation systems more care is necessary and recourse is required to careful application of through and across relationships.

For the weighing machine described in Chapter 2 and represented by the equations 3.2.5, it is clear that there is only one across variable in the system, this being with respect to ground. This gives the graph and terminal equations shown in Fig 3.5.



TERMINAL EQUATIONS

1 = APPLIED FORCE

$$2 \dot{X} = 1/L \cdot \int F$$

$$3 \dot{X} = 1/R \cdot F$$

$$4 \dot{X} = C \cdot \dot{F}$$

Fig 3.5

where a parallel circuit (because the forces are summed) occurs. Integral causality is determined by selecting the mass

as a tree element (producing a corresponding across variable as output). The terminal relationships cannot be represented on the graph, due to the problems of element descriptions in relation to through and across variables (see eqn 3.2.11).

In order to form a solution it may be noted that by formulating a vector of Through and Across variables (Kirchoff's 1st and 2nd Laws):-

$$A_L T = 0 \quad (\text{Incidence Matrix Equation})$$

$$B_L A = 0 \quad (\text{Loop Matrix Equation})$$

where the subscript 'L' refers to a linear graph and by the expression

$$A_L B_L^T = 0$$

Cutsets and tiesets can be related⁽²⁶⁾. This together with the terminal equations enables a solution to be generated⁽¹⁷⁾. (Chapter 5 Sections 3 and 4 describes this particular approach in more detail).

3.2.3 Bond Graphs

i) Variables in Use

Bond Graphs use Effort and Flow Variables⁽¹⁸⁾ for modelling engineering systems. For a single port these are described as follows.

$$E = \Phi (F \oplus F \oplus F) \quad 3.2.16$$

$$F = \Phi (E \oplus E \oplus F) \quad 3.2.17$$

where E is the effort variable

F is the flow variable.

These give the following fundamental forms.

$$E = R.F \quad 3.2.18$$

$$E = L.\dot{F} \quad 3.2.19$$

$$E = 1/C .fF \quad 3.2.20$$

where R is the resistance in any domain

L is the inductance in any domain

C is the capacitance in any domain.

Table 3.2 shows the associated variables for the five energy domains.

<u>Energy Domain</u>	<u>Effort</u>	<u>Flow</u>
Mechanical Translation	Force	Velocity
Mechanical Rotation	Torque	Angular Velocity
Electrical	Voltage	Current
Fluid	Pressure	Volume Flow Rate
Thermal	Temperature	Entropy Flow Rate

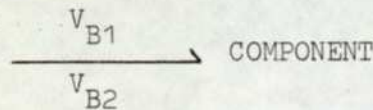
Table 3.2.

This has the advantage of:

- a) providing a convenient platform to model power flow.
- b) provide consistency in the mathematical definition of elements.

For some energy domains 'pseudo' bond graph elements are used⁽¹⁸⁾. These relax the pairings in Table 3.2. For example in compressible fluid systems, mass flow rate rather than volume flow rate has some advantages.

ii) Graphical Descriptor of Functional Relationship



where V_{B1} and V_{B2} form a variable pair,
giving

$$V_{B1} = f_B (V_{B2}) \quad 3.2.21$$

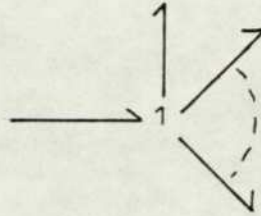
$$V_{B2} = f_B^{-1} (V_{B1}) \quad 3.2.22$$

The arrow direction represents the direction of power.

In this case it is shown entering a component.

iii) Series Junction

$$E_{\text{TOTAL}} = \sum_{i=1}^N E_i =$$

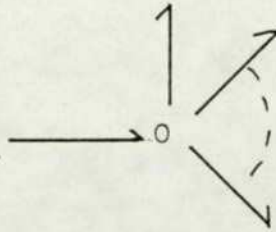


3.2.23

where the convention is to use '1' rather than 'S' for series.

iv) Parallel Junction

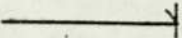
$$E_{\text{TOTAL}} = \sum_{i=1}^N F_i =$$

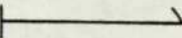


3.2.24

where the convention is to use 0 rather than 'p' for parallel.

v) Causal Assignment

a)  (COMPONENT)

b)  (COMPONENT)

As indicated by equations 3.2.21 and 3.2.22 there are two ways to define the causal influence. The approach is based on the premise that both sides of a bond must be satisfied according to a set of rules of required and desired causal influence at junctions and components. This is accomplished by the assignment of a vertical line (a) or b) above) at one end of each bond.

vi) The method of construction is to utilise directly power flow in or out of a 'bonded' combination of components. For a majority of cases one variable is constant allowing series or parallel junctions described above to be used.

For the weighing machine illustrated in Chapter 2, the force applied is the total effort necessary to move the mass, dashpot resistance and spring. Hence a series junction (as

force is an effort variable) is utilised. This gives the bond graph shown in Fig 3.6.

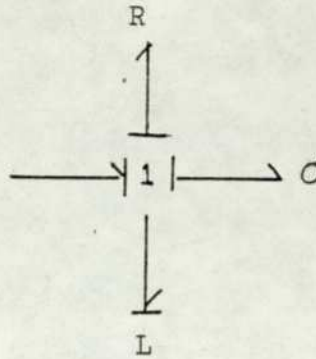


Fig 3.6

Integral causality is selected by allowing force to be applied to the mass (providing a flow variable as output). The elements can be represented on the graph as their definitions are consistent.

In order to form a solution it can be noted that

$$A_B E = 0 \text{ (Effort Matrix Equation)}$$

$$B_B F = 0 \text{ (Flow Matrix Equation)}$$

where the subscript 'B' refers to a bond graph.

And with the expression:

$$A_B B_B^T = 0$$

the effort and flow matrices can be related⁽²⁸⁾. This together with the component equations allows a solution to be generated.

3.3 Modelling Energy Transfer

Two ports (outside of fields) of particular interest are 'TF' and 'GY' terms described below. They allow transfer from one energy domain to another.

i) Transformer

Through and Across Relationships

$$A_1 = TF_1.A_2 \quad 3.3.1$$

$$T_1 = 1/TF_2.T_2 \quad 3.3.2$$

where 1 represents port 1
2 represents port 2.

For power conservation $TF_1 = TF_2$.

Effort and Flow Relationships

$$E_1 = TF_1.E_2 \quad 3.3.3$$

$$F_1 = 1/TF_1.F_2 \quad 3.3.4$$

ii) Gyrator

Through and Across Relationships

$$A1 = GY1.T2 \quad 3.2.27$$

$$T1 = 1/GY2.A2 \quad 3.2.28$$

for power conservation $GY1 = GY2$.

Effort and Flow Relationships

$$E1 = GY1.F1 \quad 3.2.29$$

$$F1 = 1/GY1.E2 \quad 3.2.30$$

These elements are of considerable importance in modelling instrument systems. They provide a means for representing the interchanges between one energy domain and another.

Because through and across pair products do not necessarily constitute power, the transformer and gyrator forward and back ratios may not necessarily have unity product.

3.4 Modelling Fields

Equations 3.2.8-3.2.10 and 3.2.18-3.2.20 can be extended to the more general multiport case. These are referred to as fields⁽¹⁸⁾. There are two types possible.

- a) Implicit
- b) Explicit.

Implicit fields represent directly the element structure of an identifiable multiport. For example a three port transformer can be modelled by a 3 port L field⁽¹⁸⁾.

Explicit fields represent mathematically a functional relationship known to be of an R, L or C form. For instance, in the electrical domain

$$\begin{bmatrix} V_1 \\ V_1 \end{bmatrix} = \begin{bmatrix} R_1 & R_2 \\ R_3 & R_4 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad 3.4.1$$

However, this form could not be subsequently represented by four single port 'R' elements. In general it would also be possible to have mixed fields, i.e. comprising R, L and C terms but the usefulness of such terms is limited in practice⁽¹⁸⁾.

3.5. Interactive Modelling of Instruments

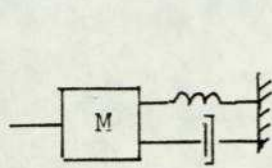
An instrument is generally composed of various sub-sections. In order to model using one of the above graphical techniques it is desirable to construct, as far as possible within the graphical medium, individual models for these sub-sections on an element by element basis. It only

then remains to connect these sub-graphs to provide an overall model. Fig 3.7 gives some examples of various subsections commonly encountered.

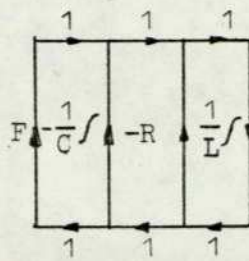
For completeness the various sub-graphs have been causally assigned. In general this is an incorrect procedure as causality should only be obtained once the full model has been constructed. (This is especially true for signal flow graphs).

It can be seen immediately how strikingly different the graphical displays represent the schematic. (The linear graph terminal relationships have not been given as these do not affect the graphical format in any way).

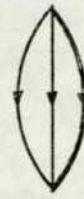
In order to observe the effects of the different graphical techniques in the modelling of instruments, five examples will now be constructed that explore fluid, mechanical, rotational, electrical and thermal systems. All of these instruments will be modelled using each of the above techniques and comments made on the suitability of each method at each stage. However as a fair amount of duplication will inevitably result only the first model will be analysed in detail for construction and structural changes. The necessary determination of parameter values for the latter four models is not described in this chapter but left to Appendix A-D.



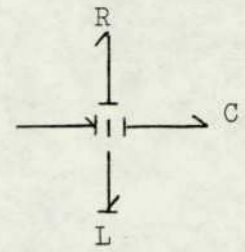
a)



b)

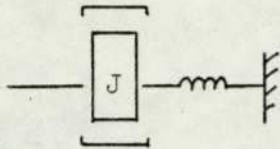


c)

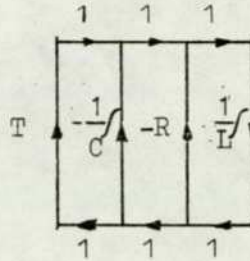


d)

MECHANICAL TRANSLATION



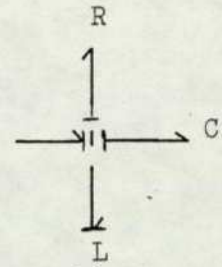
e)



f)

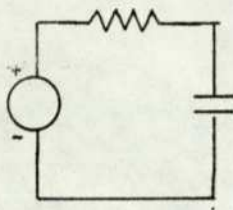


g)

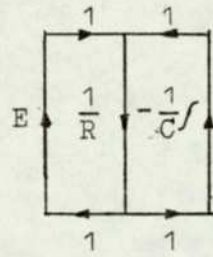


h)

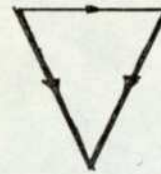
MECHANICAL ROTATION



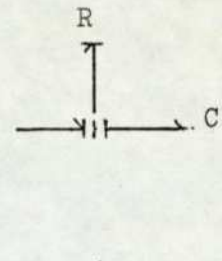
i)



j)

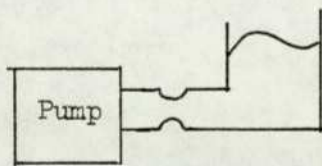


k)

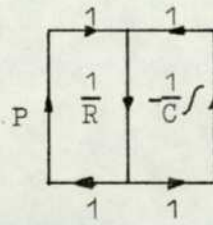


l)

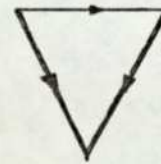
ELECTRICAL



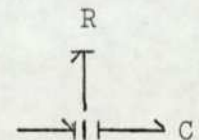
m)



n)

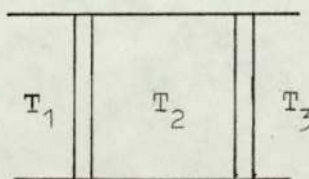


o)

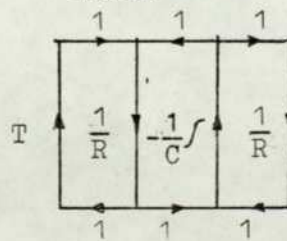


p)

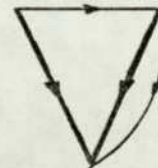
FLUID



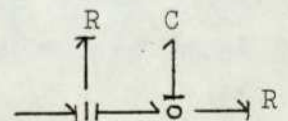
q)



r)



s)



t)

THERMAL

GRAPHICAL MODELLING OF TYPICAL SUB-SECTIONS

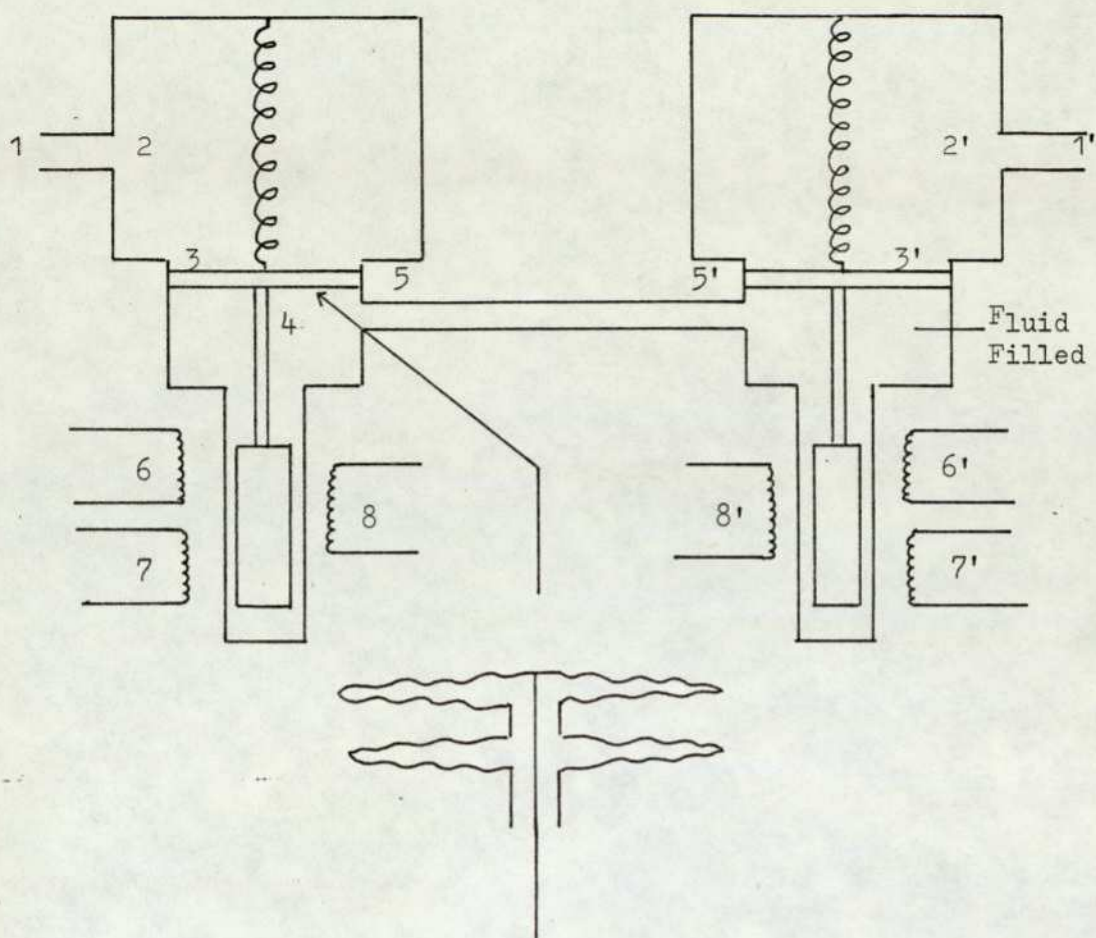
Figure 3.7

All the models have been simulated on the computer. However, the results are displayed in Chapter 6 rather than here, in order to present duplications when modelling with the developed package.

3.5.1 A Detailed Example Description of K.D.G. D.P.Cell

A Differential Pressure Cell is shown in Fig 3.8. This has been modelled in a number of reports at City University^{(29) (30)} and provides a convenient base to analyse the graphical techniques.

A brief description of the K.D.G. Differential Pressure Cell is as follows. Differential Pressure is the measured quantity. It is applied at 11'. This moves the two diaphragms in a push pull mode of operation. For connecting tube 55' is essential in this respect as it transmits an ideally incompressible fluid. The diaphragms themselves are physically connected to the cones of Linear Variable Differential Transformers (L.V.D.T's). The output of each L.V.D.T. is connected such that the sum of both movements are effectively added. Double the output is thereby produced and many higher order voltage terms are cancelled. The spring connected to 3 and 3' represents the stiffness of the diaphragms and does not exist in practice in that form.



1-2	Inlet Resistance	R
2-3	Chamber Capacitance	C
4	Compressibility Effects	C
5-5'	Connecting Tube	R-L
6-7-8	L.V.D.T.	X, V, ω , L

K.D.G. D.P. Cell

Figure 3.8

3.5.2 Block Diagram

Fig 3.9 shows a functional block diagram of the D.P.Cell. This is useful for identifying the important sections of the instrument. Essentially there are three energy domains to be analysed.

- a) Fluid
- b) Mechanical Translation
- c) Electrical.

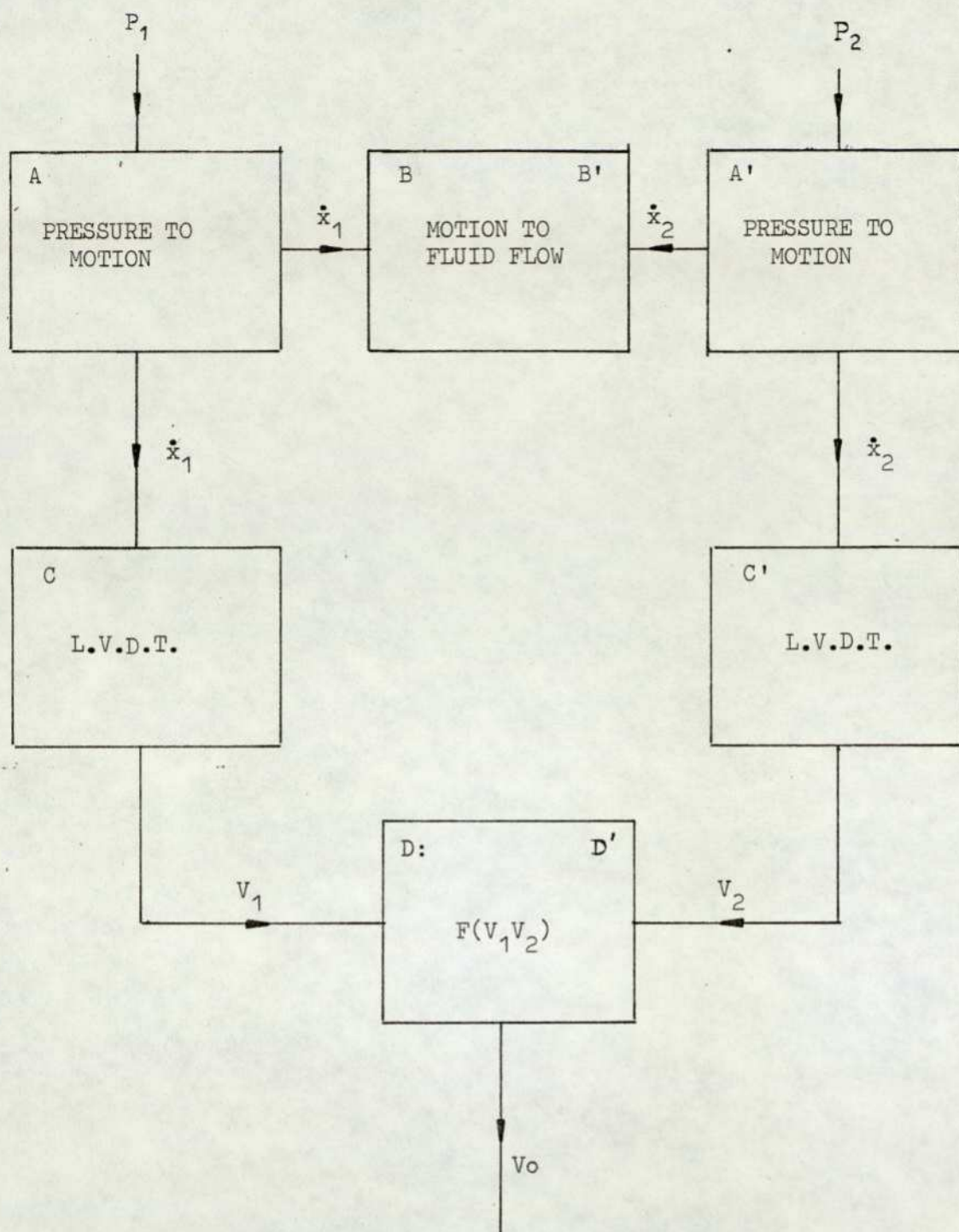
Ideally each section could be modelled independently of any other and then connected. All available simulation packages though, will analyse the system only when represented in a graphical form. Therefore this area tends to be by-passed particularly if interactive changes are to be made.

However for the purpose of describing the various graphical constructions of the D.P.Cell Fig 3.9 will be referred to in the following sections.

3.5.3 Modelling with Signal Flow Graphs

- i) Graphical Implementation For Model Equations

The Signal Flow Graph of a Multi-energy domain system can be drawn once the equations have been formulated. In a



A BLOCK DIAGRAM OF THE K.D.G. D.P. CELL.

City University report⁽²⁹⁾ these were established and are represented below.

$$\dot{g}_1 = Ar \cdot \sqrt{\frac{2 \cdot R \cdot T}{1 + \zeta}} \sqrt{\frac{p_1' - p}{p}} \quad 3.5.1$$

$$\dot{g}_1' = Ar \cdot \sqrt{\frac{2 \cdot R \cdot T'}{1 + \zeta'}} \sqrt{\frac{p_1' - p'}{p'}} \quad 3.5.2$$

$$\dot{p} = \frac{p}{V + AX} \cdot (\dot{g}_1 - A \cdot \dot{x}) \quad 3.5.3$$

$$\dot{p}' = \frac{p'}{V' + A'x'} (\dot{g}_1' - A' \cdot \dot{x}') \quad 3.5.4$$

$$\ddot{x} = \frac{A}{M} (p - p_4) - \frac{r}{M} \cdot \dot{x} - \frac{k}{M} \cdot x \quad 3.5.5$$

$$\ddot{x}' = \frac{A'}{M'} (p' - p_4') - \frac{r'}{M'} \cdot \dot{x}' - \frac{k'}{M'} \cdot x' \quad 3.5.6$$

$$p_4 = p_0 + \frac{B}{V_c} (-gf + A \cdot x) \quad 3.5.7$$

(p_0 is a common equilibrium pressure)

$$p_4' = p_0 + \frac{B}{V_c'} (gf + A' \cdot x') \quad 3.5.8$$

$$\ddot{g}f = \frac{1}{L_t} (p_4 - p_4') - \frac{Rt}{L_t} \cdot \dot{g}f \quad 3.5.9$$

where: $\dot{g}_1$ is the volume flow rate into the inlet restriction
1-2

p is the pressure applied to the diaphragms

x is the displacement of the diaphragms

p_4 is the pressure applied to the connecting
tube 5-5'

gf is the volume flow rate into the connecting
tube

r is the dashport resistance

V_c/B is the fluid capacitance.

Inherent in the above equations are the primitive
'element' forms discussed in Section 3.2.1. However it would
help to expose these terms by slightly adjusting the
equations.

Rewriting 3.5.5.

$$A.p_r = r.\dot{x} \quad 3.5.10$$

$$x = C.A.p_c \quad 3.5.11$$

$$A.(p-p_4-p_r-p_c) = M.\ddot{x} \quad 3.5.12$$

Similarly for 3.5.6

$$A.p_r' = r'\dot{x}' \quad 3.5.13$$

$$x' = C'.A'.p_c' \quad 3.5.14$$

$$A'.(p'-p_4'-p_r'-p_c') = M'.\ddot{x}' \quad 3.5.15$$

Also from equation 3.5.9

$$p_t = R_t \cdot \dot{g}f \quad 3.5.16$$

$$p_4 - p_4' - p_t = L_t \cdot \ddot{g}f \quad 3.5.17$$

where $A.p_r$ is the force applied to the first dashport resistance

$A'p_r'$ is the force applied to the second dashport resistance

$A.p_c$ is the force applied to the first diaphragm capacitance

$A'p_c'$ is the force applied to the second diaphragm capacitance.

p_t is the differential pressure applied to the tube resistance

$C = 1/K$ in eqn 3.5.11

$C' = 1/K'$ in eqn 3.5.14

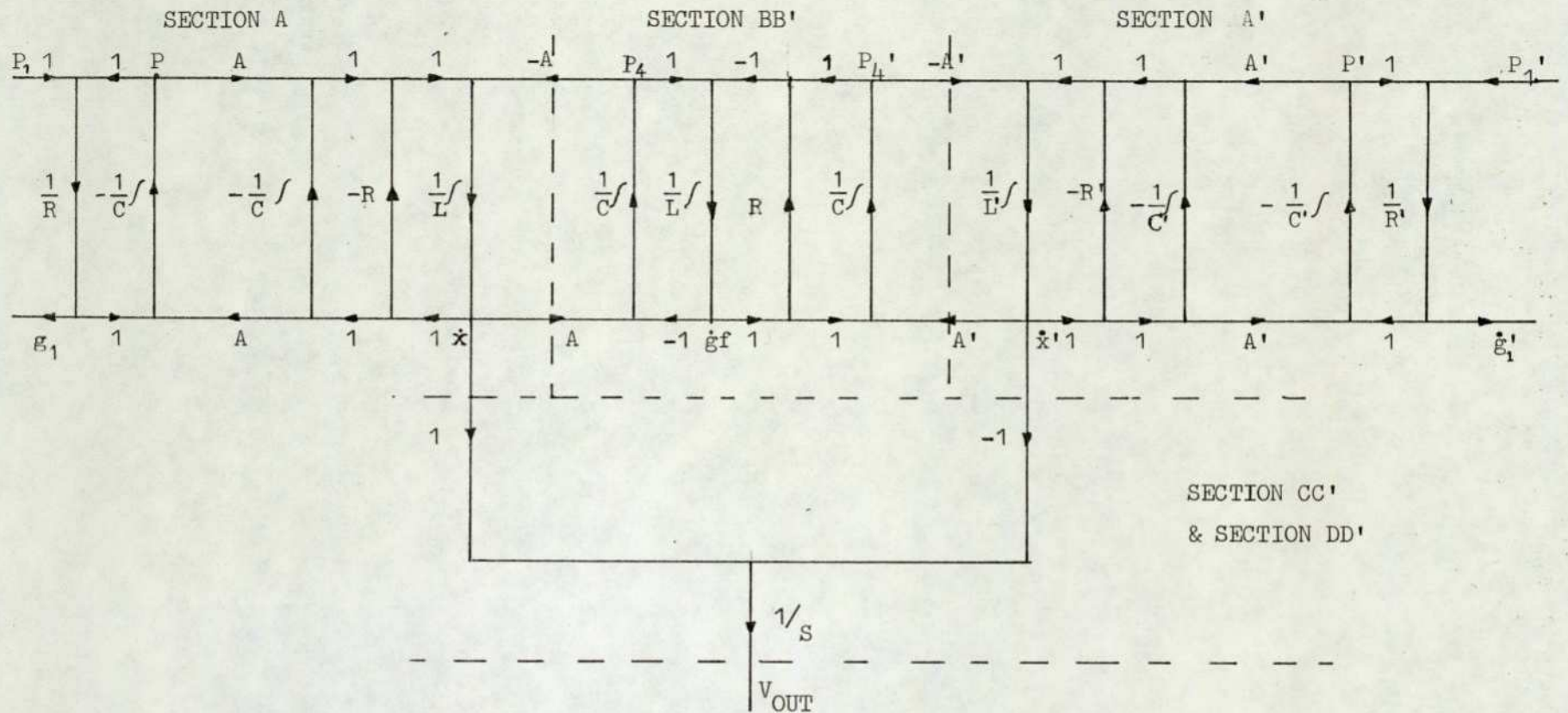
The complete signal flow graph is shown in Fig 3.10.
The implementation is as follows.

Section A: From eqn 3.5.1 and 3.5.3

R-C network using integral causality.

For eqn 3.5.10, 3.5.11 and 3.5.12:-

R-L-C network using integral causality. The conversion from mechanical to Fluid is via the area 'A'.



SIGNAL FLOW GRAPH OF K.D.G. D.P. CELL

Figure 3.10

Section A': Identical to Section A (except for parameters)

Section BB': From eqn 3.5.7, 3.5.8, 3.5.16 and 3.5.17

C-L-R-C network using integral causality.

The conversion from mechanical to fluid systems is again via the area 'A'.

Section CC' & The velocities are summed and integrated.

Section DD'

In general it can be stated that the signal flow graph must be constructed from the equations. Fig 3.10 is one possible representation of the D.P.Cell. (For a comparison with an equivalent graph see Abdullah⁽²⁹⁾). The reason for the difference here is essentially to keep the functional elements in the original form as much as possible).

There are several aspects of Fig 3.10 worth noting.

- a) The D.P.Cell is difficult to identify from the graph. There are no characteristic features as far as the model is concerned. Indeed two signal flow graphs of the same instrument can exist in which it would only be possible to identify equivalence from the original equations!
- b) Signal interaction and feedback loops are easily seen. It may be useful to enquire whether positive feedback exists,

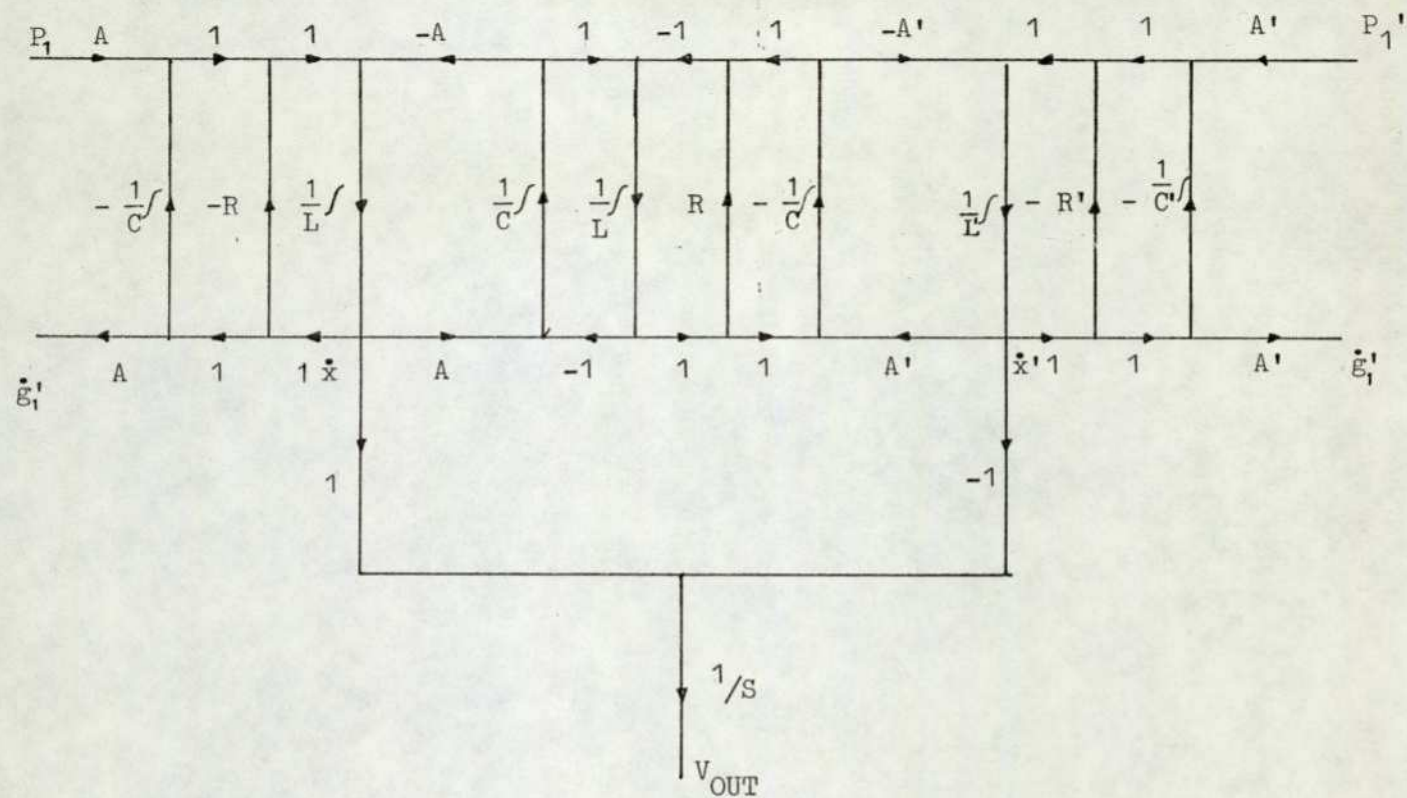
or to ascertain fast time constants. The signal flow graph is an ideal medium for inspections of this kind.

ii) Effects of Structural Changes

The model in its present form is expensive on simulation time. The system is in fact ill-conditioned due to the very small time constants of the input chambers. Removing these terms have little effect on the results⁽²⁹⁾. Fig 3.11 gives the reduced Signal Flow Graph.

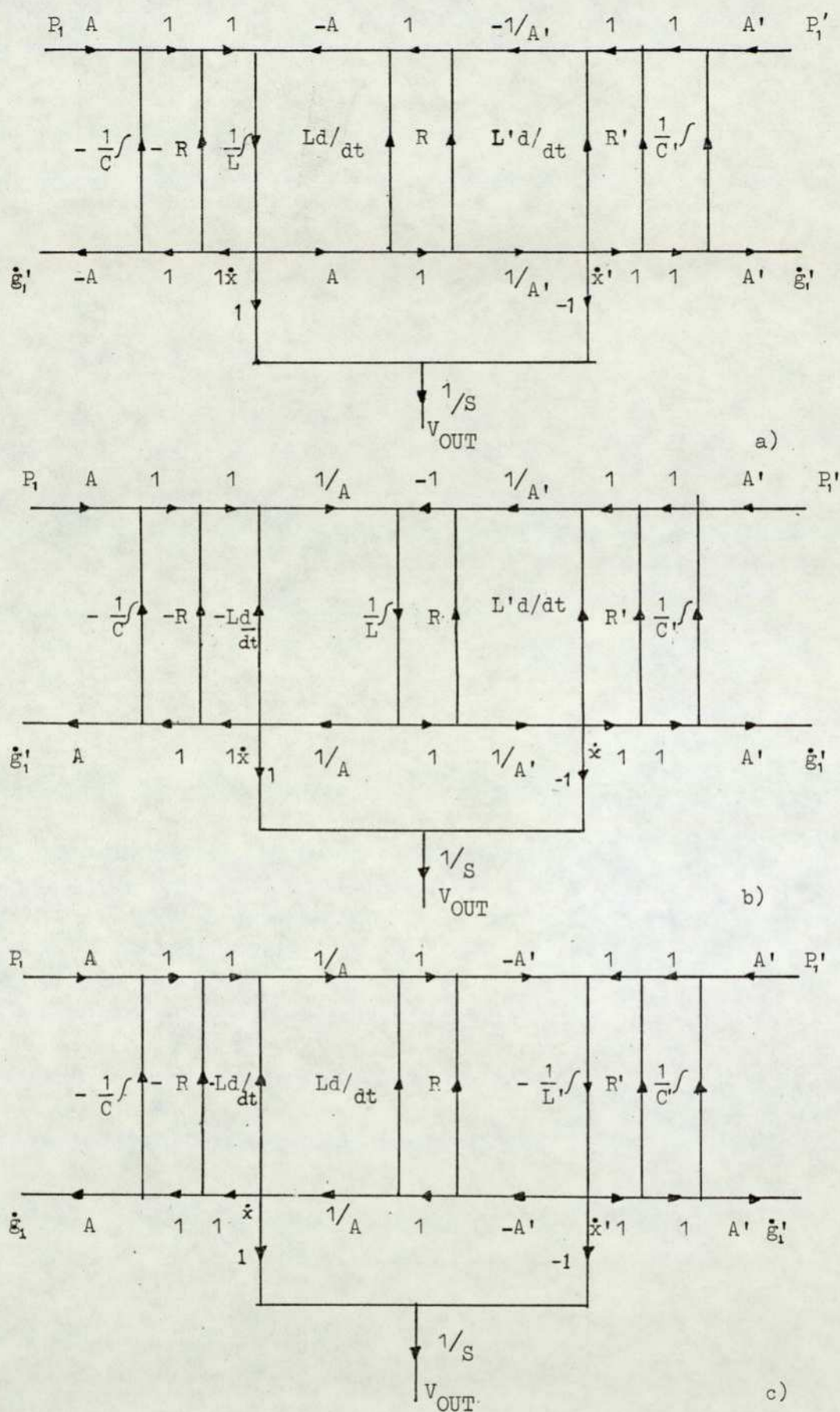
There is little change to the overall system outside the removal of these elements. In general if there are no causal conflicts 'elements' can simply be inserted and deleted. Continuing with reducing the model size of the very small capacitances in the connection tube can also be removed, as their contribution is also very small. Fig 3.12 shows the result.

In this case there are three graphs that are relevant. They correspond to the different choice of placement of the derivative terms now encountered. Of special importance is the effect that this choice has on the surrounding structure. For example in Fig 3.12 c) the diaphragm assembly is affecting the connecting tube representation. In general therefore



REDUCED SIGNAL FLOW GRAPH OF D.P. CELL (CHAMBERS NEGLECTED)

Figure 3.11



FURTHER REDUCTIONS OF SIGNAL FLOW GRAPH (ASSUMING INCOMPRESSIBLE FLUID).

Figure 3.12

- a) Insertion and deletion of an element can affect the associated nearby structure.
- b) Undesirable derivative terms can occur in the model formulation.

For interactive simulation of instruments these points clearly limit signal flow graphs.

3.5.4 Modelling with Linear Graphs

i) Construction of Linear Graph

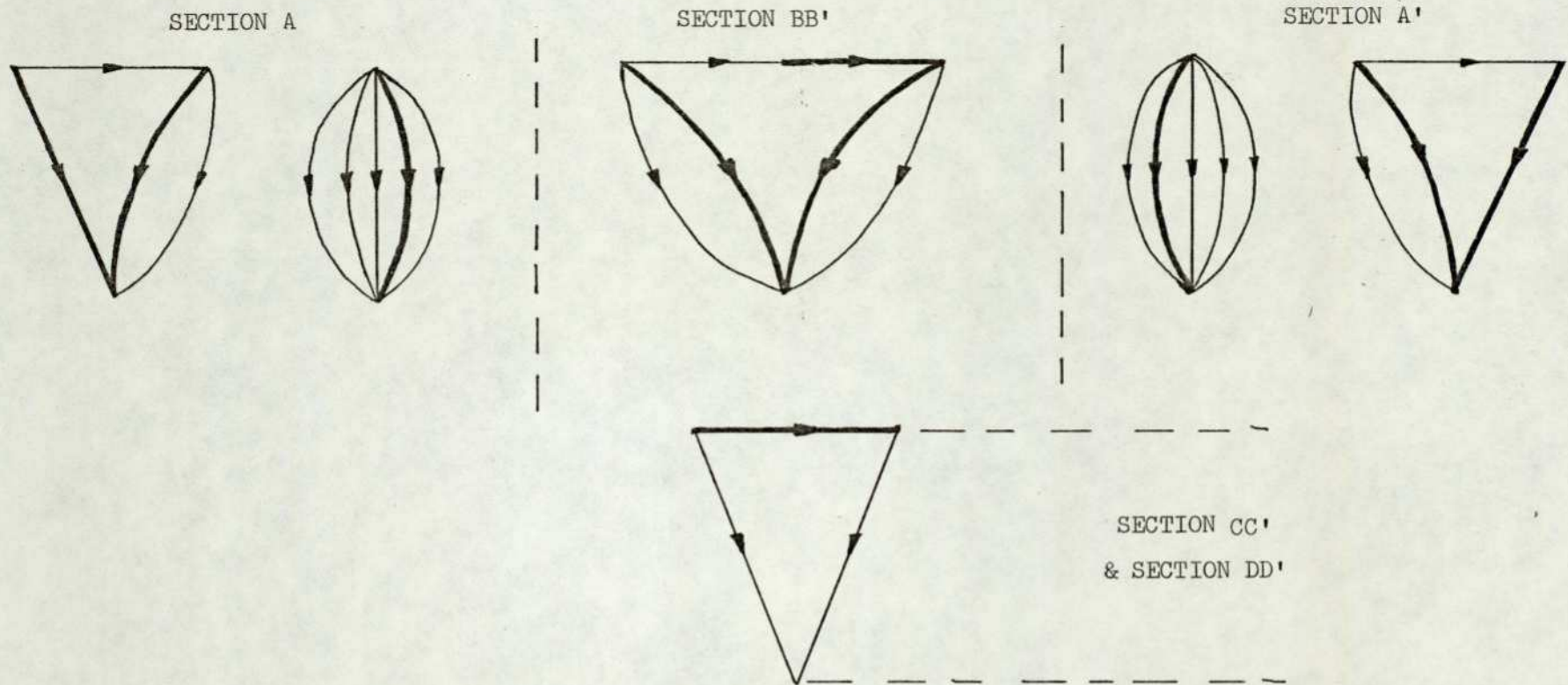
No equations are necessary to construct the linear graph. Taking each section of Fig 3.9 in turn, the graph in Fig 3.13 is produced.

Section A: R-C network topologically representable. A gyrator connects to the mechanical domain. R-L-C network is parallel as only one common displacement point. Connected to section BB' by a gyrator.

Section A': Identical to Section A.

Section BB': A C-L-R-C network. The capacitances are with respect to a reference point and are therefore down to ground. The rest of the fluidic section modelled topologically.

Sections CC' The displacements are found and summed by & Section DD' a suitable circuit network.



LINEAR GRAPH OF K.D.G. D.P. CELL

Figure 3.13

There are several points of interest.

- a) The elements are not represented on the graph.

As precise mathematical relationships of the elements are different for different energy domains, (as already emphasised in Section 3.2.2), it would be inappropriate to enter these onto the graph. They are however defined by external terminal equations.

- b) Graph readability reduced by energy changes.

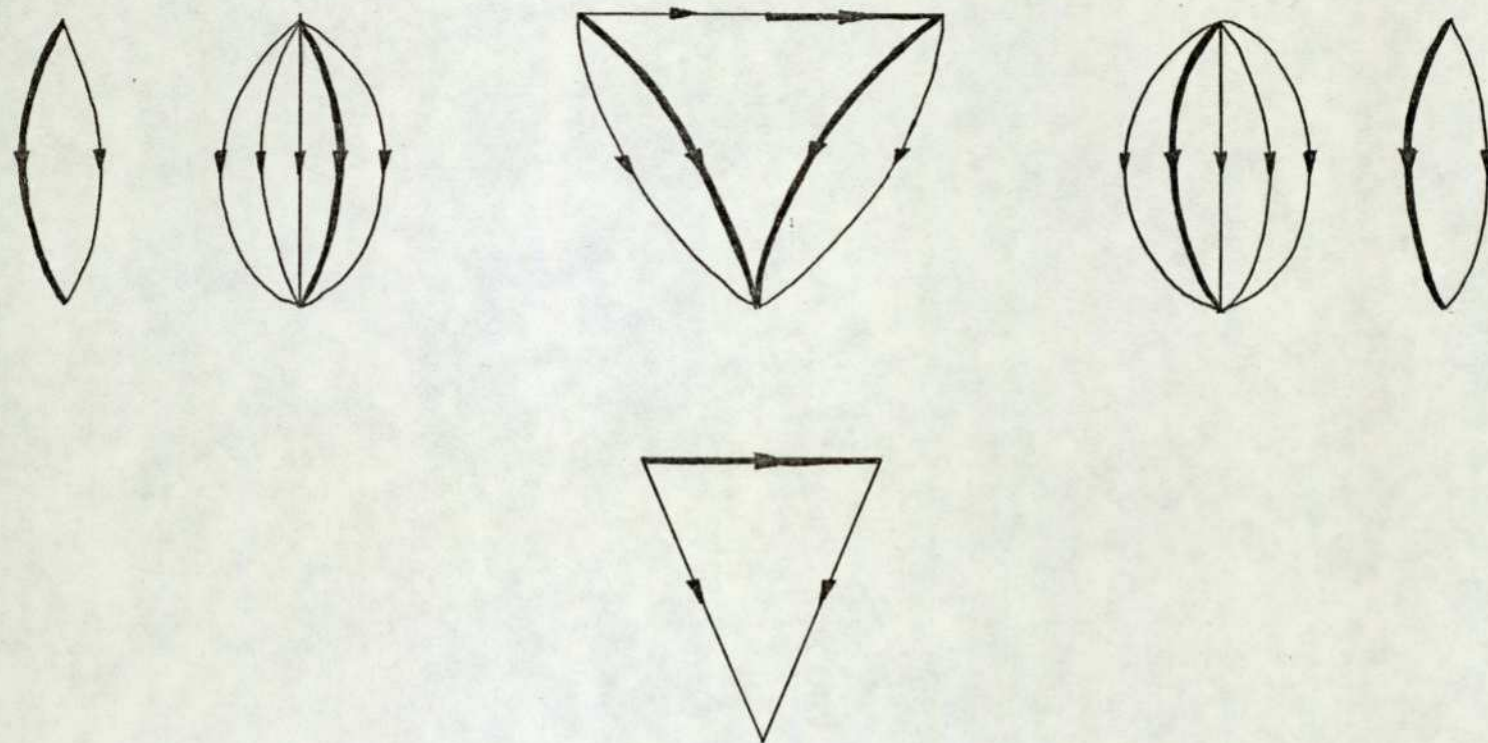
The conversion from one energy domain to another produces sub-graphs. This tends to reduce rather than enhance the overall graphical display.

In general the equations are found once the trees and co-trees have been obtained. The arrow directions are important and it is unfortunate that they do not represent the through variable topological but instead the positive flow orientation.

ii) Effects of Structural Changes

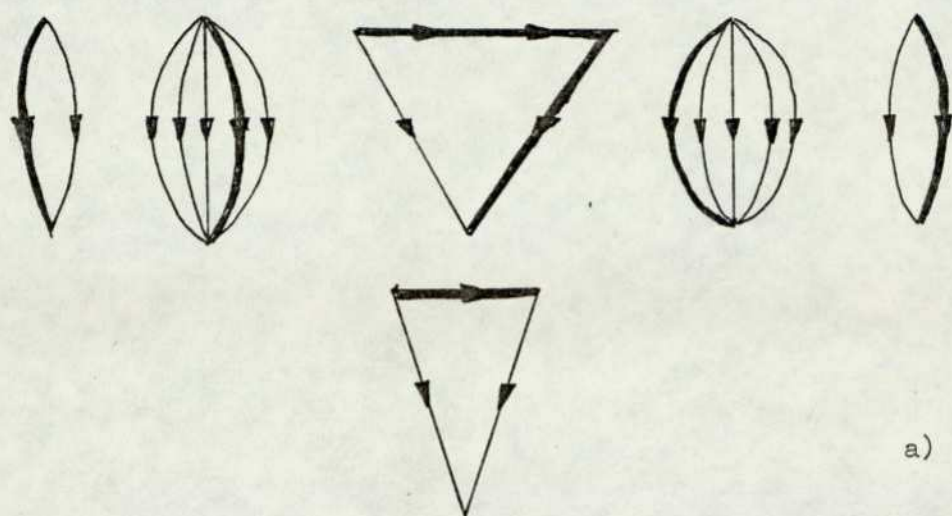
Fig 3.14 shows the elimination of the chamber elements. As with signal flow graphs the only effect has been the reduction in size of the model

Continuing this procedure and eliminating the connecting tube capacitances gives Fig 3.15.

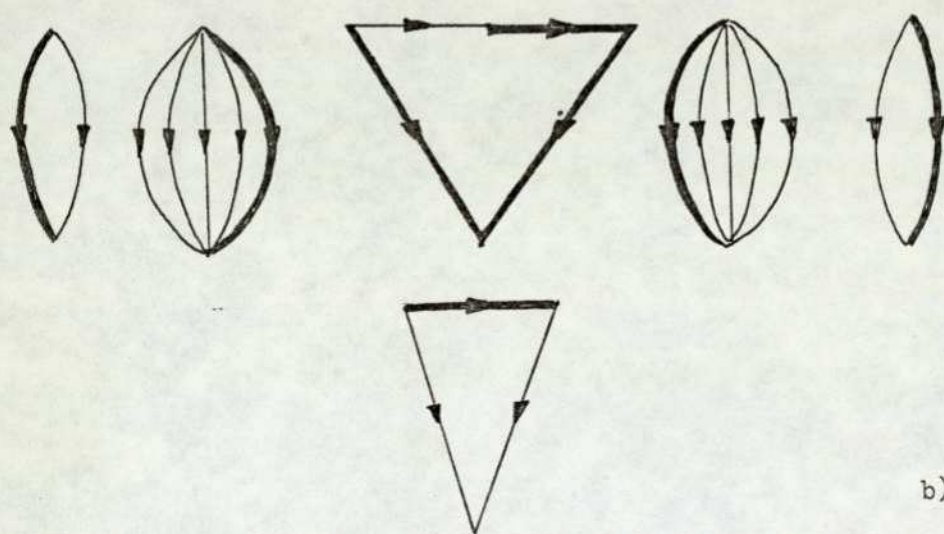


REDUCED LINEAR GRAPH OF D.P. CELL (CHAMBERS NEGLECTED)

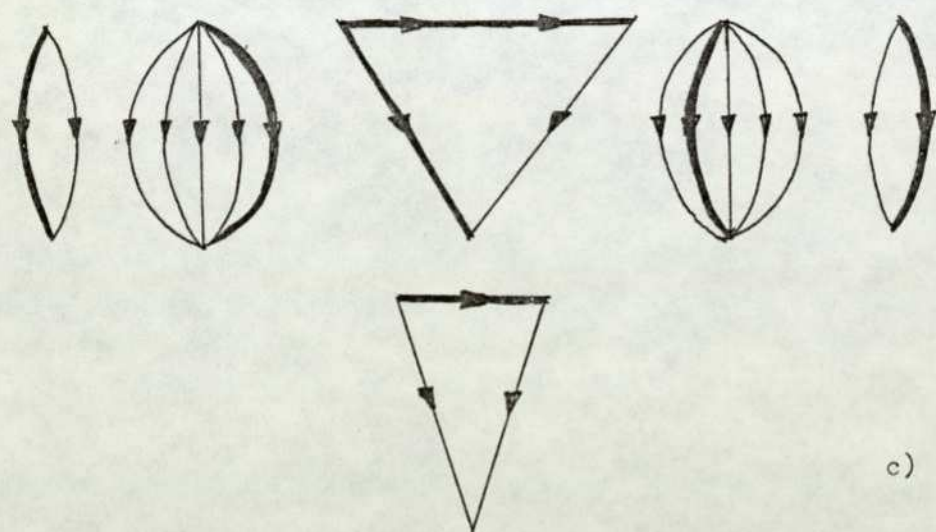
Figure 3.14



a)



b)



c)

FURTHER REDUCTION OF LINEAR GRAPH (ASSUMING INCOMPRESSIBLE FLUID)

Figure 3.15

In Fig 3.15 three possible causal assignments are given. It can be seen that

- a) The structure of the graph is unaffected by causal changes.
- b) Alternative causal assignments can be readily made.

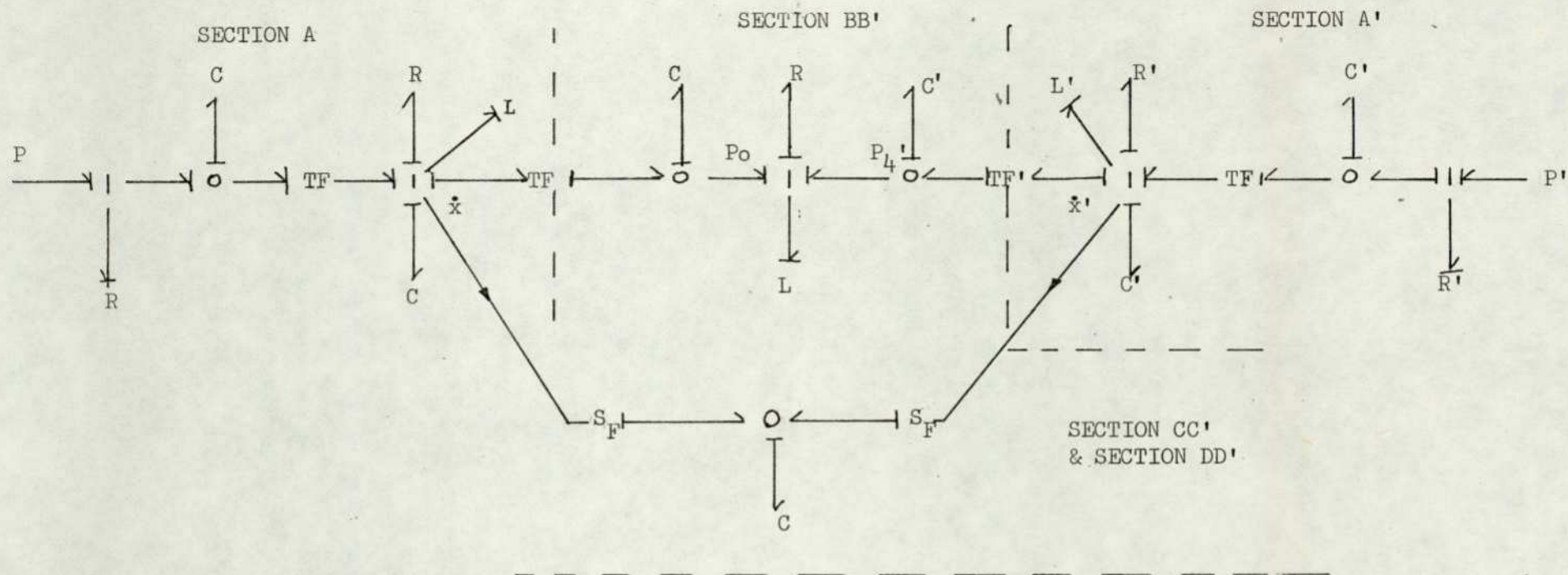
These two features are desirable for interactive modelling. Clearly changes in the structure will have less effect with this graphical representation than with signal flow graphs. The main area of difficulty is the very poor graphical format produced.

3.5.5 Modelling with Bond Graphs

i) Construction of Bond Graph

Fig 3.16 proceeds to show the bond graph version of the D.P.Cell. Considering each section in turn (Fig 3.9). (No equations are necessary for construction).

Section A: R-C network in fluid domain is connected via a transformer to the mechanical domain. The capacitance is in parallel with the transformer. The mechanical domain has a common displacement point, producing a series junction shown. A transformer connects to Section BB'.



BOND GRAPH OF K.D.G. D.P. CELL

Figure 3.16

Section A': Identical to Section A.

Section BB': C-L-R-C network. The capacitances are in parallel as they are w.r.t. ground. The L-R network is a series combination.

Section CC' The velocities are integrated and summed
& DD' by an appropriate equivalent network.

There are several points worth noting:-

a) The graph is a connected entity.

The problem of modelling multi-energy domain systems has been overcome by the insertion of appropriate 'TF' and 'GY' terms into the graph.

b) '1' and '0' junctions now occur on the graph which are not apparent on the schematic.

An essential feature of bond graphs is the power flow in or out of the series or parallel junctions. In general a set of construction rules are necessary to form the junction structures and their relationship with the components.

The equations are formed once causality has been assigned. For mechanical systems this is the dual of the linear graph.

ii) Effects of Structural Changes

Fig 3.17 shows the reduced bond graph once the chamber elements have been eliminated. Correspondingly, '1' and '0' terms from each side will also disappear.

Fig 3.18 gives the bond graph when the connecting tube capacitances are removed. There are several points of interest.

a) The arrow directions can sometimes appear ambiguous.

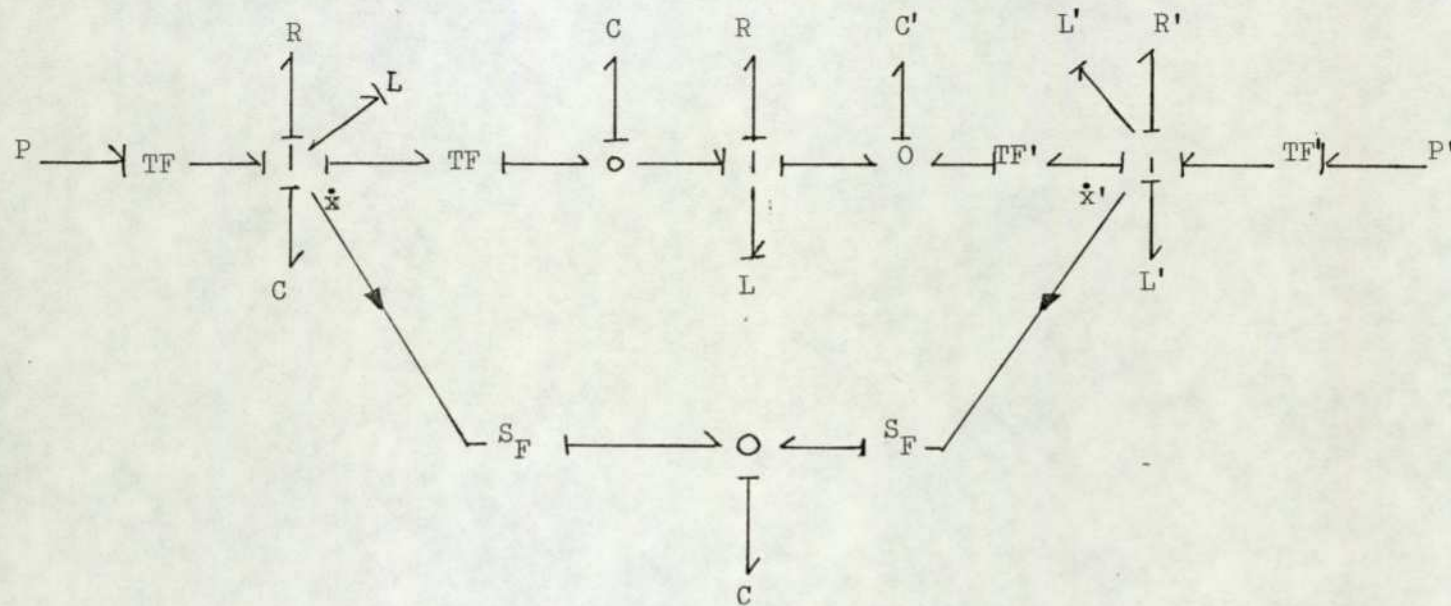
As there is no '0' or '1' on the schematic, confusion can arise as to the power direction in and out of these elements.

b) The structure of the graph is unaffected by causal changes.

As with linear graphs there is no problem with alternative representation for different causal influences.

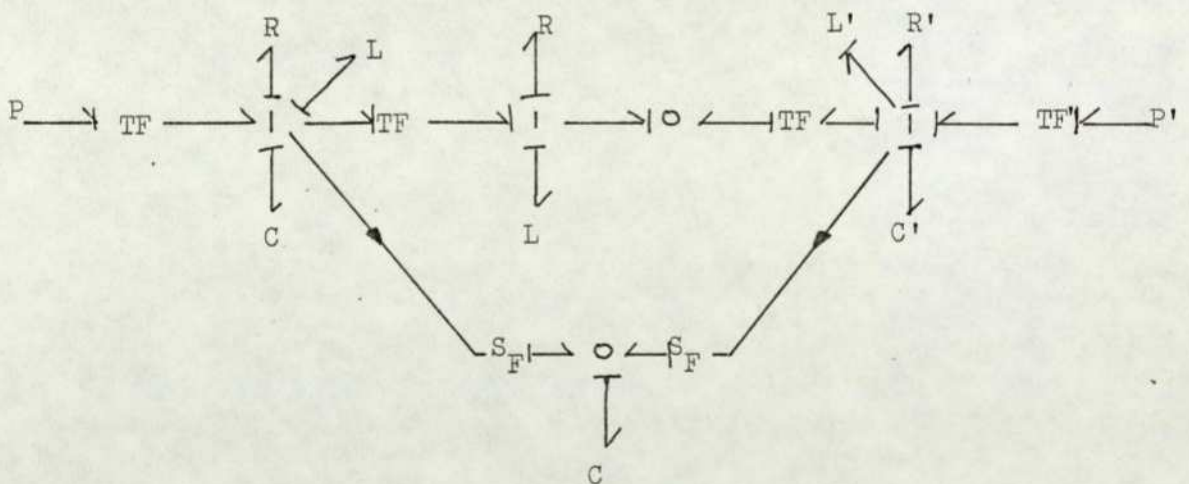
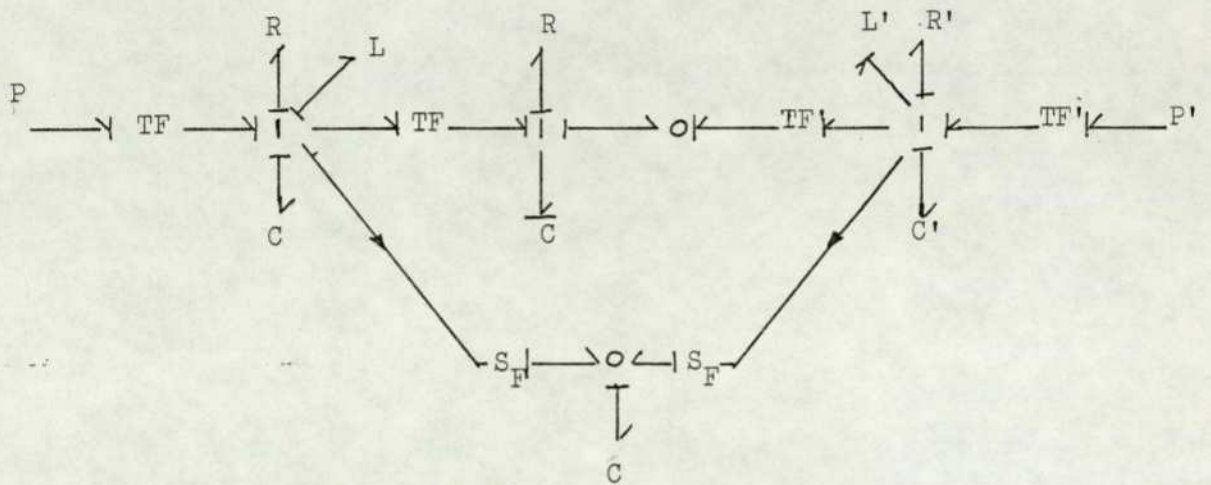
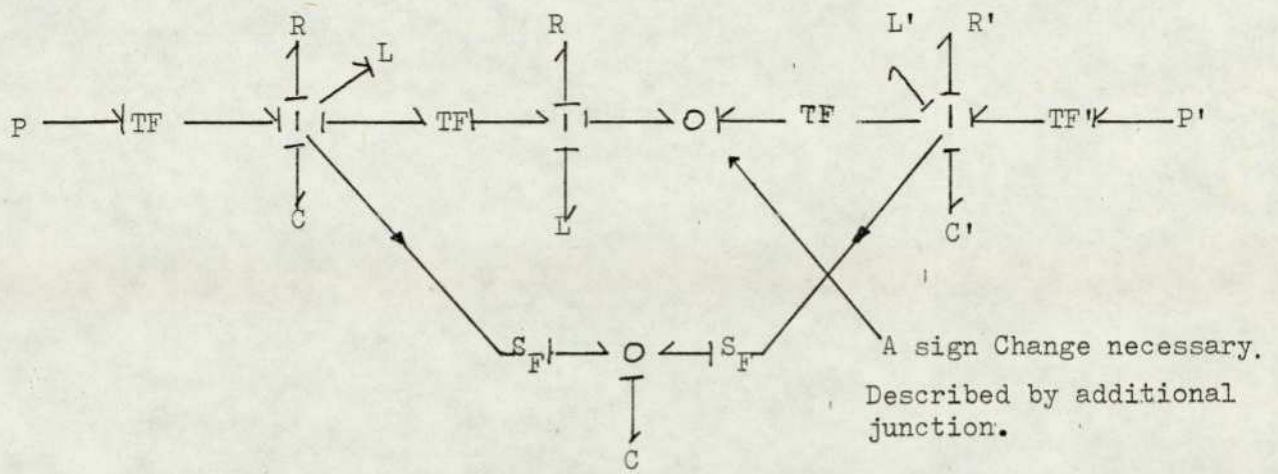
c) The bond graph has a characteristic form.

Some identity can now be established with the bond graph and the original system whereas for instance with the linear graph this is more difficult. Unfortunately the bond graph is so unique that interactive performance may suffer unless considerable familiarity of use!.



REDUCED BOND GRAPH OF D.P. CELL (CHAMBERS NEGLECTED)

Figure 3.17



FURTHER REDUCTION OF BOND GRAPH (ASSUMING INCOMPRESSIBLE FLUID)

Figure 3.18

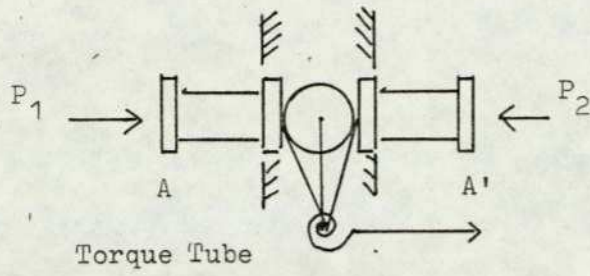
Because the elements are displayed on the bond graph, no terminal relationships are necessary. In general, bond graphs contain the highest information content of all the three techniques.

3.6 Some Further Examples

As only one instrument has been modelled up to this point, stating the relevant features of each technique may appear to be premature. Therefore four more examples, making five in all are now modelled in which it is hoped to illustrate further the points made above. However in order to condense this section structural changes will not be made and the relevant equations necessary to establish the parameters will be left to Appendix A-E.

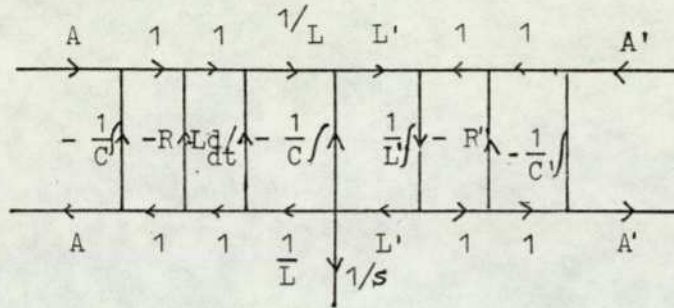
3.6.1 Barton D.P. Cell

A schematic of the D.P.Cell is shown in Fig 3.19a). The instrument is essentially a simpler version of the K.D.G. D.P.Cell. Differential pressure is applied at A and A' and this moves the Bellows Assembly and Torque Tube (the tube is into the paper). This gives a displacement measured from a pointer. Simple changes of springs provide a wide selection of different ranges. The parameters are established in Appendix A.



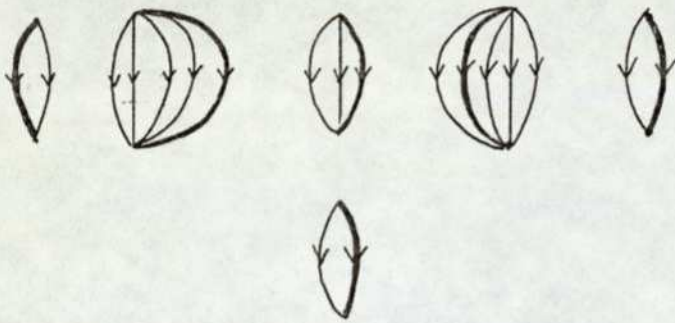
Schematic

a)



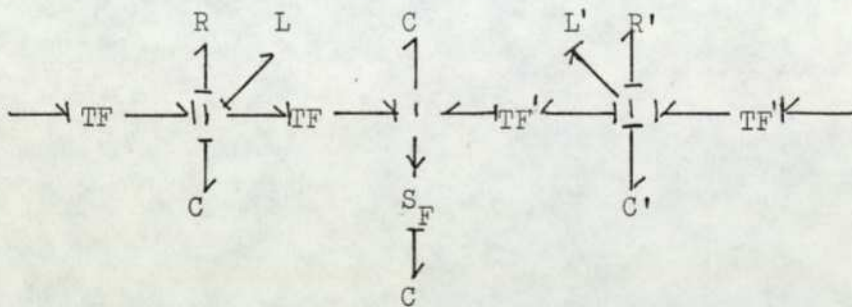
Signal Flow Graph

b)



Linear Graph

c)



Bond Graph

d)

GRAPHICAL REPRESENTATIONS OF BARTON D.P. CELL

Figure 3.19

3.6.2 Graphical Representation

The Signal Flow Graph shown in Fig 3.19b) gives a good display, as would be expected, of the internal signal flows of the device. However these are difficult to identify with the instrument particularly if structural changes are necessary. If for example an extra pair of springs were to be inserted it is not apparent from the graph how to proceed. Recourse to the original equations would be necessary.

The linear graph is displayed in Fig 3.19c). This presents six sub-graphs of the instrument and as before the terminal relationships would be necessary to evaluate the model for time or frequency response etc. It would be difficult to identify the Barton D.P. cell from this graph. An extra pair of springs in parallel would be inserted in parallel.

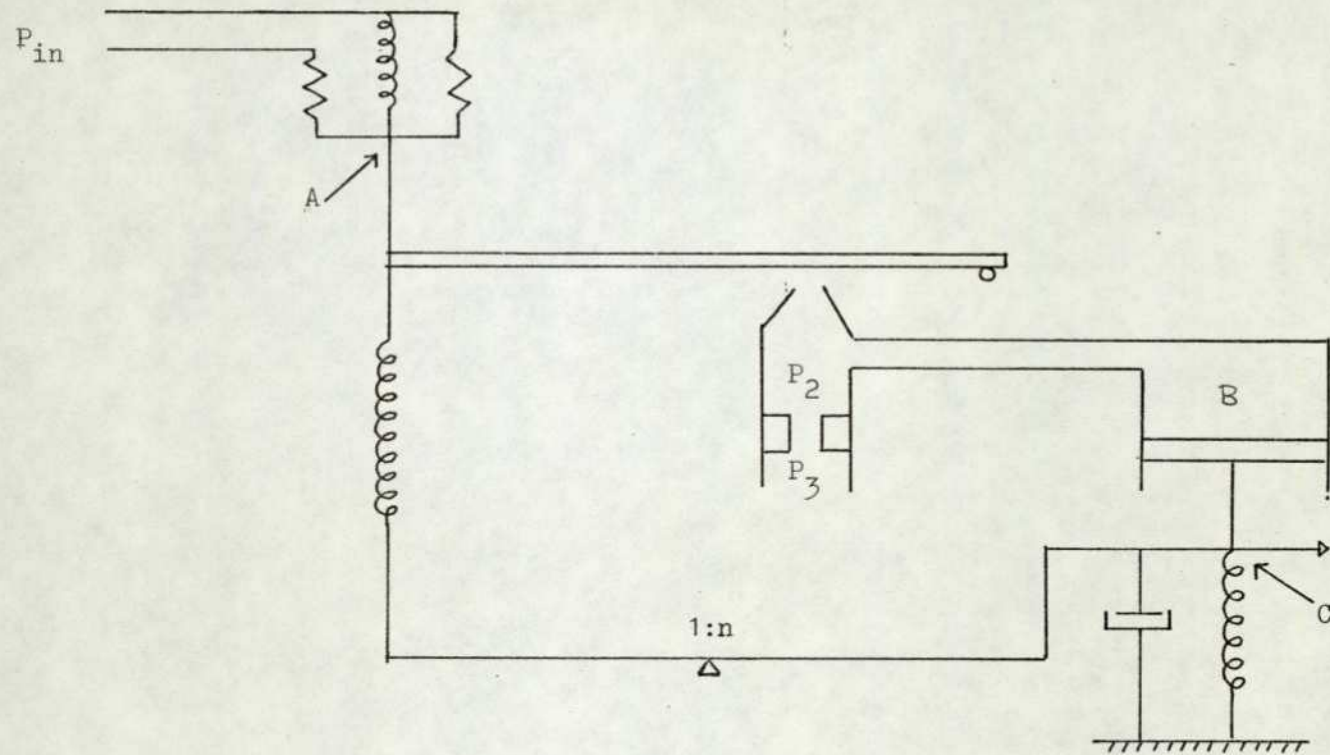
The bond graph presents the elements, connected between various '1' junctions. This is shown in Fig 3.19d). It provides some visual uniqueness of the Barton D.P. cell which can be compared to that of the K.D.G. D.P. Cell (Fig 3.16). The power direction is not difficult to identify and this must always be towards the torque tube. An extra pair of springs in parallel, however, would have to be inserted in series.

3.6.3 Description of Negretti & Zambra Proportional Controller

A schematic of this instrument is shown in Fig 3.20. A brief description is as follows. Pressure is input via bellows/diaphragm to move point 'A'. The flapper nozzle opening is then restricted and hence pressure in chamber 'B' rises. This causes 'C' to move downwards and through a lever to back off 'A'. Therefore a negative feedback path exists. For a step input accurate positioning of 'C' will be maintained. Theoretically this should be a zero order system thereby giving zero rise time. However the chamber will take time to fill in practice. The instrument is a slight re-assignment over more conventional controllers and this is reflected in the reversal of the flapper nozzle direction. The parameters are evaluated in Appendix B.

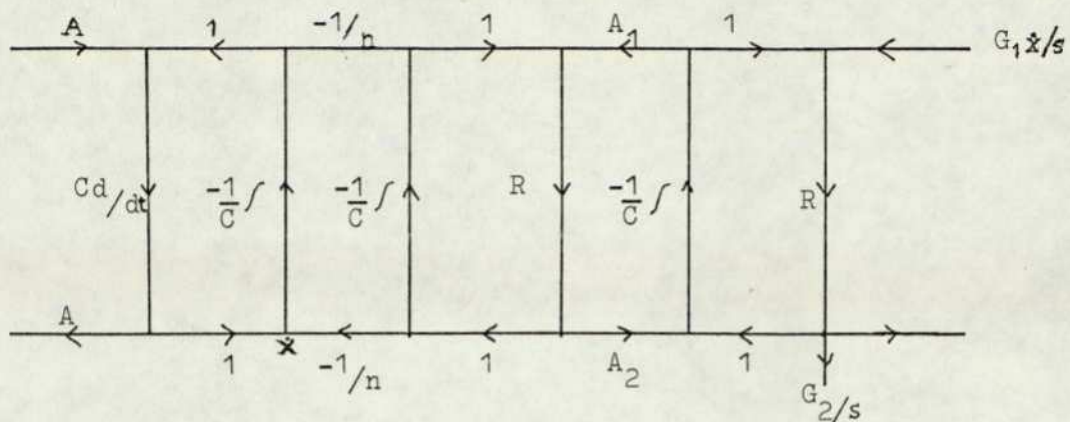
3.6.4 Graphical Representation

The Signal Flow Graph is illustrated in Fig 3.21a). This shows a derivative term due to the displacement of one spring being dependent on the other two. If minor resistances are included this term will disappear, but a stiff system is the likely result. As it is, the graph has an 'algebraic' loop (i.e. one with no rise time associated with it) and in general this will tend to set a limit on the interval of any integration method. It may be noticed that a derivative of the input is also likely to occur. This may



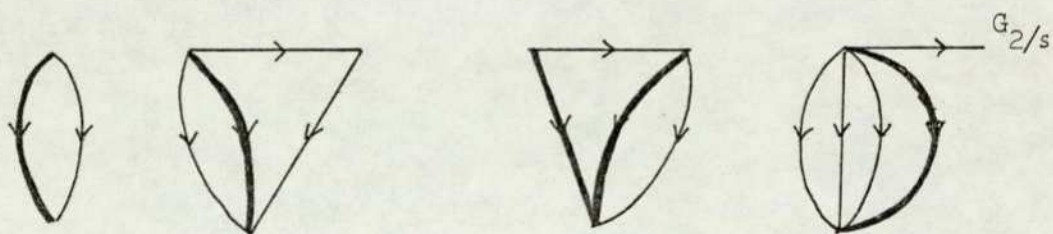
NEGRETTI AND ZAMBRA PROPORTIONAL CONTROLLER

Figure 3.20



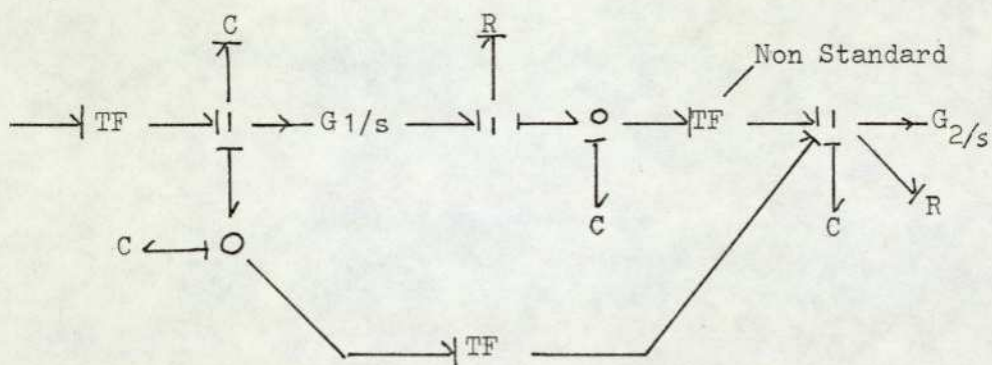
Signal Flow Graph

a)



Linear Graph

b)



Bond Graph

c)

GRAPHICAL MODELLING OF NEGRETTI & ZAMBRA PROPORTIONAL CONTROLLER

Figure 3.21

happen with any graphical representation, but this is directly visible with signal flow graphs. It is to be avoided, as for instance an impulse function would become indeterminate, and numerically hazardous.

The linear graph is described in Fig 3.21b). The signal pickoffs would be contained in the terminal relationships and these will not affect the tree and co-tree selection. The feedback path cannot be identified as this is via a transformer - this giving the two separate sub-graphs shown.

The Bond Graph of the instrument is shown in Fig 3.21c). The feedback path can be already seen. However there is ambiguity as to the direction from the '1' to the '0' junction in the feedback path. Mass flow rates rather than volume flow are more convenient variables for the connected chambers of the flapper nozzle arrangement⁽³¹⁾. This entails a transformer with differing primary and secondary ratios. Programs such as ENPORT⁽³²⁾ (the most common bond graph simulation package) find this difficult to handle. In general extra effort is always required with bond graphs if the variable and co-variable do not form a power product.

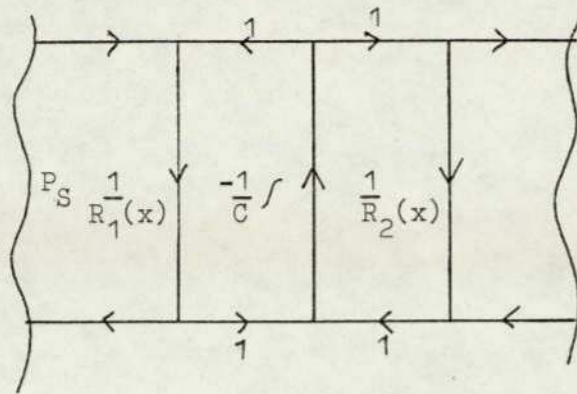
The flapper nozzle has been modelled as an equivalent circuit, the system being known to be first order. The

advantage is a smaller model linearised around an operating point. However, many of the inherent design features of the flapper nozzle are hidden. Fig 3.22 gives an expanded view of the flapper nozzle section.

With reference to Fig 3.20 there are two restrictions around chamber 'B'. In general these will depend on the displacement of the flapper nozzle (but theoretically only in the steady state, see Appendix B). If these restrictions are separately modelled as variable resistances, then an equipment model shown on Fig 3.22 can be drawn. For all three representations there is no change in causality, therefore the expanded region can simply replace the old flapper nozzle network. The steady state gain is automatically accounted for as it is the final value of the resistances. (This model is more expensive as computing time as the system is now nonlinear).

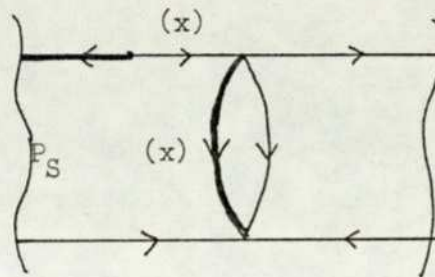
3.6.5 Description of G.E.C. Elliot Proportional Controller

A schematic of this instrument is shown in Fig 3.23. This is similar in operation to the previous proportional controller in the sense that a feedback signal offsets the measured input. However the flapper nozzle arrangement is more complicated and is shown in some detail. A short description is as follows.



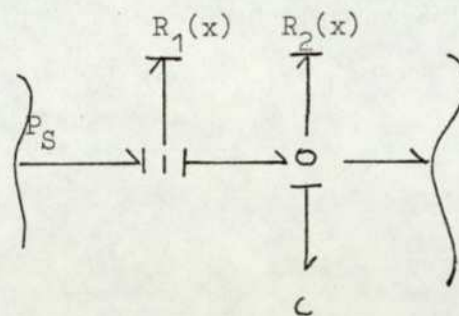
Signal Flow Graph

a)



Linear Graph

b)

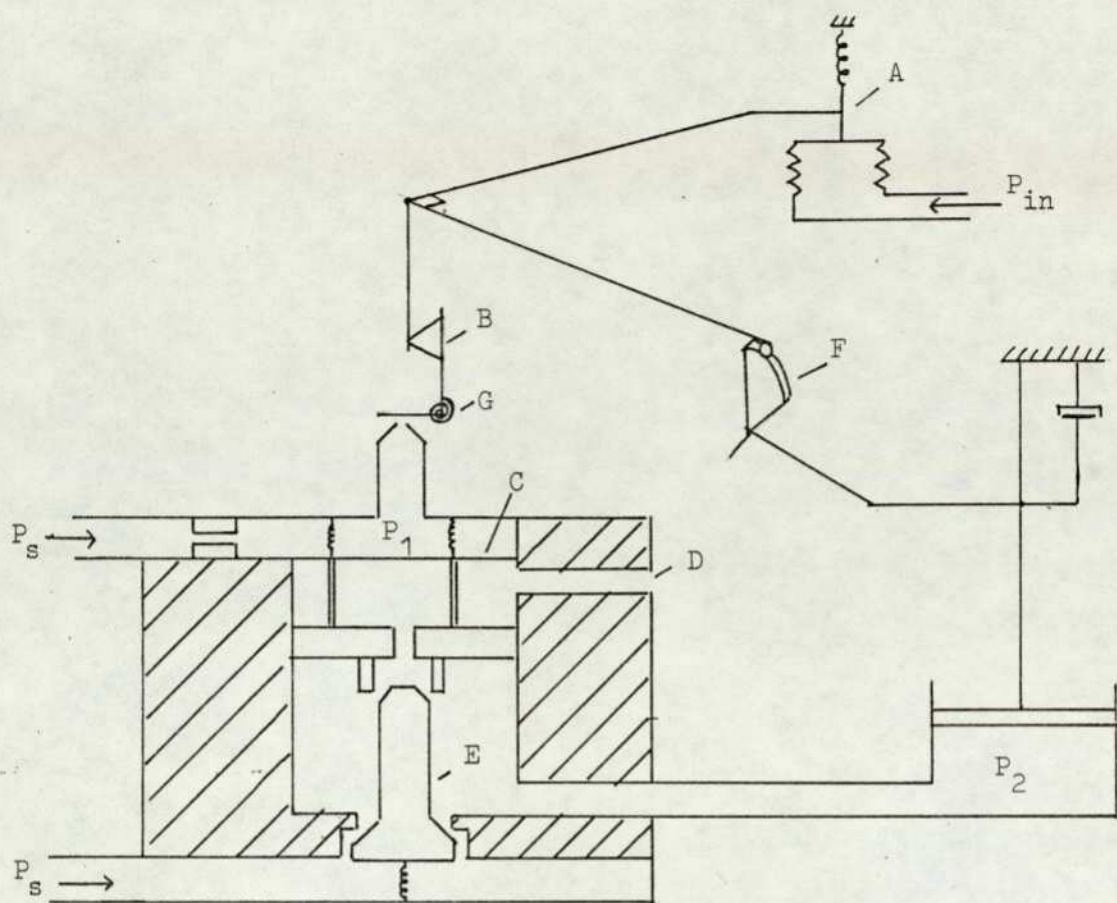


Bond Graph

c)

ALTERNATIVE FLAPPER NOZZLE ARRANGEMENT

Figure 3.22



G.E.C. ELLIOT PROPORTIONAL CONTROLLER

Figure 3.23

The pressure P_{in} moves point 'A' and by being in contact with point 'B' adjusts the flapper opening. The opening is the area between a ball valve and its seat.

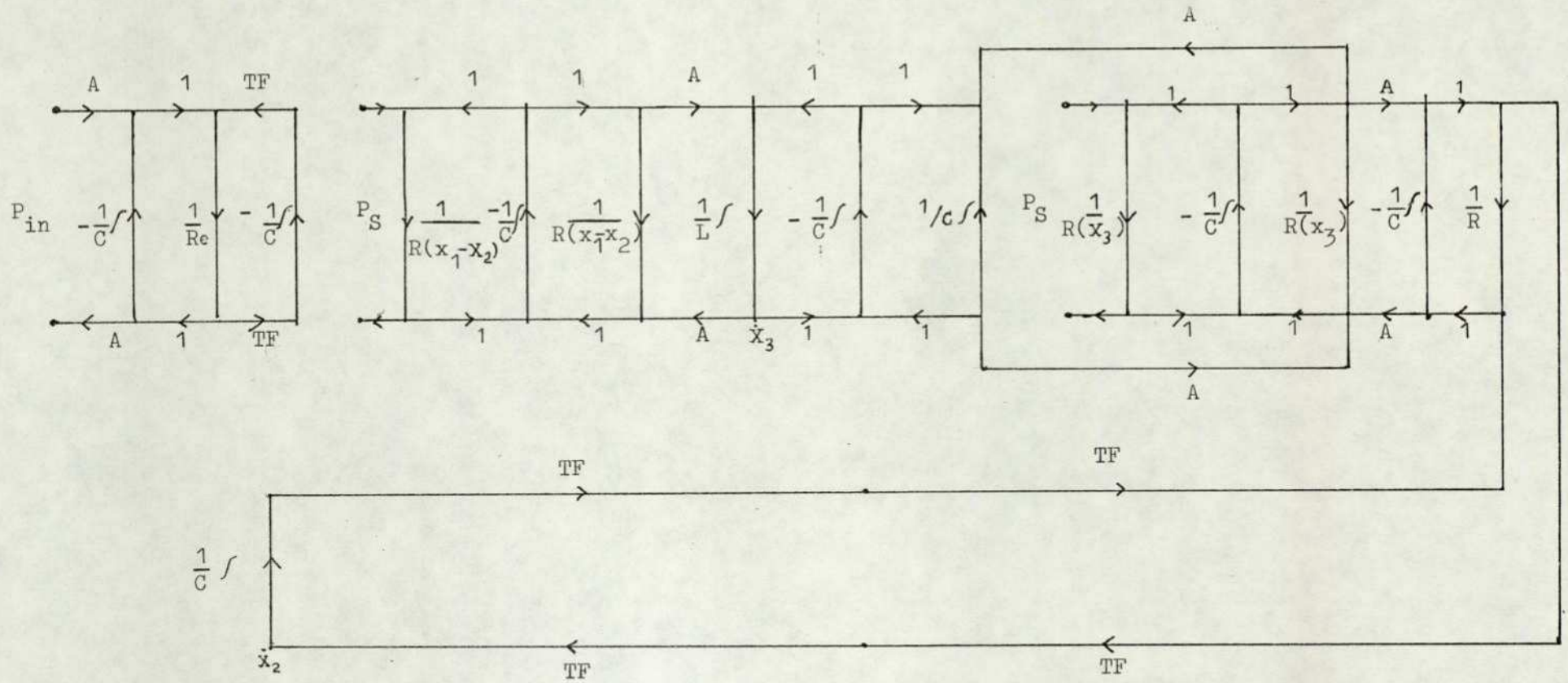
An increase in pressure P_1 moves a flexible diaphragm 'C' which in turn moves down the spool valve 'E'. This causes P_2 to increase (as the reduction to the supply is lowered) which is converted to mechanical rotation and moves cam 'F'. This in turn offsets point 'B'. There are two interesting features of this machine.

- a) The feedback is applied at right angles to the pressure, thereby avoiding any back off^{of} the measured input.
- b) The feedback can be nonlinear giving the instrument an increased range of performance.

The parameters are indicated in Appendix C.

3.6.6 Graphical Representations

The Signal Flow Graph is shown in Fig 3.24. Essentially the same picture as before is evident. However there are more feedback paths to account for. Clearly the representation becomes very poor for a more complicated model. (An extra parasitic resistor R_e is necessary to avoid differentiating the input). The feedback being at right angles is shown separately.



SIGNAL FLOW GRAPH OF G.E.C. ELLIOT PROPORTIONAL CONTROLLER

Figure 3.24

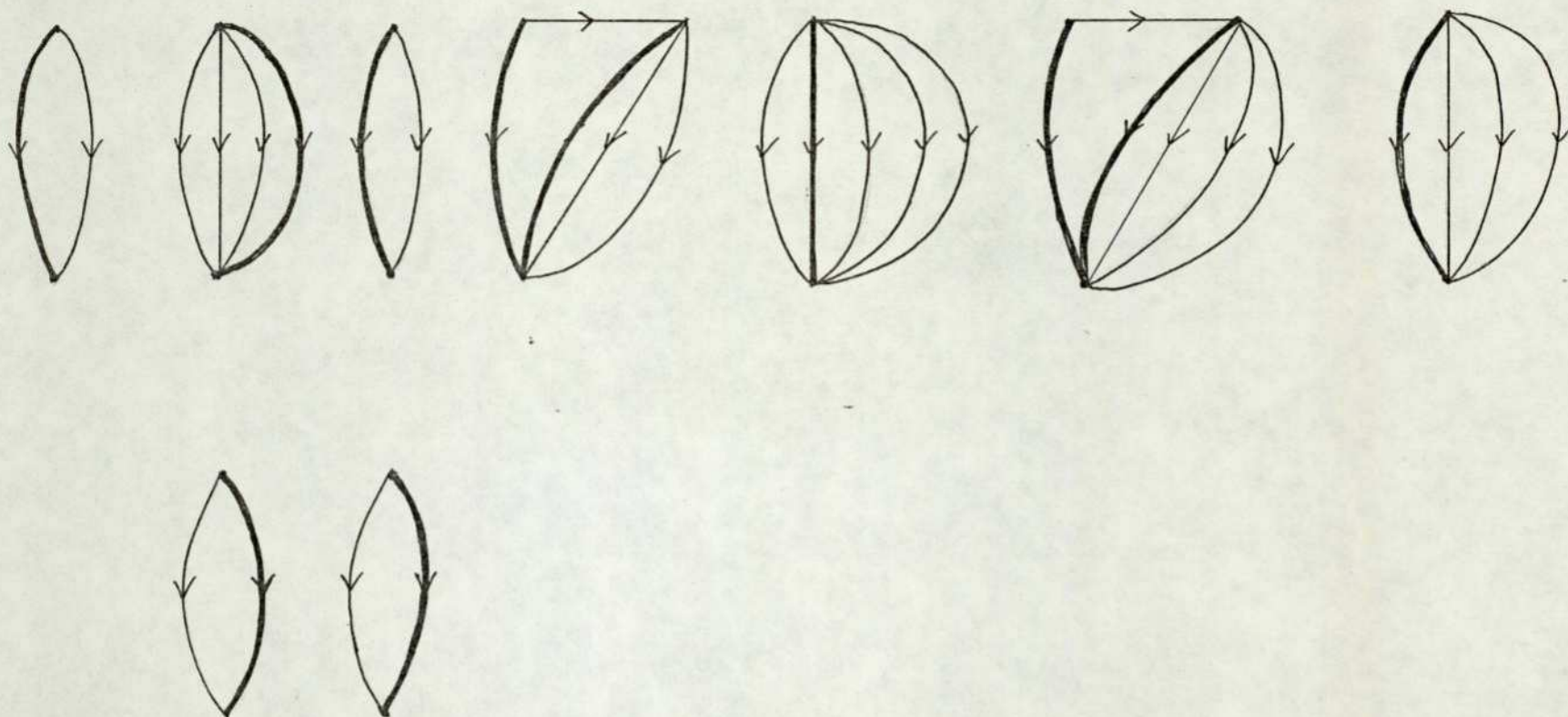
The Linear Graph is shown in Fig 3.25. There are nine separate graphs, which are related through terminal equations. The representation, although poor, has not been degraded further by model complexity.

The Bond Graph is illustrated next in Fig 3.26. In many ways this figure illustrates the growth of complexity in a more visual way, than with other representations. The two sets of nonlinear resistors can be clearly seen as well as the overall feedback path of the system. As the inputs to the flapper nozzle are at right angles it is necessary to terminate the feedback path with an extra 'C' so that no interaction can take place.

3.6.7 Pulse Cooled Thermocouple

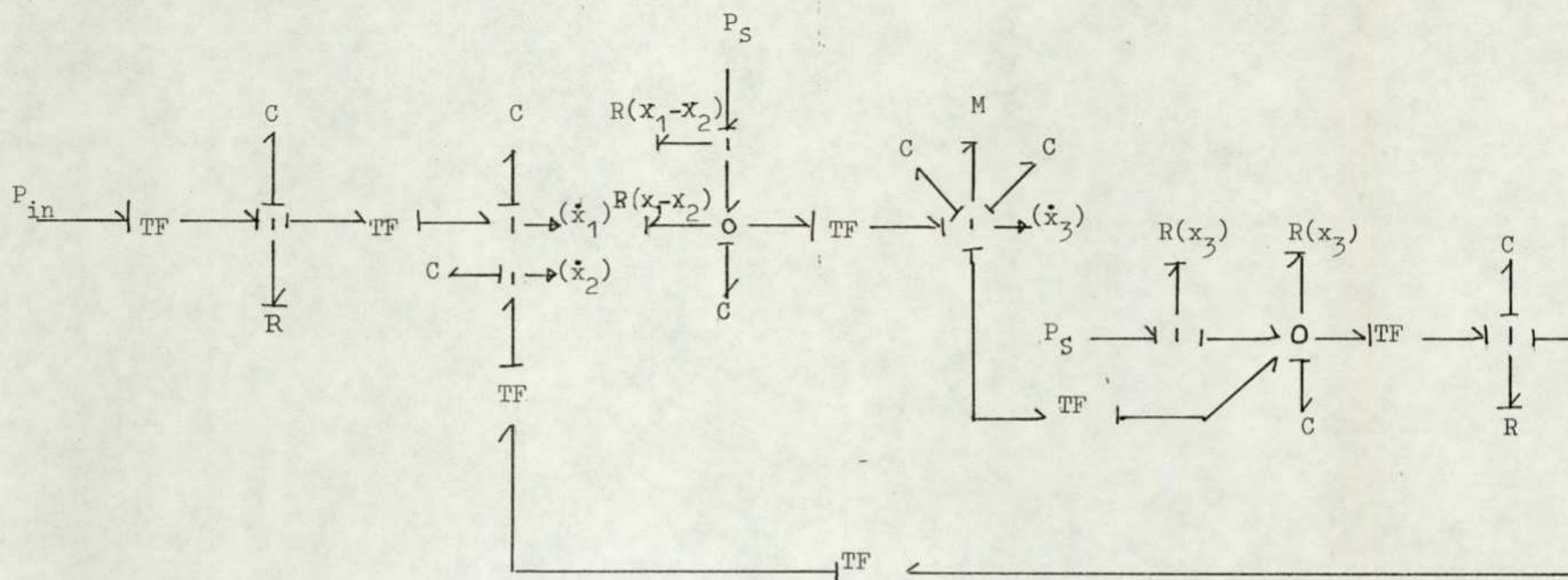
As a final example, an instrument employing thermal characteristics is modelled. A schematic of a Pulsed Cooled Thermocouple⁽³³⁾ is shown in fig 3.27a) and a description is as follows.

A thermocouple made up of Chromel-Alumel wires will work to 2000° F approximately. Hence higher temperature measurements cannot be made on a direct basis. However, use can be made of the fact that the thermocouple will have a finite rise time. If this is accurately known then the final value of the temperature can be deduced even if this is outside the transducer's range. The author claims 1%



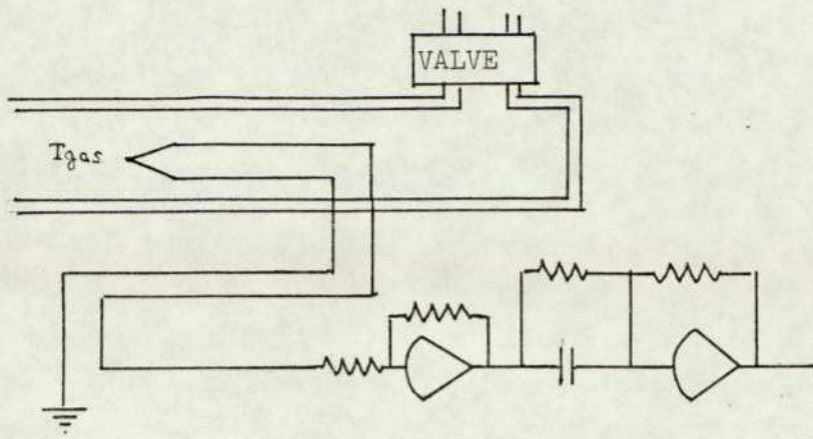
LINEAR GRAPH OF G.E.C. ELLIOT PROPORTIONAL CONTROLLER

Figure 3.25



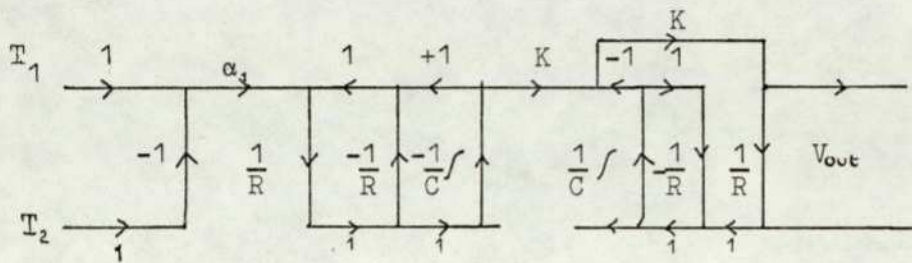
BOND GRAPH OF G.E.C. PROPORTIONAL CONTROLLER

Figure 3.26



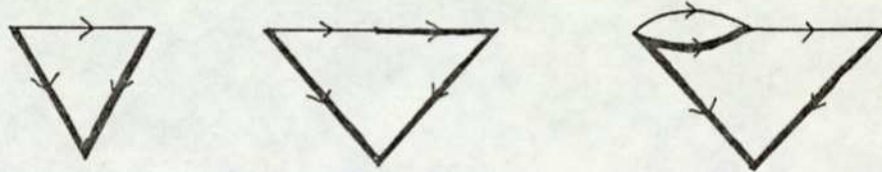
Pulse Cooled Thermocouple

a)



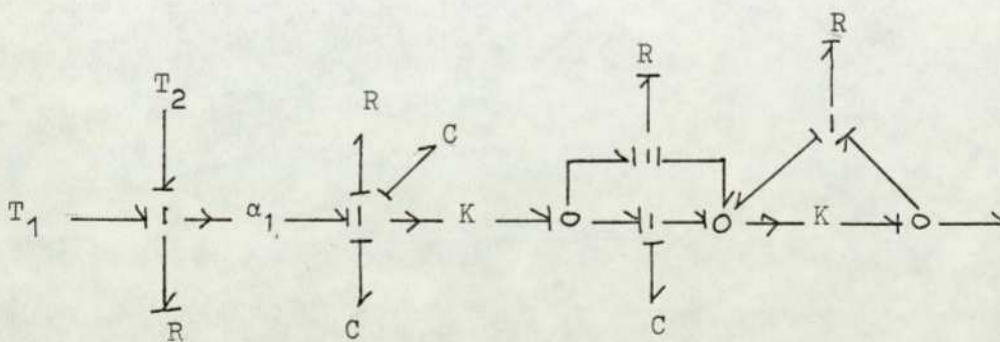
Signal Flow Graph

b)



Linear Graph

c)



Bond Graph

d)

GRAPHICAL MODELS OF PULSE COOLED THERMOCOUPLE

Figure 3.27

accuracy for this method. The process is as follows. The gas T_{gas} , which is the measured quantity, is applied to a cooled thermocouple and the e.m.f. produced is allowed to rise. This is passed through a lead network which will obtain the final gas temperature. (Because of drift the resistors of the lead network must be constantly updated over a period of time). In practice, fast gas measurements can be made as an instantaneous final value will appear as soon as the thermocouple tip starts to rise. The instrument parameters are found from Appendix D.

3.6.8 Graphical Representations

The Signal Graph is shown in Fig 3.27b). As the e.m.f. is dependent on temperature difference, there are two inputs T_1 and T_2 for this example. The signal flow graph shows phase lag then phase lead being applied to a generated voltage by the equivalent circuits shown.

The linear graph is shown in Fig 3.27 c). Where pure signal transfer is concerned, again separate sub-graphs are necessary. For this example a very poor representation is produced which is inferior to the signal flow graph.

The bond graph is shown in Fig 3.27 d). Of interest is the model of the phase lead network. Although identifiable by the feedback path, careful consideration must

be made of the relevant '1' and '0' junctions. In general it will be necessary to consult rules of construction.

3.7 Critical Summary

The various features of each graphical technique have been examined by the modelling of a variety of instruments. These are now collected together and listed (along with more general comments), giving the advantages and disadvantages of each graphical technique.

3.7.1 Signal Flow Graphs - Advantages and Disadvantages

i) Advantages

a) Good Signal Interaction

The graph is ideal for handling signal information. This is particularly the case for feedback systems where the effect of each interaction may need careful examination. Derivative of inputs can be identified.

b) Possible to Check Model Stability

The possibility of positive feedback loops can be identified at an early stage. This may then be compared with the actual instrument. Stiff system time constants can be identified, thereby providing a guide to an integration time step.

c) Widely Adaptable for Different Hardware

The technique lends itself to Digital, Analogue and Hybrid modelling. This is possible as the causal influences are known and can thereby be directly implemented.

c) Independence of Variable Assignments

There is no necessity to use through and across or effort and flow relationships. For example, displacement can be realised directly from $F = k \cdot x$ in a mechanical system where 'F' is the force, 'k' the compliance and 'x' the displacement. However using either through and across or effort and flow relationships, the displacement is found by integrating velocity - even though this may be inconvenient.

e) Large Freedom of Expression in Equation Formulation

This could be considered a disadvantage in the sense that there is no precise method of procedure. However the flexibility of combining expressions to any convenient mathematical form can be a distinct advantage for 'black box' modelling, i.e. modelling from the time, frequency response of a system.

f) Particularly Suitable where there is no Energy Interaction

Where there is no energy an interaction or, more precisely, where for all practical purposes, the flow of

energy can be neglected, signal flow graphs are an ideal medium. In these cases closed loop linear transfer functions are directly obtainable by Mason's rule⁽³⁴⁾ etc.

ii) Disadvantages

a) Generally Poor Description of Instruments

From reviewing the previous instruments it is clear that signal flow graphs provide a poor description of instruments. The main reason being the inability to represent energy interactions in a convenient manner. This is further expanded below.

Topologically Poor

There is little topological connections between the graph and the schematic. This is particularly noticeable with the inclusion of summing junctions and feedback loops which do not exist in the schematic. Alternative representations do not lead to any observable difference⁽²⁹⁾.

Not Descriptive

Assignments on a one-to-one basis with the schematic are difficult to make. Because causal changes affect the structure it is not possible to associate a section of signal and flow graph with a corresponding section of an instrument.

Any usual or unusual features of a design may not be apparent.

Complexity of Model

An example of complexity using signal flow graphs is the G.E.C. Elliot D.P.Cell in Section 3.6.5. It would appear that the signal flow graph can easily become too complicated to analyse in any detail.

Loss of Information

The graph provides very little insight into the instrument design and this is reflected in the loss of information of the drawn graph. This makes it extremely difficult, if not impossible, to convert to either a linear or bond graph form.

b) Poor For Interactive Computing

The difficulties of modelling interactively have been examined in the previous examples, particularly for the K.D.G. D.P.Cell. It is not generally possible to simply insert or delete an element or elements from the graph. Recourse must be made to the original equations. Care must be exercised so that unnecessary positive loops do not appear. However there will be almost no association with the schematic in aiding this process. Additionally

parameter values may have to be changed, i.e. in going from $P = LdV/dt$ where 'L' represents a long tube in a fluidic system, 'P' the pressure and 'V' the volume flow rate to $V = 1/LPd\dot{t}$, a change of parameter value is necessary for a change of causal influence.

3.7.2 Linear Graphs - Advantages and Disadvantages

i) Advantages

a) Structure Independent of Causal Influences

The graph once drawn can then have its tree and co-tree terms selected. This allows different causal assignments to be readily made.

b) Uses Topologically Identifiable Variables

There are advantages to using through and across variables rather than effort and flow. For example in a fluid system, mass flow rate rather than volume flow rate is constant in the steady state. The same applies for heat flow rate rather than entropy flow rate.

c) Structurally Ideal for many Energy Domains

Although this may not have been particularly well-developed in the previous examples, linear graphs are eminently suitable for electrical, fluid and thermal

systems, where there are energy interactions (and no signal flow) in a single domain. A clear topological representation is then apparent which has advantages for interactive design.

d) Unambiguous Section of Flow Directions

The direction of the arrow, producing the signed diagraph is nearly always unambiguous because it is associated with the positive power flow through a component.

e) State Equations Directly Obtainable

Once the structure has been input, together with the terminal relationships, the state equations can be obtained⁽³⁵⁾. From this further analysis can proceed in a variety of directions. If the system is linear then steady state and frequency response can also be ascertained by the method outlined in Chapter 2.

f) Easy to Modify

The graph can be directly updated with the insertions or deletion of elements. The causal influences can immediately be inspected and if necessary re-assigned.

ii) Disadvantages

a) Poor Description of Instruments

From the previous examples the following points can be observed.

Topologically Very Poor

The linear graph gives an unacceptable representation for instrument systems. In general, energy interactions and signal transfer are badly represented. Unfortunately these are common features of instrument systems.

Not Descriptive

There are no elements on the graph at all! This is because of the non-uniform description of elements in terms of through and across relationships, (see eqn. 3.2.15). However these 'landmarks' are a useful aid in identifying sections of a model.

b) No Check on Stability

The graph cannot be used to identify whether the model is stable or not, or to ascertain stiff time constants. This may be relevant in establishing a new design. However although stability checks are not possible from the graph, they can be obtained from the resulting state equations.

3.7.3 Bond Graphs - Advantages and Disadvantages

i) Advantages

a) Suitable for Multi-Energy Domain Instrument Systems

With reference to the previous examples, the bond graph representation via 'TF' and 'GY' elements gives a good representation of multi-energy systems. This is of particular interest therefore to instrument systems. More specifically, the advantages are:-

Descriptively good

All the elements are now represented on the graph. It is possible therefore to identify certain sections of the graph with an instrument system. A general mapping capability is feasible once the engineer is conversant with the bond graph language.

Complexity of Model low

The resulting bond graph gives a less cluttered description than signal flow graphs. In general where there would be two lines in a circuit, a forward and return path, there would be only one for bond graphs (18).

Good degree of Information

Bond graphs have the highest information content of all the graphical techniques⁽⁷⁾. Because the elements are represented on the graph, visual information is enhanced.

b) Structure independent of Causal Influences.

The graph once drawn is then causally assigned by vertical lines applied to one end of each bond. However as the structure is unchanged different causal assignments can be readily made.

c) State equations directly obtainable

Once the graph has been augmented then the state equations can be obtained. From this further analysis can proceed in a number of directions, i.e. time, frequency response.

d) No equations need be formed

Because all the elements are directly placed on the graph no equations or terminal relationships are required. However it is necessary that all elements are primitive (i.e. no higher than first order). For nonlinear elements one approach is to consider parameters determined around operating points.

ii) Disadvantages

a) Topologically Very Poor

One of the main disadvantages of bond graphs is that no system in any domain can be represented in a topological function. This is due to junction elements appearing which cannot directly be related to the schematic. Because of this difficulty it is necessary to be familiar with rules of construction found in the references⁽¹⁸⁾.

b) Variables tied to Power Product

The variables of bond graphs should be constrained to provide, by their product, power flow in a system. However in some cases (i.e. compressible fluid systems) this constraint can pose difficulties⁽³⁶⁾. One approach is to adopt differing primary and secondary transformers thereby allowing pseudo-bond graph variables⁽³²⁾ to be used. ENPORT a bond graph package does not however directly allow this.

c) Ambiguous Power direction possible

The K.D.G. D.P.Cell described in Section 3.5.1 gave an example of the difficulties that can occur in assigning power direction. The main problem is identifying from a schematic the associated power flow into or out of a junction. Because of the loss of physical significance error is possible.

d) Pure signal Terms Badly represented

The bond graph uses a variable and co-variable pair in the modelling process. For pure signal an 'activated' bond becomes necessary, where one of the variables is kept zero. If for example an effort variable is to be 'picked off', then an 'activated bond' is connected to a '0' junction (which, incidentally, if not available must be generated). This then guarantees a known value of effort employed. The manipulation is a compromise in bond graphs for the convenience of signal transfer. For pure integration there are no recognised procedures. Some authors⁽²³⁾ however, directly implement this onto the bond graph.

e) Poor description of Stability

As no loops are generated by the graph this technique will give a poor account of stability. (This, as with linear graphs, can be considered however once the state equations have been determined).

3.8 Conclusion

This chapter has tried to establish the usefulness of current graphical techniques for functional modelling. Because of the special interest of instrumentation, all the examples have been in this field. It has been shown that no graphical approach can fulfil all the needs and a compromise

solution will be necessary. This may take the form of selecting each technique on its merits for each particular problem. If this is to be implemented then the most suitable approach would be to have all the graphical processes available (i.e. signal flow, linear and bond graphs) in one package. (As a matter of interest it would not be possible to combine the graphs as they stand due to incompatibility constraints. For instance, a node introduced into a bond graph would have no apparent meaning).

There have, throughout this chapter, been two particular points of interest:-

- i) The graphical representation, and how well it represents an equivalent schematic of the system.
- ii) The ease of structural changes.

These two features are of prime importance in interactive functional modelling of instruments. Because no representation fulfils both these requirements a new technique will now be suggested which forms the basis of the next few chapters.

CHAPTER 4

A NEW REPRESENTATION FOR MULTI-ENERGY DOMAIN SYSTEMS

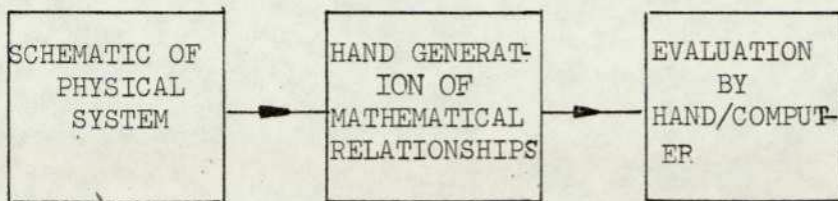
4.1 Introduction

The digital computer has made great inroads into the simulation and modelling of engineering systems⁽²⁵⁾. One of the main reasons for this is in its ability to relieve the engineer of the tedious analysis and solution phase of a problem - necessary if hand-solving methods are used.

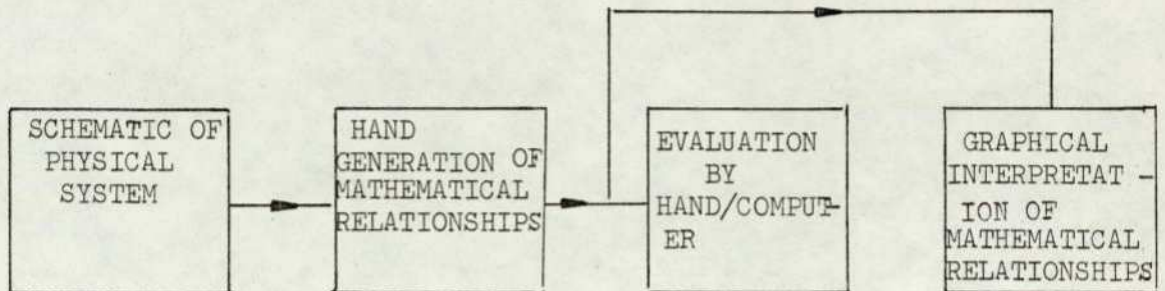
Of importance here is the 'interactive' modelling approach. In this content, as discussed in Chapter 1, it is desirable to enhance:-

- i) 'Man's ability to generate ideas, concepts etc.
- ii) The machine's ability to store, evaluate and generally tackle the more monotonous tasks.

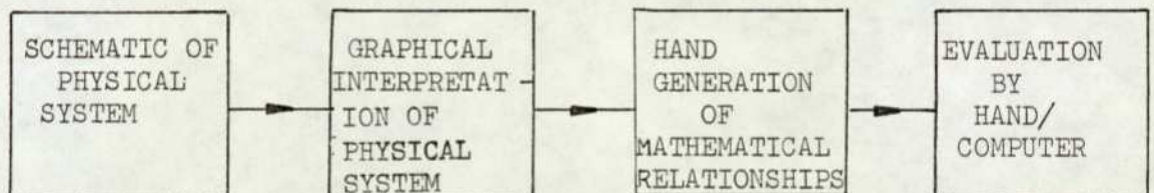
Fig 4.1 shows a 'possible' evolution of the interactive approach. Initially the computer is used only for evaluation, i.e. numerical routines or direct solution from state equations, (Fig 4.1a). There is little change in Fig 4.1b) except that a graphical format is developed - perhaps as a mnemonic aid. An example would be sets of Nonlinear Differential equations boxed and connected together in a flow diagram. However, the first important stage comes in Fig 4.1 c) as the graph can now help to produce the mathematical relationships. Finally in d) the current C.A.D. method is shown whereby a description of the physical system is fed directly into the computer via graphical interpretation and the equations developed automatically.



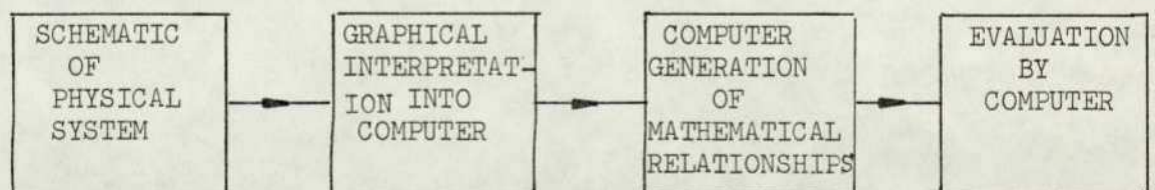
a)



b)



c)



d)

'POSSIBLE' EVOLUTION OF COMPUTER PROCESSING ALLIED TO GRAPHICAL STRUCTURES IN MODELLING

Figure 4.1

For interactive analysis using a computer it is desirable to minimise three areas where the C.A.D. response time is bad. Naturally the speed of the machine as well as good software (i.e. integration routines) are important but a particularly relevant area, where interactive modelling is concerned, is the man-machine interface at the input stage⁽³⁷⁾. As discussed in the previous chapter, the current established graphical techniques all have certain disadvantages. This may not be all that surprising as an 'a-priori' pursuit of these graphical aids is the reduction to system equations. The special problems of instrument modelling and in general modelling multi-energy systems in an interactive environment are not considered at the outset. At the moment the engineer must perform the necessary conversion process from a schematic to a graphical form, no matter how inconvenient this may be!

This chapter, therefore, proposes a new technique which allows the engineer to feed a model from a schematic in a more convenient and direct manner (provided that basically the flow is indirectional). This has happened to a large extent for electrical systems, but for multi-energy domain analysis the work appears to be in a fairly undeveloped state. Consequently a new language is developed and defined in this chapter. As it is a new technique various examples are given in the text. Chapter 5 then proceeds to describe how the state equations can be automatically developed and Chapter 6 then models the instruments described in Chapter 5 using the new method.

4.2 An Improved C.A.D. Approach For Multi-Energy Domain Systems (Structure Graphs)

It may have been noticed in the previous chapter that a particular graphical technique that employs functional relationships enjoys wide use where there is a strong topological connection. For instance signal flow graphs are used extensively for control systems and linear graphs for electrical systems. For these systems the topological approach enables faster throughput from a schematic to the computer. It is suggested therefore that wherever possible a topological formulation should be used, and this provides a basis for the method that follows.

In order to develop this approach for general system analysis with a computer, it is essential that enough information is provided so that the computer can logically analyse the system and produce the necessary equations and responses. This information is found to be (from examining Chapter 3, as well as the illustrations in this section):-

i) Elements

Elements are defined as functional input-output relationships.

ii) Interconnections

Interconnections represent the basic topological or 'bonded' network.

iii) Direction of Flow

The direction of flow contains information of sources, sinks, power direction etc.

iv) Domain

The domain specifies the engineering discipline involved.

v) Values

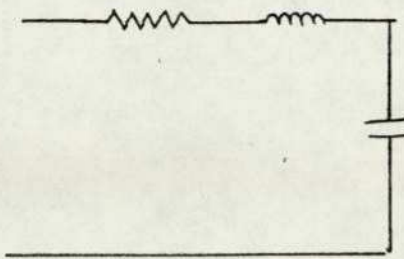
The values are the component parameters (linear or nonlinear), initial conditions etc.

With this information it is possible by the internal conversion by the computer to a more established form, to produce the equations of the system. Provided that this internal conversion is faster than the normal mapping process initiated by the engineer using an established technique, then considerable savings in interactive analysis should be possible. (In fact, even for a small mini the conversion time was found for the examples of Chapter 3 to be on average less than a second).

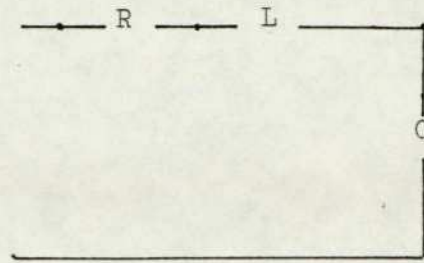
Consider Fig 4.2, Fig 4.3 and Fig 4.4. Here the series and parallel connections for five energy domains are illustrated. For each case the schematic represents a realistic physical system comprised of elements connected in a series or parallel form. (As a mass connected to ground will prevent a response, a small spring is connected in

SCHEMATIC

FUNCTIONAL TOPOLOGICAL MODEL

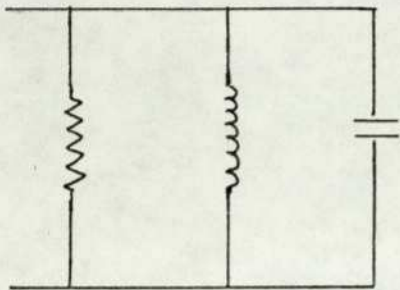


a)

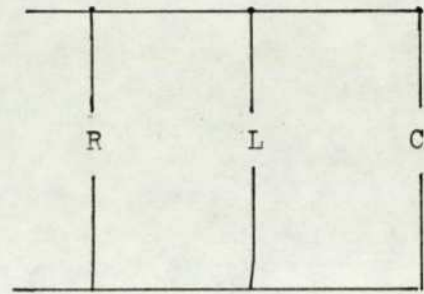


b)

SERIES CONNECTION



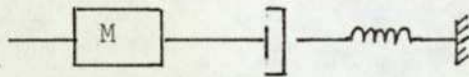
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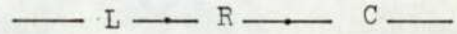
d)

PARALLEL CONNECTION

ELECTRICAL

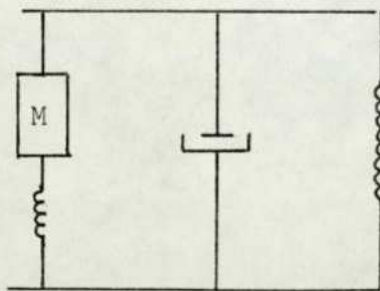


e)

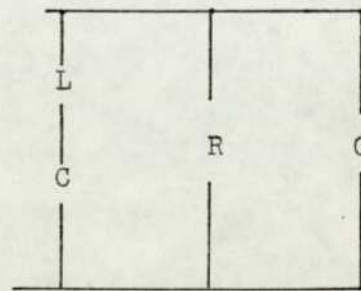


f)

SERIES CONNECTION



g)



h)

PARALLEL CONNECTION

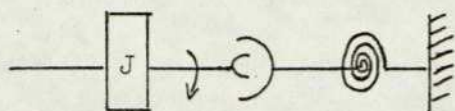
MECHANICAL TRANSLATION

FUNCTIONAL TOPOLOGICAL MODELS (ELECTRICAL/MECHANICAL TRANSLATION)

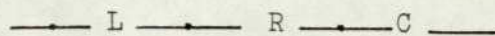
Figure 4.2

SCHEMATIC

FUNCTIONAL TOPOLOGICAL MODEL

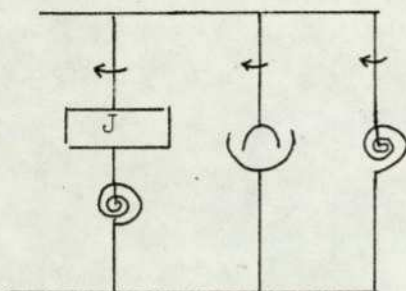


a)

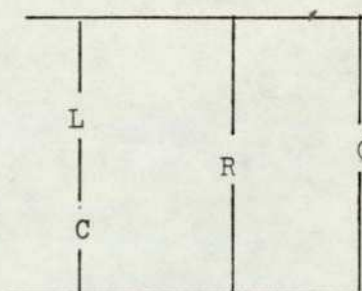


b)

SERIES CONNECTION



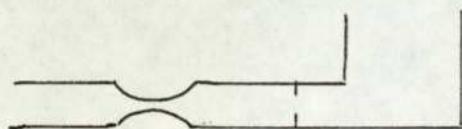
c)



d)

PARALLEL CONNECTION

MECHANICAL ROTATION

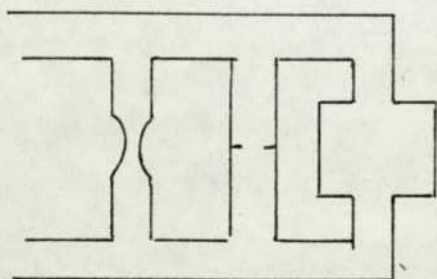


e)

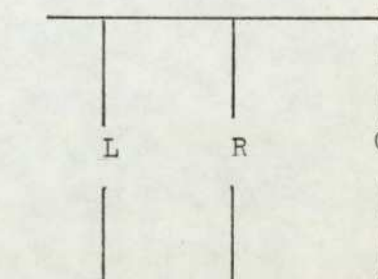


f)

SERIES CONNECTION



g)



h)

PARALLEL CONNECTION

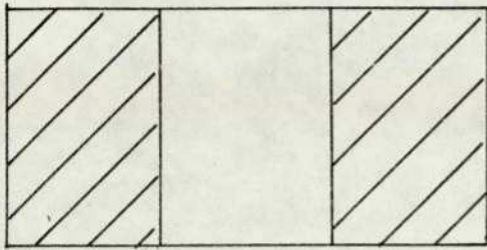
FLUID

FUNCTIONAL TOPOLOGICAL MODELS (MECHANICAL ROTATION/FLUID)

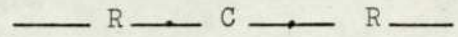
Figure 4.3

SCHEMATIC

FUNCTIONAL TOPOLOGICAL MODEL



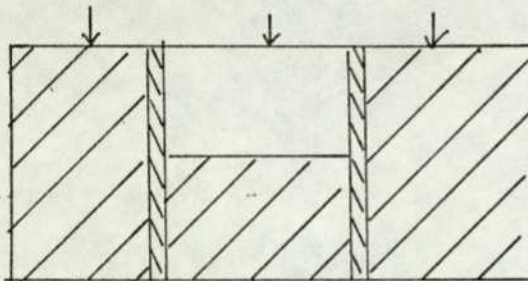
a)



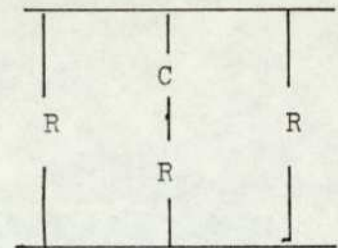
b)

SERIES CONNECTION

Temperature Gradient



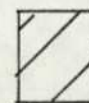
c)



d)

PARALLEL CONNECTION

KEY



THERMAL RESISTANCE



HIGH THERMAL
RESISTANCE



THERMAL CAPACITANCE

FUNCTIONAL TOPOLOGICAL MODELS (THERMAL)

Fig 4.4

series in Fig 4.2 g) and similar comments apply to the rotational domain in Fig 4.3 c). There can be no temperature gradient in Fig 4.4 c) without a small series resistor).

By equating (R-L-C) relationships as described in the previous chapters (the element type), close topological forms can be developed. A node is inserted in the functional topological models simply to delimit each element. It should be quite clear that little effort is required to determine the topological form. This allows:-

- a) Easier construction
- b) Easier structural changes to be made

thereby promoting over more conventional methods, efficient interactive modelling and design.

In order to feed the functional graph into a computer it may be noted that from the functional graph the following information can be associated.

Elements

Resistance, Capacitance, Inductance are directly represented.

Interconnections

A node separator for each element, topologically connected.

Direction of Flow

A flow variable through each element can be assigned for example.

Domain

Each element can have a domain type (not shown as this tends to clutter up the graph).

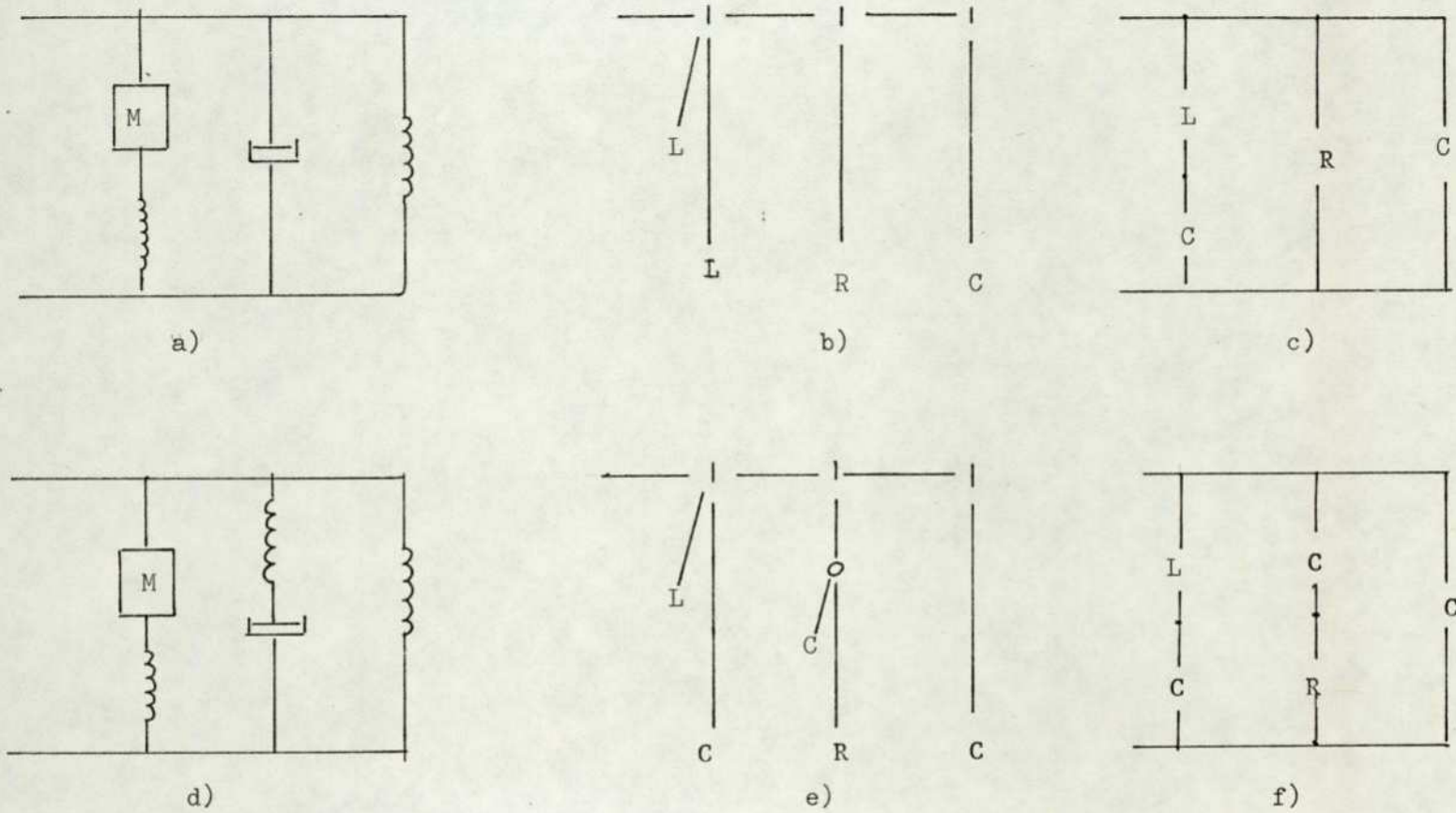
Value

Each element has a value (not shown as this tends to clutter up the graph).

As this information can be fed almost directly from a lumped equivalent schematic to the computer, this is the first step in showing that the process is more efficient for interactive modelling than those described in the previous chapters (see Fig 4.1 d)).

Because the physical structure is so directly visible from the graph, the new approach will be called structure graphs.

Fig 4.5 shows how structure graphs and bond graphs compare for one of the previous networks (mechanical domain). The bond graph version was chosen as of the three techniques



COMPARISON OF BOND GRAPHS AND STRUCTURE GRAPHS FOR A STRUCTURAL CHANGE

Figure 4.5

discussed it is the most relevant for handling general energy models. (In the figure the bond graph has not been reduced in order to show the comparison more clearly. In general a bond graph not in its final form would require extra work in feeding into a computer). As can be noted, elements in parallel in the schematic are in series in the bond graph and visa versa. Consequently the spring introduced in series in d) has its parallel equivalence in e). Clearly this may cause confusion on the part of the engineer. In general, entries for each energy domain (for bond graphs) need close inspection of the construction rules.

In essence, the computer is being asked to perform more of the routine analysis. By considering the computer as an integral part of the design process a more efficient overall interactive design strategy can be developed.

4.3 Formal Definition of Language

The structure graph language will now be formally defined. However it is by no means complete, as for example, more elements could be added as appropriate. The present set is designed for use on a small mini (or more powerful micro) and is capable of modelling a large number of multi-energy domain systems directly. It has evolved by trying to produce a flexible but unambiguous approach to modelling using the concepts described in Section 4.2.

4.3.1 Elements

An element is a single functional multiport term of the graph representing a relationship between defined input(s) and output(s). Examples of elements would be Resistance, Capacitance, Inductance, Gains, Integrations etc., defined with a relevant energy domain.

4.3.2 Nodes

A node is a reference marker on the graph. For

electrical systems	)			
	)			
fluid systems	)	—		The node is a common
	)			positional point. The
thermal systems	)			node is always static.

mechanical translation systems	)			
	)			
mechanical rotation systems	)	—		The node represents
	)			a common displacement
	)			point

One node for example (0) would be used as a common reference for all energy domains.

4.3.3 Connecting Lines or Edges

Connecting lines or edges connect the elements to the nodes or other elements and are used for transmitting and receiving variable information. For signal pickoffs dashed lines are preferable.

4.3.4 Joining Lines

Joining Lines join two nodes that are identical. They are purely for pictorial purposes.

4.3.5 Arrows

Arrows on the graph represent either

- a) direction of flow variable
- b) direction of signal transfer.

4.3.6 Structure Graph

A structure graph is a collection of elements, nodes, connecting lines and arrows combined according to rules of construction defined in Section 4.4.

4.3.7 Segment of Structure Graph

A segment of a structure graph is one that is associated with other parts by transfer to another domain or transfer by signal.

4.3.8 Variables In Use

For topological reasons as well as ease of measurement, structure graphs are through 'TH' and across 'AC' for all

energy domains. These are described in Table 4.1. Five energy domains are considered here, these being Electrical, Mechanical Translational, Mechanical Rotational, Fluid and Thermal Systems.

VARIABLE	ELECTRICAL	MECH. TRANS- LATIONAL	MECH. ROTATIONAL	FLUID	THERMAL
AC	VOLTAGE	VELOCITY	ANG. VELOCITY	PRESSURE	TEMP
TH	CURRENT	FORCE	TORQUE	MASS FLOW RATE*	HEAT FLOW RATE

Table 4.1 Variables Used in Structure Graphs

* Volume flow rate may be used for incompressible fluids.

4.3.9 Basic Multiport Elements

Name	Expression	Structure Graph Symbol
Across Source	AC	A_ where A_ can be: AI - Across Impulse AS - Across Step AR - Across Ramp
Through Source	TH	T_ where T_ can be: TI - Through Impulse TS - Through Step TR - Through Ramp
Resistance	AC = R.TH	R
Capacitance	TH = C.AC (Electrical, Fluid, Thermal). AC = C.TH (Mechanical Translation (Mechanical Rotation)	C If Linear initial value is AC(0) If Nonlinear initial value is AC(0)x C(0) * If Linear initial value is TH(0) If Nonlinear initial value is TH(0)x C(0) where (0) is the value at the start of simulation
Inductance	AC = L.TH (Electrical, Fluid, Thermal). TH = L.AC (Mechanical Translation (Mechanical Rotation)	L If Linear initial value is TH(0) If Nonlinear initial value is TH(0)x L(0) * If Linear initial value is AC(0) If Nonlinear initial value is AC(0)x L(0)
Transformer	AC1 = TF1.AC2 TH2 = TF2.TH1	TF
Gyrator	AC1 = GY1.TH2 AC2 = GY2.TH1	GY

Table 4.2

* See Chapter 5 for model of Nonlinear Capacitor and Inductor.

4.3.10 Signal Elements

Name	Expression	Structure Graph Symbol
Across to Across	$AC2 = K.AC1$	AA
Across to Across & Integrate	$AC2 = \int K.AC1 + AC2(0)$	AAI where (0) is the value at the start of simulation
Across to Through	$TH2 = K.AC1$	AT
Across to Through & Integrate	$TH2 = \int K.AC1 + TH2(0)$	ATI
Through to Across	$AC2 = K.TH1$	TA
Through to Across & Integrate	$AC2 = \int K.TH1 + AC2(0)$	TAI
Through to Through	$TH2 = K.TH1$	TT
Through to Through & Integrate	$TH2 = \int K.TH1 + TH2(0)$	TTI

Table 4.2 continued

4.3.11 Fields

Name	Expression	Structure Graph Symbol
Resistance Field	$AC_i = \sum_{j=1}^N R_{ij} TH_j$	RF Linear only
Conductance Field	$TH_i = \sum_{j=1}^N G_{ij} AC_j$	GF Linear only
Capacitive Field	$AC_i = \sum_{j=1}^N \frac{1}{C_{ij}} \int TH_j + AC(0)$	CF Linear only
Inductive Field	$TH_i = \sum_{j=1}^N \frac{1}{L_{ij}} \int AC_j + TH(0)$	LF Linear only

Table 4.2 (continued)

4.4 Rules of Construction

- i) There must be a mode separator, except for signal pickoffs, between any element connected to another element.
- ii) Each edge must have an arrow even if this provides redundant information.
- iii) There must be an actual or implied overall common reference point for each separate segment.

4.4.1 General Guidelines

- i) Fit as much of the System as possible in a topological fashion. The (0) overall common reference may or may not be included. For higher order couplings⁽⁷⁾ treat each energy domain separately.
- ii) If there is no topological model of the system directly available, then an equivalent structure should be determined. For instance an equivalent active network for a transistor or transmission line effects for capillaries in biological systems.
- iii) Fields can be used wherever they are mathematically equivalent to a section of the structure⁽¹⁸⁾. However they can be expensive as in general for an N port field N^2 elements are necessary.

4.5 Examples of Use

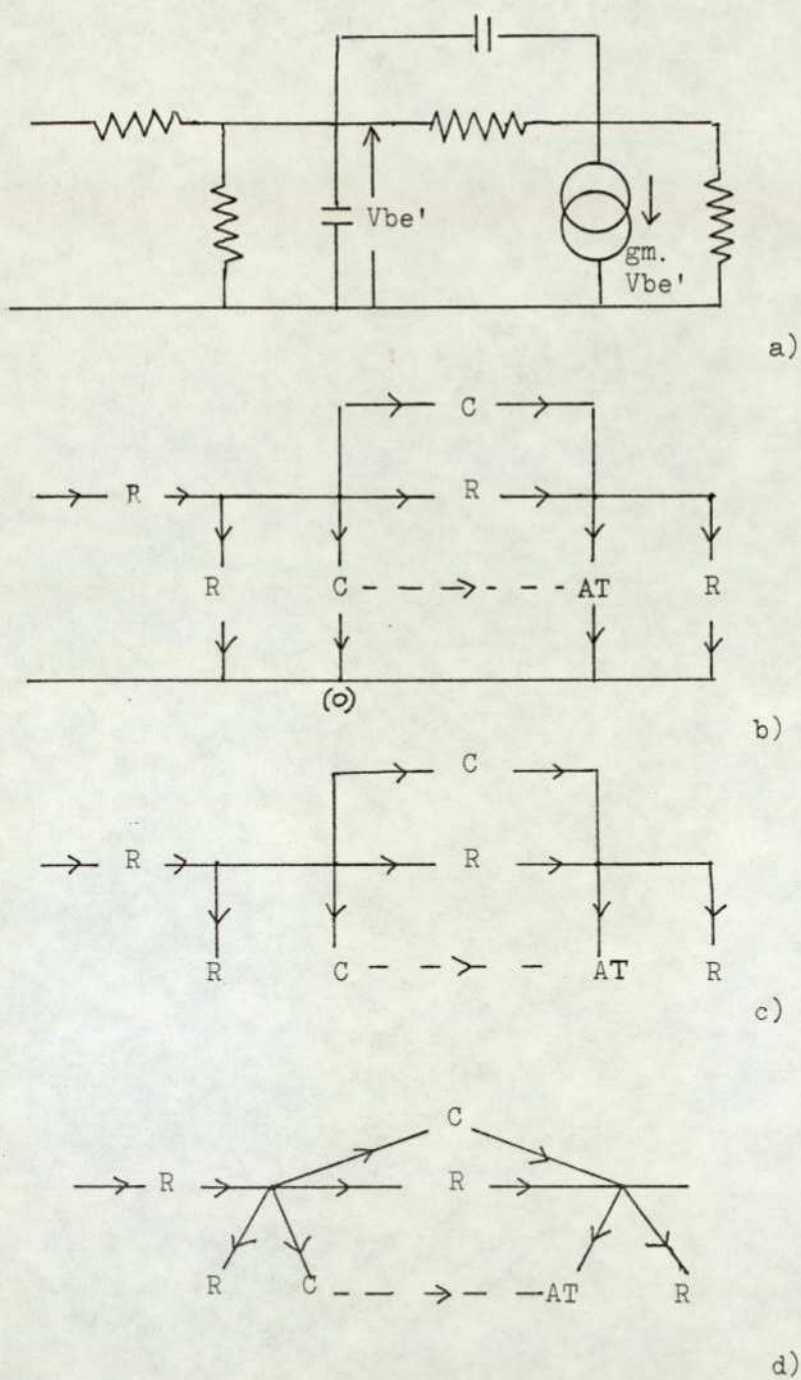
i) Hybrid π Network

Consider Fig 4.6. In a) a schematic of a hybrid π network is shown. Fig 4.6b) provides the most direct version of representing the schematic with structure graphs. An almost one-to-one correspondence is possible. The return line here represents a common earth or an overall common reference point, and is shown by the (0) node.

As can be seen arrows are inserted between an element and node. This means that for this figure two arrows are necessary for each element. The second arrow is already redundant, as electrical current can only flow in one direction. Nevertheless according to rule ii) this must be inserted.

The term $gm.V_{be}$ can be associated as an Across to Through term, if reference is made to Section 4.3.8. From Table 4.2 the structure graph symbol is found to be 'AT'.

For Fig 4.6c) the (0) node reference has been eliminated and a second (but equivalent) form of structure graph results. The question of whether to put in a (0) node or not is purely convenience on the part of the user.



EXAMPLE STRUCTURE GRAPH OF A HYBRID π NETWORK

Figure 4.6

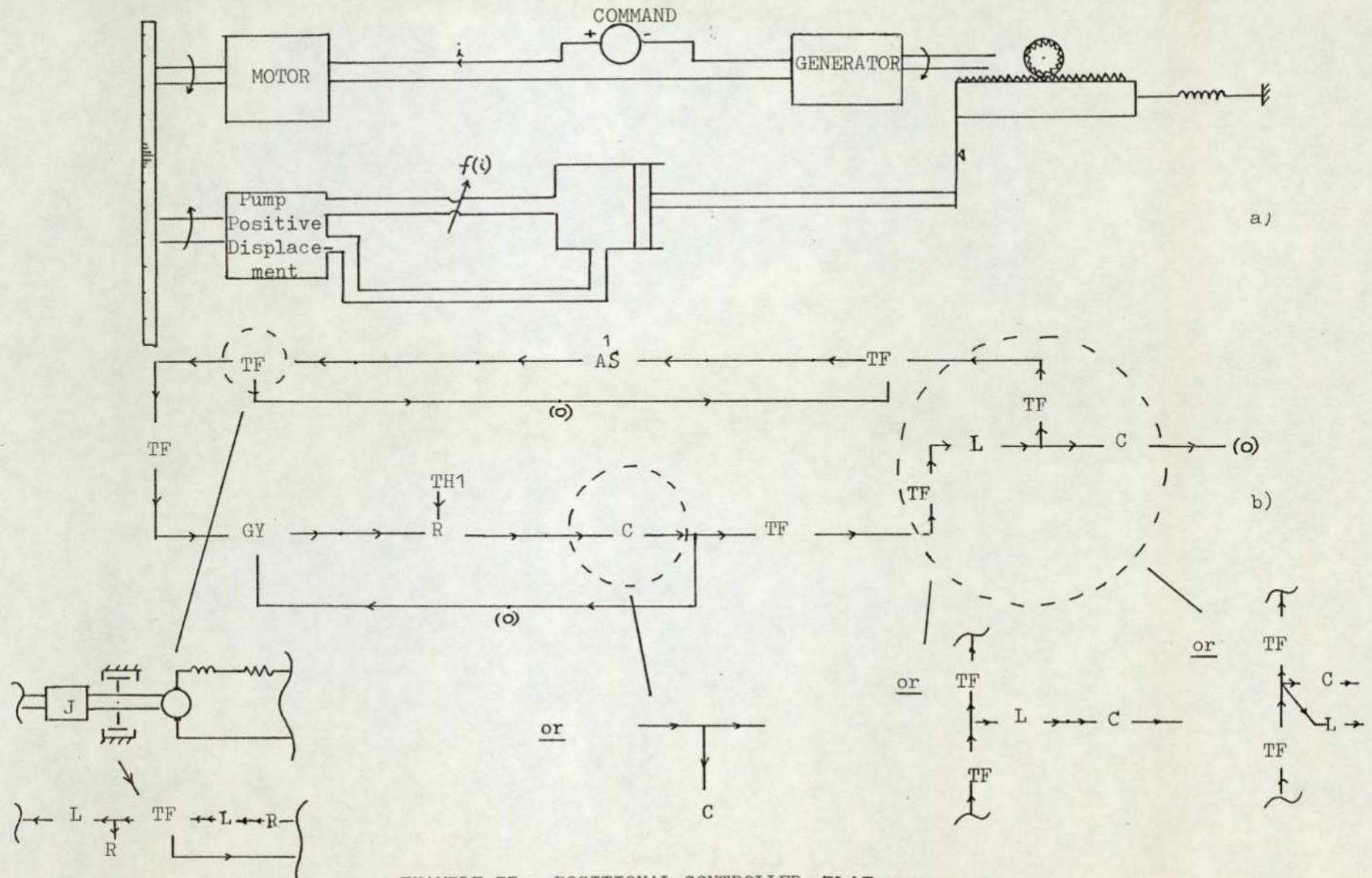
Fig 4.6 d) presents the most compact form. Here the nodes could be taken to represent a common across reference point. The only difference is the removal of the pictorial 'joining' lines defined in Section 4.3.4.

The significance of Fig 4.6 d) is that with brief familiarity of use this figure could directly be drawn from Fig 4.6 a). As it is a 'shorthand' version, it very often becomes the most convenient form of representation.

ii) Positional Controlled Flat Bed

Fig 4.7 provides a more general example involving multi-energy domains. It is a positional controlled flat bed. The motor is a 'TF' term, i.e. it associates current (through variable) with torque (through variable) and is an idealised power converter. This model can however be expanded as shown if a more accurate representation is required. Similar comments apply to the generator. The pump is a 'GY' term and associates velocity with mass flow rate.

One of the advantages of structure graphs is the alternative models that are possible. For the piston, the large volume can be represented as a capacitive term. This 'appears' to be in series with the nonlinear resistance and the conversion to the mechanical domain. Hence it is topologically correctly represented. However for a capacitive term in the fluid domain the pressure must be



EXAMPLE II: POSITIONAL CONTROLLED FLAT BED
Figure 4.7

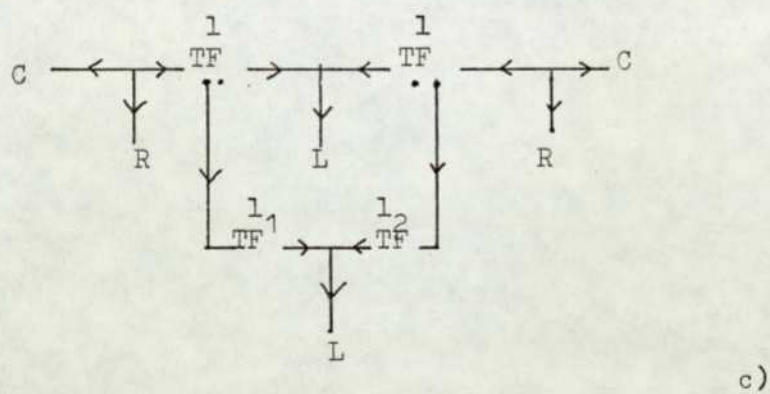
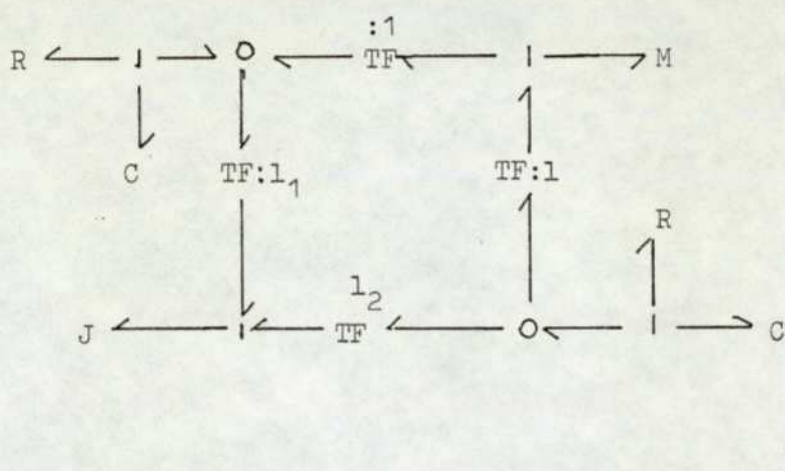
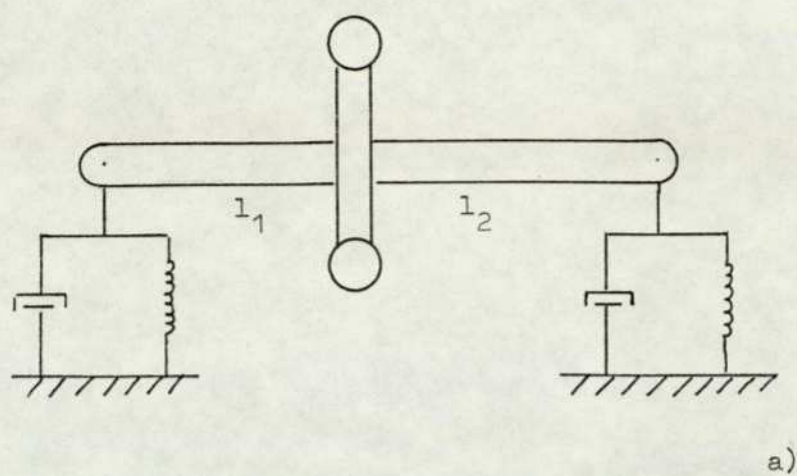
constant. Hence an alternative model is illustrated, where a common across reference point is represented instead.

For the flat bed three different models are shown. These are all equivalent as far as structure graphs are concerned.

As an example of how nonlinearities are handled, a nonlinear resistance is shown. Only single-input single-output terms are permitted with the system developed, as this allows easy entry in the form of a table. The resistance is dependent on the current flowing into the motor - and is conveniently represented as 'TH1'. No causal assignments are necessary.

iii) Higher Order System

Fig 4.8 gives an example of how structure graphs and bond graphs compare in the modelling of higher order systems. The bond graph model is taken from the literature⁽⁷⁾. As already mentioned, structure graphs cannot represent the system directly (because information is necessary about the different direction of translational and rotational movement). However, by considering common displacement points a model can be drawn as illustrated in Fig 4.6 c). The two transformers have their primary ratios in series as there is a vector sum of the translational motion (by virtue of the lever) and rotational motions (by the turning moment).



EXAMPLE III: HIGHER ORDER COUPLINGS

Figure 4.8

It is left to the reader to decide the relative merits of each representation.

4.6 Conclusions

This chapter has explained, defined and given examples of a new form of graphical modelling technique for multi-energy domain systems. By considering, with examples,

- i) A topological formulation
- ii) The necessary information from a lumped parameter schematic to the computer

an improved interactive modelling language was developed.

Section 4.3 defined the language for future reference and use. This gives a set of instructions and conditions such that a structure graph can be formally constructed. The subsequent language developed, although not a complete set, is intended to model a wide variety of multi-energy domain system.

The rest of the chapter then considered some examples, whereby the rules and concepts involved could be explained. By the modelling examples it was demonstrated that complicated systems can be represented in an almost direct manner. It is immediately possible to expand sections for more detailed representation as well as permitting

representation of the schematic in a variety of ways dependent on the modeller's preference.

In essence the extra information, provided by the user, enables the computer not only to determine the system equations, (as explained in the next chapter), but to check the validity, redundance and equivalence of the graph generated.

Because of these features, this new approach should provide a considerable improvement in the computers ability to aid the engineer to model and design general multi-energy domain engineering systems.

One area of further development could be the direct modelling of higher energy domains. By extending structure graphs the extra information could be encoded, by for example, the X,Y,Z directions and rotational movements for each 'element'. With this approach a functional model that closely represents a physical layout would be feasible.

CHAPTER 5

PROCEDURE FOR REDUCTION OF STRUCTURE GRAPHS TO STATE

VARIABLE FORM

5.1 Introduction

This chapter gives the procedure for reducing the Structure Graphs and its associated information to a state variable form. It should be pointed out that this is presented for completeness of the method, as it provides the underlying theory behind the development of the package utilised in the next chapter. It is not necessary to follow the derivations in order to model engineering systems with structure graphs.

In general there are three main ways to proceed from a structure graph:-

- a) Produce Nodal Equation
- b) Implement directly the causal relationship (Signal Flow Diagrams)
- c) State Variable Equations.

For a) nodal equations are generated using Kirchoffs 1st Law. Transforming all sources to a (TH) source form⁽³⁸⁾ this gives

$$TH = G.AC$$

5.1.1

where G is a matrix of conductances,

and by a matrix inversion all the nodal (AC) variables can be found. For pure resistive elements this provides a steady state solution. If however capacitances or inductances are present a 'companion' model is necessary, i.e. for an electrical capacitance.

$$i = C \cdot dv/dt$$

giving

$$i^{n+1} = C/\tau \cdot v^{n+1} - \frac{Cv^n}{\tau} \quad 5.1.2$$

which can be modelled as a controlled source ($C \cdot v^n/\tau$) and parallel resistor (C/τ). Hence an iteration procedure takes place that corresponds to a time solution. The main problem is the speed of solution as in general time consuming inversions are necessary for each iteration step.

For b) the causal relationships are formed. Once this is achieved then direct identification with each term, i.e. an integrator, summer, transfer function can be made. As equations are being implemented there is little problem if they are linear or nonlinear. However, in general, only the time response can be readily evaluated and the frequency response would require a fourier transform. There is normally a problem of solution time as call up models are often used - thus requiring extra work in subroutine handling etc.

The state variable form c) is the most flexible. Frequency response, steady state, transfer functions are reasonably easy to obtain. As important is the inherent compact form that relates each term as a matrix element. Because of assay vectoring this gives potentially the fastest response of all three approaches. For these reasons a state variable form will be considered in this chapter. This will allow the performance requirements specified in Chapter 2 to be met.

5.2 Producing An Incidence Matrix

Once a structure has been entered into the computer it is important to store the information in a more fundamental or primitive form. Once this has been achieved then the graph can be mapped onto an incidence matrix.

Consider a linear directed graph with 'n' nodes and 'b' branches. There exists an incidence matrix of $n \times b$ dimensions such that⁽²⁷⁾:-

$$A = [a_{ij}] \quad 5.2.1$$

where $a_{ij} = 1$ if branch j is incident at node i and the arrow is pointing away from node i .

$a_{ij} = -1$ if branch j is incident at node i and the arrow is pointing towards node i

$a_{ij} = 0$ if branch j is not incident at node i

Hence for:



there would be +1 for $a_{N1,J}$
 -1 for $a_{N2,J}$

5.2.1 Fundamental Set of Elements

Consider: (two connecting lines)

where ELE is an element of the structure graph

Using the above definitions there will be (substituting an element for a 'branch')

+1 at $a_{N1,ELE}$
 -1 at $a_{N2,ELE}$

and for

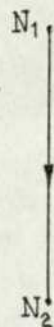


(one connecting line)

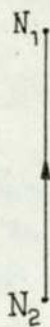
this gives +1 at $a_{N1,ELE}$

Therefore the basic structure graph represents in a diagram form, the incidence matrix.

The only exception to this is the independent and/or controlled source.



a)



b)

If the arrow in a) represents the positive direction of flow from node N_1 to node N_2 then the equivalent structure

graph would be shown as in b). Hence the sign for these terms are reversed.

From this a fundamental set can now be constructed as shown in Table 5.1. All subsequent more complicated elements are reduced to this form.

Fundamental Set of Elements

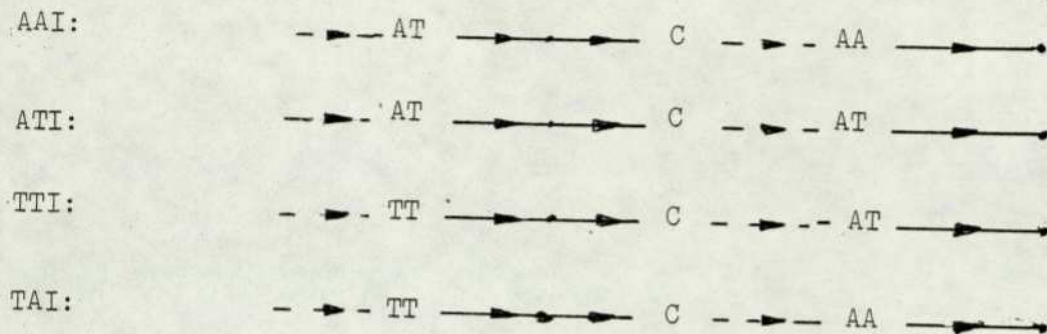
Resistor	(R)
Capacitor	(C)
Inductor	(L)
Independent AC Source	(A ₋)
Independent TH Source	(T ₋)
Controlled AC Source	(AA,TA)
Controlled TH Source	(TT,AT)

Table 5.1

5.2.2 Expanded One Port Elements

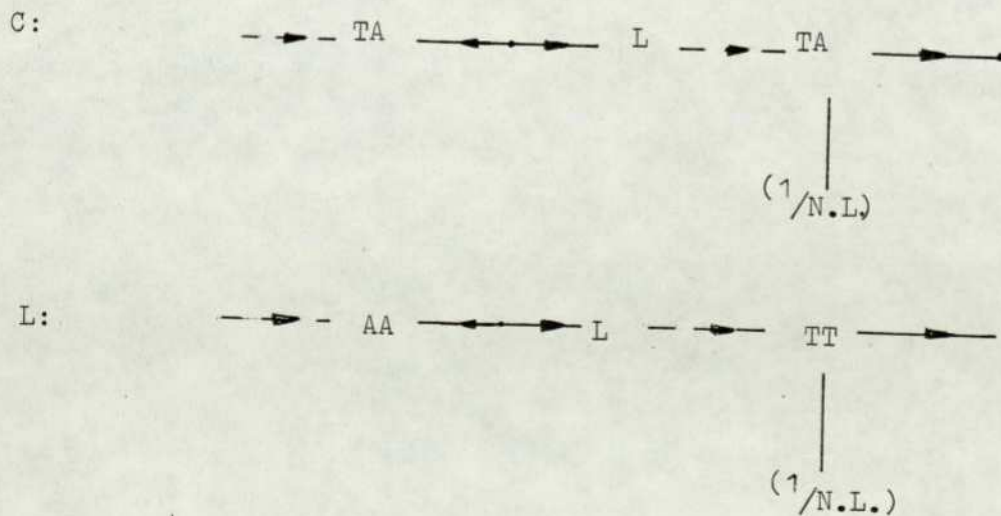
From the list given in Chapter 4 several elements are of a more complex nature. These are now expanded to the fundamental set.

Integrators



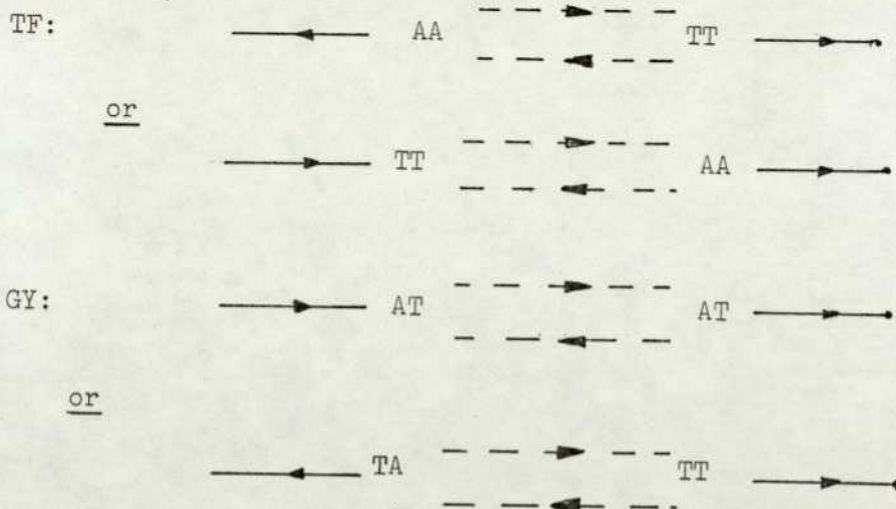
The method of integration is simply a 'TH' source feeding into a capacitor and extracting the 'AC' term.

5.2.3 Nonlinear Capacitors and Inductors



The N.L. capacitor and inductor use the other approach of a controlled 'AC' source into an inductor and extracting the 'TH' term. (This is simply to identify the element in the program). An arrow is reversed in order to provide negative feedback between 'input' and 'output'. Note that integral causality is assumed. This is to avoid differentiating the input (and table) with the corresponding errors⁽²⁶⁾ that result. As the same 'output' is varied for nonlinear variations a problem arises as to the initial condition, as this must be referenced back (for the primitive set) to an initial 'TH' term held by the inductor. In order to avoid this a modified value is necessary as shown in Table 4.2.

5.2.4 Transformers and Gyrators

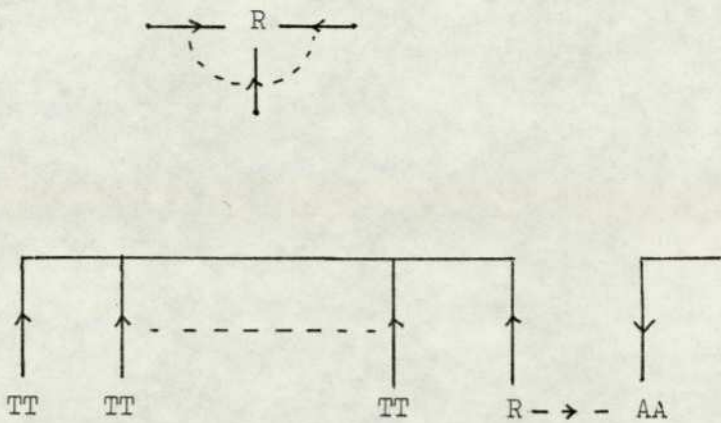


There are two models for both 'TF' and 'GY' terms. This is dependent on the overall causal selection of the system. For the nonlinear case either one or both of the sources for all the models can be controlled.

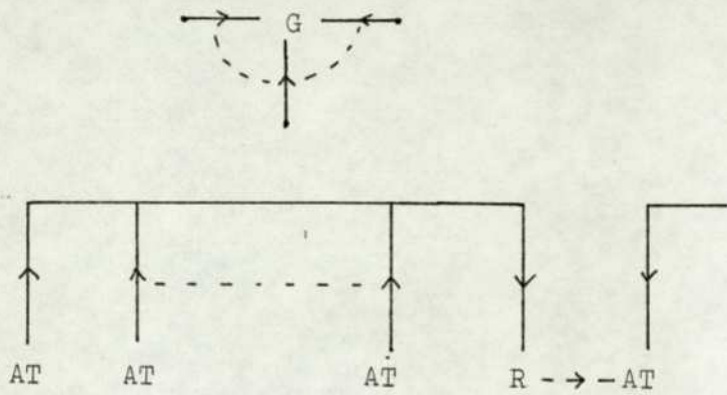
5.25 Field Elements

A Single row is illustrated. Because **the** fields are linear the inputs can be summed.

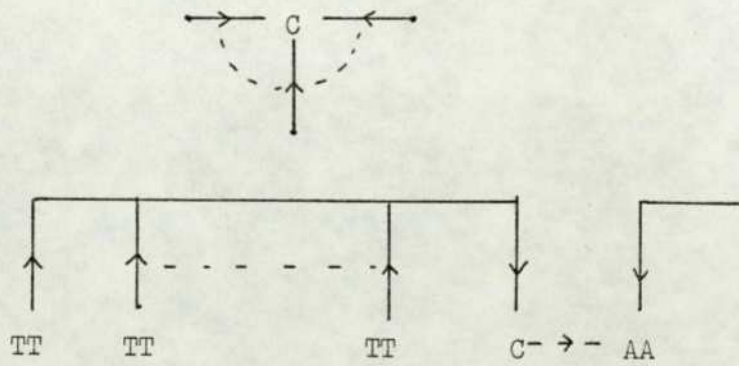
R-Field



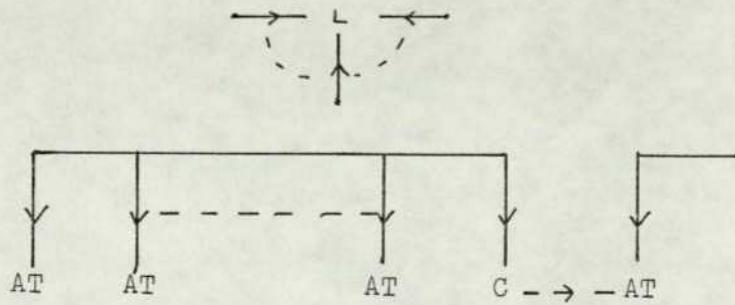
G-Field



C-Field



L-Field



5.2.6 Correcting Topology

For certain elements now discussed, extra work must be carried out to make the network compatible with forming an Incidence matrix. The following conversion or correcting process is applied:

For both mechanical translation and mechanical solution systems:-

$$TH = L.\dot{AC} \quad 5.2.2$$

$$AC = C.\dot{TH} \quad 5.2.3$$

i.e. in the mechanical translation domain $F = M.\dot{V}$; $X = C.\dot{F}$.

However because of the through and across relationships utilised, a difference arises:-

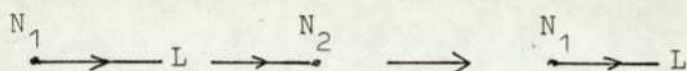
$$AC = L.\dot{TH} \quad 5.2.4$$

$$TH = C.\dot{AC} \quad 5.2.5$$

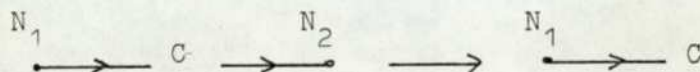
i.e. for the electrical domain $E = L di/dt$; $i = C dv/dt$.

The problem can be solved by taking the dual for the mechanical cases. Therefore all capacitances become inductances and visa-versa. (Of course the mechanical domains can be kept constant and the dual taken of the others but three rather than two domains would then need to be modified).

Also there are other elements which topologically look pleasing, but are not correct for internal representations. These are shown below.



This applies for Mechanical Translation and Mechanical Rotation.



This applies for Fluid and Thermal systems.

The two nodes are merged into one, and the arrow is always into the component. Naturally if the component is already in the right form no action need be taken.

5.2.7 Insertion of Passive Outputs

Outputs of the system for generation of graphs, tabular displays etc must of course be made available. Consider the matrix representation

$$\begin{bmatrix} AC \\ - \\ TH \end{bmatrix} = \begin{bmatrix} K_1 & | & K_2 \\ - & | & - \\ K_3 & | & K_4 \end{bmatrix} \begin{bmatrix} AC \\ - \\ TH \end{bmatrix} \quad 5.2.6$$

where the outputs on the L.H.S. are possible by providing an input vector multiplied by a specified constant.

There are in general two ways to proceed. Either:-

- a) Input vector is causally demanded
- b) Passive insertion of elements.

For a) the input vector must be made available. For example a mechanical spring may have a certain displacement.

The force is therefore

$$F = K\dot{X}dt$$

5.2.7

where K is the spring constant and X the displacement.

This has the advantage of minimising the size of the incidence matrix as all terms must be found from the elements available.

For b) extra elements are added to the system as shown by the extra



'AS' term added in series with the spring capacitance.

Provided the 'AS' source term is zero then the system remains unaffected.

For the developed package b) is utilised because no causal problems are generated in obtaining any variable at any part of the system. For all outputs whether required by the user (or internally by the program):-

'AC' (Element No) is provided by a 'TS' source in parallel.

'TH' (Element No) is provided by an 'AS' source in series.

This applies for user outputs, signal pickoffs, nonlinear terms and internal expanded elements.

5.3 Obtaining Causal Relationships

5.3.1 Forming Through Variable Dependence

Once the incidence matrix for the structure graph has been obtained then the next step is to proceed to obtain the causal relationships.

By applying Kirchoff's first law

$$A.TH = 0 \quad 5.3.1$$

this can be partitioned into two sections.

$$\begin{bmatrix} A_1 & A_2 \end{bmatrix} \begin{bmatrix} TH_1 \\ TH_2 \end{bmatrix} = 0 \quad 5.3.2$$

and by elementary matrix operation.

$$\begin{bmatrix} I & A_1^{-1} A_2 \end{bmatrix} \begin{bmatrix} TH_1 \\ TH_2 \end{bmatrix} = 0 \quad 5.3.3$$

or
$$TH_1 = A_1^{-1} A_2 TH_2 \quad 5.3.4$$

provided A^{-1} is nonsingular.

This precisely defines the causal influence as now one vector is dependent on another! This is the cutset form⁽³⁹⁾ generated for 'TH' and 'AC' variables.

The size of the generated matrices are shown below.

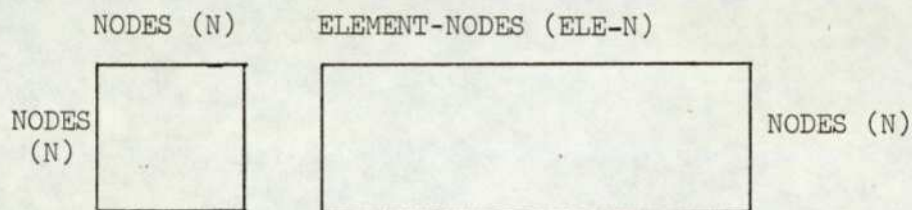


Fig 5.1

N elements are associated with the unit matrix. (The 0 node must be eliminated at this stage as this produces one row of dependency). It is important that the first N elements are selected correctly. Certain elements insist on the dependency in Eq 5.3.4 just as some elements depend on the 'AC' vector.

For structure graphs the selected order of priority is shown in Fig 5.2.

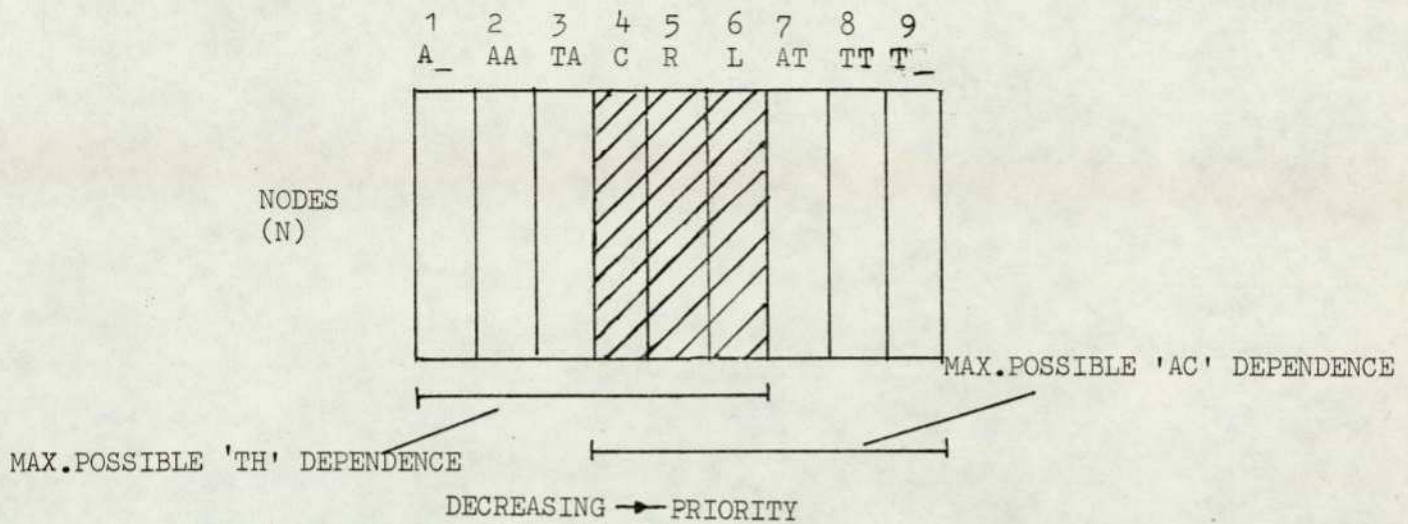


Fig 5.2.

The preferred priority is given to these elements on a left-right basis. Thus 'A_' would be considered first then 'AA' and so on. The shaded region is the overlap that can occur in defining causal relationships. In the figure the C & L elements would have a preferred integral causality. The elements outside the shaded region are not commutable, i.e. it is not possible to have independent or controlled 'AC' terms that have 'AC' dependence; it is not possible to have independent or controlled 'TH' terms that have 'TH' dependence. These would be considered causal conflicts.

Manipulation into the form of Fig 5.2 and then generating dependences as defined by eqn 5.34 will produce the 'final' causal form. Provided the 'TF' or 'GY' terms are not present then the next phase is the generating of the overall system equations.

5.3.2 Special Case For TF & GY Elements

As with bond graphs it is necessary to use a trial and error approach to implement 'TF' & 'GY' elements⁽³²⁾. An equivalent model with small parasitic resistances can be used⁽²⁷⁾ but this would be very inefficient at the solution phase of the problem. The scheme is as follows:-

- i) Put all the 'TF' and 'GY' elements immediately after the 'AC' independent and dependent sources.
- ii) If any 'TF' or 'GY' elements not in the unit matrix, insert it, and then test causality (via eqn 5.3.4 and Fig 5.2). If a causal conflict swop around the models illustrated in Section 5.24.
- iii) If at the beginning of the resistive terms put in all the remaining 'GY' elements.
- iv) If any more 'TF' or 'GY' elements to fit move along one position of the incidence matrix and proceed to ii).
- v) Test final system for causal conflict.

In essence the 'TF' & 'GY' elements are biased for 'TH' variable dependence. If therefore 'AC' variable dependence becomes evident a model can be selected. This gives

preferential treatment to integral causality. However in some instances due to an incorrect initial selection it will not be possible to form a viable unit matrix. In these cases the alternative model must be used.

As suggested, this approach is similar to the bond graph procedure for assigning causality. However for bond graphs both ends of the problem are attacked, i.e. causal assignments are first made for effort and flow sources and the procedure continues entering 'TF' & 'GY' elements wherever possible up to and including resistive terms.

5.3.3 Forming Across Variable Dependence

Equations 5.3.1 represent Kirchoff's 1st Law. Similarly for the second law

$$[B_1 \mid B_2] \begin{bmatrix} AC_1 \\ AC_2 \end{bmatrix} = 0 \quad 5.3.5$$

which by elementary matrix operation gives

$$[B_2^{-1}B_1 \mid I] \begin{bmatrix} AC_1 \\ AC_2 \end{bmatrix} = 0 \quad 5.3.6$$

provided B_2 is nonsingular producing a tie-set form.

The significance of inserting B_2 can be identified from the relationship

$$A \cdot B^T = 0^{(26)} \quad 5.3.7$$

So combining eqn 5.3.3 and 5.3.6

$$A_1^{-1} A_2 = -(B_2 B_1)^T \quad 5.3.8.$$

Therefore all of the AC dependences can be determined from the cutset matrix. This enables only the cutset form to be generated to solve the system equations.

Fig 5.3 shows the selected partitioning of the matrices. (Here the independent and dependent sources are combined as they form a common group). Of interest is the observations that some segments are not allowed, as shown by the crossed lines. They are simply not possible with the above causal assignment. For instance the term ACR means that a resistor would have a higher priority level than a capacitor, if the elements are in a loop. Similar comments apply to ACL and ARL. The B matrix would contain the transpose of the above, i.e. from the figure

$$BXY = -(AYX)^T \quad 5.3.9.$$

Hence each segment can now be obtained and is ready for inversion into a global matrix.

PARTITIONING OF A & B MATRICES

Dependent

Independent

$$\begin{bmatrix} \text{THA} \\ \text{THD} \\ \text{THC} \\ \text{THR} \\ \text{THL} \end{bmatrix} = - \begin{bmatrix} \text{ACA} & \text{ARA} & \text{ALA} & \text{ADA} & \text{ATA} \\ \text{ACD} & \text{ARD} & \text{ACD} & \text{ADD} & \text{ATD} \\ \text{ACC} & \text{ARC} & \text{ALC} & \text{ADC} & \text{ATC} \\ \text{ACR} & \text{ARR} & \text{ALR} & \text{ADR} & \text{ATR} \\ \text{ACB} & \text{ARB} & \text{ALL} & \text{ADL} & \text{ATL} \end{bmatrix} \begin{bmatrix} \text{THC} \\ \text{THR} \\ \text{THL} \\ \text{THD} \\ \text{THT} \end{bmatrix}$$

5.4.1

DETAILED PARTITIONING OF $A_1^{-1}A_2$ MATRIX

a)

Dependent

Independent

$$\begin{bmatrix} \text{ACC} \\ \text{ACR} \\ \text{ACL} \\ \text{ACD} \\ \text{ACA} \end{bmatrix} = - \begin{bmatrix} \text{BTC} & \text{BDC} & \text{BCC} & \text{BRC} & \text{BLC} \\ \text{BTR} & \text{BDR} & \text{BCR} & \text{BRR} & \text{BRC} \\ \text{BTL} & \text{BDL} & \text{BCL} & \text{BRL} & \text{BLL} \\ \text{BTD} & \text{BDD} & \text{BCD} & \text{BRD} & \text{BLD} \\ \text{BTA} & \text{BDA} & \text{BCA} & \text{BRA} & \text{BLA} \end{bmatrix} \begin{bmatrix} \text{ACT} \\ \text{ACD} \\ \text{ACC} \\ \text{ACR} \\ \text{ACL} \end{bmatrix}$$

5.4.2

DETAILED PARTITIONING OF $B_2^{-1}B_1$

b)

- AXY-X - INDEPENDENT TH VARIABLE
- Y - DEPENDENT TH VARIABLE
- BXY-X - INDEPENDENT AC VARIABLE
- Y - DEPENDENT AC VARIABLE

Fig 5.3

5.4 Formulation of the Overall System Equation

With the cutset matrix and eqn 5.3.9, together with the 'TH' & 'AC' element relationships, a global matrix can be formed. This simply connects the equations together in a convenient form for a solution.

Fig 5.4 shows the first stage of the process. It would seem appropriate to keep the through and across terms together as is shown in Eqn 5.4.3 to 5.4.7 and substitute in the element relationships defined in eqn 5.4.8 to Eqn 5.5.0. The reasons for the positioning of these relationships is described in Section 5.5.

This is rather an involved figure. However it is desirable to represent all of the equations and their suffixes together as this forms the basis of all the possible global matrices that follows.

The Independent and Dependent vectors in Eqn 5.4.1 and 5.4.2 are shown as (I) & (D) in the figure. The transposed 'A' matrix terms are generated directly from Eqn 5.3.8.

Considering each now in turn, the top row represents the dependent source terms. These are dependent on the signal pickoffs and can only come from inserted parasitic output terms discussed in Section 5.2.7.

$$\begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACD} \\ \text{THD} \end{bmatrix} \end{matrix} = - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACD} \\ \text{THD} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THC} \\ \text{ACL} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THR} \\ \text{ACR} \end{bmatrix} \end{matrix} - \begin{matrix} \text{(D)} \\ \begin{bmatrix} -\text{TA} & -\text{AA} \\ -\text{TT} & -\text{AT} \end{bmatrix} \begin{bmatrix} \text{THA} \\ \text{ACA} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACC} \\ \text{THL} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACT} \\ \text{THT} \end{bmatrix} \end{matrix} \quad \dots \quad 5.43$$

X1 X2 X3 X4 X5 X6

$$\begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{ACC} \\ \text{THL} \end{bmatrix} \end{matrix} = - \begin{bmatrix} -(\text{ACD})^T & 0 \\ 0 & \text{ADL} \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACD} \\ \text{THD} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THC} \\ \text{ACL} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THR} \\ \text{ACR} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{THA} \\ \text{ACA} \end{bmatrix} \end{matrix} - \begin{bmatrix} -(\text{ALD})^T & 0 \\ 0 & \text{ALL} \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACC} \\ \text{THL} \end{bmatrix} \end{matrix} - \begin{bmatrix} -(\text{ACA})^T & 0 \\ 0 & -\text{ATL} \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACT} \\ \text{THT} \end{bmatrix} \end{matrix} \quad \dots \quad 5.44$$

-A1 -A2 -A3 -A4 -A5 -A6

$$\begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{ACR} \\ \text{THR} \end{bmatrix} \end{matrix} = - \begin{bmatrix} -(\text{ARD})^T & 0 \\ 0 & \text{ADR} \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACD} \\ \text{THD} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THC} \\ \text{ACL} \end{bmatrix} \end{matrix} - \begin{bmatrix} 0 & -(\text{ARR})^T \\ \text{ARR} & 0 \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THR} \\ \text{ACR} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{THA} \\ \text{ACA} \end{bmatrix} \end{matrix} - \begin{bmatrix} -(\text{ARC})^T & 0 \\ 0 & \text{ALR} \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACC} \\ \text{THL} \end{bmatrix} \end{matrix} - \begin{bmatrix} (\text{ARA})^T & 0 \\ 0 & -\text{ATR} \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACT} \\ \text{THT} \end{bmatrix} \end{matrix} \quad \dots \quad 5.45$$

-A7 -A8 -A9 -A10 -A11 -A12

$$\begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{THA} \\ \text{ACA} \end{bmatrix} \end{matrix} = - \begin{bmatrix} 0 & \text{ADA} \\ -(\text{ATD})^T & 0 \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACD} \\ \text{THD} \end{bmatrix} \end{matrix} - \begin{bmatrix} \text{ACA} & 0 \\ 0 & -(\text{ATL})^T \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THC} \\ \text{ACL} \end{bmatrix} \end{matrix} - \begin{bmatrix} \text{ARA} & 0 \\ 0 & -(\text{ATR})^T \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THR} \\ \text{ACR} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{THA} \\ \text{ACA} \end{bmatrix} \end{matrix} - \begin{bmatrix} 0 & \text{ALA} \\ -(\text{ATC})^T & 0 \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACC} \\ \text{THL} \end{bmatrix} \end{matrix} - \begin{bmatrix} 0 & -\text{ATA} \\ (\text{ATA})^T & 0 \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACT} \\ \text{THT} \end{bmatrix} \end{matrix} \quad \dots \quad 5.46$$

-A13 -A14 -A15 -A16 -A17 -A18

$$\begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{THC} \\ \text{ACL} \end{bmatrix} \end{matrix} = - \begin{bmatrix} 0 & \text{ADC} \\ -(\text{ALD})^T & 0 \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACD} \\ \text{THD} \end{bmatrix} \end{matrix} - \begin{bmatrix} \text{ACC} & 0 \\ 0 & -(\text{ALL})^T \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THC} \\ \text{ACL} \end{bmatrix} \end{matrix} - \begin{bmatrix} \text{ARC} & 0 \\ 0 & -(\text{ALR})^T \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THR} \\ \text{ACR} \end{bmatrix} \end{matrix} - \begin{bmatrix} \bigcirc \end{bmatrix} \begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{THA} \\ \text{ACA} \end{bmatrix} \end{matrix} - \begin{bmatrix} 0 & \text{ALC} \\ -(\text{ALC})^T & 0 \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACC} \\ \text{THL} \end{bmatrix} \end{matrix} - \begin{bmatrix} 0 & -\text{ATC} \\ (\text{ALA})^T & 0 \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACT} \\ \text{THT} \end{bmatrix} \end{matrix} \quad \dots \quad 5.47$$

-A19 -A20 -A21 -A22 -A23 -A24

$$\begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{ACR} \\ \text{THR} \end{bmatrix} \end{matrix} = - \begin{bmatrix} \text{R} & 0 \\ 0 & \text{G} \end{bmatrix} \begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{THR} \\ \text{ACR} \end{bmatrix} \end{matrix} \quad \dots \quad 5.48$$

RG

$$\begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{THC} \\ \text{ACL} \end{bmatrix} \end{matrix} = - \begin{bmatrix} \text{Cd/dt} & 0 \\ 0 & \text{Ld/dt} \end{bmatrix} \begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{ACC} \\ \text{THL} \end{bmatrix} \end{matrix} \quad \dots \quad 5.49$$

(CL)_o

$$\begin{matrix} \text{(D)} \\ \begin{bmatrix} \text{THC} \\ \text{ACL} \end{bmatrix} \end{matrix} = - \begin{bmatrix} \text{Cd/dt} & 0 \\ 0 & \text{Ld/dt} \end{bmatrix} \begin{matrix} \text{(I)} \\ \begin{bmatrix} \text{ACC} \\ \text{THL} \end{bmatrix} \end{matrix} \quad \dots \quad 5.50$$

(CL)_i

(I)	INDEPENDENT	RG	RESISTIVE RELATIONSHIPS
(D)	DEPENDENT	(CL) _o	DERIVATIVE CAUSALITY
$\dot{X}$	STATE VECTOR	(CL) _i	INTEGRAL CAUSALITY

MATRIX FORMULATION OF OVERALL SYSTEM EQUATIONS

Fig 5.4

Eqn 5.4.4 represents the surplus capacitive and inductive terms and eqn 5.4.5 represents the resistive terms. The outputs are shown in eqn 5.4.6. Here the dependent term associated with the independent sources are grouped together. This is directly referenced in Eqn 5.4.3 as already mentioned.

The states are represented by Eqn 5.4.7. These have already been casually selected and it is assumed that there is no redundancy⁽²⁷⁾. In general an iterative procedure will be necessary to obtain a viable set for a system containing dependent sources.

5.5 Formulation of Global Matrix

By substituting Eqn 5.4.8 into Eqn 5.4.5, Eqn 5.4.9 into Eqn 5.4.4 and Eqn 5.5.0 into Eqn 5.4.7 a global matrix can be formed, some examples of which are shown in Fig 5.5. Here the notation A1-A24 and X1 to X6 have been used.

Of importance is the vector X4 which represents the outputs and X5 which represents the states. These are below the dotted line, and by simple gaussian elimination these terms can be found. As this section is the starting point for numerical work to a state variable form, for both linear and nonlinear systems, it is important (particularly for nonlinear systems) that the reduction to the state variable form be as fast and efficient as possible. In this context there are no pivot searches.

GLOBAL MATRIX REPRESENTATIONS

$$\begin{bmatrix}
 1 & 0 & 0 & K & 0 \\
 A1 & (CL)_p & 0 & 0 & A5 \\
 A7 & A8 & A9+RG & 0 & A11 \\
 A13 & A14 & A15 & 1 & A17 \\
 A19 & A10 & A21 & 0 & (CL)_t+A23
 \end{bmatrix}
 \begin{bmatrix}
 X1 \\
 X2 \\
 X3 \\
 X4 \\
 X5
 \end{bmatrix}
 =
 \begin{bmatrix}
 0 \\
 A6 \\
 A12 \\
 A18 \\
 A24
 \end{bmatrix}
 \begin{matrix}
 \\
 \\
 X6 \\
 \\
 5.5.2
 \end{matrix}$$

a)

From inspection of Eqn 5.43 to 5.47

$$\begin{bmatrix}
 1 & 0 & 0 & K & 0 \\
 A1 & (CL)_p & 0 & 0 & A5 \\
 A7 & 0 & A9+RG & 0 & A11 \\
 A13 & A6^T & A12^T & 1 & A17 \\
 A19 & -A5^T & -A11^T & 0 & (CL)_p+A23
 \end{bmatrix}
 \begin{bmatrix}
 X1 \\
 X2 \\
 X3 \\
 X4 \\
 X5
 \end{bmatrix}
 =
 \begin{bmatrix}
 0 \\
 A6 \\
 A12 \\
 A13 \\
 A17^T
 \end{bmatrix}
 \begin{matrix}
 \\
 \\
 X6 \\
 \\
 5.5.3
 \end{matrix}$$

Where $A14 = A6^T$; $A15 = A12^T$; $A24 = A17^T$ b)

Swapping around rows 4 & 5, columns 4 & 5 and eliminating column 1.

$$\begin{bmatrix}
 (CL)_p^{-1} & 0 & A5 & -A1K \\
 0 & A9+RG & A11 & -A7K \\
 A5^T & -A11^T & (CL)_t+A23 & -A19K \\
 A6^T & A12^T & A17 & 1-A13K
 \end{bmatrix}
 \begin{bmatrix}
 X2 \\
 X3 \\
 X5 \\
 X4
 \end{bmatrix}
 =
 \begin{bmatrix}
 A6 \\
 A12 \\
 A17^T \\
 A18
 \end{bmatrix}
 \begin{matrix}
 \\
 X6 \\
 \\
 5.5.4
 \end{matrix}$$

c)

Fig 5.5

By having X5 the lowest and X4 the next lowest position (as they depend on the states), it is not necessary to completely invert the global matrix. The choice of the second and third rows is arbitrary, but it is important that the elements are on the diagonal so that a nonzero value can be guaranteed, i.e. as there is to be no search for a pivot it is essential that

$ELE \neq 0$ (except for signal and source terms) 5.5.1.

The dependent sources are in fact dependent on the outputs contained in X4. Hence the only suitable position, bearing in mind the expected nonzero diagonal term, is row one.

In general the matrix will be sparse and it is essential that only nonzero elements are referenced in order to reduce the computation as much as possible.

There are further reductions that can be made to a) and b) and c) examples. However for b) the transpose of a segment poses computational difficulties in the precise positioning of the relevant terms and so will not produce much saving. In c) the reduced global matrix has the advantage of not only a smaller size to be operated only but also a significant saving in space, as one section of this matrix (shown dotted) is the transpose of the other. However the inversion of $(CL)_D$ must be considered as well as the

multiplication by K in the fourth column. It was decided that if space matrix handling routines are used the space savings would not be too important, and b) and c) would have no real benefit over a).

5.6 Producing The State Equations and Outputs

There are two ways to proceed to produce the state equations. They are identical theoretically but have important practical differences.

- A matrix solution of the system directly obtaining X4 and X5
- Numerically solving Eqn 5.5.2, 5.5.3 or 5.5.4 so that again X4 and X5 can be found.

For a) and using Eqn 5.5.4. By 2x2 partitioning gaussian elimination gives:-

$$\begin{aligned}
 & \begin{pmatrix} (CL)_T + A23 & -A19K \\ A17 & 1-A13K \end{pmatrix} - \begin{pmatrix} -A5^T & -A11^T \\ A6^T & A12^T \end{pmatrix} \times \begin{pmatrix} (CL)_D^{-1} & 0 \\ 0 & A9+RG \end{pmatrix}^{-1} \begin{pmatrix} A5-A1K \\ A11-A7K \end{pmatrix} \begin{bmatrix} X5 \\ X4 \end{bmatrix} \\
 & \quad \quad \quad (AT1) \\
 & - \begin{pmatrix} -A5^T & -A11^T \\ A6^T & A12^T \end{pmatrix} \times \begin{pmatrix} (CL)_D^{-1} & 0 \\ 0 & A19+RG \end{pmatrix}^{-1} \times \begin{pmatrix} A6 \\ A12 \end{pmatrix} \times X6 \quad 5.5.1 \\
 & \quad \quad \quad (AT2)
 \end{aligned}$$

And using the groupings AT1 and AT2 from Eqn 5.6.1

$$\begin{bmatrix} X5 \\ X4 \end{bmatrix} = AT1^{-1} . AT2 . X6 \quad 5.6.2$$

provided $AT1^{-1}$ is nonsingular, X5 represents the states and X4 the outputs.

For linear systems this is the preferred approach because it is not necessary to construct a global matrix! All the parameter terms can be inserted as soon as possible and matrix manipulation proceeded with until eqn 5.6.2 is obtained. The inversions of AT1 may not be directly possible if the states selected are not independent⁽³⁹⁾. However this is unlikely for most physical systems and will not be considered further.

For b) the values of C, L, R and K would be substituted as well as the A1-A24 terms before a solution is attempted. Hence if new values were to be used for any components only these terms would need to be changed. That is the necessary addressing and inverting of elements, as well as the terms A1-A18 being gathered for eqn 5.6.1 would handicap situations where repeated updates of the state equations are necessary. As nonlinear solutions are a requirement method b) is implemented.

As can be derived from eqn 5.6.1 there is the possibility of derivative terms in the states and outputs.

In general:

$$\dot{x} = Ax + Bu + C\dot{u} \quad 5.6.3$$

$$Y = D.x + E.u + F.\dot{u} \quad 5.6.4$$

where the state equations have been linearized (if nonlinear) around an operating point.

It is usually inconvenient to consider derivatives of inputs, particularly as in general they are non-deterministic in nature. By a simpler transpose of variables

$$x = \hat{x} + C.u \quad 5.6.5$$

giving
$$x = A\hat{x} + (AC+B).u \quad 5.6.6$$

$$Y = D.\hat{x} + (DC+E).u + F.\dot{u} \quad 5.6.7$$

However, derivatives still appear in the output equation. A simple example of this is trying to measure the current when a voltage source is connected across a capacitor (in the electrical sense). Under these conditions a solution cannot be found.

From this the steady state, frequency response, transfer function etc can be found, as discussed under the Determination of Performance Characteristics in Chapter 2.

5.7 Conclusions

This chapter has described the formulation of state equations for the structure graph. This is not a straightforward process due to the many complex elements that can be represented, as well as being partly due to the amount of freedom possible in selecting a topological model. However as the whole process can be automated on a computer this is not a serious practical problem in an interactive environment.

Section 5.2 described how a fundamental set, and from this, by decomposition, more complex elements can be generated. Clearly there is no reason why other elements cannot be added. (The process being similar to a MACRO expansion in a high level language). The section then described the precise manner of how the topology is corrected for different but equivalent structure graphs.

Section 5.3 then described how the causal influences would be determined. The whole process relies on the dependence of the set of relations on another. This is equivalent to selecting a tree in linear graphs and causal assignments in bond graphs. The difficult area of selecting the correct model for 'TF' and 'GY' was discussed and a procedure given for implementation.

With the incidence matrix finally reduced to a cutset form, sections 5.4, 5.5 and 5.6 then described how the overall system equations, global matrix and state equations could be found. It was suggested that for nonlinear systems a global matrix is preferable to the reduced equations (even though this will mean more memory space). The nonlinear method developed is similar to that of general purpose simulation routines and involves linearization around operating points.

The next chapter proceeds to demonstrate the use of a package incorporating structure graphs for the modelling of the instrument systems described in Chapter 3. The package developed from the theory contained in this chapter is described in flow chart form with explanations in Appendix E.

CHAPTER 6

MODELLING WITH THE DEVELOPED PACKAGE MEDIEM

(Multi Energy Domain Interactive Element Modelling)

6.1 Introduction

This chapter explains the practical useage of the developed package for the interactive functional modelling and design of instrument systems. It uses 'Structure Graphs', a computer aided graphical technique, which enables almost a direct mapping from the schematic to the computer. This should therefore, improve the interactive modelling and design of systems. Although developed on a small mini (a PDP 11/10) it nevertheless will model both linear and nonlinear systems and handle up to 50 elements.

The chapter is divided into two main sections:-

- i) An explanation with actual computer listings of how a simple model is entered into MEDIEM (the computer package) and processed. The important areas of both structure and parameter changes as well as the entering of nonlinear terms are explained.
- ii) The rest of the chapter is then mainly concerned with the modelling of the five instrument examples described in Chapter 3. As this is a new technique each instrument is analysed in detail on a step by step basis. The completed structure graph is then entered into MEDIEM and a listing of the model and computer print out of the response(s) given.

A summary of the Advantages and Limitations of Structure Graphs then follows. This is a similar format to the more established techniques of Chapter 3. It is given here as the instrument examples have been developed (using Structure Graph) in this chapter.

Finally a short resume is given of the features of the package. This is compared with the essential requirements described in Chapter 2.

6.2. Explanation of use of MEDIEM

The operation of the package MEDIEM (Multi-Energy Domain Interactive Element Modelling) will be described with the aid of an example. Consider again the weighing machine described in Chapter 2. A lumped schematic with the corresponding structure graph is illustrated in Fig 6.1 a) and b)

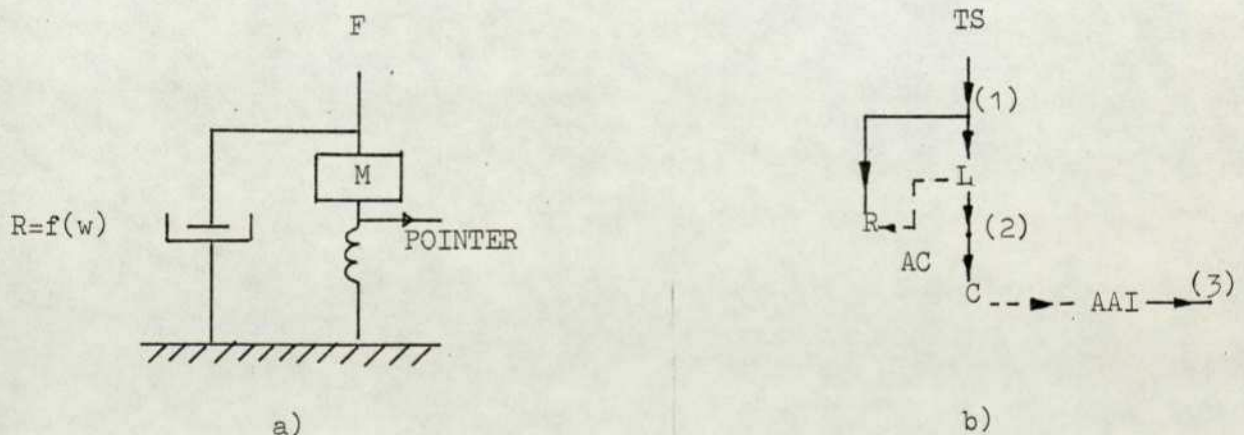


Fig 6.1
- 184 -

The weighing machine now has a nonlinear resistor (in order to kill two birds with one stone and describes how nonlinearities are handled by the package). Node (1) is a common displacement point and for the purposes of illustration the resistance is dependent on the across variable associated with the mass. (However it would just as well in this case be dependent on the across variable of either the resistance or capacitance). The next few figures describe with the computer print out how this model is represented and run on MEDIEM. All the user input is underlined.

6.2.1 Entering Structure

The structure is entered (see Fig 6.2) with a routine called 'STRU', automatically called when a new model 'NEW' is requested. Editing facilities (insert and delete) are available to allow flexibility of model formulation. The command IN inserts before the element no. N. In this case, for a new model, no value for N (or 0) is given.

Consider each line of input. First 'TS' a Through Step (corresponding to a constant force being applied to the system) is connected to node 1. As can be seen, each line contains an element connected to a node allowing rule 1 of Section 4.4., i.e. a node separator between any two edges to be automatically applied. Next the mass or an 'L' element is connected from node 1 to node 2. Here the element number

PLEASE GIVE COMMAND - TYPE KEY FOR COMMANDS OPTIONS
*KEY

COMMANDS PERMISSIBLE ARE

=====

KEY	NEW	OLD	STRU
PAR	LIST	TIM	FREQ
SAV	END		

PLEASE GIVE COMMAND - TYPE KEY FOR COMMANDS OPTIONS
*NEW

PLEASE GIVE TITLE
*MODEL 1: A WEIGHING MACHINE

IN STRUCTURE MODE, INPUT IN THE FORM OF
NO, ELEMENT, ARROW, NODE, CONNECT

EDITING COMMAND AVAILABLE ARE: - T(TITLE), I(INSERT), D(DELETED)

*I

! 1, TS, TO, 1

! 2, L, FR, 1

! 2, L, TO, 2

! 3, C, FR, 1

! 4, R, FR, 1

! 5, AAI, TO, 3, 3

!

*

Input Of Structure For Weighing Machine Example

Fig 6.2

is entered on two lines, allowing maximum flexibility of arrow assignment. Element 5 is an across-across and integrated controlled source, providing a pickoff for measuring displacement.

This element is connected to a dummy node (node 3). This is a result of a practical implementation of the model rather than a part of structure graphs. A 'connect' input is used to assign the pickoff point. Therefore element 3 has two connect lines associated with it. In essence therefore, the program package will allow

- i) A direct step by step construction of the instrument,
- ii) Direct control over arrow direction.

6.2.2 Entering Parameters

The parameters are requested whenever additional elements have been added in 'STRU'. This of course applies for a new model. In order to speed up the process only the first element number need be specified. A pointer will successively link to the end of user's model.

Fig 6.3 shows how this is entered into the computer. Typing the first element number, no.1, the computer asks for the domain and value. As the system is mechanical translation 'M' is entered for all the elements. This provides the additional and necessary information for

PARAMETER FORMAT FOR LINEAR SYSTEMS IS DOMAIN, VALUE1, VALUE2
IF NONLINEAR TYPE "NL" AT THIS POINT

PLEASE TYPE ELEMENT NUMBER

*1
1 = M , 1.0
2 = M , 0.1
3 = M , 1.0
4 = NL

ENTER ENERGY DOMAIN, CONTROLLING INPUT FOR REPEAT (TF & GY) JUST TYPE "
*M , AC2

NO OF X-Y PAIRS IS: 2

!1.0, 5.0

!1.1, 5.15

IF A NONLINEAR "C", "L" OR AN INTEGRATOR :
PLEASE FEED IN INITIAL VALUE (EITHER CHARGE OR MOMENTUM FOR "C" OR "L"
*

5 = M , 1.0

PLEASE TYPE ELEMENT NUMBER

*

PLEASE GIVE COMMAND - TYPE KEY FOR COMMANDS OPTIONS

*STRU

IN STRUCTURE MODE, INPUT IN THE FORM OF
NO, ELEMENT, ARROW, NODE, CONNECT

EDITING COMMAND AVAILABLE ARE:- T(TITLE), I(INSERT), D(DELETED)

*D3

*14

!3, C , FR, 2

!

*

Input Of Parameters For Weighing Machine Example

Fig 6.3

specification of the model. For the resistance 'NL' is specified allowing the controlling input to be requested. There is no need to consider causal influences. The number of pairs is requested and the nonlinearities entered as a data table. (Because the domain is not directly entered into a drawn structure graph, it was felt better to enter this in the 'PAR' section).

6.2.3 Entering Structural Changes

Element 3, the capacitance is connected to the wrong node. In order to change this 'STRU' is again entered. The editor is line orientated, therefore, the line must be re-typed. First it is deleted, then inserted as shown in Fig 6.3. The parameter is re-entered at the top of Fig 6.4.

6.2.4 Entering Time Controls

The time controls are now entered using 'TIM'. A fairly standard procedure is applied here where (see Fig 6.4)

- 1) Outputs
- 2) Time input (min, max, step, rate of print)
- 3) Min-max value of plot

are all input by the user.

PARAMETER FORMAT FOR LINEAR SYSTEMS IS DOMAIN, VALUE1, VALUE2
IF NONLINEAR TYPE "NL" AT THIS POINT

PLEASE TYPE ELEMENT NUMBER

* 3
3 = M, 1.0
4 =

PLEASE TYPE ELEMENT NUMBER

*

PLEASE GIVE COMMAND - TYPE KEY FOR COMMANDS OPTIONS

* TIM

IN TIME DOMAIN PLEASE TYPE COMMAND - K FOR KEY

* 0

PLEASE TYPE IN OUTPUTS

* AC5

*

*

IN TIME DOMAIN PLEASE TYPE COMMAND - K FOR KEY

* I

PLEASE FEED IN INITIAL VALUE, FINAL VALUE, STEP, RATE

* 0.0, 10.0, 0.1, 1

IN TIME DOMAIN PLEASE TYPE COMMAND - K FOR KEY

* MM

MIN PLOT VALUE, MAX PLOT VALUE

* 0.0, 2.0

IN TIME DOMAIN PLEASE TYPE COMMAND - K FOR KEY

* E

Specification Of Time Controls for Weighing Machine Example

Fig 6.4

Unfortunately, computer space allowed for only one integration routine to be made available. However, there were excellent results produced in using the sequential euler - a semi-implicit integration routine⁽⁴¹⁾.

6.2.5 Listing Model

To list the model it is necessary to select the command 'LIST'. To do this one must first exit from 'TIM' using the command 'E'. The printout for the weighing machine is shown in Fig 6.5. Two lines of 'L' are apparent; the nonlinear dependence of element 4 is entered under the parameter values; value 2 is the second term of a ramp input or the initial condition of the element variables, or as shown the Y input of the table.

6.2.6 Running Model

To run the model 'TIM' is again selected (see Fig 6.6). A number of different run modes are possible. Pressing 'PT' (plot tektronix) the user generated model is evaluated and plotted. A printout will also be given clarifying the 'AC' variable of element 2. The resulting graph is shown in Fig 6.7 (1).

6.2.7 Entering Temporary Parameter Changes

It may be found that the model response needs modifying. However, if only parameter modifications are to

PLEASE GIVE COMMAND - TYPE KEY FOR COMMANDS OPTIONS
*LIST

TYPE EITHER

- A) TERMINAL OUTPUT
- B) LINE PRINTER OUTPUT

*A

MODEL 1: A WEIGHING MACHINE

OUTPUTS ARE: AC 5

TIME: 0.000E-01 1.000E+01 1.000E-01 PLOTTING RATE IS : 1

FREQ: 0.000E-01 0.000E-01 0.000E-01 LOG. IS -1.0

PLOTTING IN TIME - RANGE IS : 0.000E-01 2.000E+00

PLOTTING IN FREQUENCY - RANGE IS : 0.000E-01 0.000E-01 0

NO	ELEMENT	ARROW	NODE	CONNECT	DOM.	VALUE1	VALUE2
1	TS	TO	1	0	M	1.000E+00	0.000E-01
2	L	FR	1	0	M	1.000E-01	0.000E-01
2	L	TO	2				
3	C	FR	2	0	M	1.000E+00	0.000E-01
4	R	FR	1	0	M	AC 2 1.000E+00 1.100E+00	0.000E-01 5.000E+00 5.150E+00
5	AAI	TO	3	3	M	1.000E+00	0.000E-01

Computer Listing of Weighing Machine Example

Fig 6.5

PLEASE GIVE COMMAND - TYPE KEY FOR COMMANDS OPTIONS
*TIM

IN TIME DOMAIN PLEASE TYPE COMMAND - K FOR KEY
*K

COMMANDS ARE:

T - TIME	
PA - PARAM. CHANGE/LIST	
E - EXIT TO MONITOR	FD - FREQUENCY DOMAIN
MM - MIN-MAX.	ST - STEADY STATE
PP - PLOT PRINTER	TG - TABULATE GT42
PT - PLOT TEKTRONIX	TP - TABULATE PRINTER
O - OUTPUT	

IN TIME DOMAIN PLEASE TYPE COMMAND - K FOR KEY
*PT

AC 2 BECOMES AN AC VARIABLE W.R.T. (Ø) NODE

IN TIME DOMAIN PLEASE TYPE COMMAND - K FOR KEY
*PA

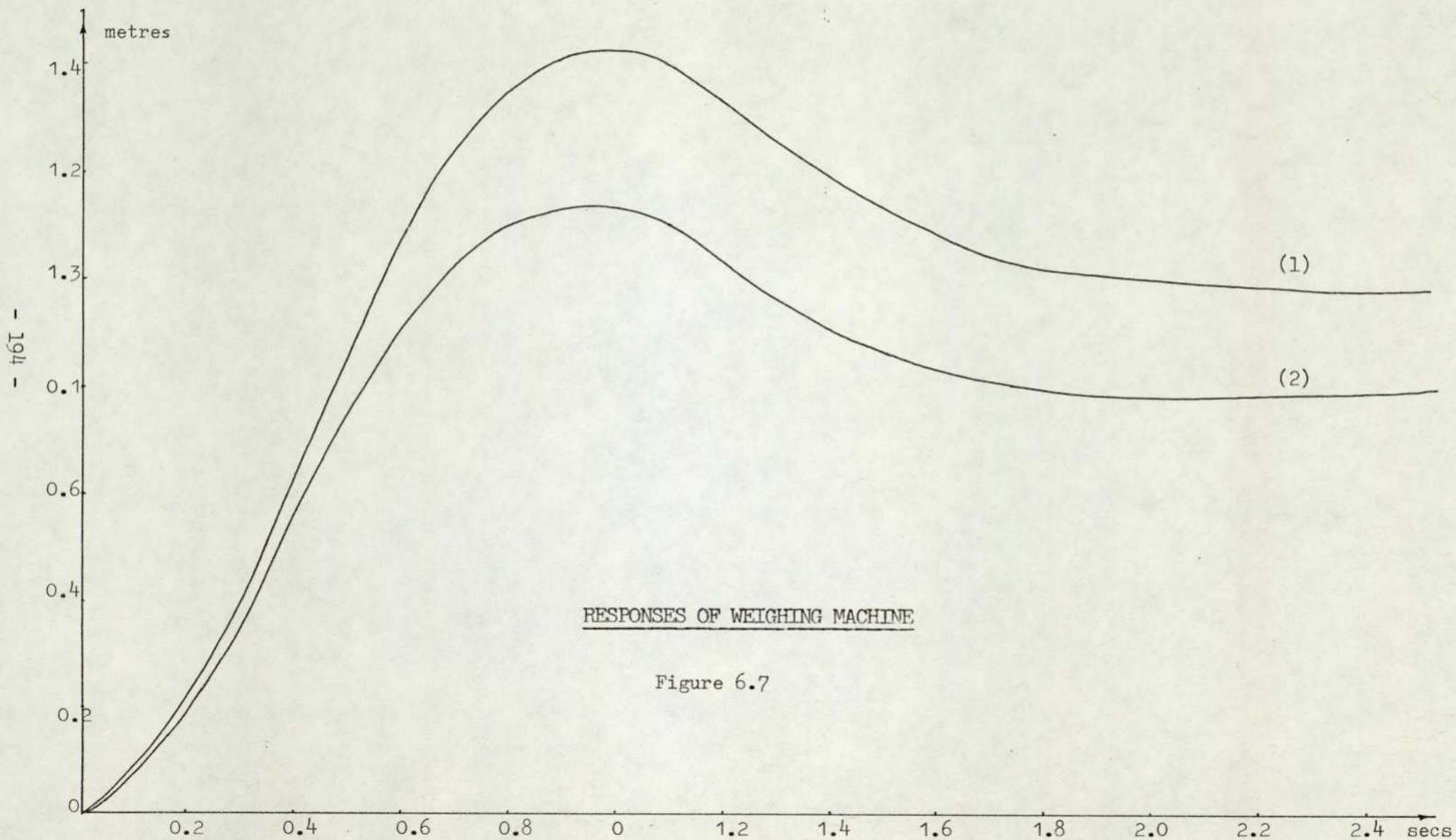
IN LOCAL MODE
TYPE M - FOR MODIFY OR L - FOR LIST
M

PLEASE FEED IN ELEMENT NUMBER
#3

PLEASE FEED IN VALUE1, VALUE2
*Ø.9, Ø.11

Running Model of Weighing Machine Example

Fig 6.6



be made a local mode of operation can be used. This is specifically the case when new states are not required to be generated. In Fig 6.6 element 3 is changed to 0.9 m/N and an initial value of 0.11 (TH(0), see Table 4.2) is also specified. The temporary parameters are checked in Fig 6.8 by typing 'L'. (As these changes are temporary in nature the parameter will be returned to their original values on return to command level). Typing again 'PT' gives the graph 6.7 (2). Clearly there has been some backoff of the applied force, giving a lower displacement.

A steady state solution may be required. However the package in its present form cannot evaluate the steady solution for a nonlinear system. As can be seen from Fig 6.8 an error message results clearly advising the user the procedure to adopt.

6.3 Modelling Instrument Examples

This section will now describe the construction and results of the instrument examples of Chapter 3. Because they will be modelled using the new graphical technique, they will be constructed on a step-by-step basis. The results are given using the line printer output.

6.3.1 K.D.G. Differential Pressure Cell

The K.D.G. D.P. cell can be constructed as various subsections (as described in Chapter 3). These are illustrated

IN LOCAL MODE
TYPE M - FOR MODIFY OR L - FOR LIST
L

LATEST TEMP. PARAMETERS

1	0.1000E+01	0.0000E+00
2	0.1000E+00	0.0000E+00
3	0.9000E+00	0.1100E+00
5	0.1000E+01	0.0000E+00

IN LOCAL MODE
TYPE M - FOR MODIFY OR L - FOR LIST

IN TIME DOMAIN PLEASE TYPE COMMAND - K FOR KEY
*PT

IN TIME DOMAIN PLEASE TYPE COMMAND - K FOR KEY
*ST

STEADY STATE NOT PERMISSIBLE WITH DATA TABLES

IN TIME DOMAIN PLEASE TYPE COMMAND - K FOR KEY
*E

Modifying Parameters (Locally) of Weighing Machine Example

Fig 6.8

in Fig 6.9. In general it is only necessary to identify the elements of the K.D.G. D.P. Cell, the connections being almost automatic.

i) Chamber

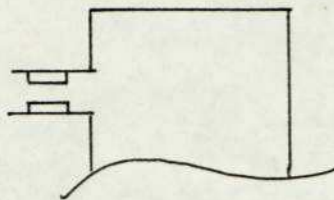
An R-C network in the fluid domain shown in Fig 6.9b).

ii) Diaphragm

An equivalent model may take the form of c) or e). The topology, although in such case different, is still identifiable as similar by the program. This is helpful to the engineer interested only in inputting the model as easily as possible. There are two X(displacement points) in Fig 6.9f) which of course are the same. However with the additional information of the energy domain this can be directly processed by the computer and internally corrected.

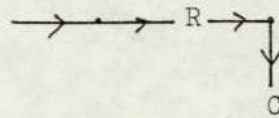
iii) Connecting Tube

The connecting tube is modelled in Fig 6.9 h) or i). Because the capacitance is seemingly connected from the diaphragm to the tube this can be input in series. However it is also possible to consider the pressure across the capacitance being constant thereby employing one node in i). Again this can be interpreted by the computer once the energy domain is apparent.

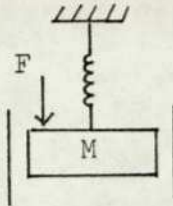


a)

CHAMBER

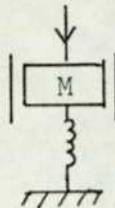


b)



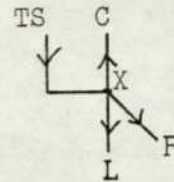
c)

or

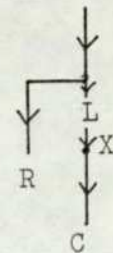


e)

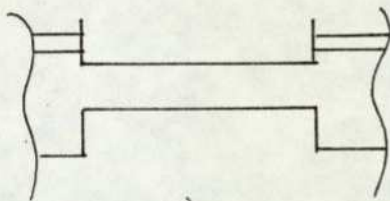
DIAPHRAGM



d)



f)

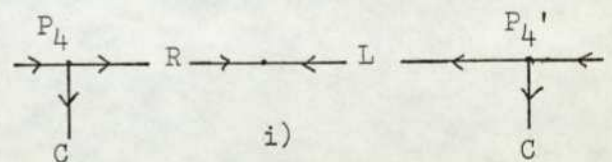


g)

or



h)



i)

CONNECTING TUBE

STRUCTURE GRAPH MODELS OF THE SUBSECTION OF A K.D.G. D.P. CELL

Figure 6.9

Fig 6.10a) shows the resulting structure graph. (The L.V.D.T's and summation of outputs are shown by the integrated and summed velocities of elements 5 and 15). 'GY' rather than 'TF' (as in bond graphs) converts from the fluid to mechanical translation and vice versa. There is no problem in the positioning of these two port devices, as they will always 'connect' one energy domain to another. It may be noted that:

- a) The graph is highly descriptive.
The elements are represented on the graph producing a unique but identifiable representation.
- b) No ambiguity of arrow direction.
The arrows simply give the direction of flow through the component.

As with the previous examples in Chapter 3 it may be desired to remove the chamber and compressibility effects. This gives Fig 6.10 b). As there are no causal influences to consider the graph is suitable for interactive analysis. Also because the components can be identified topologically removal or inversions require no special training.

It would at this stage be useful as well to point out the main disadvantages. These are:-

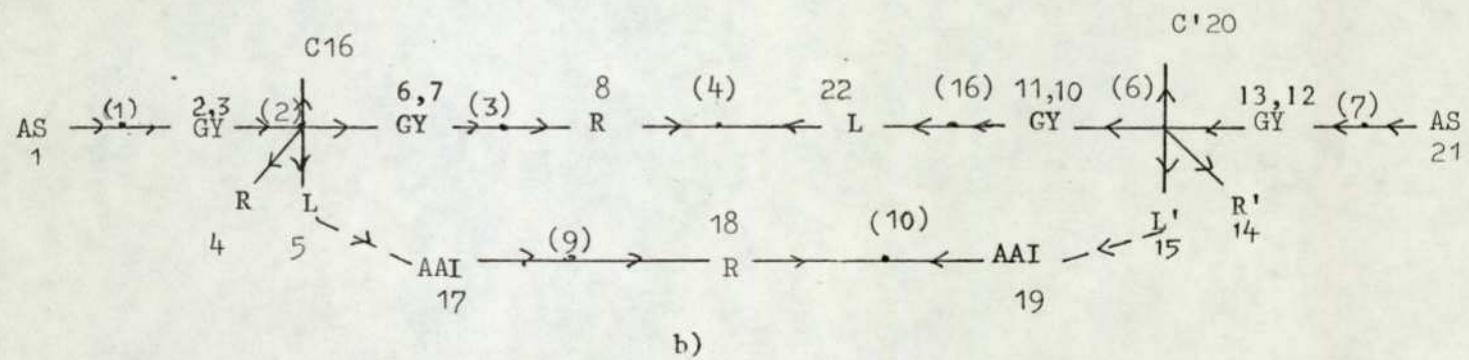


Figure 6.10

- c) Graph cannot show stability.
- d) Graph cannot show energy interactions.
- e) States are not possible to obtain by simple hand manipulation.

This indicates that not all of the disadvantages of Chapter 3 have been overcome. However c) and d) would, by definition, occur with a purely topological representation, and e) is inherent in the concept of a computer aided graph, i.e. one that is dependent on a computer for a solution.

The model is entered into MEDIEM and a listing is shown in Fig 6.11. As the system is linear both time and frequency responses were found. Fig 6.12 gives the time response (7 divisions per range) and Fig 6.13 the frequency response. The frequency response is dependent on an input being selected by the user. In this case the two inputs give identical results. The steady state value can also be found, this being 6.183×10^{-4} (displacement in metres).

6.3.2 Barton D.P. Cell

The construction and structure graph of the Barton D.P. Cell is shown in Fig 6.14.

i) Bellows & Spring Assembly

Fig 6.14 a) gives the schematic, where the spring represents all the combined effects of the input mechanical

D.P. CELL WITHOUT COMPRESSION TERM

OUTPUTS ARE: AC 18

TIME: 0.000E-01 1.500E+00 1.000E-02 PLOTTING RATE IS : 1

FREQ: 1.000E-03 1.000E+03 -1.000E+00 LOG. IS -1.0

PLOTTING IN TIME - RANGE IS : 0.000E-01 1.000E-03

PLOTTING IN FREQUENCY - RANGE IS : -1.500E+02 -3.000E+01 -1

NO	ELEMENT	ARROW	NODE	CONNECT	DOM.	VALUE1	VALUE2
1	AS	TO	1	0	F	2.000E+03	0.000E-01
2	GY	FR	1	0	FM	1.000E+03	0.000E-01
3	GY	TO	2	0	FM	1.000E+03	0.000E-01
4	R	FR	2	0	M	2.150E+00	0.000E-01
5	L	FR	2	0	M	1.100E-02	0.000E-01
16	C	FR	2	0	M	1.540E-04	0.000E-01
6	GY	FR	2	0	MF	1.000E+03	0.000E-01
7	GY	TO	3	0	MF	1.000E+03	0.000E-01
8	R	FR	3	0	F	5.260E+08	0.000E-01
8	R	TO	4				
22	L	TO	4	0	F	3.800E+07	0.000E-01
22	L	FR	16				
10	GY	FR	6	0	MF	1.000E+03	0.000E-01
11	GY	TO	16	0	MF	1.000E+03	0.000E-01
12	GY	FR	7	0	MF	1.000E+03	0.000E-01
13	GY	TO	6	0	MF	1.000E+03	0.000E-01
14	R	FR	6	0	M	2.150E+00	0.000E-01
15	L	FR	6	0	M	1.100E-02	0.000E-01
20	C	FR	6	0	M	1.540E-04	0.000E-01
17	AAI	TO	9	5	E	1.000E+00	0.000E-01
18	R	FR	9	0	E	1.000E+00	0.000E-01
18	R	TO	10				
19	AAI	TO	10	15	E	1.000E+00	0.000E-01
21	AS	TO	7	0	F	-2.000E+03	0.000E-01

RANGE FROM: 0.000E-01 TO 1.000E-03

6.16x10⁻⁴

metre

0.000E-01
 1.000E-02
 2.000E-02
 3.000E-02
 4.000E-02
 5.000E-02
 6.000E-02
 7.000E-02
 8.000E-02
 9.000E-02
 1.000E-01
 1.100E-01
 1.200E-01
 1.300E-01
 1.400E-01
 1.500E-01
 1.600E-01
 1.700E-01
 1.800E-01
 1.900E-01
 2.000E-01
 2.100E-01
 2.200E-01
 2.300E-01
 2.400E-01
 2.500E-01
 2.600E-01
 2.700E-01
 2.800E-01
 2.900E-01
 3.000E-01
 3.100E-01
 3.200E-01
 3.300E-01
 3.400E-01
 3.500E-01
 3.600E-01
 3.700E-01
 3.800E-01
 3.900E-01
 4.000E-01
 4.100E-01
 4.200E-01
 4.300E-01
 4.400E-01
 4.500E-01
 4.600E-01
 4.700E-01
 4.800E-01
 4.900E-01
 5.000E-01
 5.100E-01
 5.200E-01
 5.300E-01

* MODEL
 -- EXPERIMENTAL

Computer Time Response of K.D.G. D.P. Cell
 Fig 6.12

-68.12 DB

PC 13 = *

RANGE FROM: -1.500E+02 TO -3.000E+01

* * * * *

*

*

*

*

*

*

*

*

*

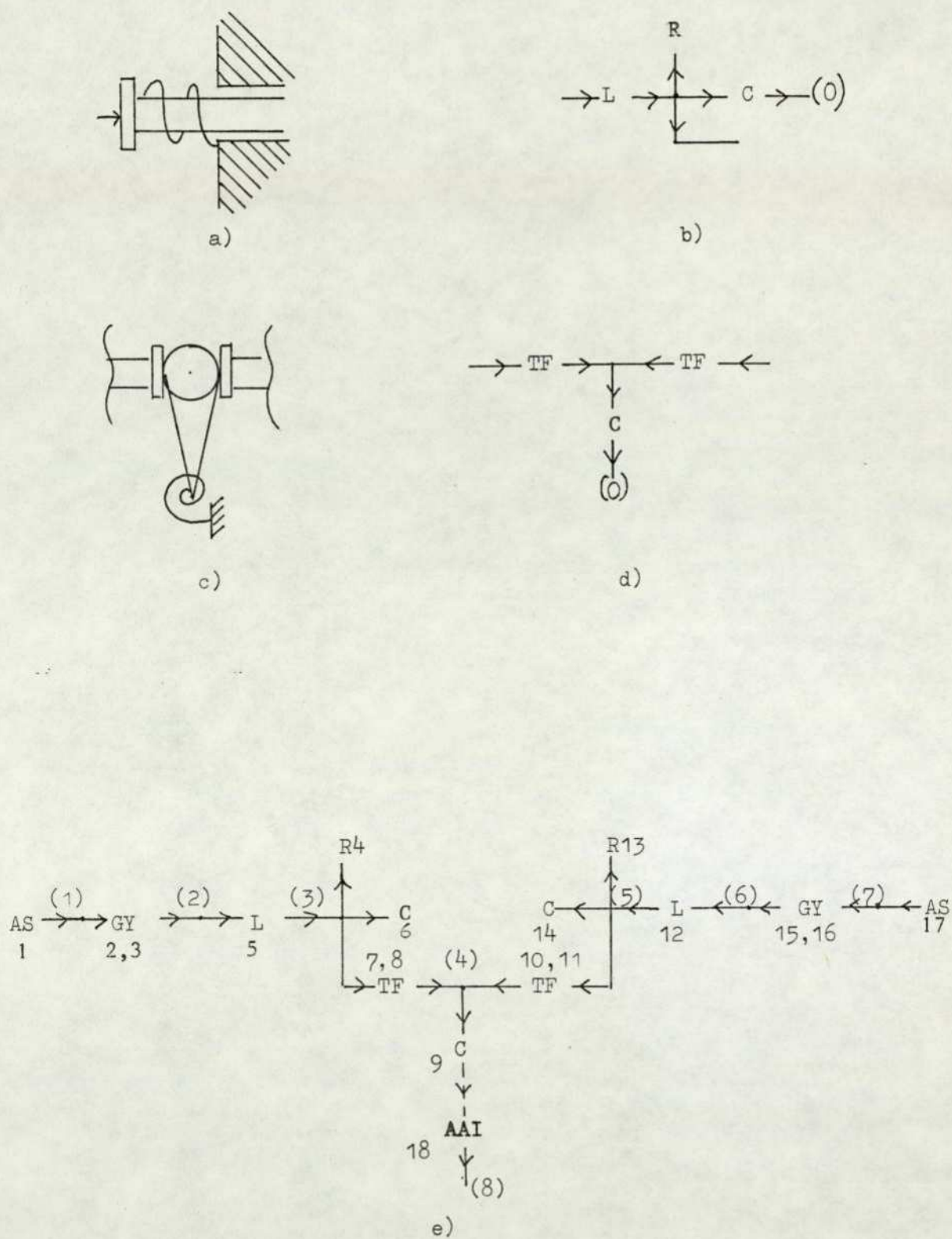
*

20dB/decade

1.000E-03
1.780E-03
3.170E-03
5.630E-03
1.000E-02
1.780E-02
3.170E-02
5.630E-02
1.000E-01
1.780E-01
3.170E-01
5.630E-01
1.000E+00
1.780E+00
3.170E+00
5.630E+00
1.000E+01
1.780E+01
3.170E+01
5.630E+01
1.000E+02
1.780E+02
3.170E+02
5.630E+02
1.000E+03

Computer Frequency Response of K.D.G. D.P. Cell

Fig 6.13



SUBSECTION AND STRUCTURE GRAPH OF BARTON D.P. CELL

Figure 6.14

capacitance. The structure graph shown in b) models the system in a direct topological fashion. The 'C' term can either go to node (0), a common reference node or not as desired. The resistance to motion is the viscous friction of the walls, and is therefore w.r.t. ground.

ii) Torque Tube Assembly

The schematic is illustrated in Fig 6.14 c). The structure graph shows directly the conversion from mechanical translation to mechanical rotation and the resultant torque being applied to the equivalent circular spring. The node here can be associated with a common angular displacement point. In practice the constraints of the language make it difficult to model the torque tube in any other way.

The resultant structure graph is shown in Fig 6.14 e). For a comparison with the other graphical techniques see Fig 3.16. In particular the bond graph representation is almost the dual of Fig 6.14 e).

A computer listing of the structure graph is given in Fig 6.15 and the time and frequency responses given in Fig 6.16 and Fig 6.17 respectively (7 divisions per range).

BART. SIM

OUTPUTS ARE: AC 18

TIME: 0.000E-01 1.000E+00 1.000E-03 PLOTTING RATE IS : 10

FREQ: 1.000E+00 1.000E+04 -1.000E+00 LOG. IS -1.0

PLOTTING IN TIME - RANGE IS : 0.000E-01 1.000E-01

PLOTTING IN FREQUENCY - RANGE IS : -1.000E+02 0.000E-01 -1

NO	ELEMENT	ARROW	NODE	CONNECT	DOM.	VALUE1	VALUE2
1	AS	TO	1	0	F	2.000E+03	0.000E-01
2	GY	FR	1	0	FM	7.470E+02	0.000E-01
3	GY	TO	2	0	MF	7.470E+02	0.000E-01
5	L	FR	2	0	M	1.050E-02	0.000E-01
5	L	TO	3				
4	R	FR	3	0	M	4.590E+00	0.000E-01
6	C	FR	3	0	M	3.680E-04	0.000E-01
7	TF	FR	3	0	MR	2.000E-02	0.000E-01
8	TF	TO	4	0	MR	2.000E-02	0.000E-01
9	C	FR	4	0	R	1.020E+00	0.000E-01
18	AAI	TO	8	9	E	1.000E+00	0.000E-01
17	AS	TO	7	0	F	2.000E+03	0.000E-01
16	GY	FR	7	0	FM	7.470E+02	0.000E-01
15	GY	TO	6	0	MF	7.470E+02	0.000E-01
14	C	FR	5	0	M	3.680E-04	0.000E-01
13	R	FR	5	0	M	4.590E+00	0.000E-01
12	L	FR	6	0	M	1.050E-02	0.000E-01
12	L	TO	5				
11	TF	FR	5	0	MR	2.000E-02	0.000E-01
10	TF	TO	4	0	MR	2.000E-02	0.000E-01

Computer Listing of Barton D.P. Cell

Fig 6.15

AC 18 = *

RANGE FROM: 0.000E-01 TO 1.000E-01

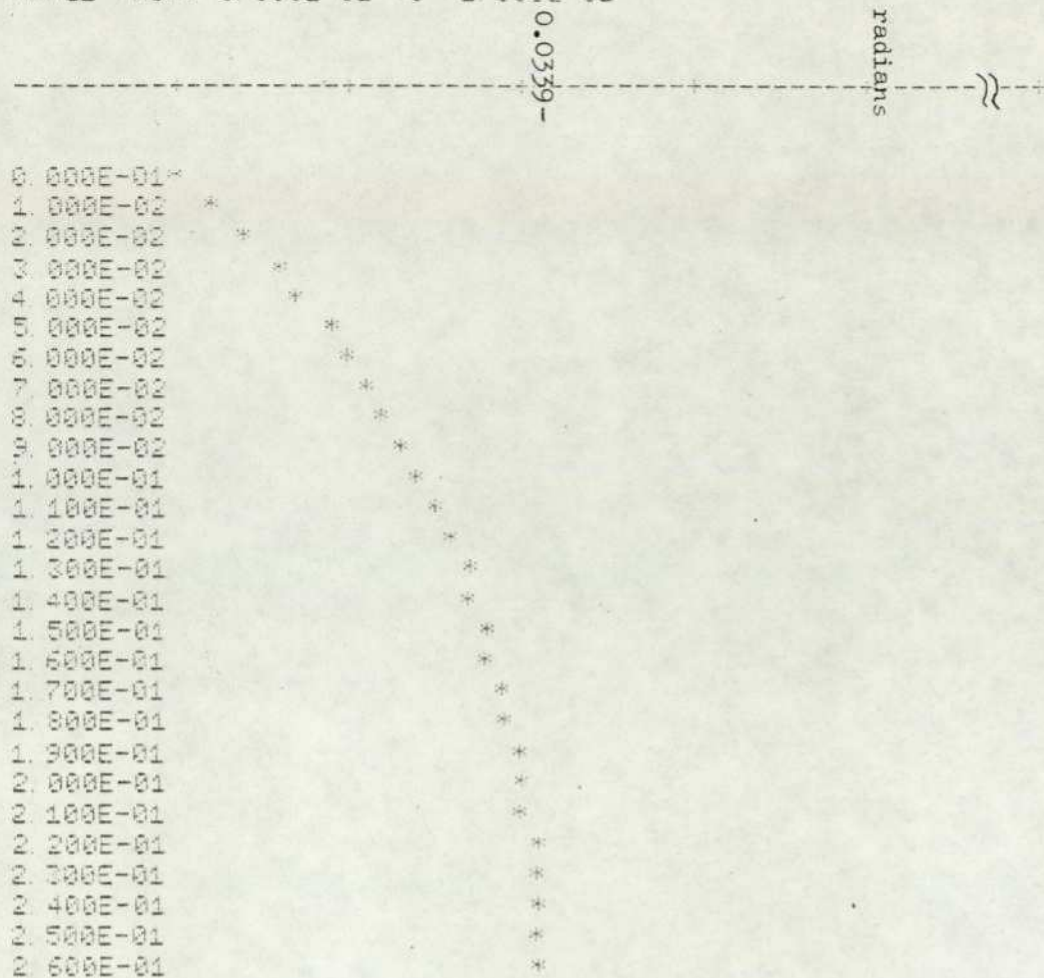


Fig 6.16

AC 18 = *

RANGE FROM: -1.000E-02 TO 0.000E-01

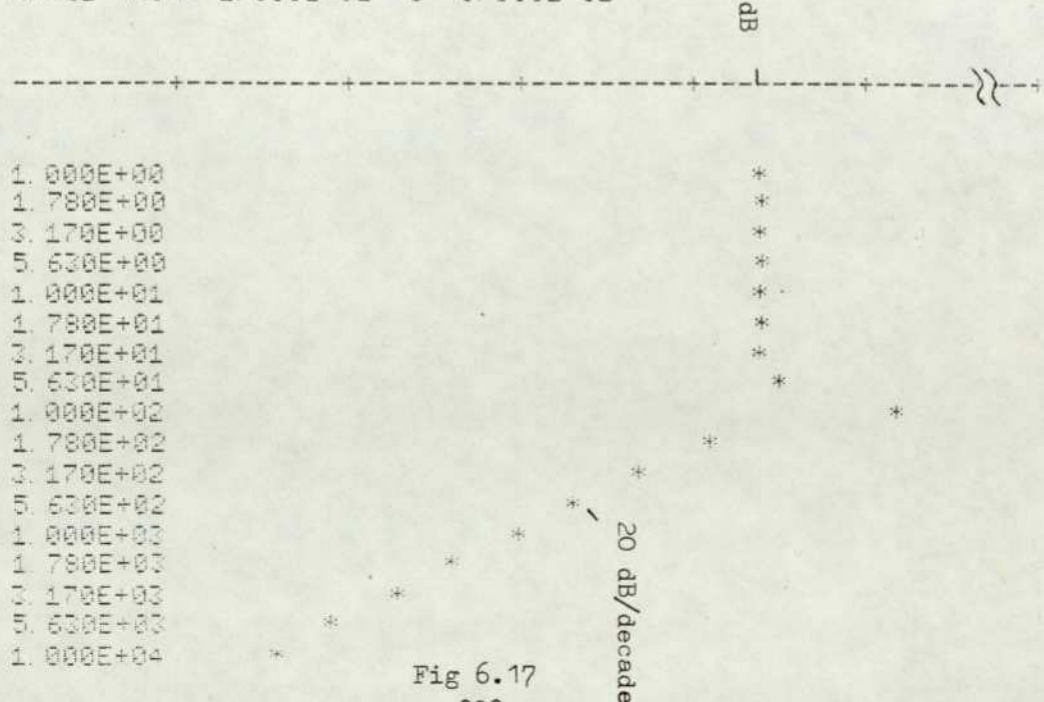


Fig 6.17

6.3.3 Negretti & Zambra Proportional Controller

Fig 6.18 describes the various sections of the Negretti & Zambra Proportional Controller. This example is the nonlinear version only.

i) Input Bellows

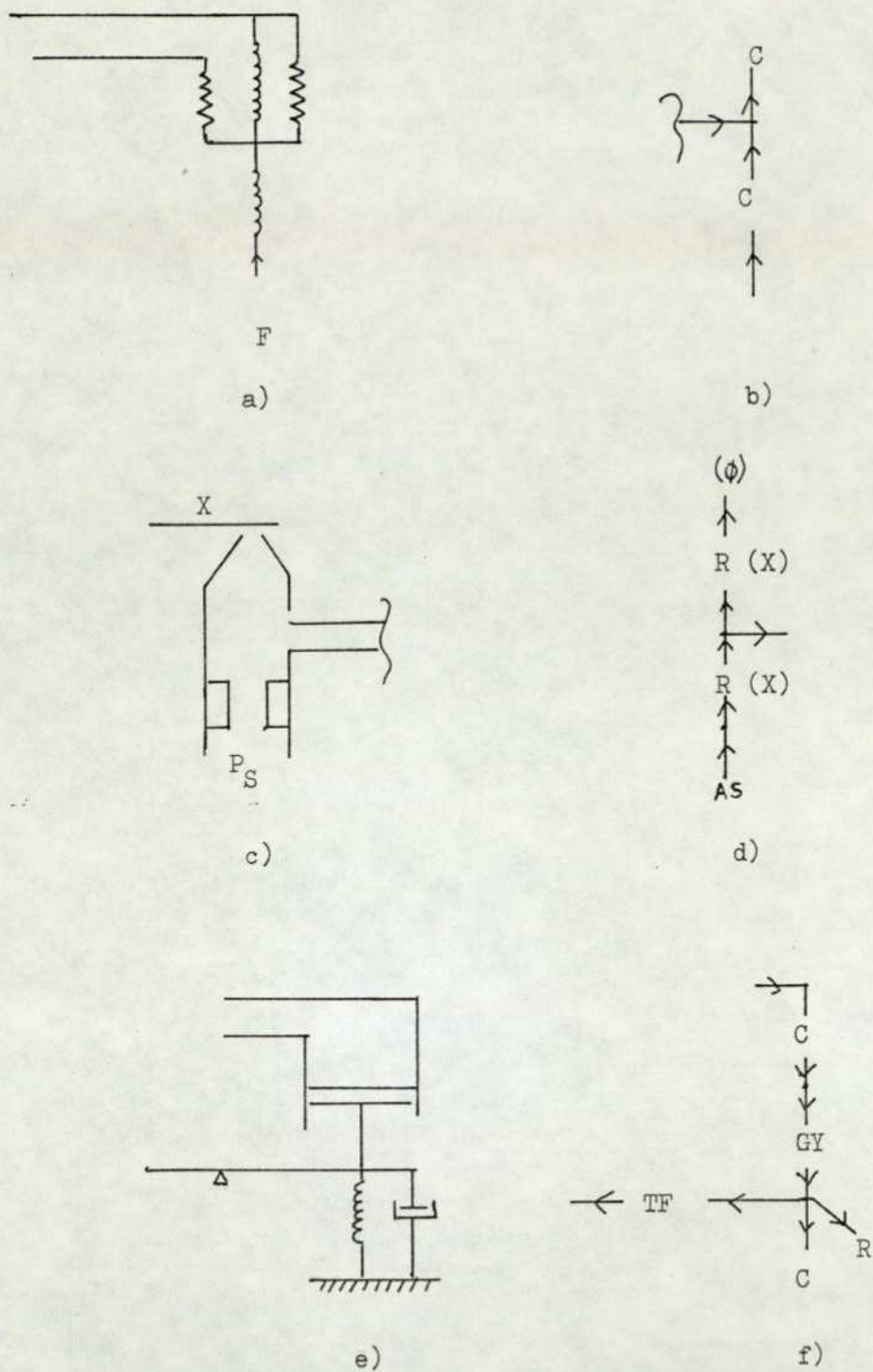
This is modelled in Fig 6.18 b). If desired an extra joining line (see section 4.3.4) can be added to make the input signal enter vertically.

ii) Flapper Nozzle

A direct correspondence of the schematic shown in Fig 6.18 c) can be drawn in d). The restrictions can be identified as nonlinear resistors dependent on displacement.

iii) Chamber and Feedback Path

The schematic of the chamber (connected to the flapper nozzle) and the feedback is illustrated in Fig 6.18 e). The structure graph is shown in Fig 6.18 f). The capacitance of the chamber can be entered as a parallel term to ground - as a common node can be associated with pressure. However from a topological viewpoint it is more convenient to represent the element connections in the manner shown.



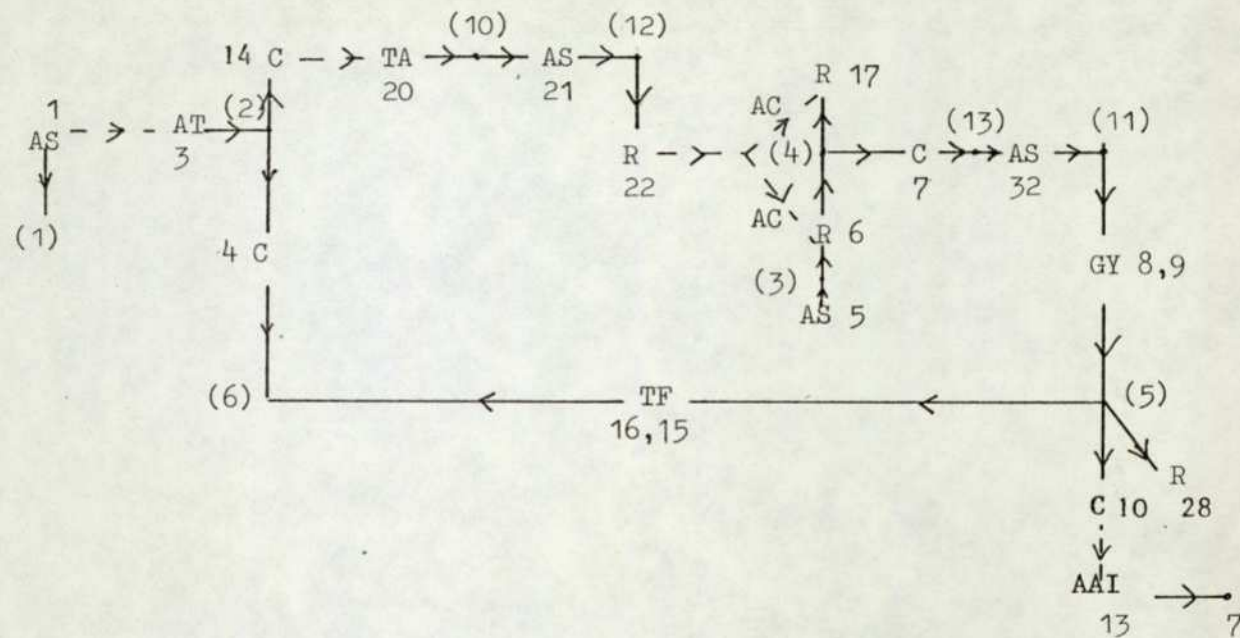
STRUCTURE GRAPH MODELS OF THE SUBSECTIONS OF A
NEGRETTI AND ZAMBRA PROPORTIONAL CONTROLLER

Figure 6.18

The resultant structure graph is shown in Fig 6.19. There are several points to be noted here. First there is a derivative of input if a normal 'GY' is used to transfer from the pressure to mechanical domain. This is because mass flow rate cannot be determined (as the rise time of the input section is zero). An appropriate message is given. However it is known that force will be applied to remove the flapper, so an 'AT' i.e. Pressure to Force gain term can be used. Alternatively a parasitic resistance can be included at node (2) for instance - but this will affect the transient response.

Various additional offset terms (Fig 6.20) are also necessary to run the controlled element model, i.e. Element 21 (Across Step) is an offset for the initial flapper displacement; element 32 has been added to offset the initial output — with no displacement of the chamber. It may be noted from the computer listing in Fig 6.20 that elements can be inserted and deleted to produce the final model.

The nonlinear response is shown in Fig 6.21 (7 divisions per range). This takes about 3 min (for the full run) on a PDP 11/10. The scale is a measure of the number of pointer divisions moved.



STRUCTURE GRAPH OF NEGRETTI AND ZAMBRA PROPORTIONAL CONTROLLER (WITH CONTROLLER RESISTORS)

Figure 6.19

PROPOPTIONAL CONTROLLER (NOT POSSIBLE TO HAVE DERIVATIVE INPUTS)

OUTPUTS ARE: AC 13

TIME: 0.000E-01 2.000E+00 1.000E-02 PLOTTING RATE IS : 1

FREQ: 0.000E-01 0.000E-01 0.000E-01 LOG. IS -1.0

PLOTTING IN TIME - RANGE IS : 0.000E-01 7.000E-01

PLOTTING IN FREQUENCY - RANGE IS : 0.000E-01 0.000E-01 0

NO	ELEMENT	ARROW	NODE	CONNECT	DOM.	VALUE1	VALUE2
1	AS	TO	1	0	F	1.000E+03	0.000E-01
3	AT	TO	2	1	FM	9.461E-04	0.000E-01
14	C	FR	2	0	M	4.880E-05	0.000E-01
4	C	FR	2	0	M	4.490E-05	0.000E-01
4	C	TO	6				
5	AS	TO	3	0	F	2.500E+05	0.000E-01
6	R	FR	3	0	F	AC 22	0.000E-01
						2.161E-05	7.067E+08
						2.245E-05	6.698E+08
						2.324E-05	6.370E+08
						2.398E-05	6.075E+08
						2.468E-05	5.806E+08
						2.535E-05	5.559E+08
						2.599E-05	5.334E+08
						2.660E-05	5.149E+08
						2.719E-05	4.951E+08
						2.776E-05	4.763E+08
						2.832E-05	4.587E+08
						2.886E-05	4.419E+08
						2.939E-05	4.259E+08
						2.991E-05	4.107E+08
						3.041E-05	3.960E+08
						3.091E-05	3.820E+08
						3.140E-05	3.686E+08
						3.188E-05	3.556E+08
						3.236E-05	3.431E+08
						3.283E-05	3.309E+08
6	R	TO	4				

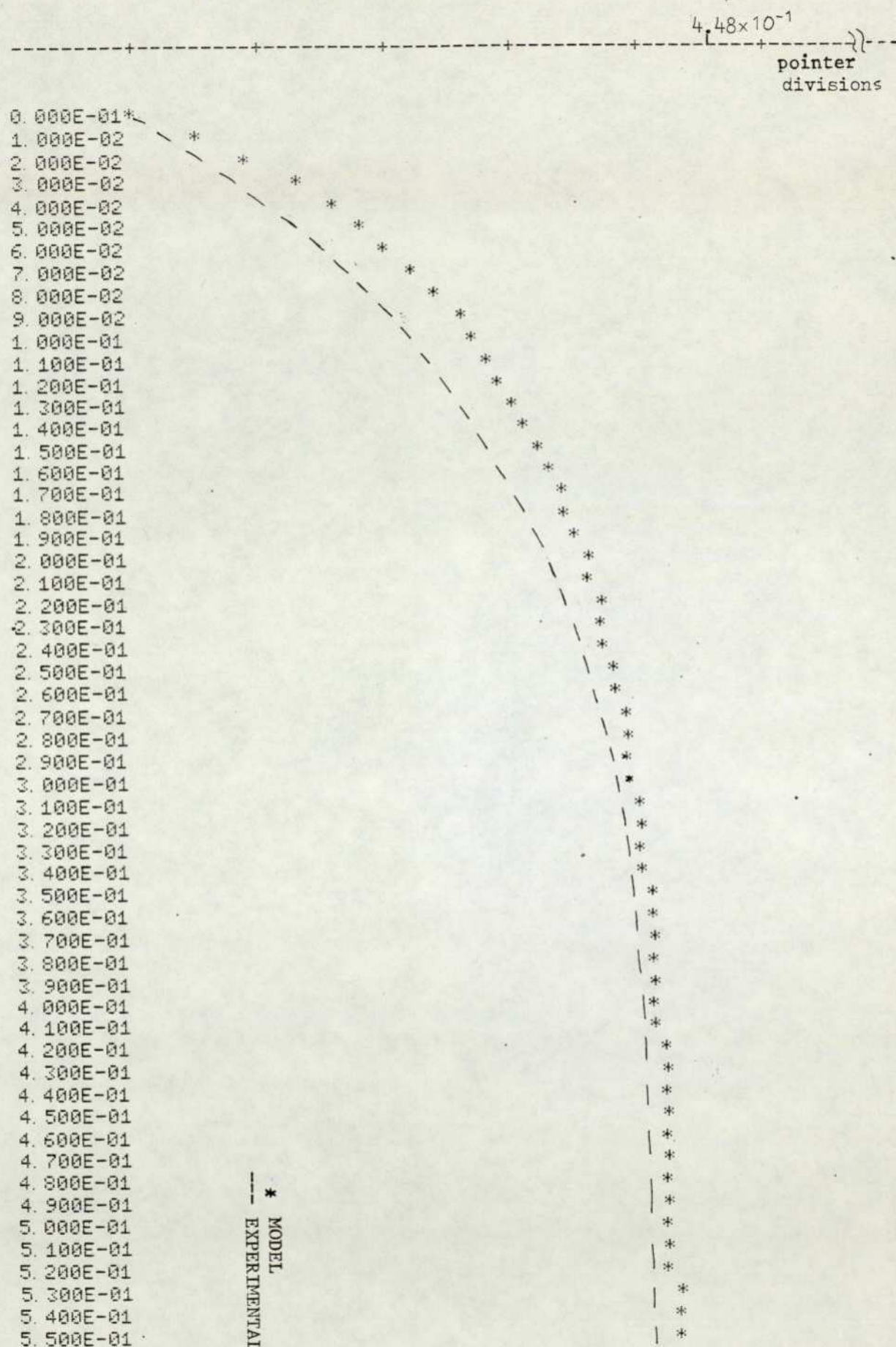
Computer Listing Of Negretti & Zambri Proportional Controller

Fig 6.20

17	R	FR	4	0	F	RC 22	0.000E-01
						2.161E-05	6.524E+08
						2.245E-05	6.384E+08
						2.324E-05	6.269E+08
						2.398E-05	6.173E+08
						2.468E-05	6.092E+08
						2.535E-05	6.022E+08
						2.599E-05	5.967E+08
						2.660E-05	5.948E+08
						2.719E-05	5.906E+08
						2.776E-05	5.869E+08
						2.832E-05	5.838E+08
						2.886E-05	5.810E+08
						2.939E-05	5.786E+08
						2.991E-05	5.765E+08
						3.041E-05	5.746E+08
						3.091E-05	5.730E+08
						3.140E-05	5.716E+08
						3.188E-05	5.704E+08
						3.236E-05	5.693E+08
						3.283E-05	5.684E+08
7	C	FR	4	0	F	6.015E-09	1.200E+05
7	C	TO	13				
32	AS	FR	13	0	M	-1.200E+05	0.000E-01
32	AS	TO	11				
8	GY	FR	11	0	FM	6.426E+01	0.000E-01
9	GY	TO	5	0	FM	9.867E+01	0.000E-01
10	C	FR	5	0	M	1.606E-05	0.000E-01
28	R	FR	5	0	M	2.000E-04	0.000E-01
15	TF	FR	5	0	MF	-1.658E+01	0.000E-01
16	TF	TO	6	0	MF	-1.658E+01	0.000E-01
20	TA	TO	10	14	E	2.035E-05	0.000E-01
21	AS	FR	10	0	E	2.161E-05	0.000E-01
21	AS	TO	12				
22	R	FR	12	0	E	1.000E+00	0.000E-01
13	ARI	TO	7	10	M	7.140E+02	0.000E-01

Fig 6.20 (Continued)

RANGE FROM: 0.000E-01 TO 7.000E-01



Time Response Of Negretti & Zambra Proportional Controller

Fig 6.21

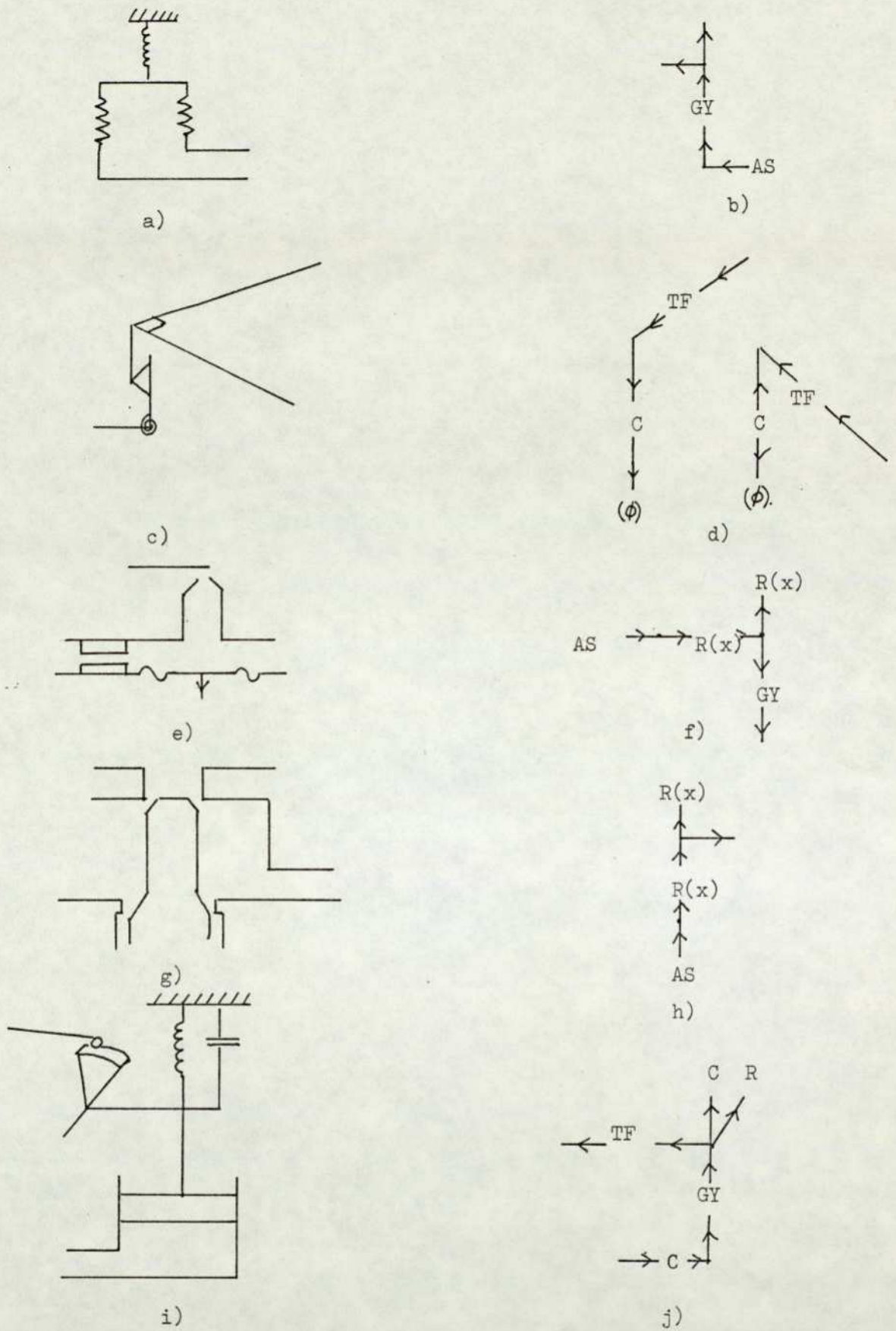
6.3.4 G.E.C. Elliot Proportional Controller

Fig 6.22 describes the sub-sections of the G.E.C. Elliot Proportional Controller. As these are similar to the previous examples they will not be discussed in as much detail. It should now be apparent that building a system using structure graphs is in many cases a direct process requiring minimal conversion from a schematic to the graphical form.

The resultant structure graph is illustrated in Fig 6.23. For this example only one side of the resistances shown in Fig 6.22 h) will be nonlinear. The mass of the plunger in h) and the fluid capacitance in e) are neglected as these are very small and simply slow down the simulation. The parasitic resistance (see Section 3.6.6) is shown as element 37. Element 21 represents the combined spring effects. The computer listing as shown in Fig 6.24 and Fig 6.25 gives the time response (7 divisions per range). This example shows the comparative ease at which a complex system can be constructed. This was certainly borne out by the difficulty of modelling this example on a computer with the more established techniques.

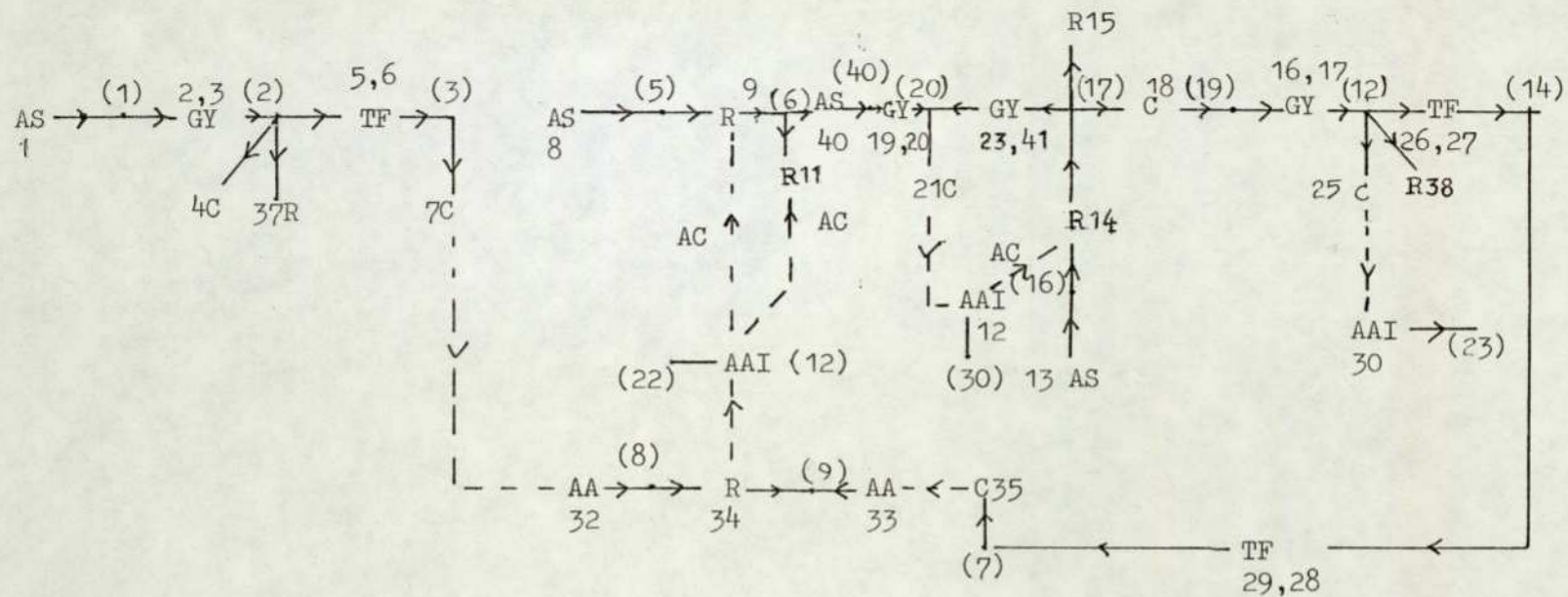
6.3.5 Pulse Cooled Thermocouple

Fig 6.26 shows the sub-sections and structure graph of the pulsed cooled thermocouple. The sections are now explained.



STRUCTURE GRAPH MODELS OF THE SUBSECTIONS OF A G.E.C. ELLIOT
PROPORTIONAL CONTROLLER

Figure 6.22



STRUCTURE GRAPH OF G.E.C. PROPORTIONAL CONTROLLER

Figure 6.23

G. E. C. PROPORTIONAL CONTROLLER

OUTPUTS ARE: AC 30

TIME: 0.000E-01 1.000E+00 1.000E-02 PLOTTING RATE IS : 2

FREQ: 0.000E-01 0.000E-01 0.000E-01 LOG. IS -1.0

PLOTTING IN TIME - RANGE IS : 0.000E-01 5.000E-04

PLOTTING IN FREQUENCY - RANGE IS : 0.000E-01 0.000E-01 0

NO	ELEMENT	ARROW	NODE	CONNECT	DOM.	VALUE1	VALUE2
1	AS	TO	1	0	F	1.000E+03	0.000E-01
2	GY	FR	1	0	FM	1.292E+03	0.000E-01
3	GY	TO	2	0	FM	1.292E+03	0.000E-01
37	R	FR	2	0	M	1.000E-03	0.000E-01
4	C	FR	2	0	M	4.762E-05	0.000E-01
5	TF	FR	2	0	MM	1.250E+01	0.000E-01
6	TF	TO	3	0	MM	1.250E+01	0.000E-01
7	C	FR	3	0	M	1.900E-04	0.000E-01
8	AS	TO	5	0	F	2.500E+05	0.000E-01
9	R	FR	5	0	F	AC 42	0.000E-01
						0.000E-01	2.819E+09
						1.427E-05	2.015E+09
						1.464E-05	2.050E+09
						1.507E-05	2.086E+09
						1.544E-05	2.122E+09
						1.588E-05	2.158E+09
						1.635E-05	2.195E+09
						1.685E-05	2.233E+09
						1.740E-05	2.271E+09
						1.798E-05	2.310E+09
						1.862E-05	2.349E+09
						1.934E-05	2.388E+09
						2.013E-05	2.428E+09
						2.102E-05	2.467E+09
						2.203E-05	2.506E+09
						2.391E-05	2.545E+09
						2.454E-05	2.584E+09
						2.613E-05	2.623E+09
						2.805E-05	2.662E+09
						3.042E-05	2.701E+09
						3.348E-05	2.741E+09
						3.761E-05	2.779E+09
						4.364E-05	2.819E+09
9	R	TO	6				

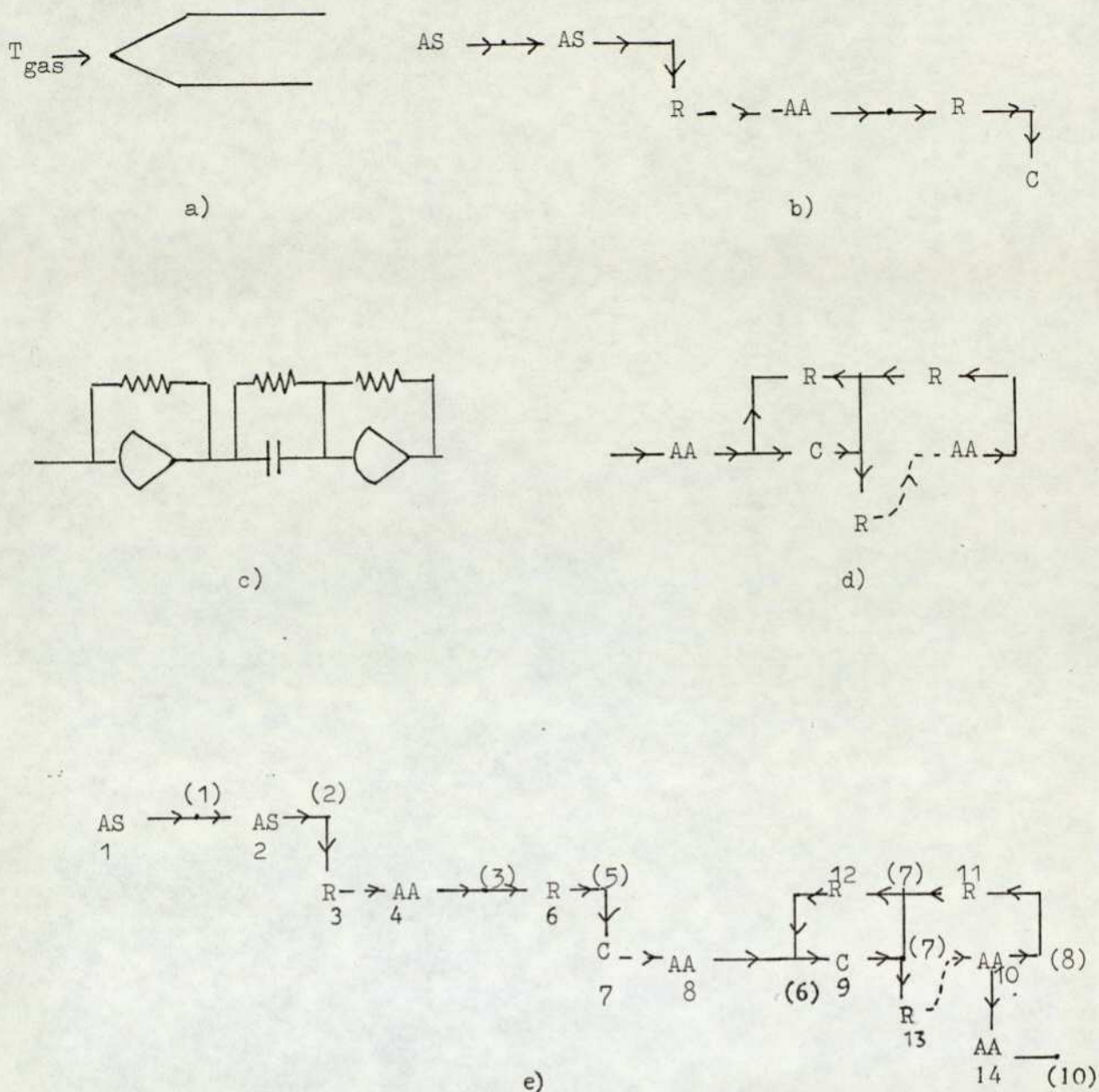
Computer Listing Of G.E.C. Elliot Proportional Controller
Fig 6.24

11	R	FR	6	0	F	AC 42	0.000E-01
						1.427E-05	2.924E+09
						1.464E-05	2.978E+09
						1.507E-05	2.833E+09
						1.544E-05	2.789E+09
						1.588E-05	2.747E+09
						1.635E-05	2.705E+09
						1.685E-05	2.705E+09
						1.739E-05	2.624E+09
						1.798E-05	2.584E+09
						1.862E-05	2.545E+09
						1.934E-05	2.506E+09
						2.013E-05	2.467E+09
						2.102E-05	2.428E+09
						2.203E-05	2.288E+09
						2.319E-05	2.349E+09
						2.454E-05	2.310E+09
						2.613E-05	2.270E+09
						2.805E-05	2.232E+09
						3.042E-05	2.193E+09
						3.348E-05	2.153E+09
						3.761E-05	2.114E+09
						4.364E-05	2.075E+09
40	AS	FR	6	0	F	-1.060E+05	0.000E-01
40	AS	TO	40				
19	GY	FR	40	0	MF	1.324E+03	0.000E-01
20	GY	TO	20	0	MF	9.457E+02	0.000E-01
21	C	FR	20	0	M	3.706E-05	0.000E-01
41	GY	FR	17	0	FM	-2.793E+03	0.000E-01
23	GY	TO	20	0	FM	-1.324E+03	0.000E-01
12	ARI	TO	30	21	E	1.000E+00	0.000E-01
13	AS	TO	16	0	F	2.500E+05	0.000E-01
14	R	FR	16	0	F	AC 12	0.000E-01
						0.000E-01	1.000E+12
						1.500E-05	4.800E+09
						2.500E-05	2.650E+09
						3.500E-05	2.000E+09
						4.500E-05	1.650E+09
						5.500E-05	1.250E+09
						6.500E-05	1.000E+09
						7.500E-05	9.000E+08
						8.500E-05	8.000E+08
14	R	TO	17				
15	R	FR	17	0	F	1.000E+12	0.000E-01
18	C	FR	17	0	F	6.756E-09	0.000E-01
18	C	TO	19				
16	GY	FR	19	0	FM	6.426E+01	0.000E-01
17	GY	TO	12	0	FM	4.867E+01	0.000E-01
25	C	FR	12	0	M	1.606E-05	0.000E-01

Fig 6.24 (Continued)

38	R	FR	12	0	M	2.000E-04	0.000E-01
26	TF	FR	12	0	FM	1.745E+01	0.000E-01
27	TF	TO	14	0	FM	1.745E+01	0.000E-01
28	TF	FR	14	0	FM	1.250E+01	0.000E-01
29	TF	TO	7	0	FM	1.250E+01	0.000E-01
35	C	FR	7	0	M	1.900E-04	0.000E-01
32	AA	TO	8	7	F	1.000E+00	0.000E-01
33	AA	TO	9	35	F	1.000E+00	0.000E-01
34	R	FR	8	0	F	1.000E+00	0.000E-01
34	R	TO	9				
42	AAI	TO	22	34	E	-1.000E+00	4.364E-05
30	AAI	TO	23	25	E	1.000E+00	0.000E-01

Fig 6.24 (Continued)



THE CONSTRUCTION AND A STRUCTURE GRAPH OF A PULSE COOLED THERMOCOUPLE

Figure 6.26

i) Thermocouple Transducer

The temperature is w.r.t. a reference. This can be accounted for by two across steps in series, one being an offset. To account for the rise time on R-C network is represented, (Fig 6.26 b).

ii) Phase Lead Network and Gain

The Phase Lead Network is modelled in Fig 6.26 d). A resistive term allows a summation of temperature.

The structure graph is shown in Fig 6.26 e) and the computer listing in Fig 6.27. An extra gain (element 14) is included in order to invert the signal. The time response is given in Fig 6.28 and the frequency response in Fig 6.29 (both 7 divisions per range). The instrument should have a zero rise time⁽³³⁾ but in practice a finite rise time is expected. The frequency response illustrates this by being in the MHz and above region.

6.4 Summary of Advantages and Limitations of Structure Graphs.

6.4.1 Advantages

i) Suitable For Multi-Energy Domain Systems

Because of the topological association provided by the generalised 'TF' and 'GY' elements a good representation of

PULSE COOLED THERMOCOUPLE

OUTPUTS ARE: AC 14

TIME: 0.000E-01 1.000E-07 1.000E-10 PLOTTING RATE IS : 10

FREQ: 1.000E+06 1.000E+10 -1.000E+00 LOG. IS -1.0

PLOTTING IN TIME - RANGE IS : 0.000E-01 1.000E-01

PLOTTING IN FREQUENCY - RANGE IS : -1.000E+02 0.000E-01 -1

NO	ELEMENT	ARROW	NODE	CONNECT	DOM.	VALUE1	VALUE2
1	AS	TO	1	0	T	1.000E+03	0.000E-01
2	AS	FR	1	0	T	-2.000E+01	0.000E-01
2	AS	TO	2				
3	R	FR	2	0	T	1.000E+00	0.000E-01
4	AA	TO	3	3	E	4.000E-05	0.000E-01
6	R	FR	3	0	E	1.000E+06	0.000E-01
6	R	TO	5				
7	C	FR	5	0	E	3.933E-07	0.000E-01
8	AA	TO	6	7	E	1.000E+00	0.000E-01
9	C	FR	6	0	E	3.930E-07	0.000E-01
9	C	TO	7				
13	R	FR	7	0	E	1.000E+08	0.000E-01
10	AA	TO	8	13	E	-1.000E+08	0.000E-01
11	R	FR	8	0	E	1.000E+06	0.000E-01
11	R	TO	7				
12	R	FR	7	0	E	1.000E+06	0.000E-01
12	R	TO	6				
14	AA	TO	10	10	E	-1.000E+00	0.000E-01

Computer Listing Of Pulse Cooled Thermocouple

Fig 6.27

AC 14 = *

RANGE FROM: 0.000E-01 TO 1.000E-01

0.38178×10^{-2}

volts

0.000E-01*

1.000E-09 *

2.000E-09 *

3.000E-09 *

4.000E-09 *

5.000E-09 *

6.000E-09 *

7.000E-09 *

8.000E-09 *

9.000E-09 *

1.000E-08 *

1.100E-08 *

1.200E-08 *

1.300E-08 *

1.400E-08 *

1.500E-08 *

1.600E-08 *

1.700E-08 *

1.800E-08 *

1.900E-08 *

2.000E-08 *

2.100E-08 *

2.200E-08 *

2.300E-08 *

2.400E-08 *

2.500E-08 *

2.600E-08 *

2.700E-08 *

2.800E-08 *

2.900E-08 *

3.000E-08 *

3.100E-08 *

3.200E-08 *

3.300E-08 *

3.400E-08 *

3.500E-08 *

3.600E-08 *

3.700E-08 *

3.800E-08 *

3.900E-08 *

4.000E-08 *

4.100E-08 *

4.200E-08 *

4.300E-08 *

4.400E-08 *

4.500E-08 *

4.600E-08 *

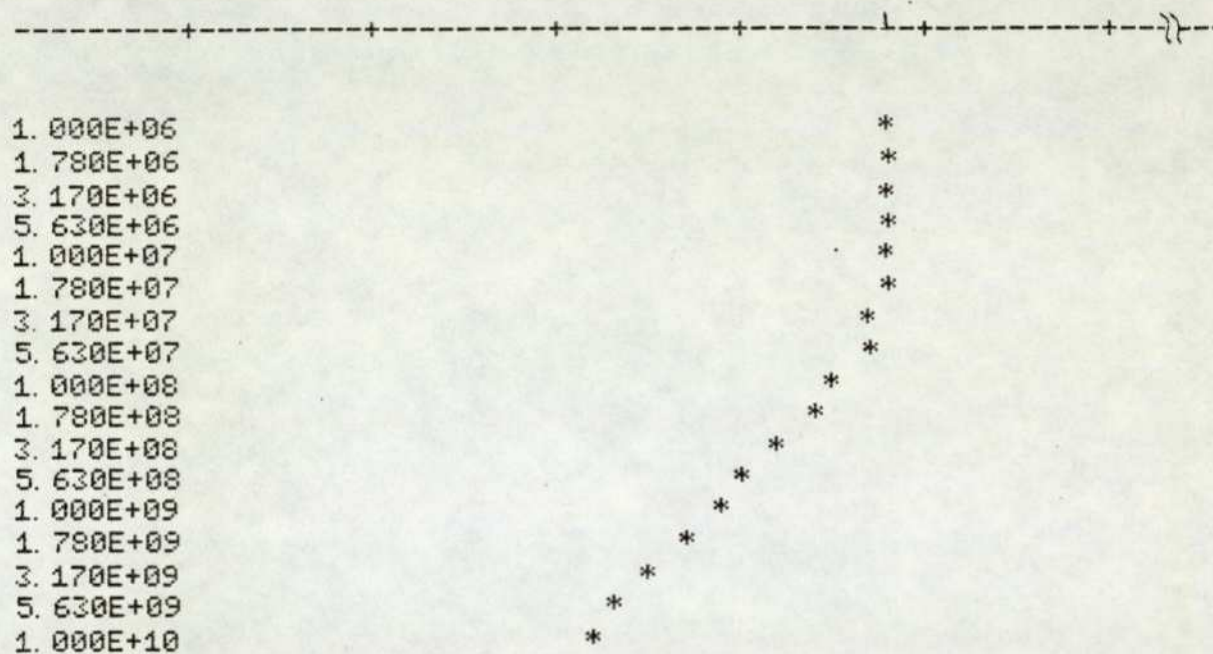
4.700E-08 *

4.800E-08 *

Time Response Of Pulse Cooled Thermocouple

AC 14 = *

RANGE FROM: -1.000E+02 TO 0.000E-01



Frequency Response Of Pulse Cooled Thermocouple

Fig 6.29

multi-energy domain systems is possible.

ii) Direct Topological representation of Lumped Parameter Schematics

In many cases the drawn schematic can be immediately encoded in the structure graph form. This allows in many cases:

- a) Ease of construction
- b) Ease of modification

providing a convenient basis for interactive analysis.

iii) Structure Independent of Causal Influences

All the causal effects will be assigned internally by the computer, and the user need not, under normal circumstances, be concerned with this aspect.

iv) State Equations Generated

The state equations once generated allow the time on response and for linear systems, the steady state and frequency response, to be found.

v) No Equations need be Formed

The fact that no equations need be formed is a direct consequence of ii). For nonlinear elements a table is constructed, for instance, thus allowing a direct representation of data obtained experimentally.

vi) Unambiguous Direction of Flow

The direction of flow is always through a component thereby allowing a fairly unambiguous assignment.

6.4.2 Disadvantages

i) Poor Description of Stability

As with all the more descriptive graphical techniques, the implicit feedback loop of the various elements and their interactions are hidden. This means that positive feedback loops, time constants of sub-systems etc can not be easily recognised.

ii) Not Possible to Directly Obtain State Equations etc

The graph can be considered as being dependent on a computer for solution. By definition a 'computer aided graph' would, if it was to be efficient to the user, perform

much of the routine decomposition to equation form. This may give the impression of remoteness to the user, whereby if the model does not give the expected answers, it is difficult - without recourse to the actual equations to know how to proceed further. In defence of this however it may be said for a complex system the equation may not provide much help to the user.

iii) Poor description of higher order coupling

This has already been mentioned in Chapter 4. For 2 or 3 dimensional mechanical problems, the schematic (with appropriate arrows and angles) gives a complete description. The structure graph on the other hand must treat each new direction on a separate basis. This will in general involve the useage of nonlinear transformers and gyrators⁽¹⁸⁾, and thereby limit except in the simplest cases, the effectiveness of the system in an interactive environment.

iv) Cannot directly model equations, Logic networks etc

A general mathematical expression would have to be considered in the form of the elements, a table of which for the MEDIEM package is given in Chapter 4. However for many problems the equation form is the most convenient to consider. Many packages allow the user to re-compile and load, so extra code can be written into the source file. This would be inconvenient with this package.

However a process of coding the equations into a primitive set would be possible and this would be partially provided by a more extensive list of elements available.

Not suitable for Development of Physical Model

This has already been stated in the introduction that the thesis is concerned with functional modelling. Component layout problems, material properties, ergonomics - all essential for a successful product, would not gain by the modelling technique described.

Physical models are more distributed in nature and are described by partial differential equations which can be solved by other techniques, such as the finite difference and finite element methods.

6.5 Conclusions

This chapter has presented a new computer package developed for the interactive functional modelling of instruments.

Comparing with Section 2.2 of Chapter 2, the essential features for model formulation and evaluations have been met. These are:-

- i) A model can be entered logically and easily - with the Structure Graph Language and built in line editor.
- ii) An interactive control language is provided with prompts for the user at each stage.
- iii) Outputs can be generated at any part of the system.
- iv) Attempts have been made to minimise delays by efficient use of data structures, sparse matrix handling techniques, special integration techniques etc.
- v) A large selection of error messages are provided.

Comparing with Section 2.3, the essential features for obtaining the performance characteristics have been met. These being:-

- i) A steady state solution (Linear Case only however).
- ii) A transient response (Linear and Nonlinear Case).
- iii) A Frequency response (Linear Case).

The program facilities allow:-

- a) Up to 50 elements - with no restriction on element numbering.

- b) Up to 50 Nodes - with no restriction on node numbering.
- c) Up to 10 Nonlinear terms - with no restriction on a controlling input.
- d) Up to 30 X-Y data pairs.
- e) Up to 5 energy domains, these being:-
 - * Electrical Systems
 - * Mechanical Translation Systems
 - * Mechanical Rotation Systems
 - * Fluid Systems
 - * Thermal Systems
- f) Up to 10 independent sources.
- g) Up to 5x5 Field size (Fields can only be Linear).

There are two modes of operation. The first allows file handling, model creation and structural change. A local mode is brought into operation as soon as the model's state equations have been formed. In this latter mode rapid changes of parameters are possible.

Automatic file protection is provided. Before any processing, the user's current model is automatically saved. This protects against either hardware (or software) faults destroying the current model. This in effect allows a user scratchpad without in any way corrupting an already working saved named file.

CHAPTER 7.

ENHANCEMENTS OF PACKAGE

7.1 Introduction

This chapter examines the enhancement of the package MEDIEM which has been developed for the PDP 11/10 Digital Equipment Corporation mini computer. This is a small machine as already mentioned with 48K core and two 8½ (single density) floppy disc drives. Consequently, although a nonlinear simulation package using structure graphs has been produced this was achieved with considerable manipulation of routines and overlay procedures. Further work as described in this chapter is really intended for a larger machine - such as the new Instrument Systems Centre Prime 550 computer recently provided by the Science Research Council.

The first area to be examined is the conversion of physical components of a system into functional input-output relationships or elements. Physical components of an instrument such as length, thickness could be encoded by either call up models discussed in Section 7.2 or by dedicated design in the instrument design variable space described in Section 7.3.

Graphical enhancement of the structure graph language is then discussed. There are problems as the language permits very general graphs to be drawn. However an approach using a sub-set is suggested and details given of how they can be implemented.

Finally the extension of the package by the addition of general purpose routines is described. The time solution phase is an obvious area of improvement as only one integration routine is currently available. However, design aids described in Chapter 2 are also mentioned particularly from the point of view of local parameter changes.

7.1 Call Up Models

The package has been designed so that linear or nonlinear relationships can be entered as parameters. However this information must be obtained by the user. It is suggested that a bank of call up models could be stored on the computer and referenced according to:-

- i) The element type.
- ii) The energy domain.

For example a spring in the mechanical translation domain could be required. Two pieces of information are necessary, these being:-

- a) A capacitance (entered for the element).
- b) The mechanical translation domain (entered for the energy domain).

Note that this information is already entered by the user in the current stage of development of the package. If

a model is now specifically developed, prompting could be given as follows.

Type in one of the following:-

- a) Cantilever spring
- b) Helical
- c) Membrane.

If say b) is chosen then the computer could then prompt.

Please give the required information on design parameters:

- i) thickness
- ii) no. of turns
- iii) type of material.

Providing a spring constant or nonlinear relationship as desired.

This would aid considerably in the formulation and subsequent modification of instrument models as a wide range of alternative designs could be immediately implemented. However it must be admitted that large number of call up models would be required for even a small number of instrument systems.

A flowchart of how this could be implemented on the present package (MEDIEM) is given in Fig 7.1. The routine PAR is described in Appendix 5. A select subroutine module (based on a symbol table preferably) and a specific parameter entering element module (such as for a helical spring) would be required.

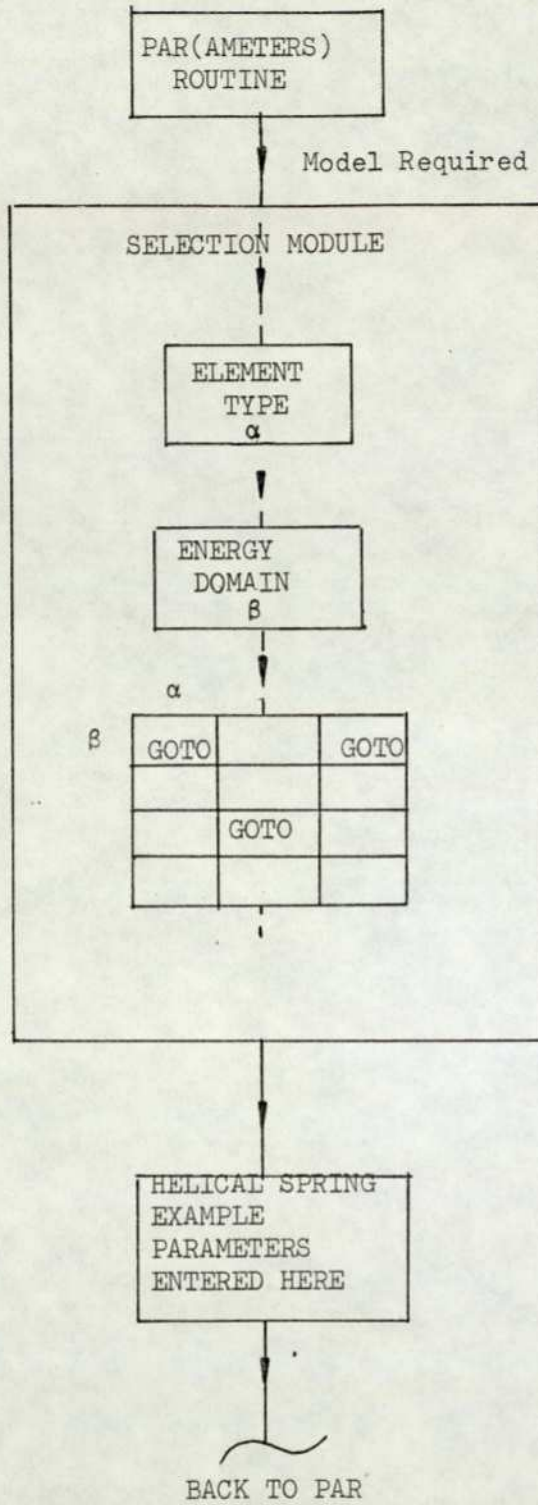
7.3 Designing in The Instrument Design Parameter Space

The foregoing approach of call up models is orientated around functional input-output relationships or elements of a system. This means:

- i) Instrument design parameters must be encoded into element relationships.
- ii) Each element (there may be more than one) that contains a specific design parameter has to be updated.

For example in the K.D.G. D.P. Cell described in Chapter 3 the user may require the following design parameters to be modified.

For the diaphragm: Vary the diameter
For the connecting tube: Vary the length.



PROCESS TO INCORPORATE CALL UP MODELS

Figure 7.1

This means that for the diaphragm equivalent model

- a) The mass
- b) The spring
- c) The damping coefficient

must all be updated. (In fact as there are two diaphragms it is likely that six elements will need to be modified).

For the connecting tube equivalent model

- 1) The resistance
- 2) The inductance

will have to be changed.

Clearly an approach that modifies directly the relevant 'elements' of a system can be highly desirable. However it must be pointed out that this is only feasible if a specific program (or package) has been developed for the instrument or class of instruments under examination.

It would not therefore be appropriate to consider this using MEDIEM. However it is possible to extract the global matrix and the addresses of the parameters. (A simple gaussian elimination of this once the parameters have been entered will produce the state equations). This information could then be utilised in a specific program orientated for a

particular instrument (assuming no structural changes). Fig 7.2 shows how this process can be implemented. (The information can be extracted from routine PUT2B as described in Appendix E).

7.4 Graphical Enhancement

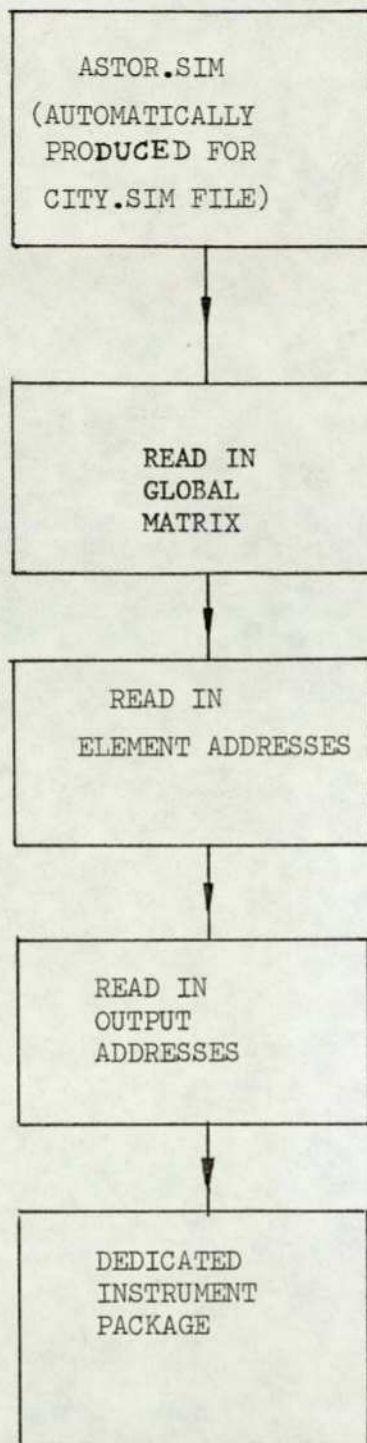
Providing graphics for the package would enable a display of the model to be generated. This has the following immediate advantages:

- a) provide visual identification
- b) reduce errors in construction.

The following will now present some ideas on how a graphic facility can be added onto the current package. For simplicity signal pickoffs and nonlinear influences will not be discussed. They present additional problems as the structure graph language is so general. (See Chapter 4 for some examples). A similar criterion applies to joining lines, i.e. a line connecting two identical nodes.

7.4.1 General Considerations

The basic requirements of a graphics package is the ability to draw a dot and straight line between two points. For structure graphs each line will have a beginning and end



FLOWCHART FOR EXTRACTING SYSTEM EQUATIONS FROM MEDIEM

Figure 7.2

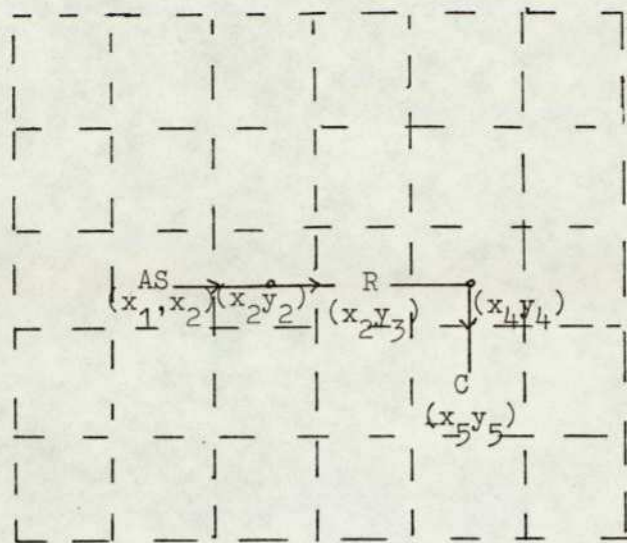
point going from either a node to an element or element to a node. Consider Fig 7.3.

A simple R-C network is shown. The placement and direction of each line can be initiated by two methods.

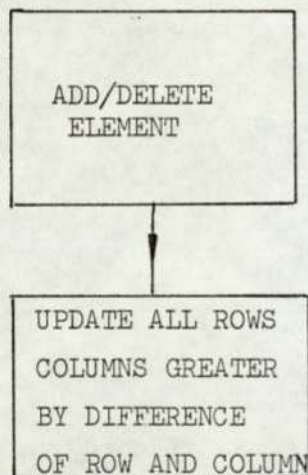
- i) Each element and each node has a pair of co-ordinates.
- ii) Each element and each node has a separate defined space or area.

The co-ordinate entry is very flexible, but suffers from fairly detailed information being requested of the user. The defined space or grid could on the other hand be numbered in some convenient manner, as well as being expanded or contracted as required by the user.

In both cases if an element is inserted in series then all the subsequent rows and columns of the elements must be updated. Clearly problems can arise, as for instance elements disappearing off the screen, or when contracting elements overlap. In general extra facilities will be required in order to either control or re-draw a particular line or segment of the graph. As the grid overlay appears to have no serious disadvantages this approach will now be considered further.

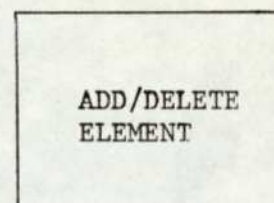


a)



SERIES

a)



PARALLEL

b)

A POSSIBLE COMPUTER DISPLAY OF STRUCTURE GRAPHS

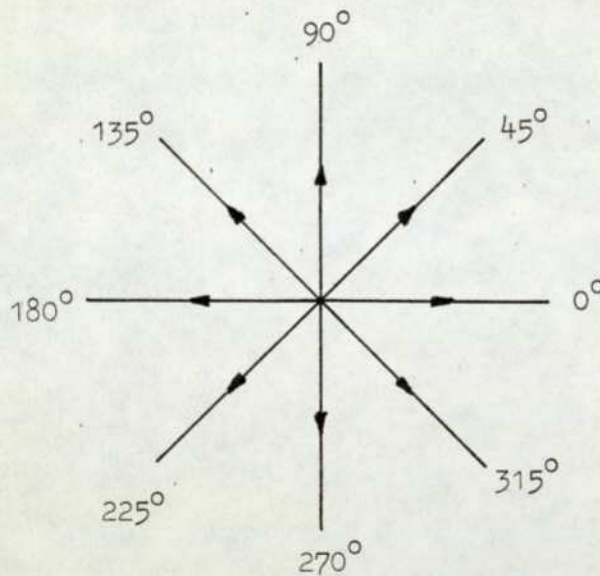
Figure 7.3

7.4.2 Suggested Approach

Using the screen grid two additional pieces of information are required.

- i) Section area
- ii) Section area/angle.

i) Has already been discussed. For ii) either another section or an angle could be generated at say 45° intervals, i.e.



This can be implemented in two ways.

- i) Supplied when the model is constructed
- ii) Added to the model at some convenient time.

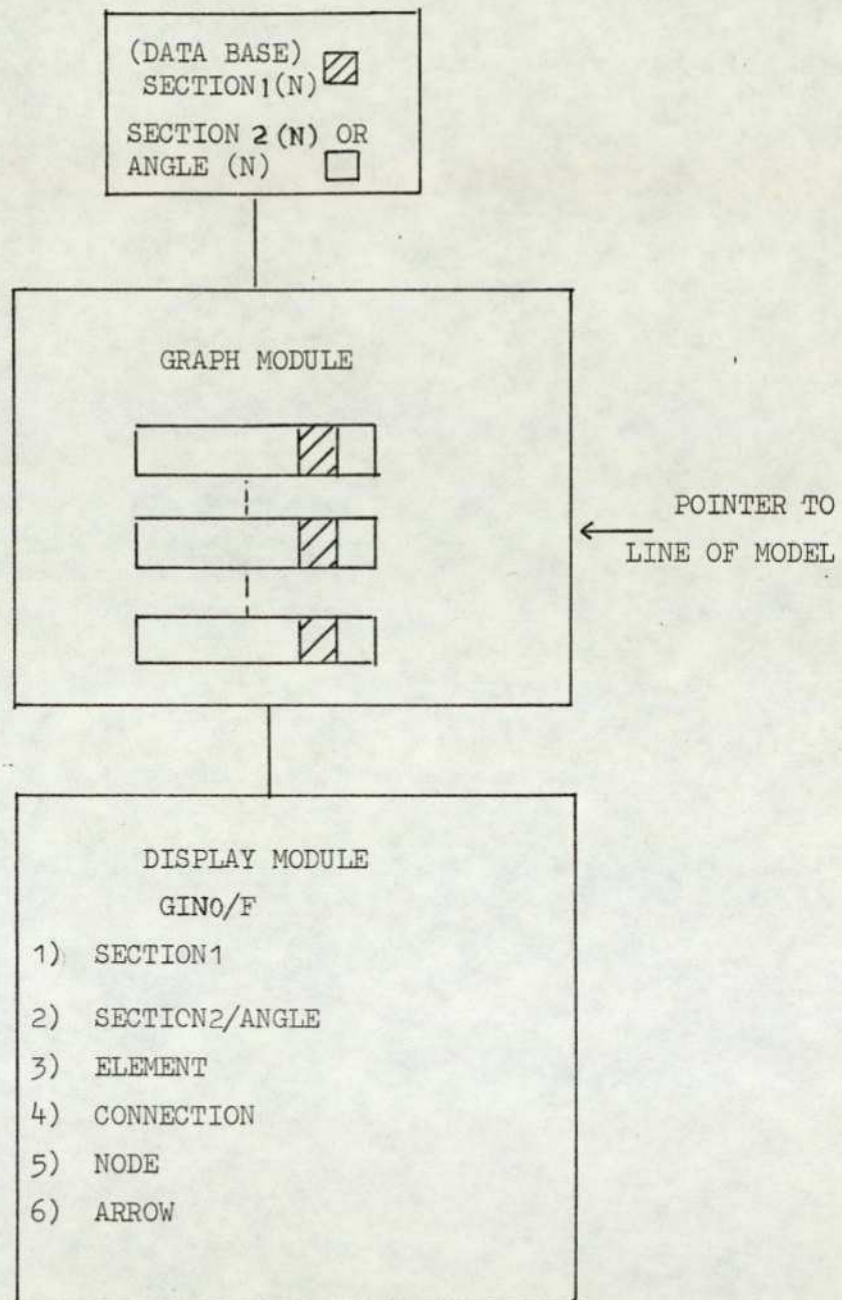
The second approach would seem the most suitable particularly as the graph may need some extra manipulation when constructed.

Fig 7.4 shows how this could be implemented using the package MEDIEM. Two more arrays are necessary to store the section and section or angle. A graph module could then simply write in for each line of input (see Chapter 4 for examples of complete lines of input) to additional information necessary for graphical enhancement.

A display module using GINO/F (for PRIME) would then construct each line of the graph in the order shown. Additional commands for correction could then be called, to correct the displayed model.

7.4.3 Input Devices

As mentioned in Chapter 2, a variety of input devices are possible, the most common being:-



FLOWCHART FOR GRAPHICAL ENHANCEMENT OF MEDIEM

Figure 7.4

- i) Keyboard
- ii) Light pen
- iii) Thumbwheels
- iv) Tablet.

i) The Keyboard entry would simply consist of feeding in numerical information for section areas or angles. Ideally the result will be displayed directly.

ii) A light pen mode of input has advantages as sections can be directly located on the screen. For angular information the direction can be displayed in one corner of the screen or as the angle information is also quantised, a rough guess made with the light pen and the picture constructed to the nearest permissible angle.

iii) Thumbwheels will have the same advantages as for light pen input. However the extra accuracy may help if any corrections are necessary.

iv) A tablet is ideal for entering the structure. (It may be possible to consider a general graphical display in this mode). However it is particularly poor if insertions or deletions are to be made as mentioned in Chapter 2.

7.5 General Purpose Additional Routines

7.5.1 Improving the time solution phase

The package at the moment only has one integration routine - a sequential euler⁽⁴¹⁾. Although this has a good performance and is especially suitable for mini computers, this cannot be considered sufficient for a more general purpose package.

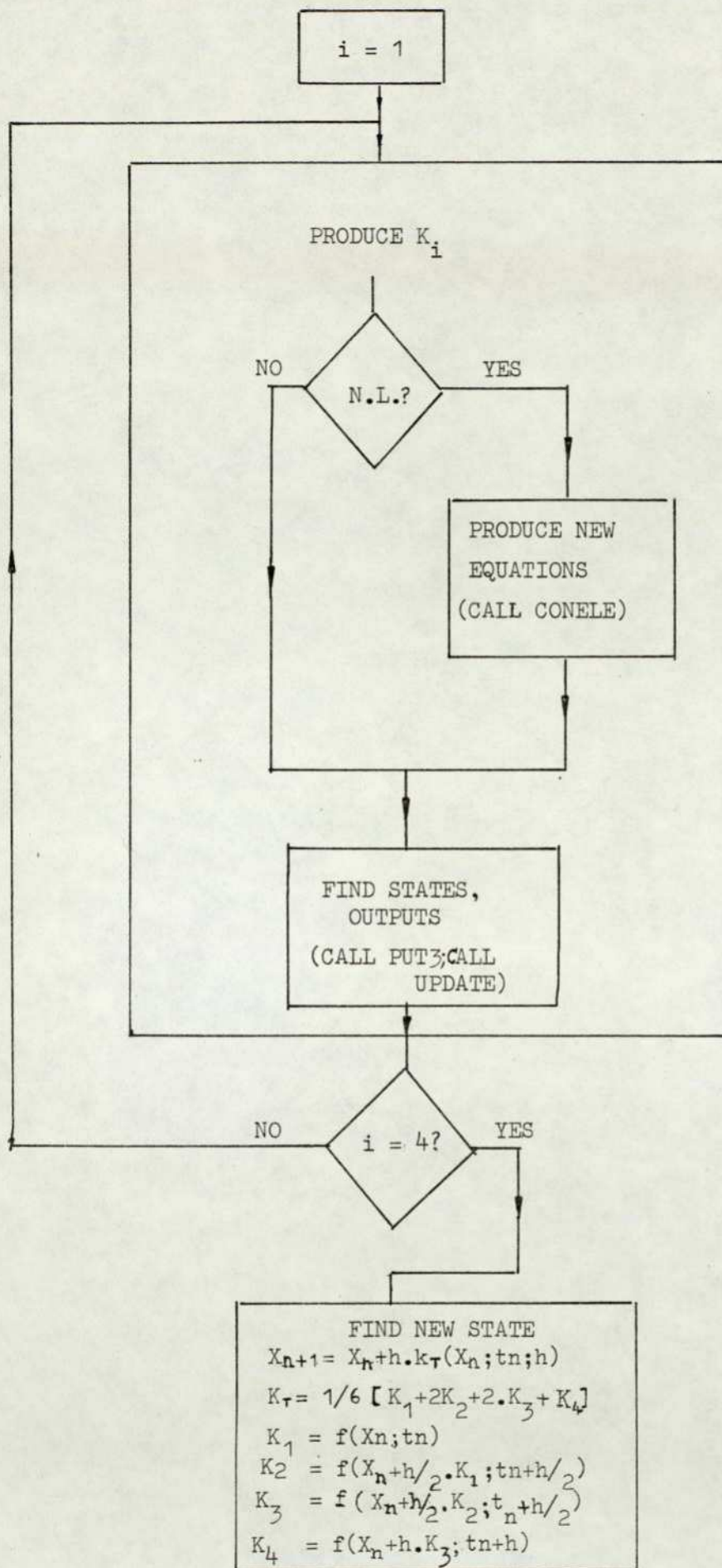
Two methods for improving the time solution phase will be discussed.

- i) Runge Kutta.
- ii) Base Two Algorithm.

i) The Runge Kutta approach is well-known and will not be discussed here. Fig 7.5 gives a flowchart of how this could be implemented on MEDIEM for a 4th order algorithm.

However, Runge Kutta is a particularly poor integration technique for stiff systems - especially if these are linear. For this case a new method is suggested for implementation.

ii) An interesting technique for solving the transient response of stiff linear systems, using a minicomputer can be found in the references⁽⁴²⁾. This uses a base two algorithm which is briefly described below.



FLOWCHART FOR IMPLEMENTATION OF 4TH ORDER RUNGE KUTTA

Fig 7.5

For a unit, step or ramp input, an augmented set (shown by '-') of state equations can be formulated, i.e.

$$\dot{\bar{x}}(t) = \bar{A}\bar{x}(t) \quad 7.1$$

$$\bar{y}(t) = \bar{K}\bar{x}(t) \quad 7.2$$

This has immediate advantages for the solution phase as a state transition matrix is all that is required.

i.e.
$$\bar{x}(t) = \exp(\bar{A}t) \cdot \bar{x}(0) \quad 7.3.$$

Assume this has been solved for a very small time interval 'h' giving

$$E1 = \exp(\bar{A}h)$$

$$\text{then } E2 = \exp(2\bar{A}h) = \exp(\bar{A}h) \times \exp(\bar{A}h) = E1 \times E1$$

$$E3 = \exp(4\bar{A}h) = \exp(2\bar{A}h) \times \exp(2\bar{A}h) = E2 \times E2$$

and so on.

Hence a solution proceeding along the time axis in a modulo 2 manner can be directly found. For a stiff system this will drastically reduce the computation time. For example if a time interval of 1×10^{-20} is selected for 20

seconds then 2×10^{21} computational steps are normally required. However for a base two algorithm

$$\text{No. of steps} = \frac{\log_2 2 \times 10^{21}}{\log_2 2} = 71 \quad 7.4$$

In order to refine the results, especially in the latter stages of the simulation, different initial step sizes can be used, i.e. 0.5×10^{20} , etc.

The package was originally envisaged to incorporate this routine, and consequently only impulses, steps and ramps were included as independent inputs. However memory limitation precluded its development.

As a fair amount of work would be necessary to include this algorithm no flowcharts are given. In general there are two main areas:

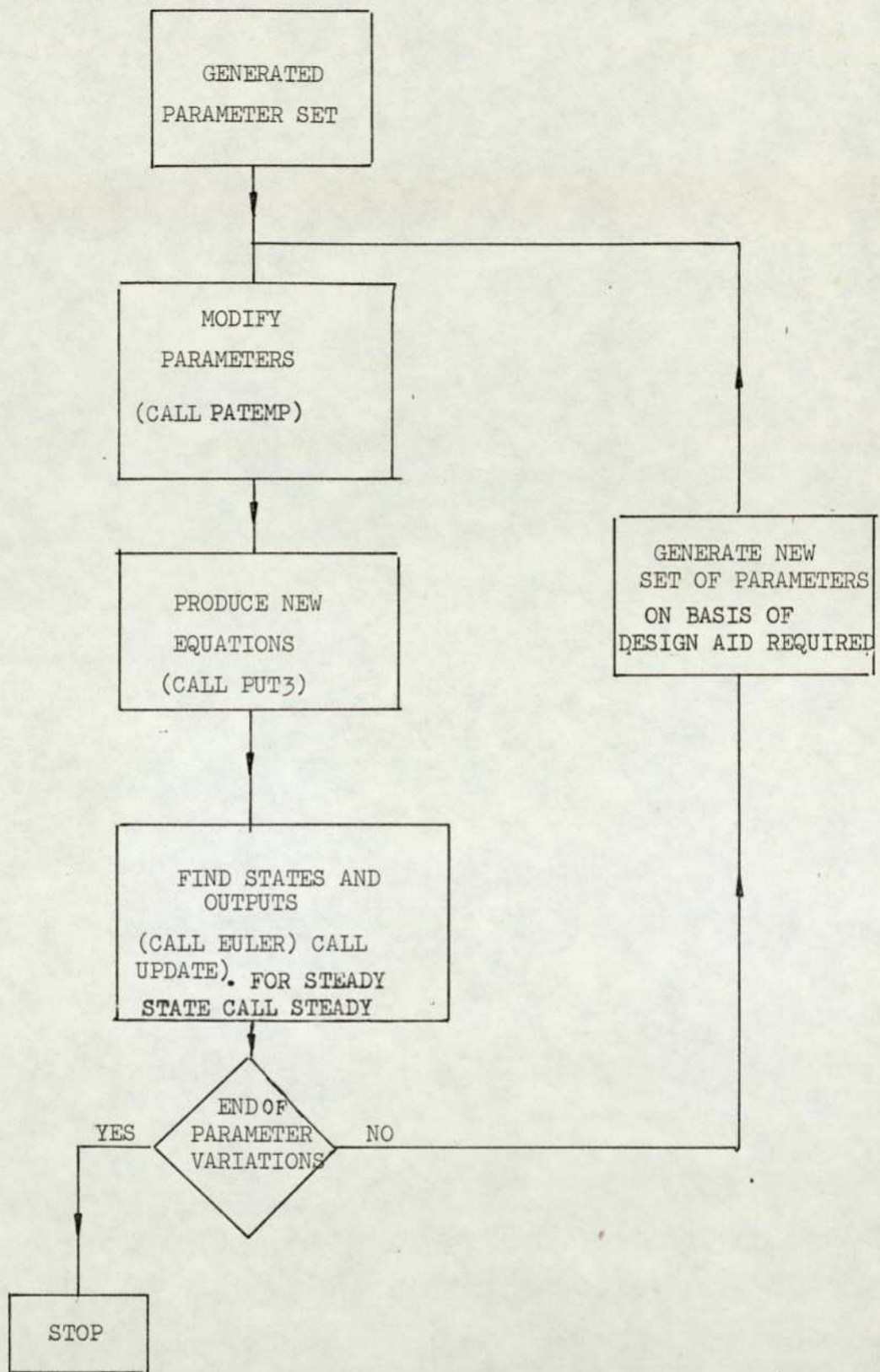
- a) Matrix manipulation and organisation of state equations and generation of a numerical solution for $\exp(\bar{A}h)$
- b) Extra user control over the simulation.

7.5.2 Parameter Design Aids

In general all of the design aids specified in Chapter 2 can be implemented. In particular:-

- i) Sensitivity Analysis
- ii) Monte Carlo Simulation
- iii) Optimization Routines,

are areas where improvement in the design of instrument systems can be made. In all of these cases it is expected that structural changes will not be required. Therefore use can be made of the local mode facility. A general flowchart of how parameter modifications can be made is shown in Fig 7.6. Control over the generation of new parameter sets will, in the case of optimization routines, be dependent on the output generated from the state equations.



GENERAL PARAMETER MODIFICATION ROUTINE

Figure 7.6

CHAPTER 8

CONCLUSION

8. Conclusion

This thesis has been concerned with the interactive functional or lumped parameter modelling of instruments. A computer package has been developed that:-

- i) Models multi-energy domain systems in a new manner.
- ii) Produces computer responses suitable for analysis by the instrument engineer.

In this way the computer becomes a design tool enabling the engineer to rapidly develop and test his ideas - thereby aiding new and improved designs.

The package has been developed on a small mini (PDP 11/10) and written in the machine translatable language of FORTRAN. Therefore it is entirely practical that the package could be of use to many companies of all sizes in the instrument field. A brief summary of points i) and ii) is now given.

- i) A new language has been developed in response to the conclusions of Chapter 3. In this chapter five instruments were modelled using signal flow graphs, bond graphs and linear graphs but no technique was found to be entirely suitable. In particular they have all been developed such that the equations of a system can be obtained by hand, once

the graph has been constructed. However this is unnecessary if a computer is to be used as the equation formulation part can be automated. Indeed providing a logical sequence can be determined for obtaining the system equations, any graphical format can be developed!

Given this freedom of the graphical format the main constraint can be decided on the necessary information flow. In analysing a schematic certain features are apparent, and are encoded into a graphical format.

- a) Element Type
- b) Element Connection(s)
- c) Energy Domain
- d) Assumed Direction of Flow of Variables
- e) Element Value(s).

This information is necessary and sufficient for modelling a general multi-energy domain system.

The developed language called 'Structure Graphs' attempts to minimise the effort required to translate this information into the computer. It is defined and its rules of construction with examples are given in the text. In essence, a close topological representation of the schematic is realised (for basically undirectional systems) enabling ease of construction and modification of the user's model.

ii) The instrument engineer requires three basic responses in order to conveniently analyse a system.

- a) Transient Response
- b) Steady State
- c) Frequency Response.

With these responses it is then possible to determine a wide range of instrument performance characteristics.

In order to obtain the responses, a state variable formulation was utilised. Chapter 5 gives details of how the 'computer aided graph', 'structure graphs' can be decomposed into state variable form. It is clear that this is not suitable for manipulation by hand.

From the theory of Chapter 5 a computer package was developed. This will:-

- * Model up to 50 elements
- * Model up to 10 nonlinearities (single input-output relationship)
- * Model up to 5 ports (Fields can only be linear)
- * Built-in editor for ease of insertion and deletion of lines
- * Efficient manipulation of sparse matrices
- * Local mode for parameter changes
- * Built-in protection of user's current model.

In order to determine the validity of the developed package, five instruments (described in Chapter 3) were simulated. A detailed description of the construction of these models and results via use of the package were given in Chapter 6.

Although this package has been developed from the requirements of instrument systems, it is not limited to this field. The modelling of process control systems, biological systems, electronic networks etc, are possible alternative uses. This is particularly the case if interactive environments are envisaged.

A chapter was devoted to enhancements, as there are many possible avenues along which further work could proceed. In particular there are two distinct directions that can be taken, these being:-

- a) Enhancement of the general modelling and design capabilities of the package.
- b) Dedicated packages being built to handle specific areas of instrument design and evaluations.

For a) graphical displays of the model, improvement in integration routines, optimization etc., as well as 'call up' models (i.e. subroutines to help determine values from physical components) are relevant areas of interest.

For b) the direct manipulation of the state equations originating from changes of instrument design variables (i.e. length of connecting tube, discharge coefficients etc) will allow an efficient platform to analyse in detail specific types of instrument systems.

APPENDICES

Appendix A

Determination of Parameters For The Barton D.P. Cell (1 5/8")

Bellows and Assembly

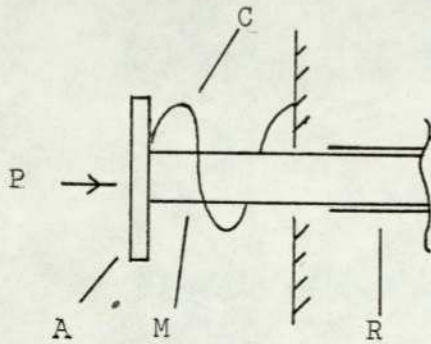


Fig A.1

This can be represented as

$$F = P.A \quad A.1$$

$$F = L.\ddot{x} + R.\dot{x} + k.x \quad A.2$$

where F is the applied force.

Each one of these terms can be found either from manufacturer's data or experiment.

Assuming a flat plate $A = 1.338 \times 10^{-3} \text{ m}^2$.

The mass can be determined from geometrical considerations and liquid densities etc.

This is found to be $1.0542 \times 10^{-2} \text{ Kg}$

The Spring rates determine the range over which the instrument works. There are two here to consider. In this case a 1.5/8" bellow and the smallest range (0-30 in $\text{H}_2\text{O} = 31 \text{ N/m}^2$) is chosen.

The Bellow rate is $1.2613 \times 10^3 \text{ N/m}$

The Spring rate is $1.454 \times 10^3 \text{ N/m}$.

Giving an overall value of C of $3.6828 \times 10^{-4} \text{ m/N}$.

The value of R can be determined from Massey⁽⁴³⁾.

$$R = \frac{3}{4} \cdot \pi \cdot \xi \cdot l \cdot (D/c)^3$$

A3

$$\xi = 1.1 \times 10^{-3} \text{ Pa.s}$$

$$D = 7.46 \times 10^{-3} \text{ m}$$

$$c = 3.9 \times 10^{-4} \text{ m}$$

$$l = 12 \times 10^{-3} \text{ m}$$

Substituting these values gives

$$R = 2.18 \times 10^{-1} \text{ N sec/m}$$

Torque Tube

$$l = 20 \text{ mm}$$

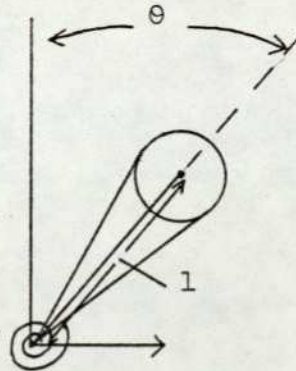


Fig A.2

The Torque tube ratings from the manufacturer are given in the translational domain. It is necessary to convert this by the relationship

$$C_{TT} = \frac{1}{\text{Torque Tube Rate}} \times \frac{1}{l^2} \quad (\text{as } \theta \text{ is small})$$

giving a value of $1.019\text{N}^{-1}\text{m}^{-1}$ for the 1.5 p.s.i. (pounds per square inch) manufacturer range.

As the system is considered symmetrical the rest of the Barton D.P. Cell assumed corresponding values.

Appendix B

Determination of Parameters For Negretti & Zambra Proportional Controller

Input Mechanism

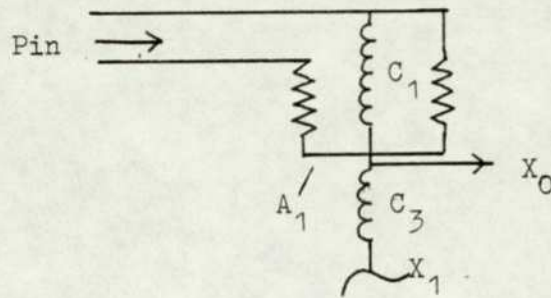


Fig B.1

By applying a pressure with the feedback lever held

$$x_o = \frac{P_{in} A_1 C_1 C_3}{(C_1 + C_3)}$$

B.1

By measurement $\Delta P_o / \Delta X_o / |X_1|$ gives 4.521×10^7 N/m

By applying a displacement at X_1 and keeping Pin constant

$$\Delta x_1 / \Delta x_0 |_{P_{in}} \text{ gives } 1.920$$

$$\& X_o = X_1 C_1 / (C_1 + C_3)$$

B. 2

Hence with a measured value of 0.449×10^{-4} for C_3

$$C_1 = 0.488 \times 10^{-4} \text{ m/N}$$

Resubstituting C_1 & C_3 into B1 gives A_1

Flapper Nozzle Arrangement

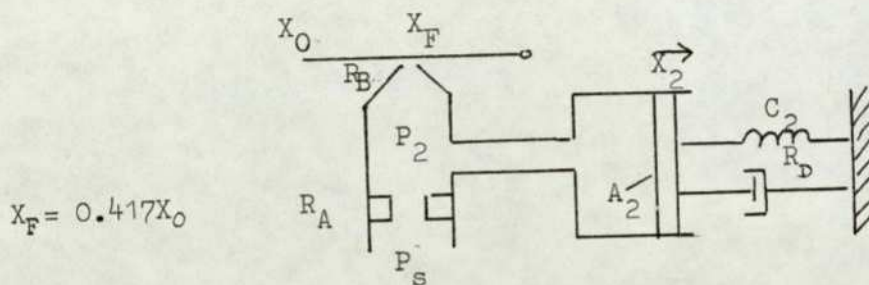


Fig B.2

$$R_D = 3/4 \cdot \pi \zeta \cdot l (D/C)^3 \quad (43) \quad \text{Nsec/m}$$

$$\zeta = \text{viscosity} = 7.2 \times 10^{-1} \quad \text{Pa. s}$$

$$l = \text{length} = 30 \times 10^{-3} \quad \text{m}$$

$$D = \text{diameter} = 6 \times 10^{-3} \quad \text{m}$$

$$c = \text{annular gap} = 0.1310^{-3} \quad \text{m}$$

A simplified diagram above presents the problem. From Zalmanson⁽⁴⁷⁾ the equation for a pressure change in the nozzle can be written

$$P_S - P_2 = R_A \cdot G_A$$

$$P_2 - P_{ATM} = R_B \cdot G_B \quad (P_{ATM} = \text{atmospheric pressure})$$

where R_A = the restriction resistance term between P_S and P_2

$$R_A = \frac{P_S - P_2}{A_A \sqrt{\frac{2g \cdot P_S^2}{RT} \cdot \frac{k}{k-1} \left[\left(\frac{P_2}{P_S} \right)^{2/k} - \left(\frac{P_2}{P_S} \right)^{\frac{k+1}{k}} \right]}} \quad k = 1.4$$

at $P_2/P_S < 0.53$ (i.e. super critical) $T = 20^\circ\text{C}:-$

$$R_A = \frac{P_S - P_2}{A_A \sqrt{\frac{2g \cdot P_S^2}{RT} \cdot \frac{k}{k+1} \left(\frac{2}{k+1} \right)^{2/(k-1)}}} \quad \text{B.3}$$

For R_B = the restriction term between P_2 and P_{ATM} (i.e. the flapper nozzle outlet term):-

$$R_B = \frac{P_2}{A_B \sqrt{\frac{2g}{RT} \cdot P_2^2 \cdot \frac{k}{k-1} \cdot \left[(P_3/P_2)^{2/k} - (P_3/P_2)^{(k+1)/k} \right]}}$$

at $P_{ATM}/P_2 < 0.53$:-

$$R_B = \frac{P_2}{A_B \sqrt{\frac{2g}{RT} P_2^2 \frac{k}{k+1} \left(\frac{2}{k+1} \right)^{2/(k-1)}}} \quad B.4$$

There is also a capacitance associated with the chamber.
Using a perfect gas law:

$$\frac{dm}{dt} = \frac{1}{RT} [\dot{P}_2 V + \dot{V} \cdot P_2] \quad B.5$$

Now $\dot{V} = A_2 \cdot \dot{X}_2$ and $\dot{X}_2 = \dot{P}_2 A_2 C_2$ (assuming forward motion - the feedback path is negligible).

This gives

$$\frac{dm}{dt} = \frac{\dot{P}_2 [V_0 + A_2^2 C_2 P_2]}{RT} ; V_0 = \text{initial volume of chamber} \\ = V_{01} + (P_2 - 1.2 \times 10^{+5}) \times A_2^2 C_2$$

$$C_{CHAM} = \frac{(V_0 + A_2^2 \cdot C_2 P_2)}{8.3979 \cdot 9 \times 10^4}$$

$$A_2 = 15.567 \times 10^{-3} \text{ m}^2; C_2 = 16.057 \times 10^{-6} \text{ m/N}; \text{ initial } V_0 = 3.875 \times 10^{-5} = V_{01}.$$

There are two ways to approach the problem. Either the full expression can be used in a nonlinear simulation or some linearization around an opening region of interest can be considered.

To carry out these calculations it is first necessary to consider the flapper nozzle assembly in more detail.

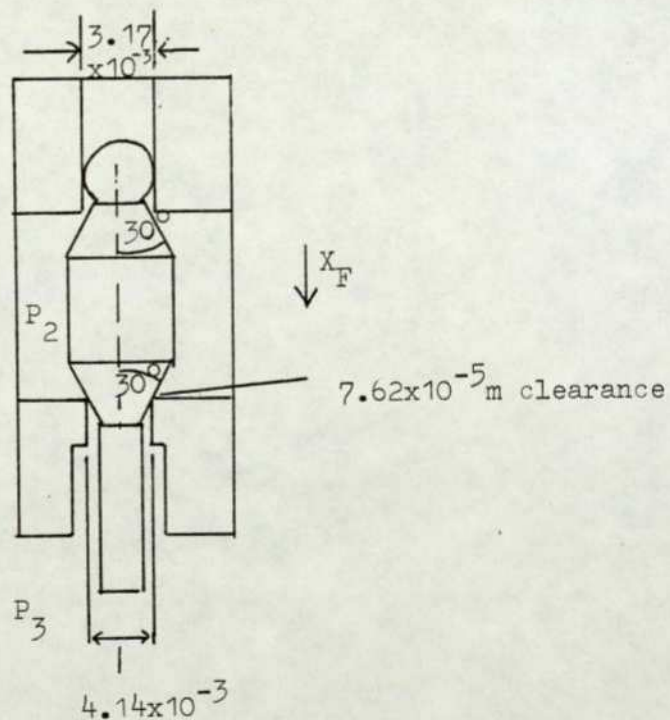


Fig B.3

Geometry of poppet and holder

Fig B.3 shows the specific geometry of the poppet and holder.

From Andersen⁽³¹⁾ the flow area for small strokes is

$$A = \pi . d . \sin \theta X \text{ (where } d \text{ is the diameter of the seat)} \quad \text{B.6}$$

θ is the poppet angle (30°).

As well as this a discharge coefficient must be found, before the effective area in the previous equations can be utilised.

From Andersen the coefficients used were

$$C_{12} = -0.2307 . (P_2/P_1) + 1.03228 .$$

$$C_{23} = -0.26 . (P_3/P_2) + 0.984 .$$

$$\text{Giving } A_A = (-0.307 (P_2/P_1) + 1.93228) \times 4.9373 \times 10^{-3} . X \quad \text{B.7}$$

$$A_B = (-0.26 (P_3/P_2) + 0.984) \times 6.4635 \times 10^{-3} \times (7.62 \times 10^{-5} - X) \quad \text{B.8}$$

These are quite general and can be used throughout the full range.

In the steady state the mass flow rate will be constant. Therefore the denominators of expressions B.3 and B.4 can be equated. The results over the full range are tabulated in Table B.1 in increments of $2 \times 10^3 \text{ N/m}^2 (P_2)$.

Digression

In this example a resistance term represents the restriction. However it cannot be assumed that the resistance is directly related to the physical extraction of the passage. As can be seen from eqn B.3 and B.4 in general

$$R = f(X, P)$$

where X is the minimum passage width,
 P is the pressure difference across the
lumped resistance
and R here represents the pressure drop per
mass flow rate.

Close inspection of Table B.1 will show that the resistance (R) is the steady state value. However these terms are used to calculate the transient response - thereby leading to an 'inherent' error in the solution as the mathematical model is not correct. In practice this approach is used extensively in the literature⁽⁴⁴⁾ as the errors will only become severe for large changes of signal.

$P_2 \times 10^5$ $X_F \times 10^{-3}$ Flow $\times 10^{-4}$ $R_A \times 10^8$ $R_B \times 10^8$ $C_{CHAM} \times 10^{-9}$

1.2	2.1610	1.8395	7.0671	6.5235	6.0159
1.22	2.2449	1.9109	6.6984	6.3844	6.2011
1.24	2.3236	1.9779	6.3704	6.2693	6.3862
1.26	2.3980	2.0412	6.9749	6.1728	6.5714
1.28	2.4683	2.1011	5.8065	6.0920	6.7566
1.30	2.5352	2.1588	5.5586	6.0219	6.9417
1.32	2.599	2.2123	5.3338	5.9666	7.1269
1.34	2.6601	2.2528	5.1491	5.9482	7.3121
1.36	2.7192	2.3028	4.9505	5.9059	7.4972
1.38	2.7764	2.3513	4.7633	5.869	7.6824
1.40	2.8319	2.3988	4.5866	5.8375	7.8676
1.42	2.8860	2.441	4.4188	5.8099	8.0527
1.44	2.9388	2.4288	4.2591	5.7859	8.2379
1.46	2.9905	2.5326	4.1065	5.7648	8.4231
1.48	3.0411	2.5755	3.9604	5.7465	8.6082
1.50	3.0908	2.6176	3.8203	5.7304	8.7934
1.52	3.1397	2.659	3.6856	5.7164	8.9786
1.54	3.1879	2.6998	3.5558	5.7041	9.1638
1.56	3.2355	2.7401	3.4305	5.6932	9.3489
1.58	3.2826	2.780	3.3094	5.6835	9.5341
1.60	3.3292	2.8194	3.1922	5.6750	9.7193
1.62	3.3754	2.8586	3.0784	5.6671	9.9044
1.64	3.4213	2.8974	2.9682	5.6602	10.090
1.66	3.467	2.9361	2.8609	5.6538	10.275
1.68	3.5125	2.9747	2.7566	5.6476	10.46
1.70	3.558	3.0132	2.655	6.6418	10.645

$P_2 \times 10^5$ $X_F \times 10^{-3}$ Flow $\times 10^{-4}$ $R_A \times 10^8$ $R_B \times 10^8$ $C_{CHAM} \times 10^{-9}$

1.72	3.6033	3.0516	2.556	5.6364	10.83
1.74	3.6847	3.1205	2.4355	5.5760	11.015
1.76	3.6942	3.1286	2.3653	5.6255	11.201
1.78	3.7397	3.1671	2.2734	5.6203	11.386
1.80	3.7855	3.2059	2.1835	5.6146	11.571

Table B.1

Ex:

Considering the region around $1.2 \times 10^5 \text{ N/m}^2$ (P_2).

This gives $\delta P_2 / \delta X_F = 2.3557 \times 10^9 \text{ N/m}^3$

Also $R_A // R_B = 3.3922 \times 10^8 \text{ N sec (Kg-m}^2)$

Giving $\tau = R_A // R_B \times C_{CHAM} = 2.041 \text{ secs}$

The concept of gain now appears to have disappeared. However this is not quite true. From network theorems⁽⁴⁵⁾ it can be shown that a change in resistance is equivalent to keeping that resistance constant and placing a generator in series with it (corresponding to the changed across variable that must accompany the result). Hence a varying resistor can be decomposed into a constant resistance and gain.

In more general terms a gain element is a useful feature in a graphical language. This is amply demonstrated in the bond graph language where 'activated' bonds (i.e. one variable expressed) are commonly employed.

Feedback Lever

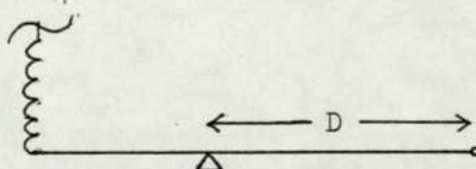


Fig B.4

The feedback gain can be varied according to the relationship

$$F_G = \frac{0.71176x(D-59)}{D-5} \quad \text{B.9}$$

D is set at 64 mm for the case simulated.

Collecting all of the data together (for the linearized version) (and operating at 20°C)

$$\begin{aligned} C_1 &= 0.488 \times 10^{-4} \text{ m/N} \\ A_1 &= 0.94592 \times 10^{-3} \text{ m}^2 \\ C_2 &= 16.057 \times 10^{-6} \text{ m/N} \\ R_D &= 5 \times 10^3 \text{ N sec/m} \\ A_2 &= 15.56 \times 10^{-3} \text{ m}^2 \\ C_3 &= 0.449 \times 10^{-4} \text{ m/N} \\ R_A // R_B &= 3.922 \times 10^8 \text{ N-sec/(Kg-m}^2) \quad @ \quad 1.2 \times 10^5 \text{ for } P_2 \\ C_{CHAM} &= 6.0154 \times 10^{-9} \text{ Kg-m}^2/\text{N} \quad V_O = 3.875 \times 10^{-5} \text{ m}^3 \\ \delta P_2 / \delta X_F &= 2.3557 \times 10^9 \text{ N/m}^3 \quad @ \quad 1.2 \times 10^5 \text{ for } P_2 \\ F_G &= 60.32 \times 10^{-3} \\ P_S &= 2.5 \times 10^5 \text{ Pa} \\ P_{ATM} &= 1.0 \times 10^5 \text{ Pa} \end{aligned}$$

A pickoff point with gain of 714.0 was used.

For different operating points new values of $\delta P_2 / \delta X_F$ and must be found.

Or alternatively from Table B.1 a full nonlinear simulation could be considered with:

$$R_A = f_A (X_F) \quad B.10$$

$$R_B = f_B (X_F) \quad B.11$$

$$C_{CHAM} = f_C (X_F) \quad B.12$$

However it must be stressed that the flow relationships used are only for small variations. (In fact large changes in ' X_F ' would also be incorrect for the chamber capacitance as can be verified from equation B.5).

Appendix C. Mathematical Relationships for G.E.C. (Model 1172) Proportional Controller.

Input Mechanism To Flapper Nozzle.

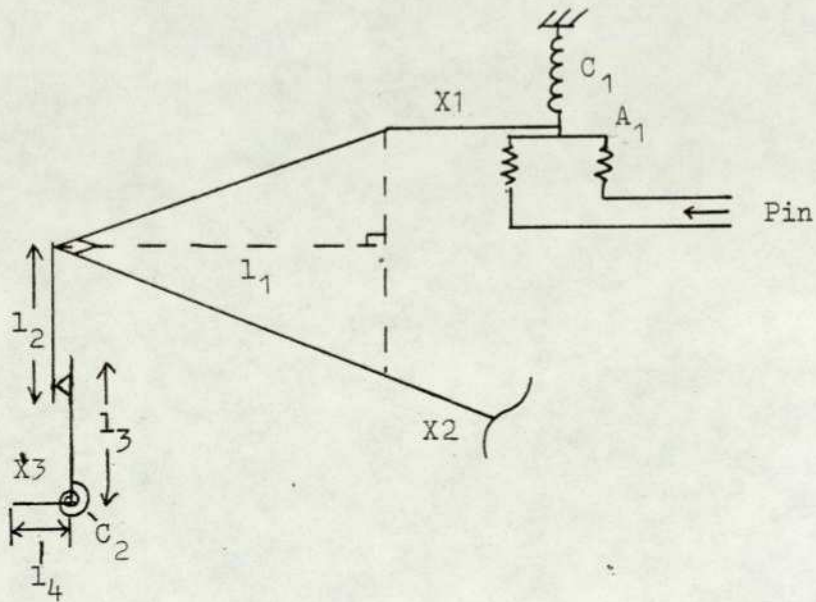


Fig C.1

From diagram C.1 a displacement X_1 is found from

$$\begin{aligned} X_1 &= P_{in} A_1 C_1 = 0.774 \times 10^{-3} \times 0.04762 \times 10^{-3} \\ &= 3.6857 \times 10^{-8} \cdot P_{in} \text{ m.} \end{aligned}$$

C.1

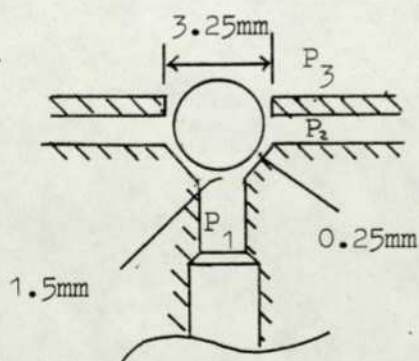
The system of levers l_1 ; l_2 ; l_3 and l_4 relates the inputs X_1 and X_2 to X_3 by the formula

$$X_3 = \frac{(X_1 - X_2) \times l_2 \times l_4}{l_1 \times l_3} \quad \text{C.2}$$

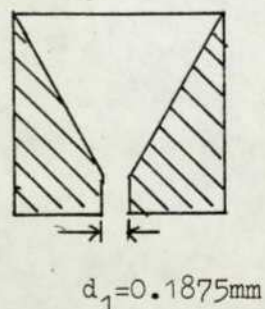
where l_1 is an imaginary line drawn at right angles to the plane of the paper providing the essential component of force necessary to move X_3 .

Flapper Nozzle Arrangement

Section 1 Ball Valve Assembly



a)



b)

The same approach will be taken as that described in Appendix B.

The effective area of the ball valve is slightly less straightforward than for the conical poppet.

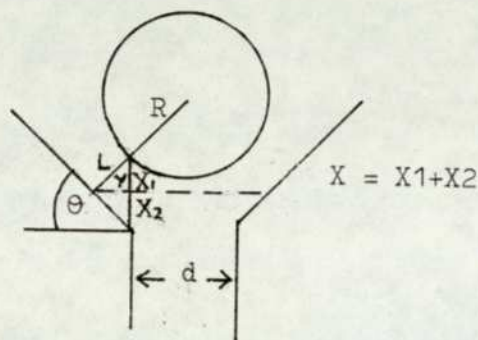


Fig C.3

Fig C.3 shows the situation in more detail. It is convenient to split up the vertical distance of the ball to seat into X_1 and X_2 .

$$\text{Then } \tan \theta = \frac{Y}{X_1} \text{ as well as } \tan \theta = \frac{X_2}{Y}$$

$$\text{or } X_1 + X_2 = Y \left[\frac{1}{\cos^2 \theta \cdot \tan \theta} \right] \quad \text{C.3}$$

Also from Fig C.3 the minimum area can be expressed as

$$\begin{aligned} A &= \frac{\pi (d/2 + Y)^2 - (d/2)^2}{\sin \theta} \\ &= \frac{\pi (dY + Y^2)}{\sin \theta} \end{aligned}$$

Substituting Y from C.3

$$\begin{aligned} A &= \frac{\pi d X \cos^2 \theta \cdot \tan \theta + X^2 \cdot \cos^4 \theta \tan^2 \theta}{\sin \theta} \quad (X = X_1 + X_2) \\ &= \pi d X \cos \theta \quad (\theta = 31^\circ) \end{aligned} \quad \text{C.4}$$

To this must again be added a coefficient of discharge.
This was found to be⁽³¹⁾

$$C_{23} = -0.241 \cdot (P_3/P_2) + 0.966$$

For Fig C.2b) the effective area is:

$$\frac{C_{12} \cdot \pi \cdot d_1^2}{4}$$

C.5

and C_{12} for the nozzle assumed to be 0.95.

Using the same approach as before (Appendix B), a table can be constructed. The change in volume is considered so small that a constant capacitance is assumed (based on a volume measurement).

$P_2 \times 10^5$	$X_F \times 10^{-5}$	$\text{Flow} \times 10^{-5}$	$R_A \times 10^9$	$R_B \times 10^9$	$C_{\text{CHAM}} \times 10^{-11}$
1.06	4.364	5.1082	2.819	2.0751	1.68
1.08	3.7606	"	2.779	2.1142	"
1.10	3.3477	"	2.7407	2.1534	"
1.12	3.0423	"	2.7015	2.1926	"
1.14	2.8045	"	2.6624	2.2317	"
1.16	2.6126	"	2.6232	2.2709	"
1.18	2.4536	"	2.5841	2.31	"
1.20	2.3190	"	2.5449	2.3492	"
1.22	2.2031	"	2.5058	2.2883	"
1.24	2.1021	"	2.4666	2.4275	"
1.26	2.0130	"	2.4275	2.4666	"
1.28	1.9337	"	2.3883	2.5058	"

$P_2 \times 10^5$	$X_F \times 10^{-5}$	$Flow \times 10^{-5}$	$R_A \times 10^9$	$R_B \times 10^9$	$C_{CHAM} \times 10^{-11}$
1.30	1.8625	"	2.3492	2.5449	"
1.32	1.7982	"	2.31	2.5841	"
1.34	1.7394	5.1076	2.2711	2.6235	"
1.36	1.6853	5.1054	2.2329	2.6628	"
1.38	1.633	5.1019	2.1953	2.7049	"
1.40	1.5881	5.0968	2.1582	2.7468	"
1.42	1.5442	5.0905	2.1216	2.7895	"
1.44	1.5070	5.0325	2.0856	2.8333	"
1.46	1.4640	5.0732	2.05	2.8779	"
1.48	1.4272	5.0623	2.0149	2.9236	"

This is quite interesting as the flow rate remains constant due to back pressure in the chamber being small, i.e. choked. Under these circumstances one concept of a resistance related to a restrictive gap can be identified uniquely.

The gain around the $1.08 \times 10^5 \text{ N/m}^2$ point (approximate starting point of system) is $4.843 \times 10^8 \text{ kN/m}^3$, and the time constant is 0.02 secs. This time constant is very small for the overall system, and this is the expected result, as the volume discharged into is very small.

Spool Valve Assembly

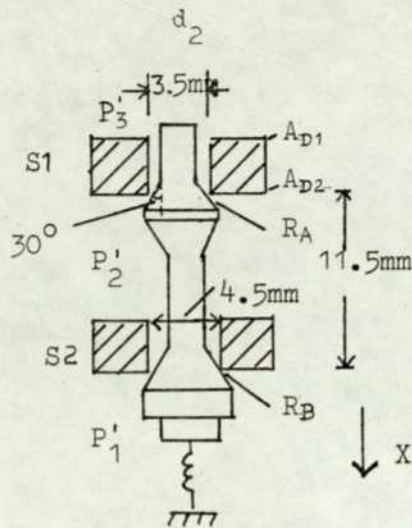


Fig C.4.

The effective areas are calculated as shown in Appendix B.

Giving discharge coefficients of

$$C_{12} = -0.24 \times (P_2' / P_1') + 0.966$$

$$C_{23} = -0.24 \times (P_3' / P_2') + 1.0366$$

It would help to understand the action of this part and so the two conditions of excitement are now described.

For Increasing Pressure

With reference to Fig C.4, the valve is pushed off its seat (Section S2) by the downward movement of Section S1. This allows pressure P_2' to rise. However in doing so, together with auxiliary feedback, S1 is forced upwards. Therefore the process consists of discharging in a varying volume with a varying restriction until some equilibrium state (as shown) is reached. In the simplest (and most usual case) collisions are minimal.

For Decreasing Pressure

Section S1 moves upwards due to the reduced pressure from the ball valve and P_2' is correspondingly lowered. But this lowers S1, again in conjunction with auxiliary feedback. Therefore the operation is that of discharging into a varying volume with varying restrictions until some equilibrium point is reached. In the simplest (and most usual) case collisions are minimal.

Unfortunately for this device it is not possible to eliminate P_2' , as in the previous case (thereby allowing a relationship for resistance based only on displacement), i.e. for either charging or discharging:-

$$R_A = f_A(X_A; P_2') \quad C.6$$

$$R_B = f_B(X_A; P_2') \quad C.7$$

Families of curves for both restrictions are shown in Fig C.5 a) and b). It must immediately be stated that technically these curves are invalid as there is no static position of displacement X against pressure P_2' i.e. the process will either change to supply or discharge to atmospheric, whereas the equations themselves relate only to steady flow conditions. Under these circumstances the time to fill or discharge should only be taken as being in the right order. Nevertheless this obviates a more complicated analysis, even though now a two dimensional table is necessary to simulate over the full range. It would be useful at this point to see if an appropriate time constant can be found.

For any constant value of P_2 to keep the position static

$$P_3' \cdot A_{D1} = P_2' \cdot A_{D2} \quad C.8$$

Where A_{D1} - upper area of diaphragm assembly

A_{D2} - lower area of diaphragm assembly.

For $P_3' = 1.08 \times 10^5 \text{ N/m}^2$; $P_2' \approx 1.25 \times 10^5 \text{ N/m}^2$

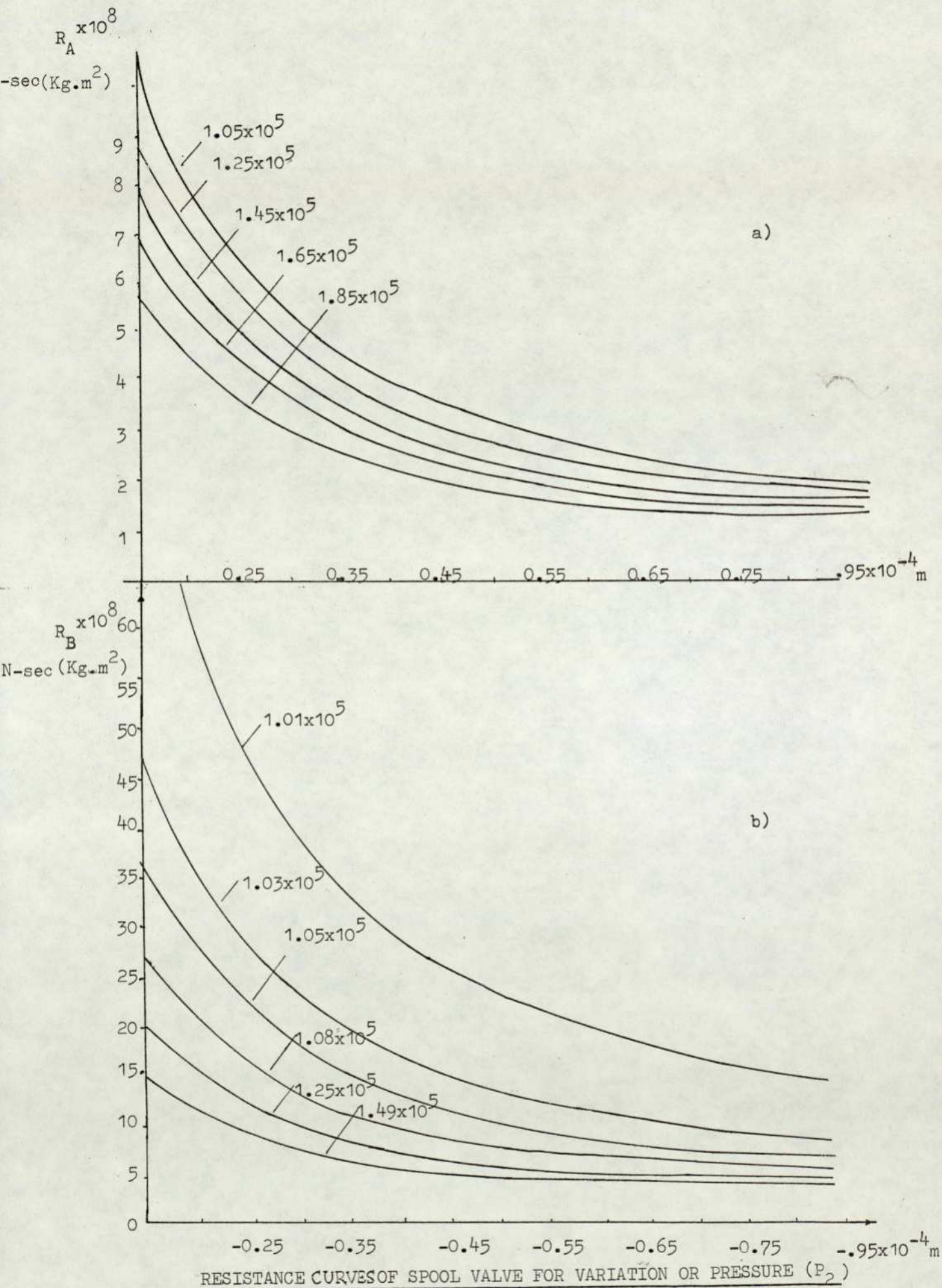


Figure C.5

If this is used as a static value and perturbations are made around this point a resistance value of $R_A = 1.54 \times 10^8 - 9.5 \times 10^8 \text{ N sec/(Kg-m}^2\text{)}$ will occur and for $R_B = 4 \times 10^8$ to 18 N sec/(Kg-m) .

Using the same value of capacitance as in Table B.1, i.e. $\approx 6.7566 \times 10^{-9} \text{ Kg-m}^2/\text{N}$ this gives a range of time constants for discharging of $1.04 - 6.418 \text{ sec} = \tau_{11} - \tau_{12}$ and for charging of $2.7 - 12.161 \text{ sec} = \tau_{21} - \tau_{22}$.

Although this is without any feedback these seem to be high, however it must be remembered that the system is now either discharging to atmospheric or charging to the supply and so the actual time to charge or discharge a few kN/m^2 will be fairly small.

For say a 2 kN/m^2 change this gives

$$25 \times 10^5 e^{-t/\tau} = 23 \times 10^5 \text{ giving } 5t = 0.4 \text{ to } 2.675 \text{ sec}$$

$$(150-25) \times 10^5 \times (1 - e^{-t/\tau}) = 2 \times 10^5 \text{ giving } 5t = 0.2 \text{ to } 0.9807 \text{ sec.}$$

With feedback these would be reduced further. It is quite interesting that there seems to be a trade off with size of perturbations against restriction opening providing some automatic levelling in the response time.

Feedback Mechanism

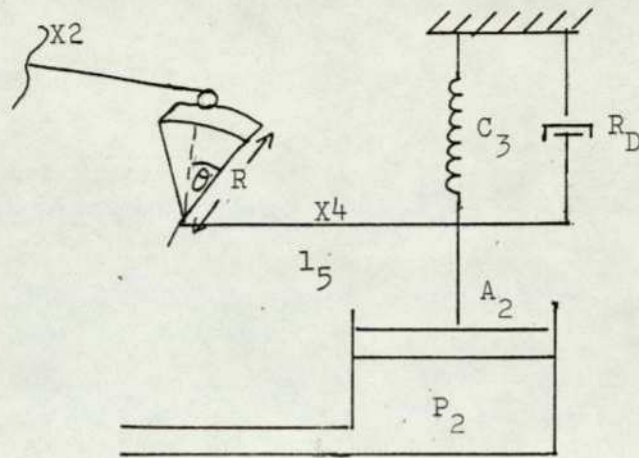


Fig C.6

X_4 can be related to pressure P_2 by the expression

$$\begin{aligned} X_4 &= P_2 \cdot A_2 \cdot C_3 = P_2 \times 15.56 \times 10^{-3} \times 16.057 \times 10^{-6} \\ &= 2.5 \times 10^{-7} P_2 \end{aligned}$$

C.9

The feedback cam is slightly more difficult to evaluate. As it is linear there should be a linear relationship with change in R to change in θ° . This was measured as $0.1 \times 10^{-3} \text{ m}$.

$$\text{Therefore } \Delta R = 0.1 \times 10^{-3} \Delta \theta$$

C.10

$$\text{and } = \frac{x_4}{l_5} \times \frac{180}{\pi}$$

$$\text{giving } x_2 (= \Delta R) = \frac{5.73 \times 10^{-3}}{15} \cdot x_4 \text{ m}$$

The initial value of x_2 can be determined from the value operating characteristics already discussed.

Gathering all the terms together at 20°C

A1	=	$0.774 \times 10^{-3} \text{ m}^2$
C1	=	$0.04762 \times 10^{-3} \text{ m/N}$
l_1	=	0.045m
l_2	=	0.0005m
l_3	=	0.025m
l_4	=	0.018m
l_5	=	0.1m
C2	=	0.6 rad/Nm
d	=	$1.5 \times 10^{-3} \text{ m}$
d_1	=	$0.1875 \times 10^{-3} \text{ m}$
d_2	=	$3.5 \times 10^{-3} \text{ m}$
d_3	=	$4.5 \times 10^{-3} \text{ m}$
A_{D1}	=	$0.7553 \times 10^{-3} \text{ m}^2$
A_{D2}	=	$0.253 \times 10^{-3} \text{ m}$

$$\begin{aligned}
C_D &= 3.706E-5 \text{ (combined Diaphragm \& Spool} \\
&\quad \text{Valve Spring) m/N} \\
A_2 &= 15.56 \times 10^{-3} \text{ m}^2 \\
C_3 &= 16.057 \times 10^{-6} \text{ m/N} \\
R_D &= 5 \times 10^3 \text{ N sec/m. (see Appendix B)} \\
\frac{\Delta R}{\Delta \theta} &= 0.1 \times 10^{-3} \text{ m/deg.} \\
G_{BALL} &= 4.843 \times 10^3 \text{ KN/m}^3 \text{ @ } P_{20} = 1.08 \times 10^5 \text{ N/m}^2 \\
R_A &= \text{Variable} \\
R_B &= \text{Variable} \\
C_{CHAM} &= 6.7566 \times 10^9 \text{ Kg-m}^2/\text{N @ } P_2 = 1.25 \times 10^5 \text{ N/m}^2 \\
P_1 &= 2.5 \times 10^5 \text{ N/m}^2 \\
P_3 &= 1.0 \times 10^5 \text{ N/m}^2
\end{aligned}$$

Because of the variable terms, only a nonlinear simulation is attempted, where

$$R_A = f_A(X; P_2)$$

$$R_B = f_B(X; P_2)$$

Appendix D. Mathematical Relationships of Pulsed Cooled Thermocouple

The thermocouple will be represented by a two port.
This is

$$\begin{bmatrix} V \\ Q_{\text{gas}} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} I \\ T_{\text{gas}} \end{bmatrix}$$

where the terms V and I represent the electrical port and T_{gas} and Q_{gas} the thermal part. The system is biased into an operating region.

To derive the terms of the matrix the contribution from each part will now be calculated

$$a_{11} = \Delta V / \Delta I | T_{\text{gas}} \quad \text{D.1}$$

This represents the resistance of wires etc. For copper, diameter 10^{-3} m and a matched pair of leads (1 metre length for each lead) this gives

$$R = \frac{\rho l}{A} = \frac{1.725 \times 10^{-8} \times 2 \times 10^3}{7.854 \times 10^{-7}} \simeq 43.9 \Omega$$

$$a_{12} = \Delta V / \Delta T_{\text{gas}} | I \quad \text{D.2}$$

From Temperature Measurement with Thermocouples⁽⁴⁶⁾ there is a constant term of $40 \mu V/^{\circ}C$ up to $1000^{\circ}C$. Therefore the e.m.f. is

$$\begin{aligned} V &= 40 \times 10^{-6} (T_{\text{gas}} - T_0^{\circ}C) \\ &= \alpha_0 (T_{\text{gas}} - T_0) \end{aligned} \quad \text{D.3}$$

where T_0 is assumed to be $20^{\circ}C$

As well as this there is the rise of the thermocouple associated with the thermal capacitance of the junction, i.e.

$$Q_{\text{gas}} = C_d \cdot \frac{dT_{\text{gas}}}{dt} \quad \text{D-4}$$

From designing Thermocouples for Response Rate⁽⁴⁷⁾ this can be equated to

$$hcA_C (T_G - T_J) = M_C dT_J / dt \quad \text{D.5}$$

(where the temperature suffix G and J refer to the gas and thermocouple junctions respectively) and this can be rearranged to give

$$T_{\text{gas}} = T_J + \tau \frac{dT_J}{dt} \quad \text{where } \tau = M_C / hcA_C \quad \text{D.6}$$

Therefore the response is represented by a first order system.

The value of τ can be found from the empirical formula

$$\tau = \frac{2.19 \times 10^5 \times (dx39.3701)^{1.25} \times (23.7303 \times G)^{-15.8} \sqrt{9/5T+459}}{(9/5T + 459)} \quad D.7$$

where the formula has been adjusted for M.K.S. units.

Using $T = 3000^\circ\text{C}$; $G = 0.5 \text{ Kg m}^2/\text{sec}$; $d = 10^{-3}$ this gives

$$\tau = 0.3933 \text{ secs}$$

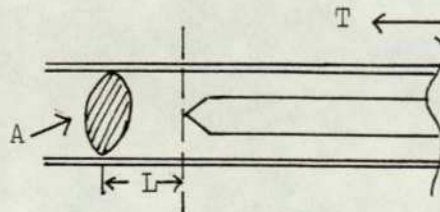
$$a_{21} = \Delta \dot{Q}_{\text{gas}} / \Delta I | T_{\text{gas}}$$

D.8

This term is the gas flow influenced by the Peltier effect⁽⁴⁸⁾. This is considered to be negligible.

$$a_{22} = \Delta Q_{\text{gas}} / \Delta T_{\text{gas}} | I$$

This represents the thermal resistance of the gas. Using a value of thermal conductancy of air at 3000°C of 0.17584.



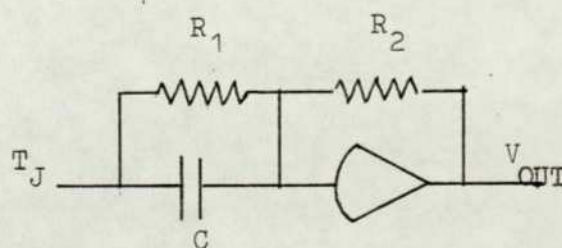
The value of $a_{22} = 0.39248A/L$ for a per unit change in temperature. This is difficult to estimate and so will be left in this form.

Giving

$$\begin{bmatrix} V \\ Q_{gas} \end{bmatrix} = \begin{bmatrix} 43.9 & \frac{40 \times 10^{-6} (T_{gas} - 20^{\circ}C)}{T_{gas} \cdot (1 + 0.3933 \cdot d/dt)} \\ 0 & 0.17584 \times A/L \end{bmatrix} \begin{bmatrix} I \\ T_{gas} \end{bmatrix}$$

However the upper row would be the only terms of interest as the thermocouple will be providing essentially very little interactions with its environment. The resistance of the lines being small was also neglected in the simulation.

For the phase lead network shown below



$V_{OUT}/T_J = sCR_2 + R_2/R_1$ choosing $CR_2 = \tau$; $R_2/R_1 = 1$ this gives

$$V_{OUT} = T_G = T_J + \tau dT_J/dt,$$

i.e. V_{OUT} always represents the gas temperature (eqn.D.6 above)

FLOWCHARTS

OF

PACKAGE

Appendix E

Flowcharts and Description of Computer Package

This appendix gives the flowcharts and description of the package MEDIEM which has been developed for interactive use on the PDP 11/10 minicomputer. The programming language used was FORTRAN, but in order to provide some universality FORTRAN commands and statements described in this Appendix have been limited to minimal usage.

By package standards MEDIEM is fairly small. It has approximately 4,000 lines of sourcecode (i.e. high level language) as opposed to some 40,000-100,000 lines for some commercial packages. However even in this case maximal use was made of the available core and back up floppy disc storage.

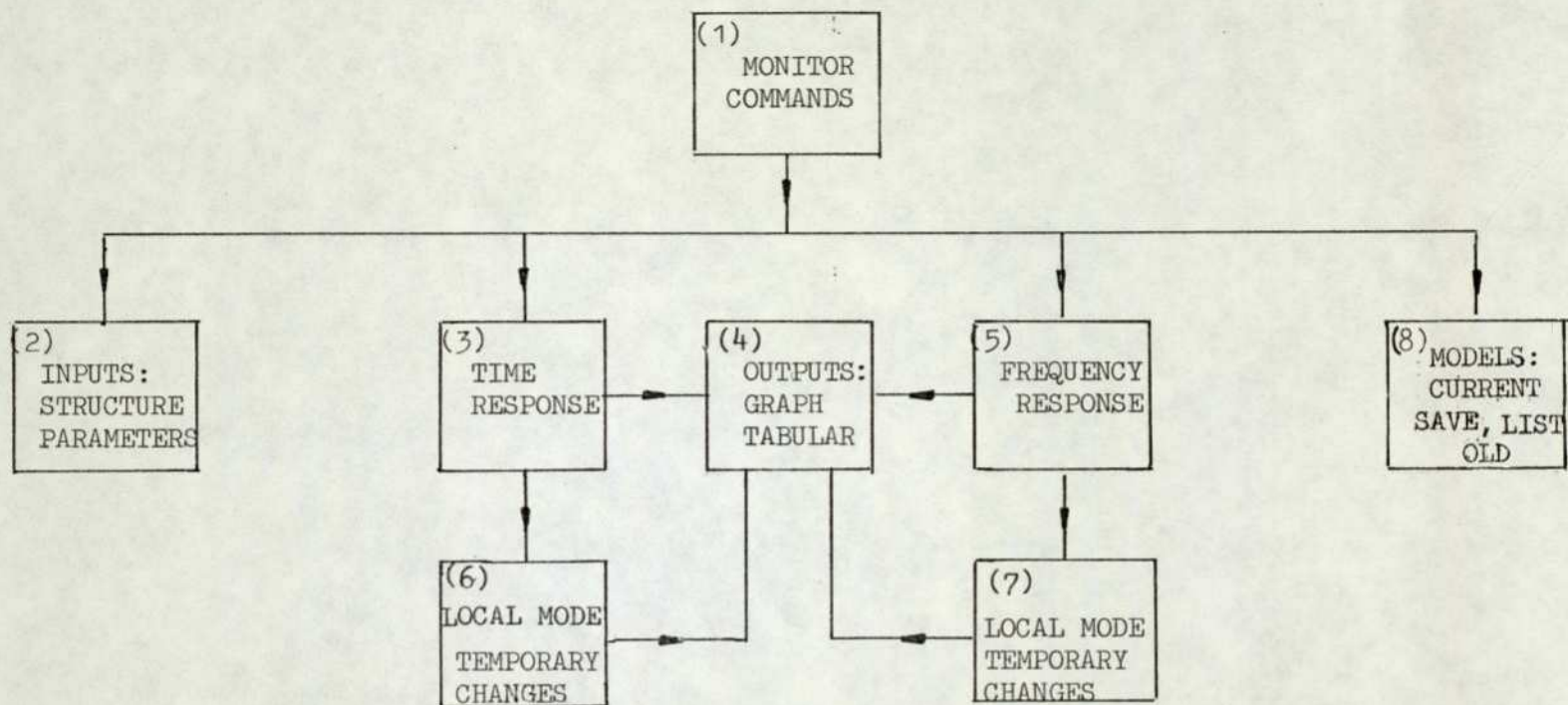
The PDP range of machines use normal overlay procedures, and although not specifically discussed in the Appendix, as each system configuration is different, it is essential that the evaluation section of the program is resident in core. This may present some difficulties for transparent overlay systems (although at the moment the size of the package would present no problem to the Prime 550 - The Instrument Systems Centre's new mini computer).

Unfortunately due to limitations of core and back up memory, some fairly standard ideas on program construction have had to be modified⁽⁴⁹⁾. Specifically it has not been possible to employ modular construction for all the main sections of the package. In other words, two clearly separate sub-sections may well have been combined. However, of more importance, it has not been possible to include certain describable features in an interactive instrument package. These are explained in Chapter 7. However the essential criteria for a package outlined in Chapter 2 have been met.

The routines are displayed in flowchart form with explanations and they try to follow a logical progression from input to output. In practice there are parallel modes of operation as for instance time and frequency response generation of state equations, so it is not possible to completely fulfill this objective. As an extra aid, an alphabetical list of routines with their page numbers is given at the end of this Appendix (page 371).

The Overall Composition of The Simulation Package

Fig E.1 shows the main areas that the package consists of. Each section will now be briefly explained. The arrows refer to an accessible module, in much the same as as a subroutine is accessible from a main program.



COMPOSITION OF COMPUTER PACKAGE

Figure E.1

Section 1

When first entering the program the monitor (or in fact the operating system) for the package is made resident. This controls all calls to the subroutines. To a large extent this approach guarantees a fairly modular form of construction, as each section can be individually constructed.

Section 2

Input of the model in the form of a structure and parameters is entered in this section. This was illustrated in Chapter 6 for the models developed in Chapter 3.

Section 3

Once a model has been built then a time domain solution may be required. This would generate the various state equations (for either a linear or nonlinear response).

Section 4

The precise way the information is to be displayed is referenced in Section 4. For the PDP 11/10 the program will allow four different modes, there being graph or plot on a V.D.U. or graph or plot on a line printer.

Section 5

A frequency response may alternatively be derived. (This is only for linear systems). Again the state equations are generated and the various local and output controls initialised.

Section 6

A local mode is possible when the state equations have been generated. This is to save re-generation, when only parameter values are modified. (This can only vary constant parameter terms, but the model can be non-linear). Listings are also permitted at this stage. However in order to prevent confusion local changes do not overwrite the original model.

Section 7

The same approach follows for the Frequency response. (However only linear models are possible as before).

Section 8

When a model has been constructed and evaluated by computer, it can be saved if desired. In general this section allows manipulation of complete models so that a suite of user programmes can be built up.

It should be noted that the precise nature of each section and how they communicate with other areas is to a certain extent, dependent on the computer used. The rest of this Appendix will now discuss each of these sections in detail in the form of flow charts, explanations and where appropriate give the necessary computational theory.

Section 1

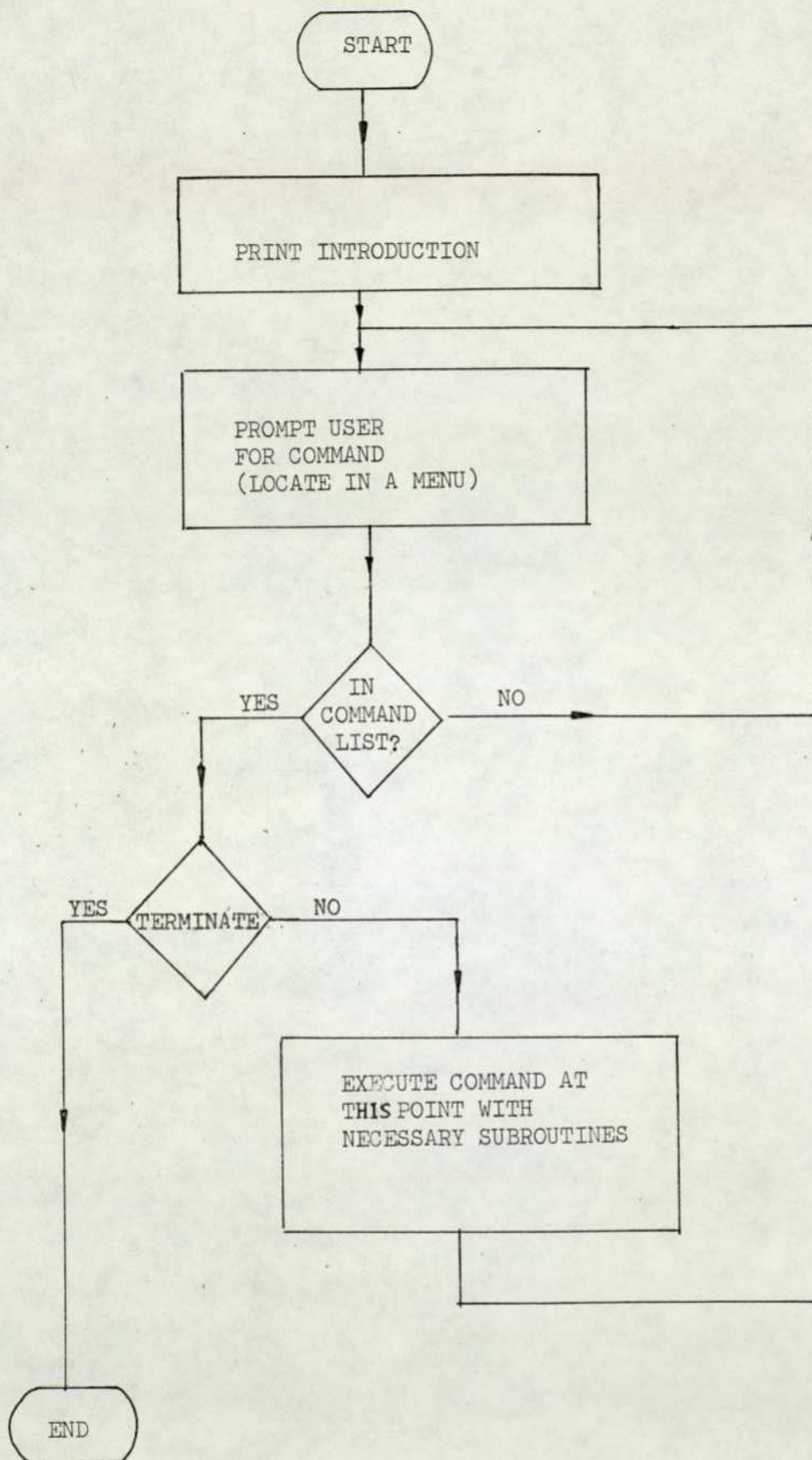
Fig E.2 gives a flow chart of MON. This prints an introduction and prompts the user for one of the following commands.

```
COMM; NEW; OLD; STRU  
PAR; LIST; TIM; FREQ;  
SAVE; END.
```

The command list, located in a subroutine MENU for overlay purposes, can be added to as desired without loss of generality to the flowchart or program.

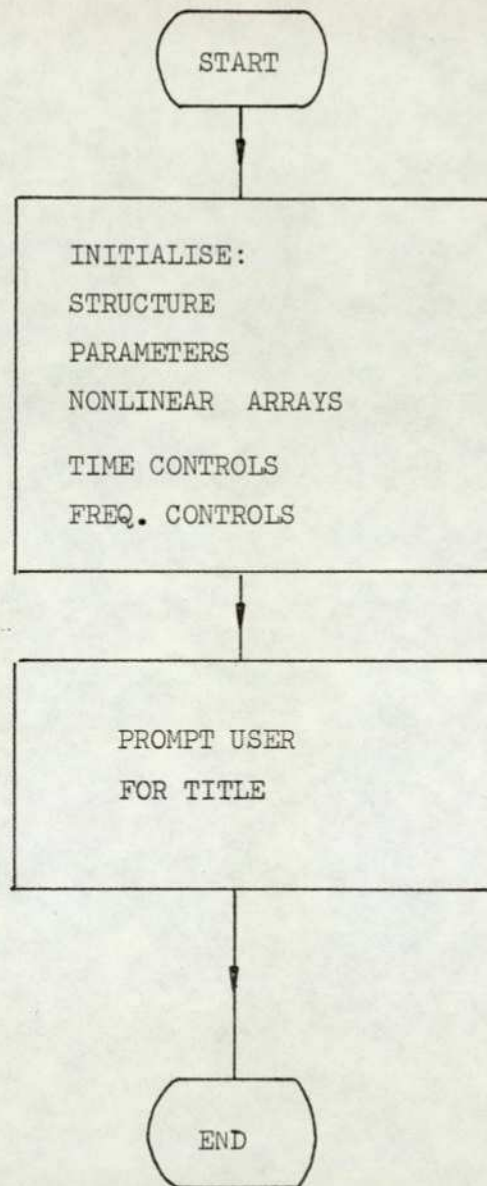
Section 2

The first subroutine described here is NEW, which initialises the necessary arrays and common blocks for the input of a new structure. The flow chart of this is shown in Fig E.3.



MON: MONITOR SECTION OF PROGRAM

Figure E.2



NEW: INITIALISE NEW MODEL

Figure E.3

First of all, a title for the new model is entered. After this the program automatically calls STRU, which is shown in Fig E.4, E.5 and E.6. The routine STRU allows a flexible update of the structure. In essence, both insertion and selection of elements at any point in a model is possible, thereby allowing any changes to be made at relevant points in a structure, and not considered as 'add on' sections at the end. In order to be completely general there is no restriction on node or element numbering, (excepting that they are inside the range of values allowable). Each 'line' of the structure consists of:

ELEMENT NO, ELEMENT TYPE, ARROW SIGN, NODE, CONNECT.

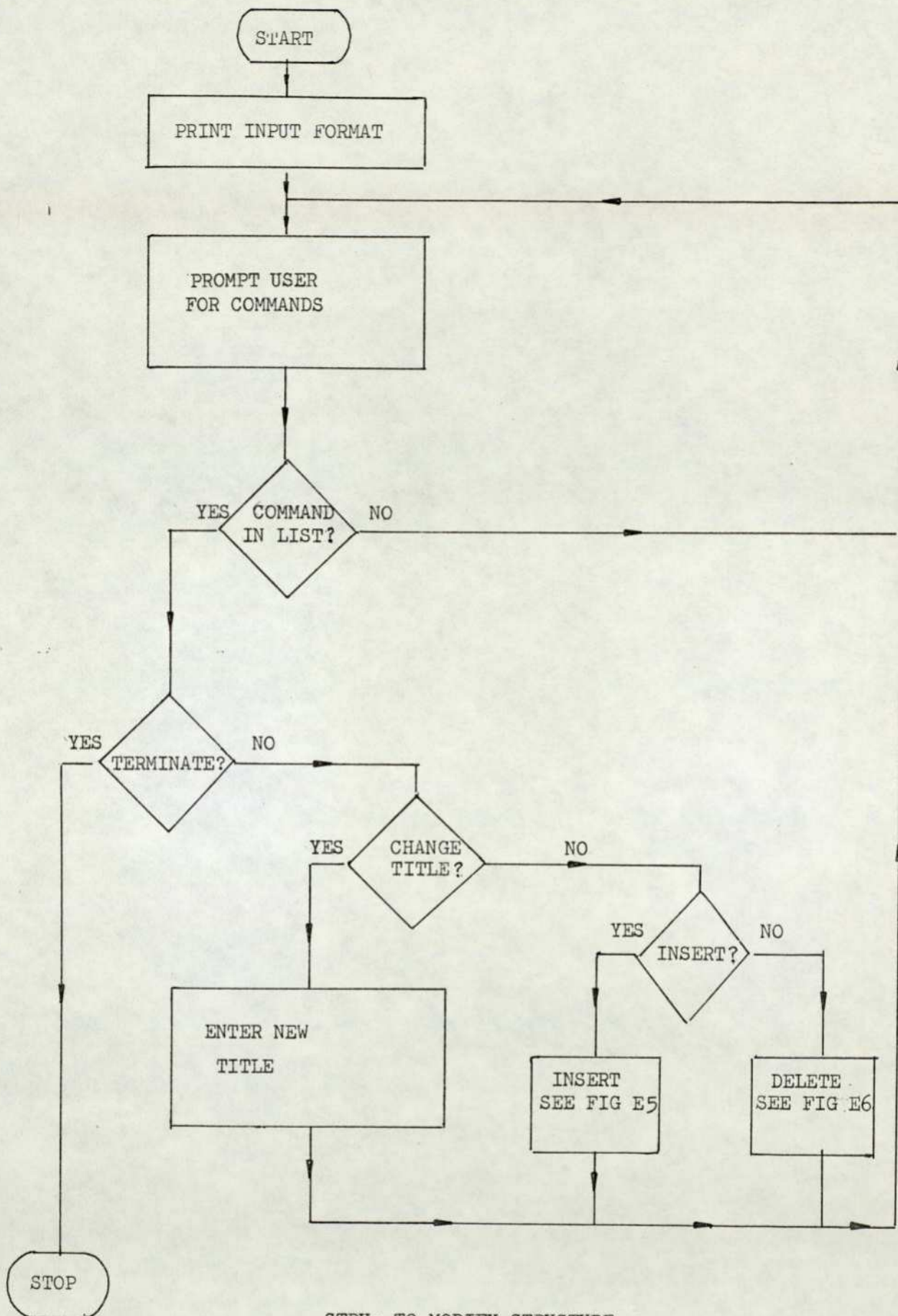
These lines are linked together by array, conveniently called LINK (). Hence all that is necessary is to run through the array link to obtain the relevant 'lines' of information. For example lines 1, 3, 4 could be held in the first three locations of link, i.e.

LINK (1) = 1

LINK (2) = 3

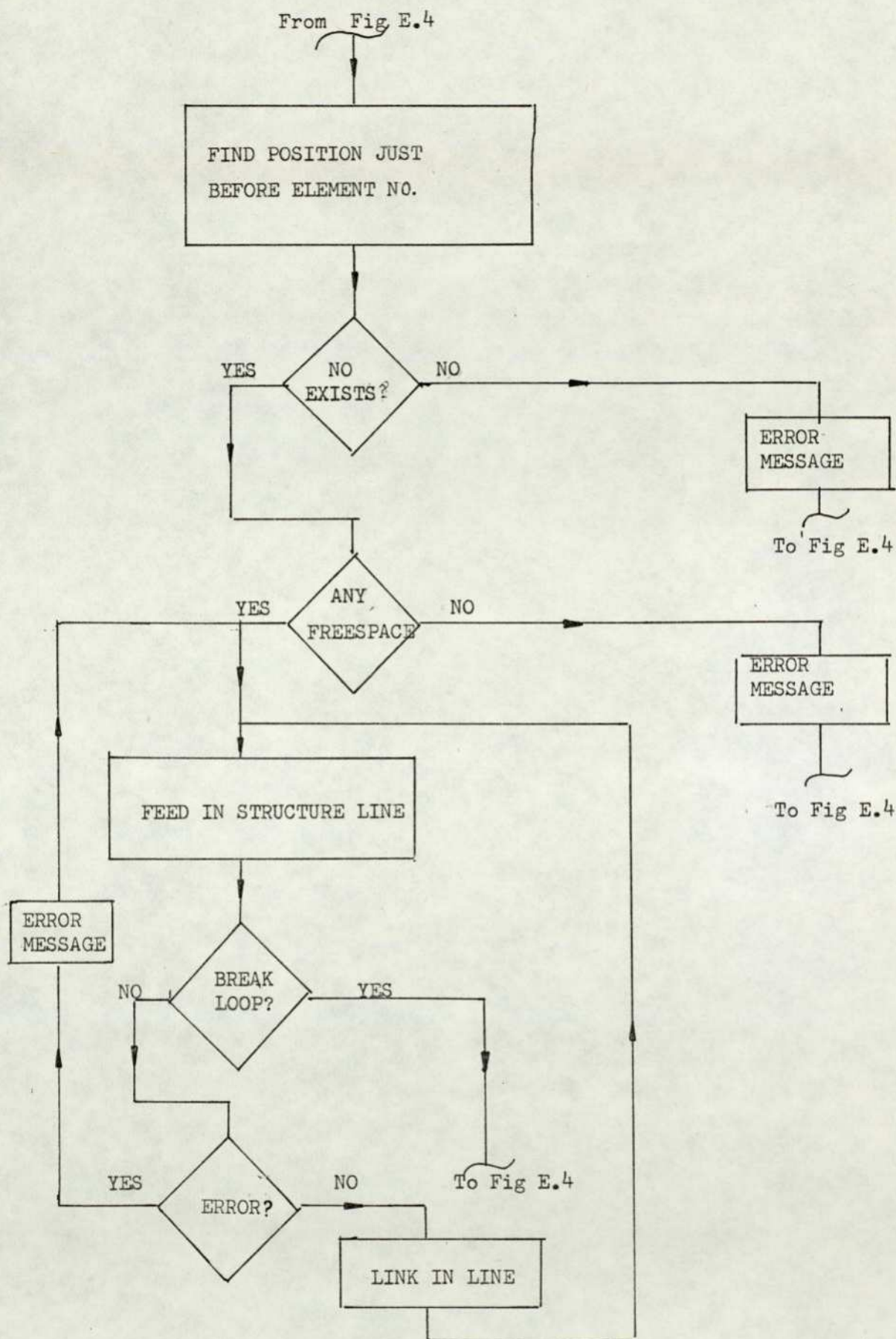
LINK (3) = 4

where line 2 was deleted. This approach may appear unnecessarily complicated for a small mini, especially with limitations of core and back up memory. However, it was considered essential as true interactive changes are often required in a real time simulation program. (In general



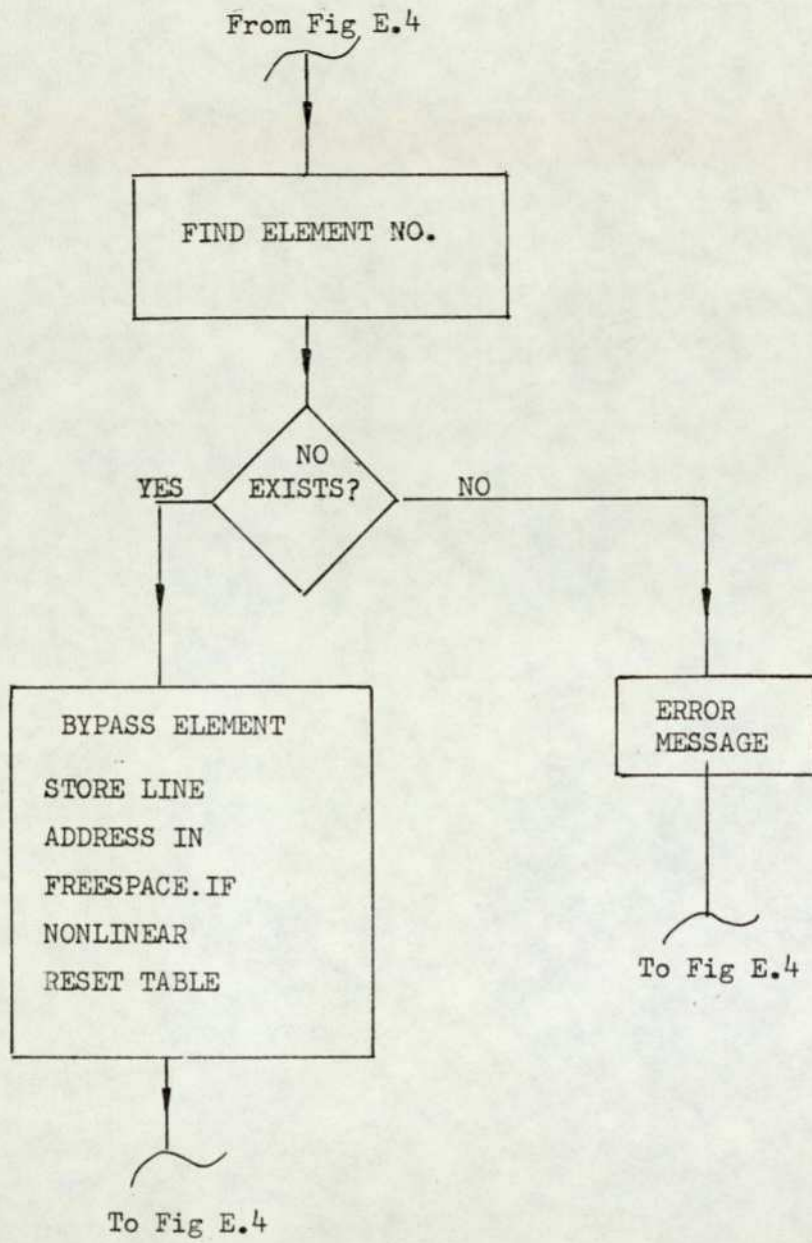
STRU: TO MODIFY STRUCTURE

Figure E.4



INSERT SECTION OF STRU

Figure E.5



DELETE SECTION OF STRU

Figure E.6

graphical facilities should also be available but the necessary library functions were found to be too expensive on storage space).

Fig E.7 describes the PAR routine. This is automatically entered from STRU if any structural changes have been made. The procedure followed is to find the element number specified and or successively link from this position to the end of the file. This allows two conditions to be fulfilled, namely allowing any element value to be updated and permitting a means for rapid input of parameters for a new model. Nonlinear elements are entered by specifying 'NL' in the parameter line. This calls routine NONLIN (Fig E.8), which will ask for a nonlinear expression to be entered in the form of a data table. An initial condition for the nonlinear element is possible if they are 'C', 'L' or integrator terms.

In general these routine exit back to command level (MON) whenever the user desires. This is considered essential as the user may be unsure whether a model has been entered correctly, requires changes or simply abandoned! The structure and parameters will not be lost however (unless NEW or OLD specified) and can be listed or SAVED for further work later on. If in any altered change a line is input incorrectly it will not be accepted and the last correct line entered will stand.

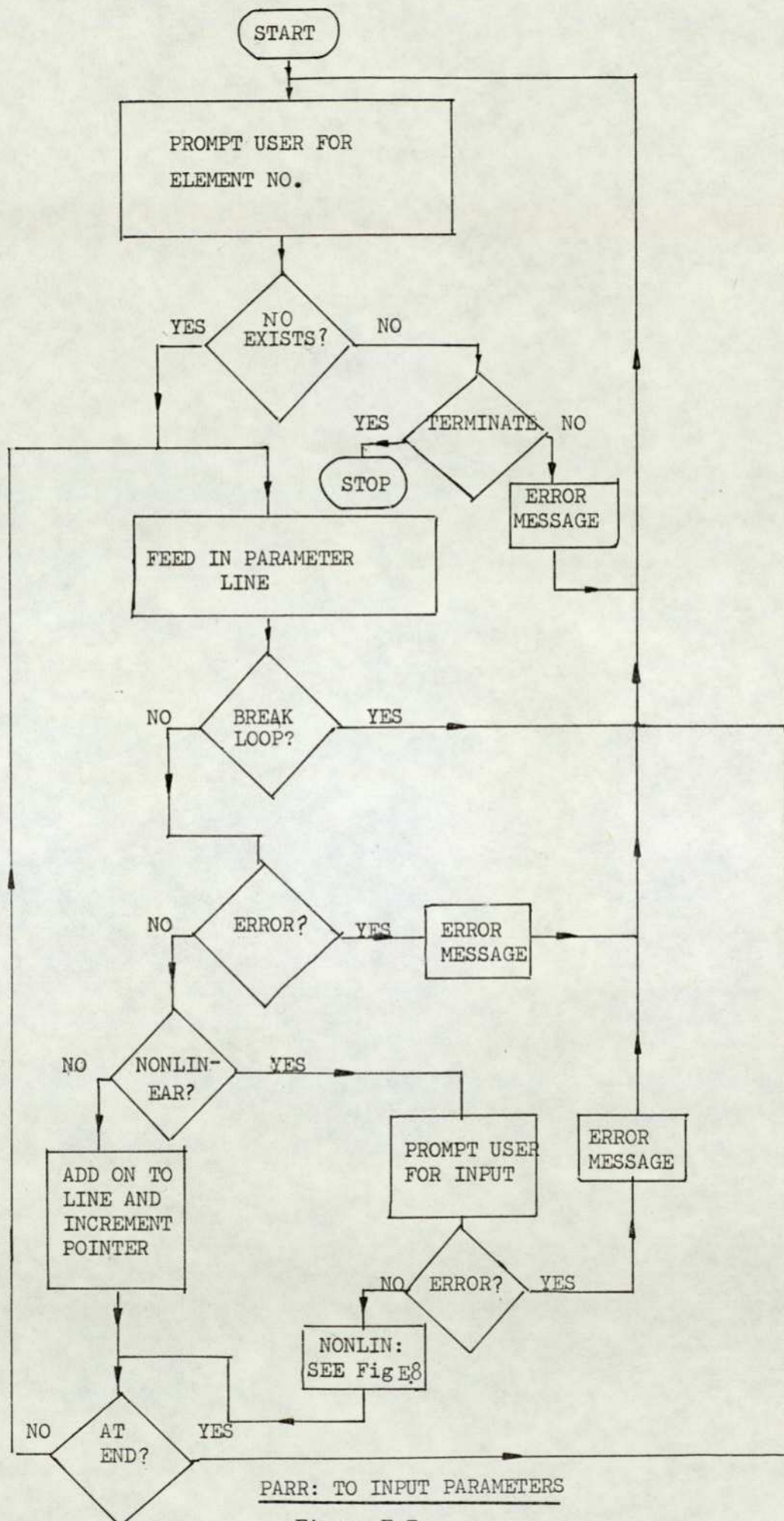
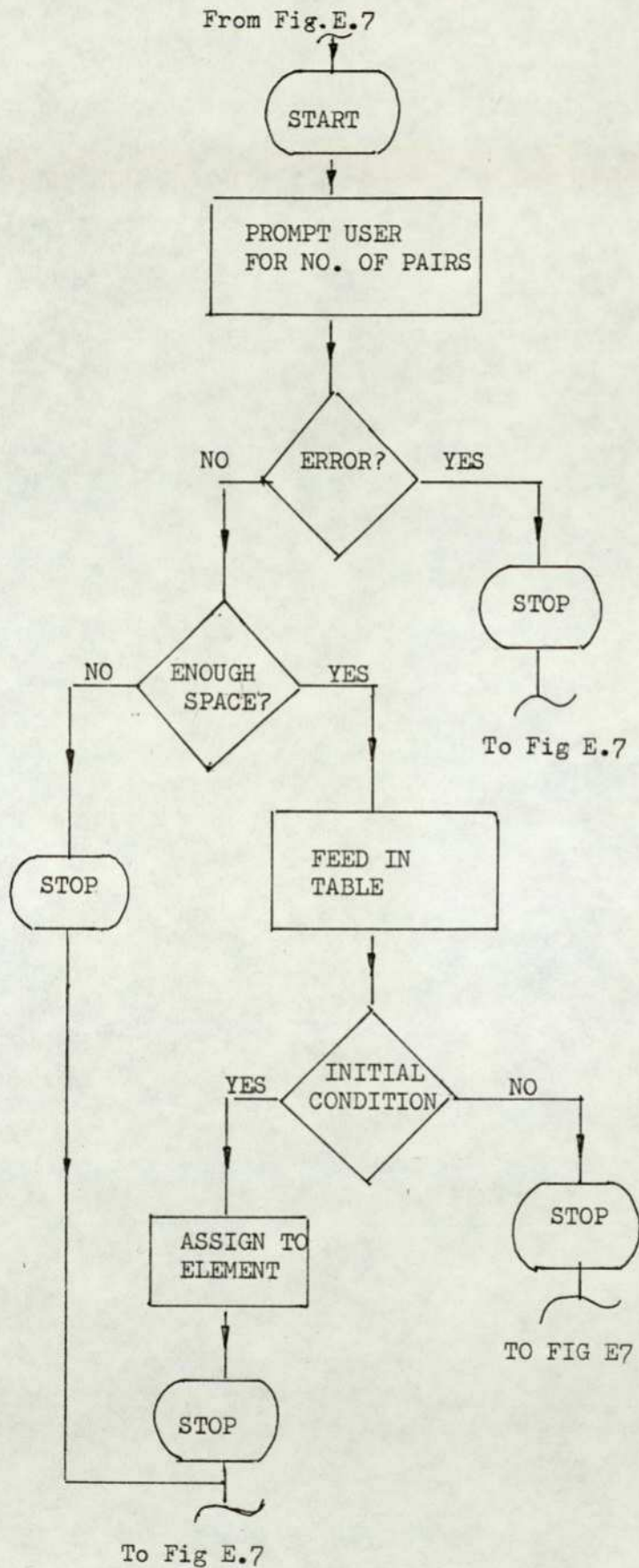


Figure E.7



NONLIN: INPUTTING DATA TABLES

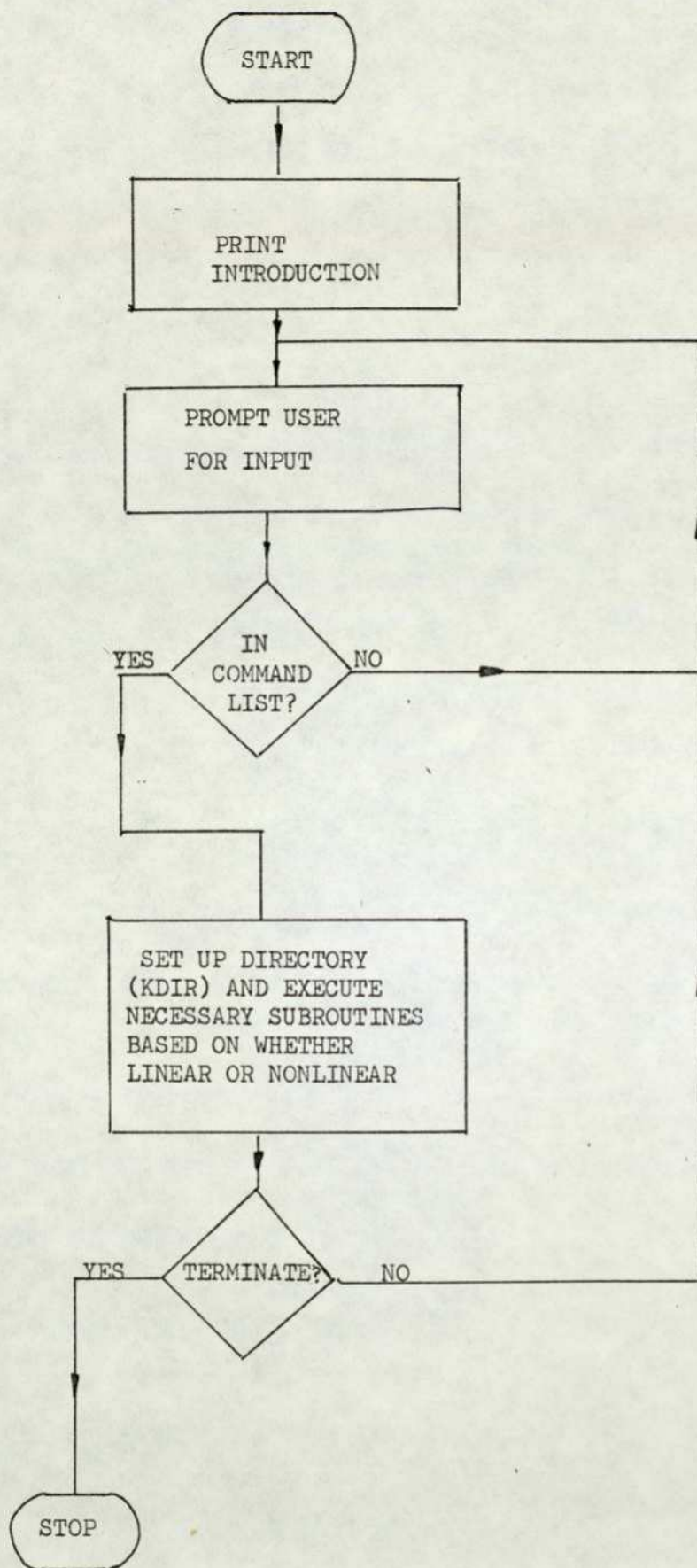
Figure E.8

The next section to be described, with reference to Fig E.1, is the time response. With the structure and parameters entered the routine TIM(TIME) is called to provide the control and execution of this phase. A flowchart is shown in Fig E.9. The section is in essence similar to MON, but operating at a lower level. The commands available modify timing; outputs; max-min ranges; to specify the type of output format and the display format. As the section will evaluate the time response from a variety of different conditions a directory is always specified (which is outside of user control). This has the following meanings (referenced as KDIR).

- 1) RETURN TO MONITOR
- 2) CALL DEFAULT SAVE AND RETURN TO MONITOR
- 3) SET UP GLOBAL MATRIX
- 4) REDUCED FORM OF GLOBAL MATRIX
- 5) MODIFY GLOBAL MATRIX FOR PARAMETER CHANGES.

For 2) a default routine called CITY.SIM automatically stores the developed model. This has the following advantages.

- a) It allows for a possible system crash or program fault possibly destroying a constructed model before being SAVED.



TIM: TIME DOMAIN SOLUTION OF PROBLEM

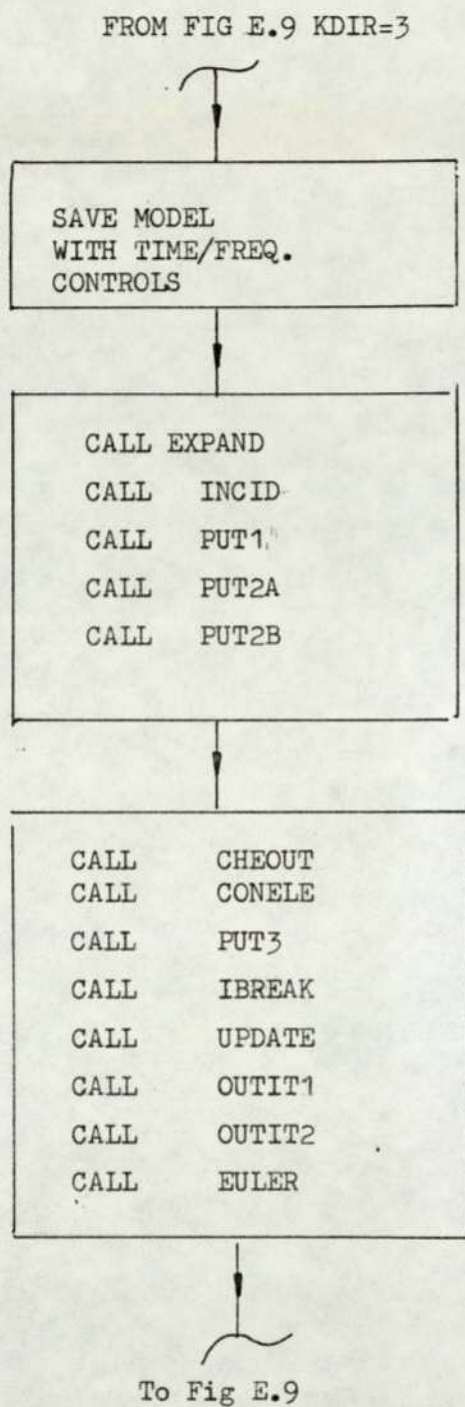
Figure E.9

- b) It frees memory in core for other uses.

However up to 15 secs can be lost in the interactive speed of response by this approach.

KDIR=3 will initiate all the operations that are necessary to produce the state equations and their evaluation. A flow chart of the possible routines called is shown in Fig E.10. For KDIR=4 the necessary state equations have already been found, and KDIR=5 allows parameter modifications to affect the state equations by initially modifying the global matrix. For nonlinear systems this is generalised and KDIR=5 is operative for each iteration step.

Returning to KDIR=3 Fig E.10 gives the routines that can be called. This situation arises when a new model has been generated or there are structural changes, or nonlinear terms implemented. As can be seen, a considerable amount of computer programming is involved, as well as some internal organisation so that the available core is not exceeded. The routine names are arbitrary, but the general approach is to label those sections that have a specific task to perform. An outline of the process is as follows. The model is modified by expanding elements in the EXPAND routine. Then the incidence matrix (INCID) is formed to determine causality. This is put into the global matrix by PUT1, PUT2A, PUT2B. The rest of the routines are then controlled by a checkout module (CHEOUT) which handles both the linear and nonlinear evaluation, CHEOUT controls as



GENERAL SEQUENCE OF CALLS FOR KDIR=3

Figure E.10

follows. First the parameter values are calculated, if nonlin, in CONELE, then the state equations are found by guassian elimination (in PUT3). After this the evaluation of the state equation (under the time controls already specified) is performed. A break routine (IBREAK) gives user control over the simulation. The output equations are updated in (UPDATE) and either plots (in OUTIT1) or tabulations (in OUTIT2) are generated. EULER (Euler) then provides the necessary integration routine.

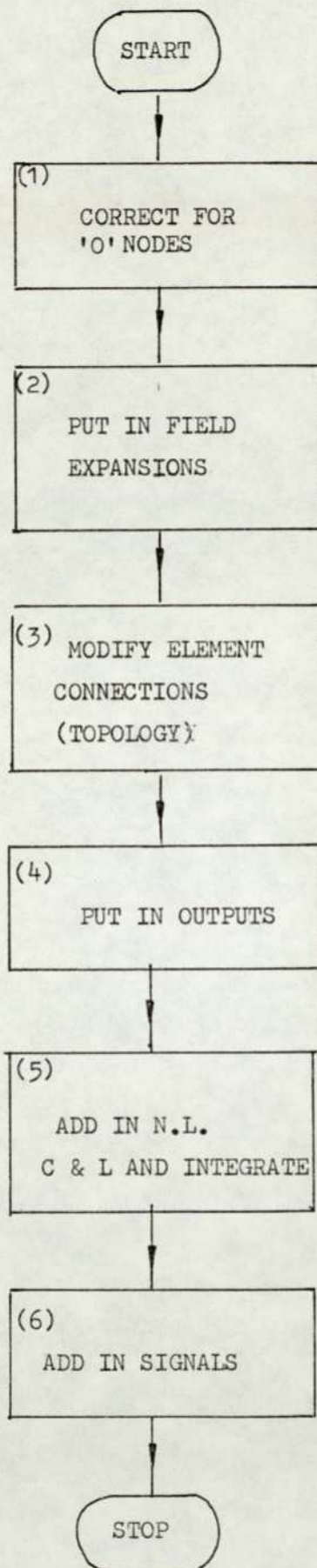
The routine EXPAND is shown in Fig E.11. This is split up into six main sections, as it is of some importance. It is also an area where interest may be shown if updating the package at a later stage. The order is important. Passes are made through the model, (one for each section of EXPAND), ending with a 'processed' form suitable for entering into an incidence matrix.

The first section of EXPAND, section (1) is illustrated in Fig E.12. It is important to eliminate '0' modes, (in effect the complete line), as the corresponding incidence matrix will otherwise have redundancy. For example:

```
1,C ,FR,1 ..... 1st Line of Element
1,C ,TO,0 ..... 2nd Line of Element
```

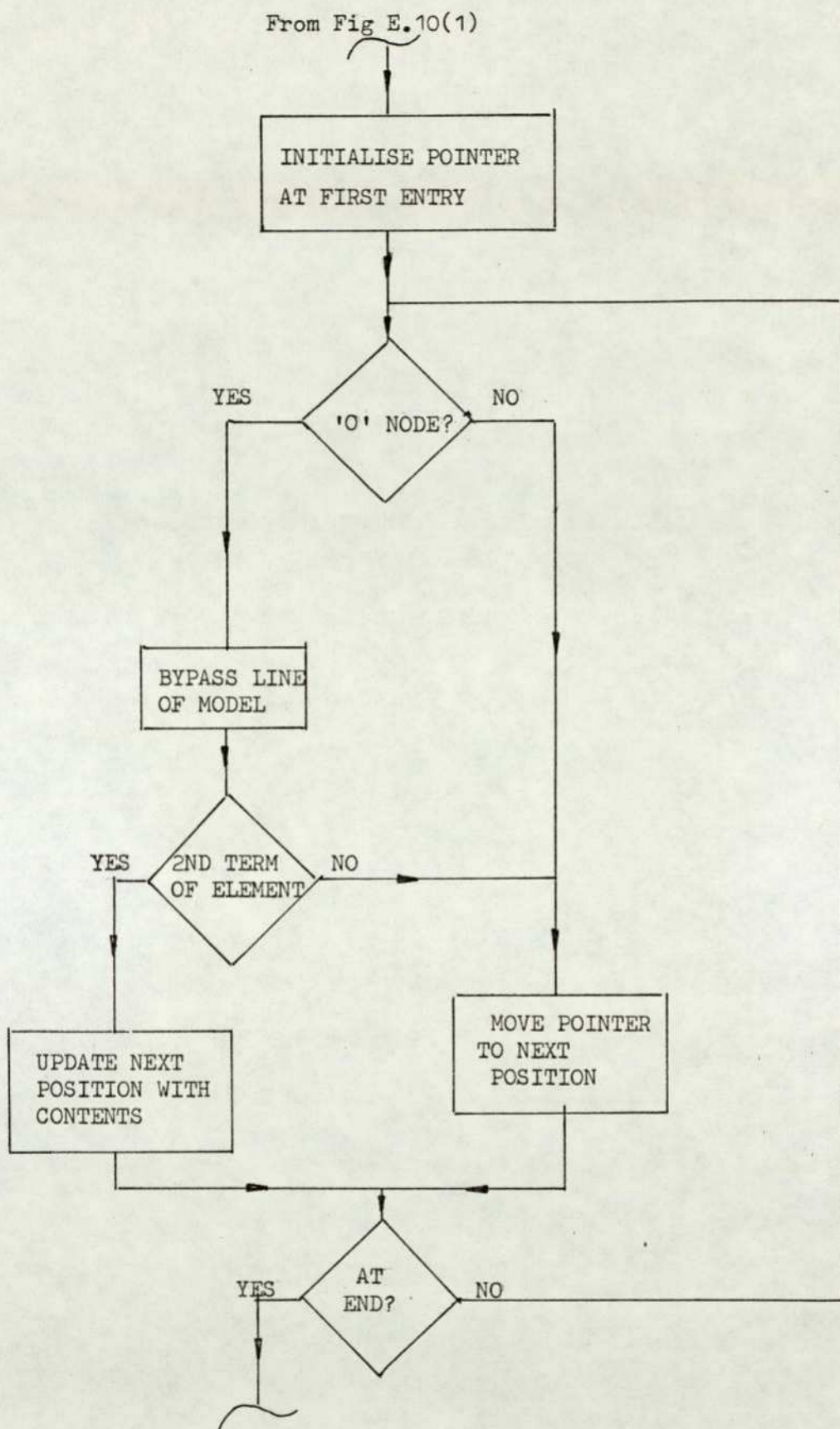
becomes

```
1,C ,FR,1
```

EXPAND: EXPANSION OF MODEL

Figure E.11



FLOWCHART FOR CORRECTION OF 'O' NODES

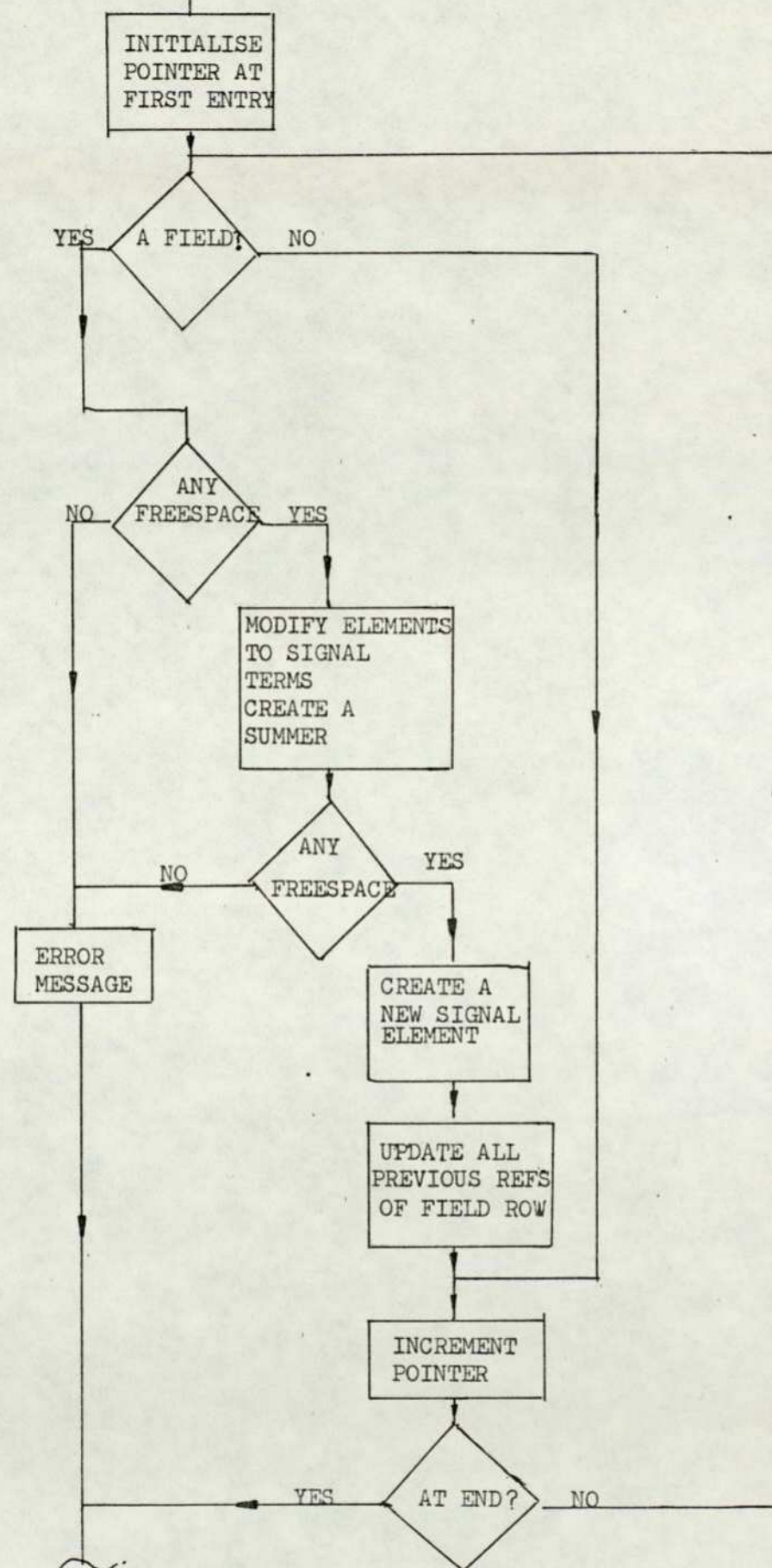
Figure E.12

As this reduces the model it is advantageous to consider first as it effectively cuts the time necessary to handle the other passes. To find any element a pointer looks through each line with the LINK process described earlier, and in general this method is used throughout the next three sections.

Fig E.13 describes the insertion of fields into the model. These elements are expanded with specifically signal terms replacing the input elements, and a summer and output added to interface to the rest of the structure. (The actual models used were described in Chapter 5). Because two extra elements/row must be found, freespace must be identified and utilized. As this is a common requirement, a subroutine FREE is available. This is shown in Fig E.14. If there are any available lines, then the first available (on a queue basis) in stepping through the element array from 1-150 is used. Hence, on average three lines are available for each element, which it is hoped will provide for all the EXPAND routine requires.

Returning to Fig E.12, when a field has been entered it is necessary to check and if necessary update all user outputs, the reason being that the interface introduced is now the true output to be referenced. Hence it is important that the output expression module be put after the fields so that pickoffs can be correctly assigned.

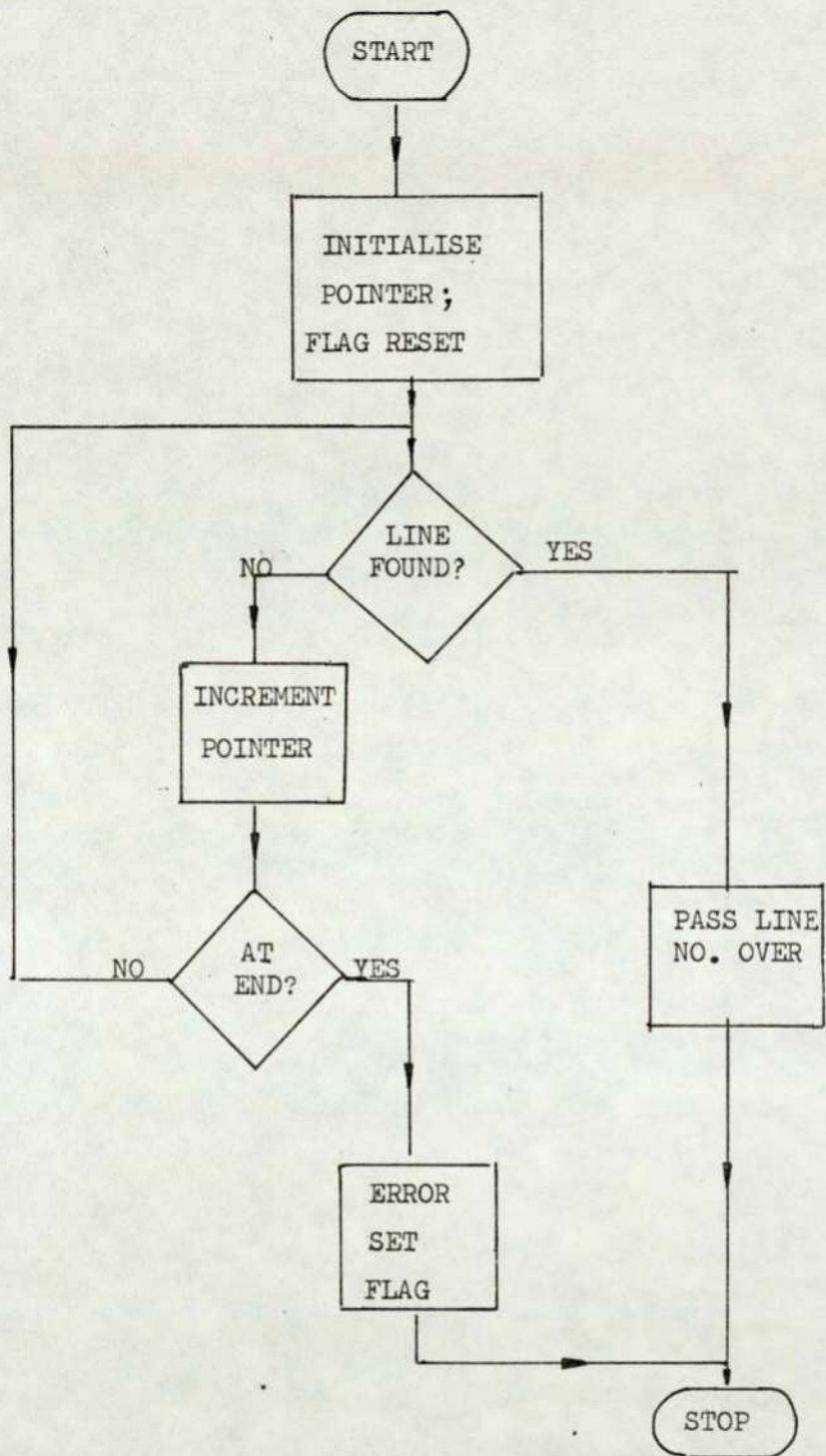
From Fig E.10 (2)



To Fig E.10 (2)

FLOWCHART OF FIELD EXPANSIONS FOR A SINGLE ROW

Figure E.13



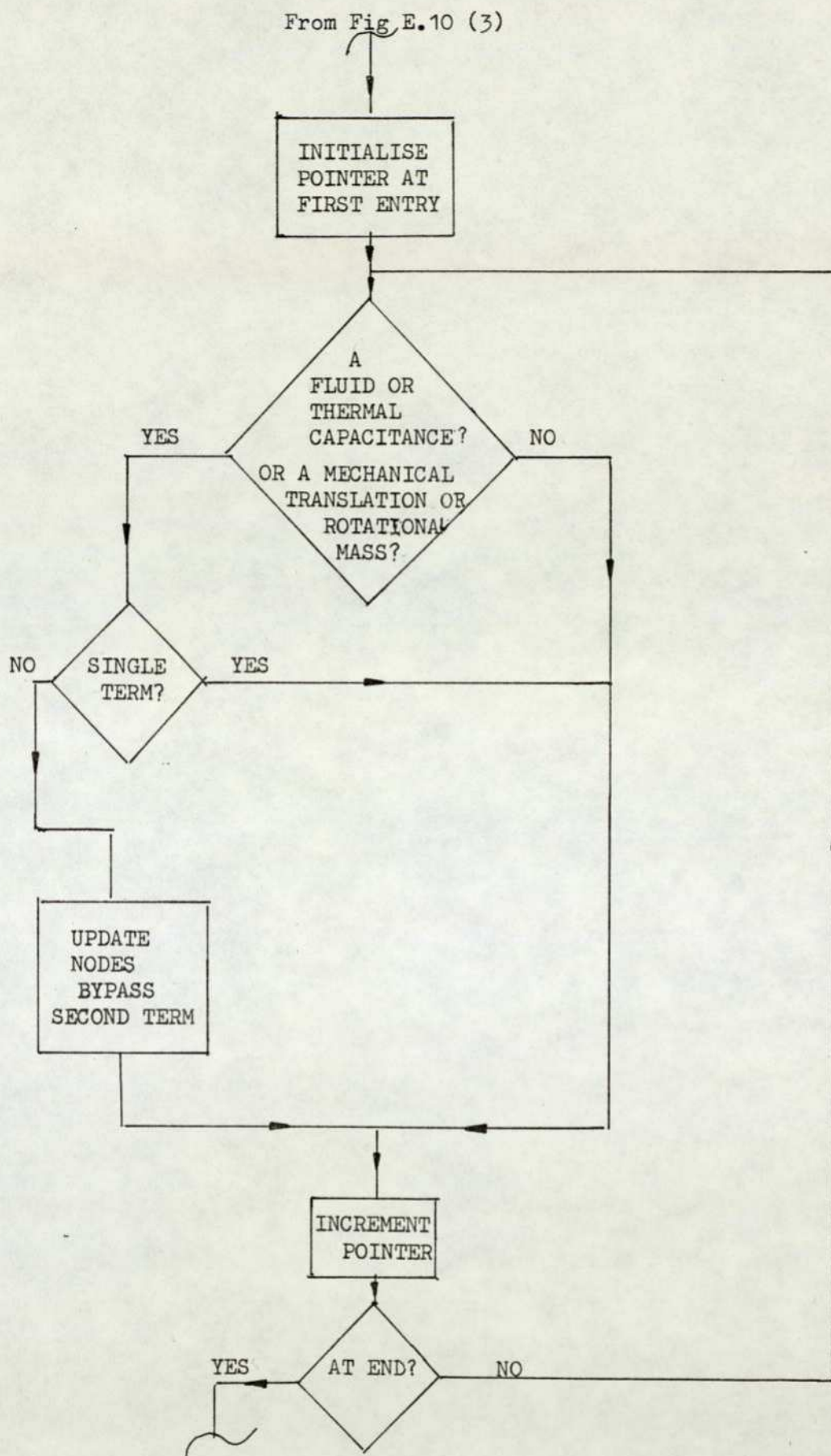
FREE: TO IDENTIFY A FREESPACE

Figure E.14

The next section (Section 3) modifies the element connections (topology). There is a slight preference here, again over outputs, as in general deletion takes place thereby providing a reduction in the model size. Certain elements may be topologically convenient to model in series, but must in fact be in parallel to the rest of the system, or connected to the 0 node. This is a fairly simple matter to consider with the LINK array. (See Fig E.15).

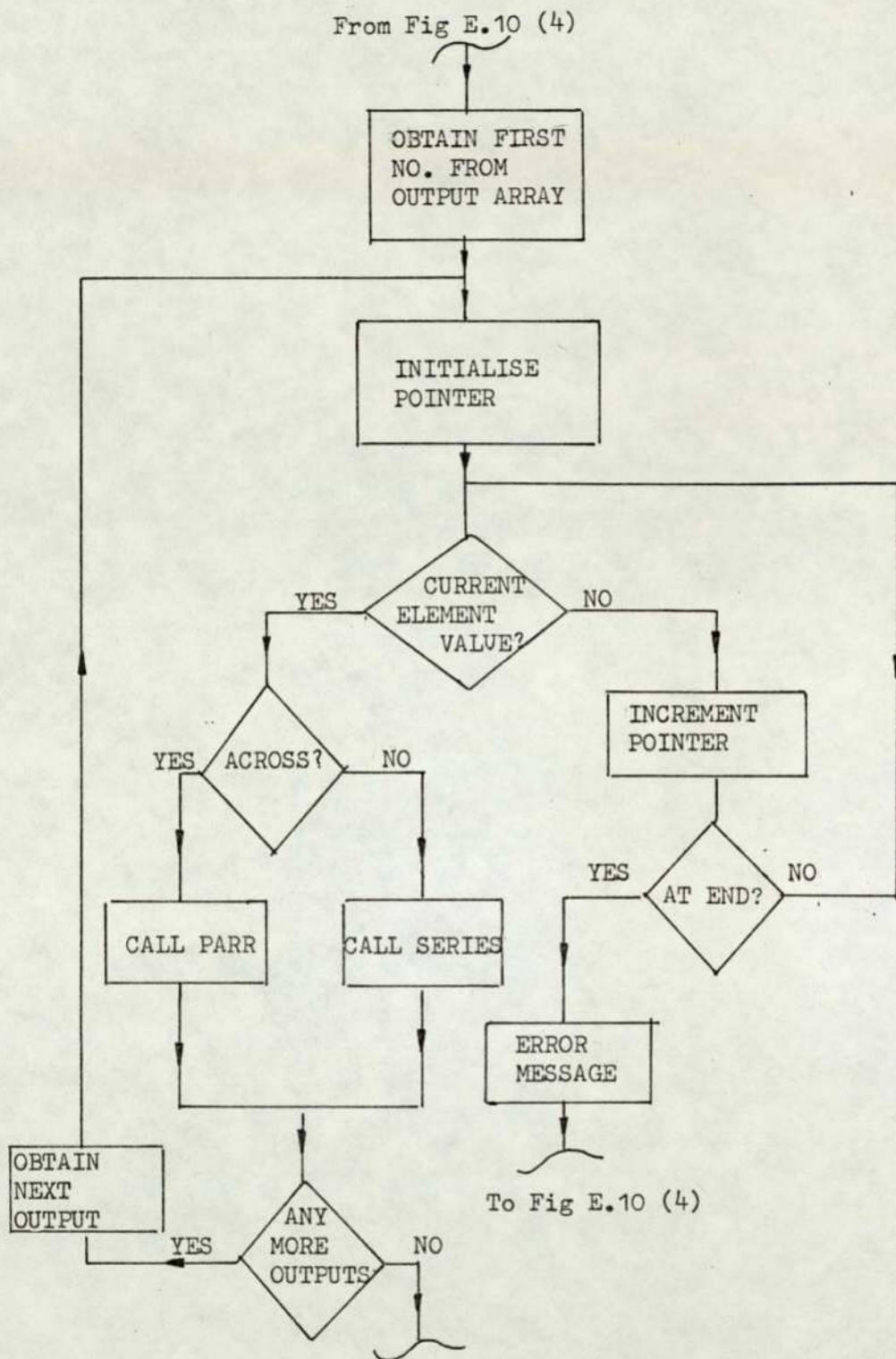
The outputs are now implemented. The method has been described in Chapter 5. A flowchart is shown in Fig E.16. The user has already given the information whether it is across or through. Either a parallel passive element or series passive element is then inserted respectively. The flowcharts of both series and parallel insertions are described in Fig E.17 and Fig.18.

Taking SERIES first, a two term element must be inserted. Once this is done another array in conjunction with the output array references the address of this inserted element. Hence in reality only passive elements can be observed. For PARR, whether an across component of single terms or an across of a two term element must be ascertained. As before this is also separately addressed. Both routines (SERIES and PARR) are used extensively in the EXPAND and INCLD routines.



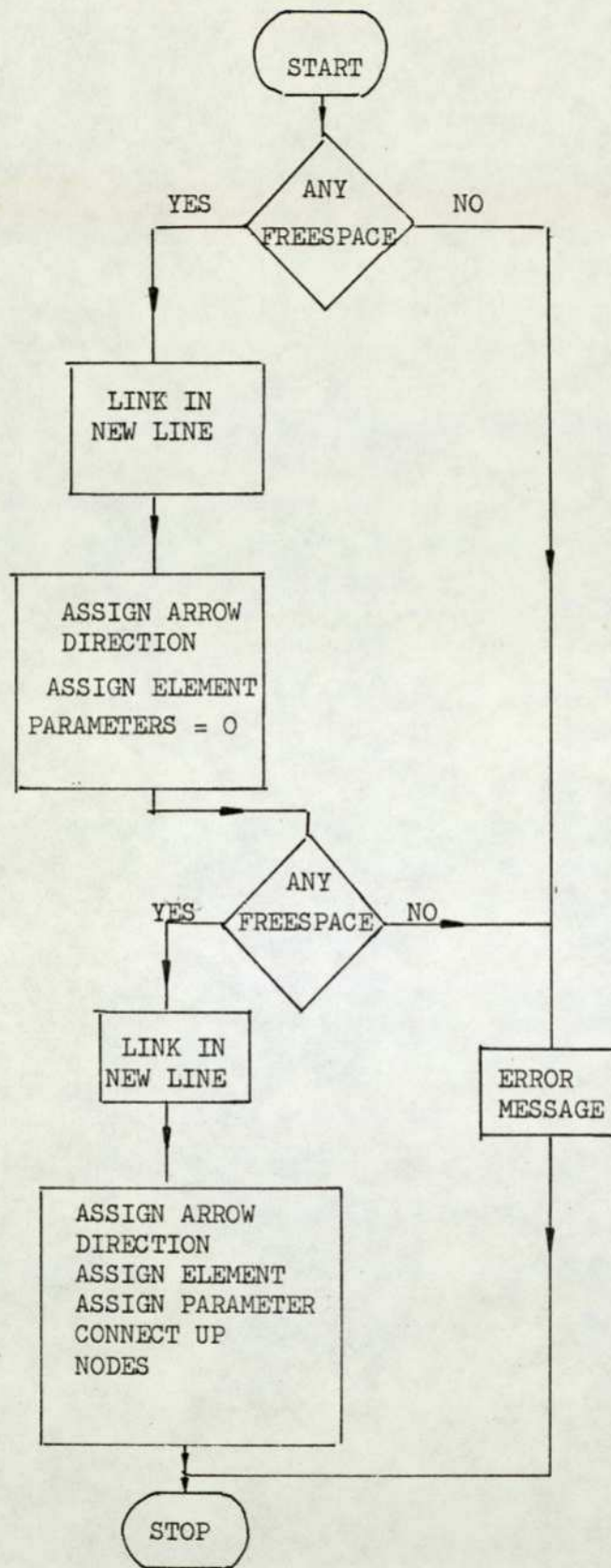
Flowchart of changes to element connections

Figure E.15



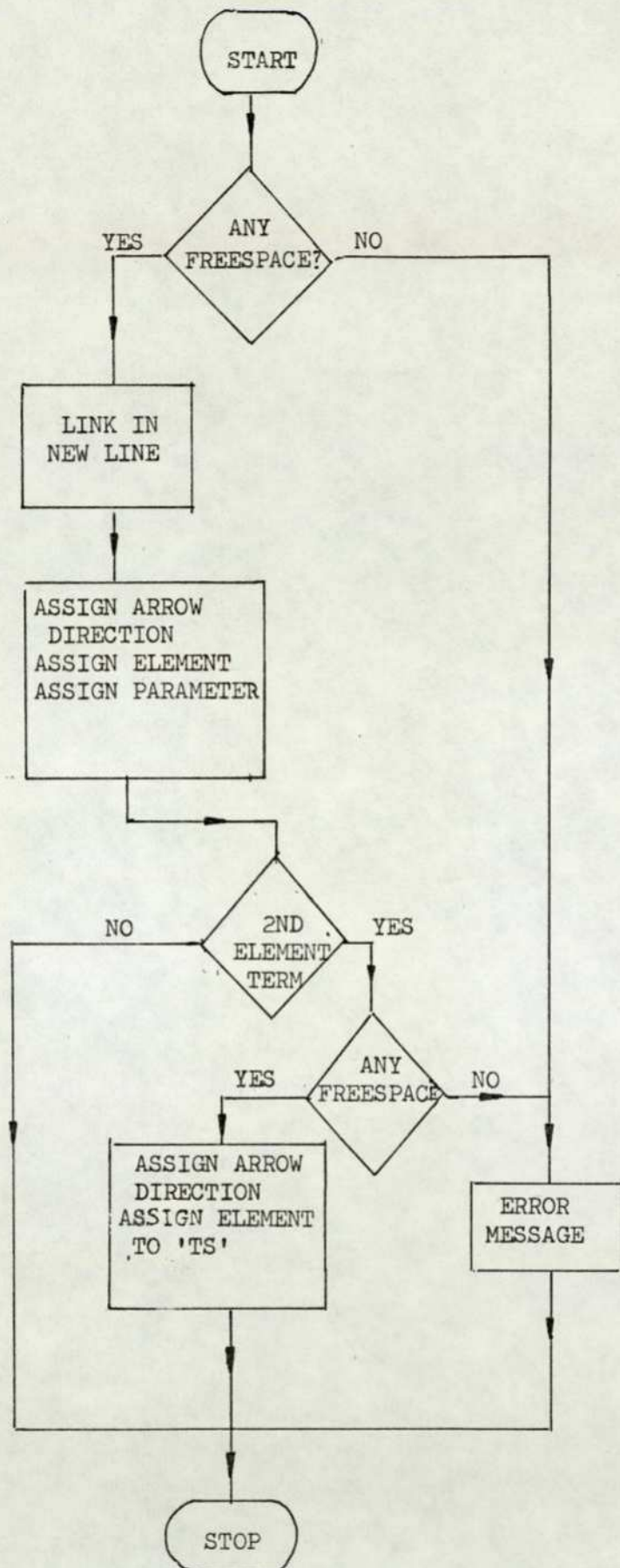
IMPLEMENTATION OF OUTPUTS (LIN/NONLIN)

Figure E.16



SERIES: INSERTS OF A PASSIVE ELEMENT IN SERIES

Figure E.17



PARR: INSERTING A PASSIVE ELEMENT IN PARALLEL

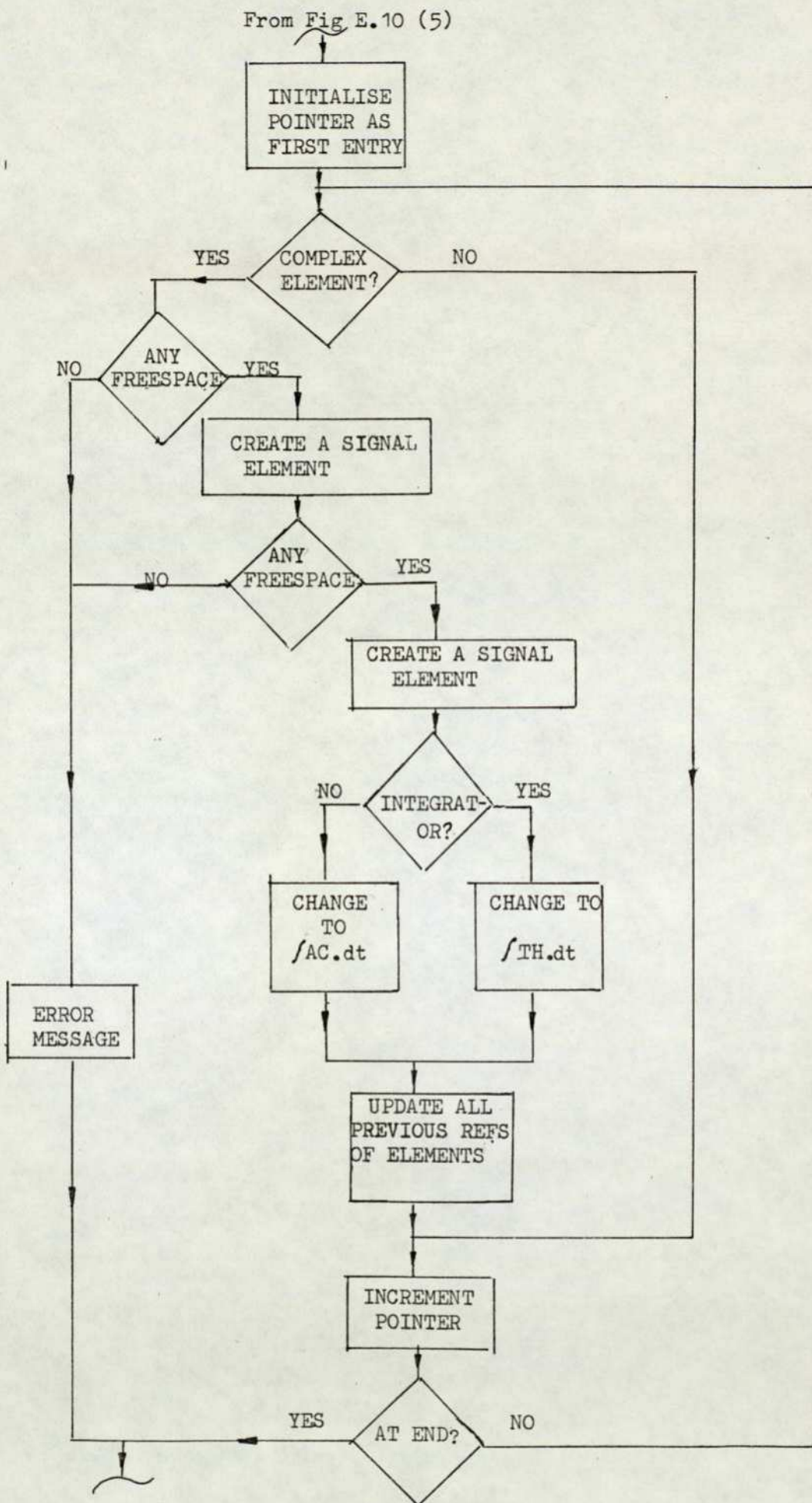
Figure E.18

The nonlinear terms are also considered at this stage. In fact the program makes no distinction here as they are also generated by referencing either a through or across passive element—which provides the source of the nonlinear effect.

Moving on to Fig E.19, the more complex term (N.L. Capacitor and Integrators) are now modelled. These can become five or six elements eventually. It is thought wiser to consider these terms after the output references, so that each model can perform the individual updating necessary w.r.t. the interfaces generated between the models and the rest of the system. The flowchart shows all three types of element generated. In general the interconnections are identical, and it is only the elements that are different.

Once all the preceeding terms have been implemented the signal terms are entered. This is shown in Fig E.20. There are four types of signal and although they need no further reduction they again must have passive elements inserted. The signal routine described in Fig E.21 is considered another common utility routine.

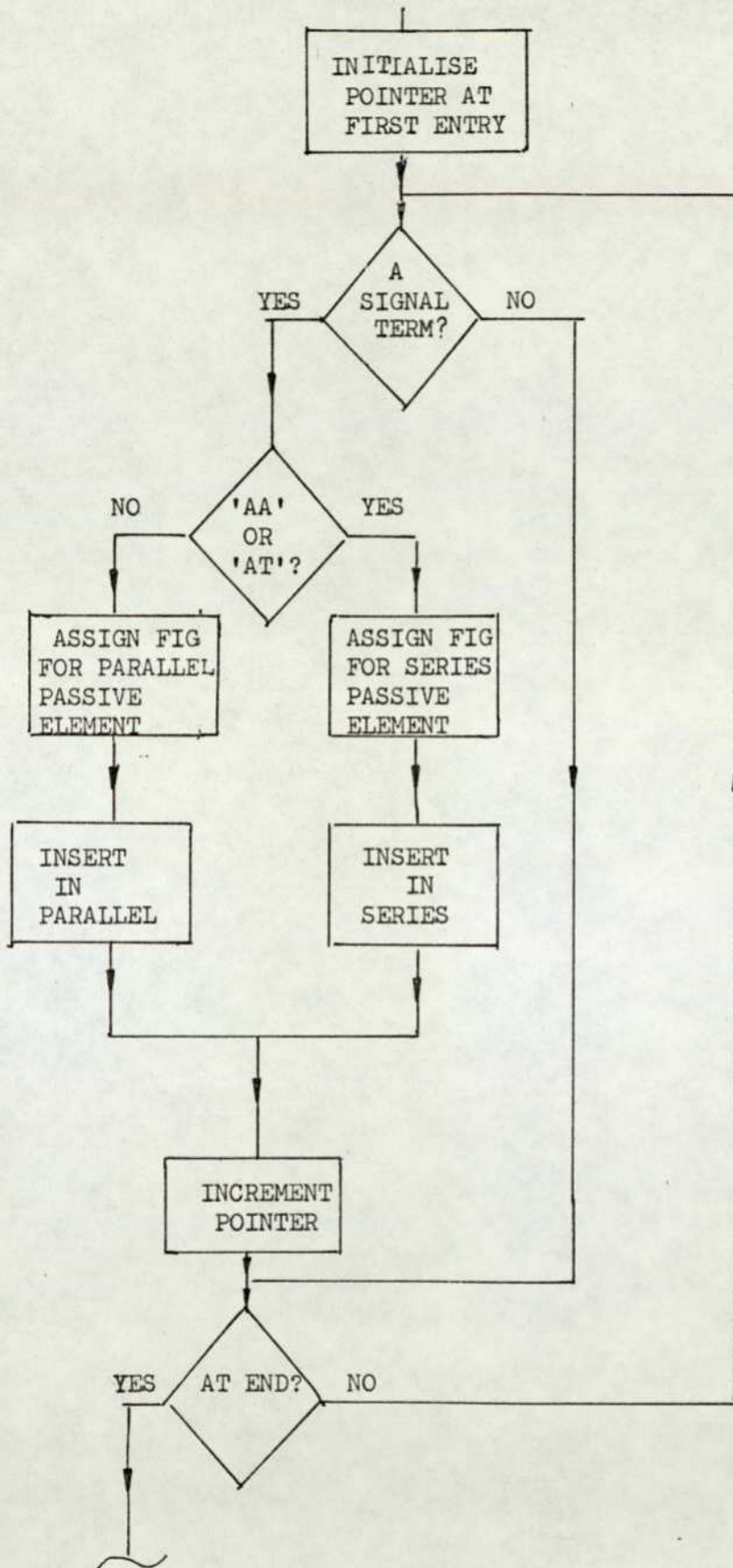
The next routine and its allied subroutines to be called is INCID. This determines the incidence matrix and the 'TH' & 'AC' dependences. A flowchart of the main areas of this routine is shown in Fig E.22. This is a large subprogram, and unfortunately due to overall memory space, has had to accommodate one or two other routines (as for EXPAND) which are separate functions in their own right.



COMPLEX ELEMENT INSERTION

Figure E.19

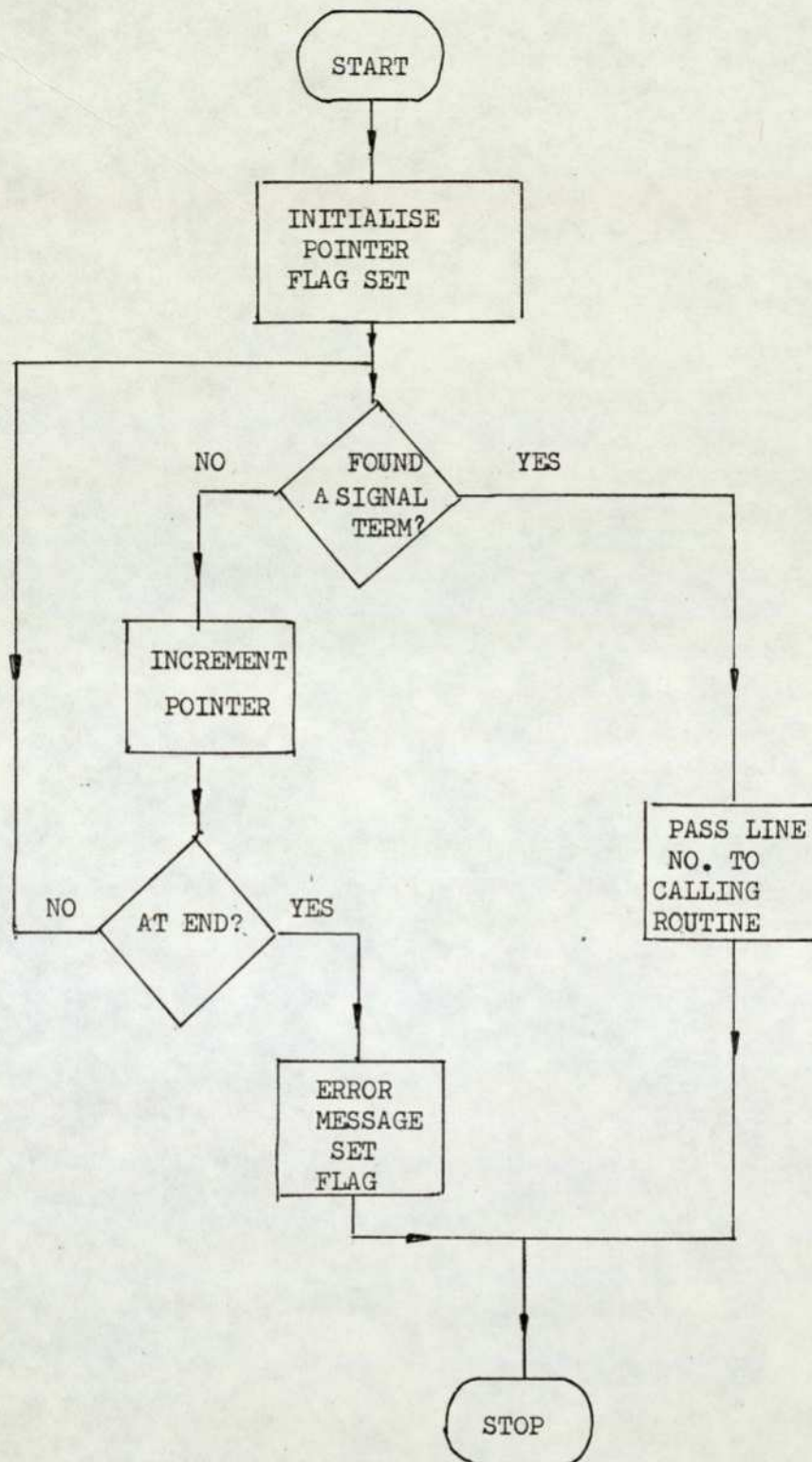
FROM FIG E.10 (6)



To Fig E.10 (6)

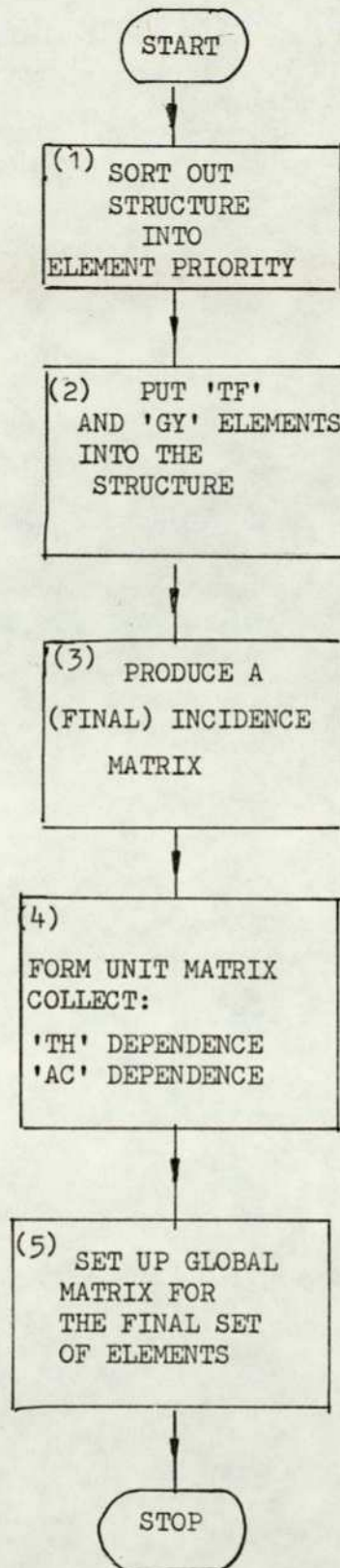
INSERTION OF SIGNAL ELEMENTS

Figure E.20



SIGNAL: TO FIND WHERE SIGNALS ORIGINATE

Figure E.21



INCID:TO PRODUCE AND COLLECT PREFERRED CAUSAL INCIDENCE MATRIX

Figure E.22

In forming causality it is necessary to start with a preferred form. This means that the elements have to be sorted into their correct priority level. Fig E.23 shows a flowchart of how this is achieved. The process of sorting can be programmed in many ways, each technique having features for a particular type of situation⁽⁵⁰⁾. For the particular system here, the main points are:

- a) Only necessary to sort out groups of elements as order within each group is unimportant.
- b) Only necessary to consider each sorted term once.

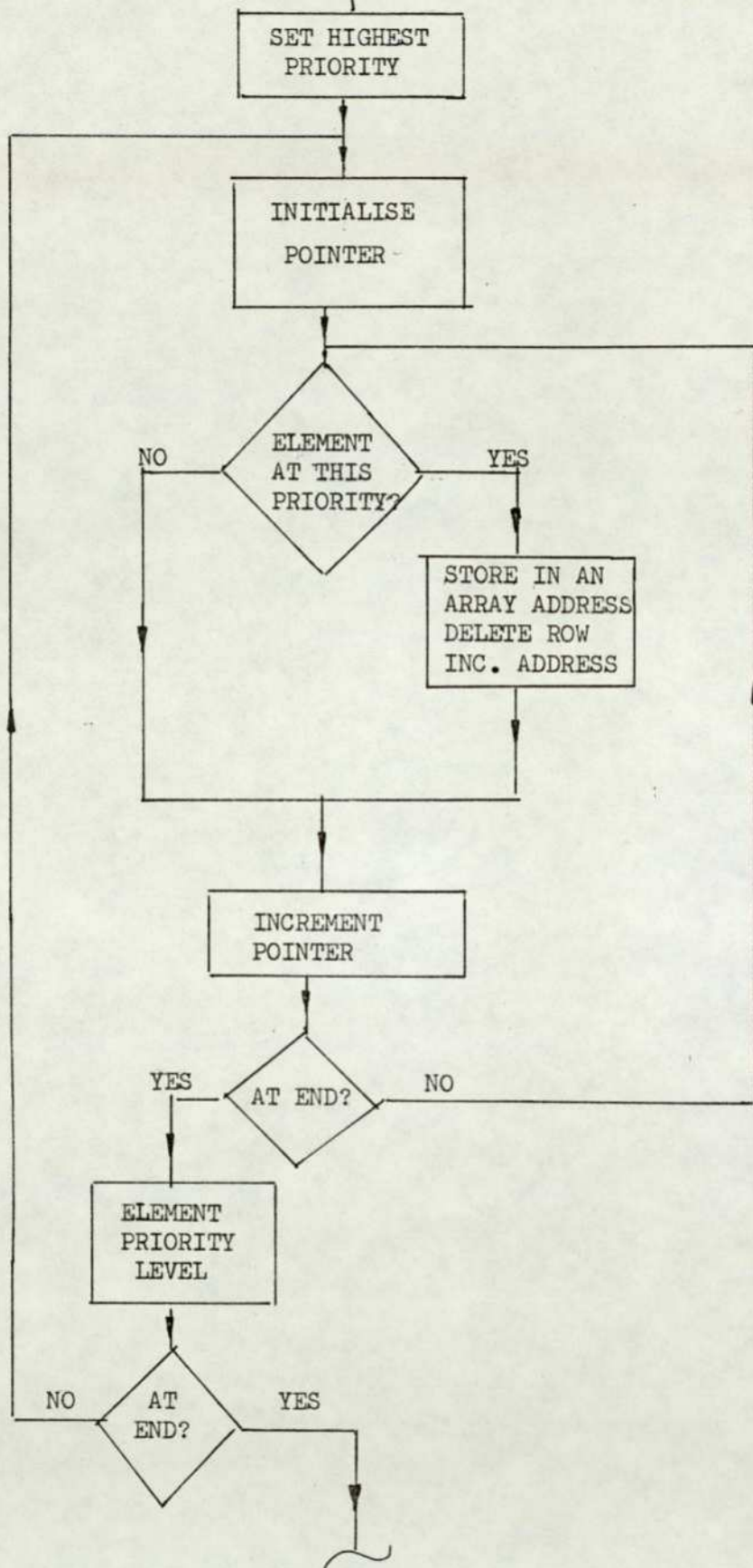
Therefore, if as an example

```
1,AS ,TO,1
2,R ,FR,1
2,R ,TO,2
3,C ,FR,2
4,C ,FR,2
```

the grouping will be

```
1,AS ,TO,1
3,C ,FR,2
4,C ,FR,2
2,R ,FR,1
2,R ,TO,2
```


From Fig E.22 (1)



To Fig E.22

SORTING THE STRUCTURE INTO CAUSAL LEVELS

Figure E.23

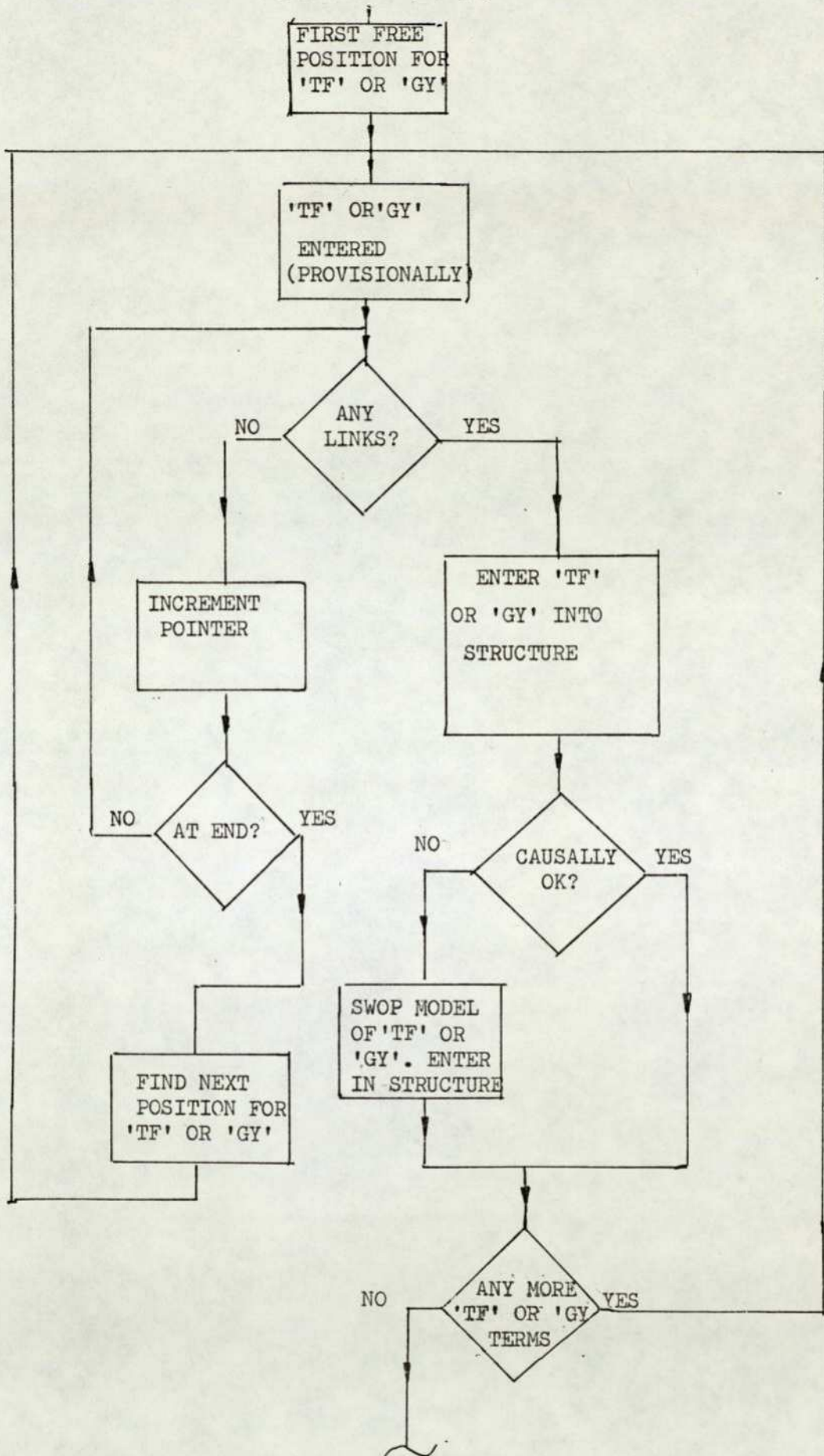
For a) it can be clearly seen that it is not necessary to sort out elements 3 and 4. For b) once each group has been formed then no more processing need be considered as the pointer can then proceed to the next lower priority grouping level. This is implemented in Fig E.23, where again link processing is used this time to avoid those elements already processed.

In general the sorting time (using this approach) has been found to be negligible in relation to other aspects of routine INCID.

Fig E.24 describes how to fit in the 'TF' or 'GY' elements into the structure. This can only be accomplished at this stage, as the 'TF' or 'GY' models depend on how well they interact with the overall system causality. The algorithm for implementing was described in Chapter 5. Fig E.24 shows how the 'TF' or 'GY' model is determined for any position in the structure starting from the first feasible position and incrementing until all the remaining 'TF' or 'GY' elements have been placed. The advantage of using linked lists is again apparent here, as the models can be inserted without having to re-sort.

The overall model being generated is checked for viability as all the 'TF' and 'GY' terms are included. Fig E.25 now considers the final incidence matrix where 'TH' dependences and 'AC' dependences can be ascertained. The

FROM FIG E.22 (2)

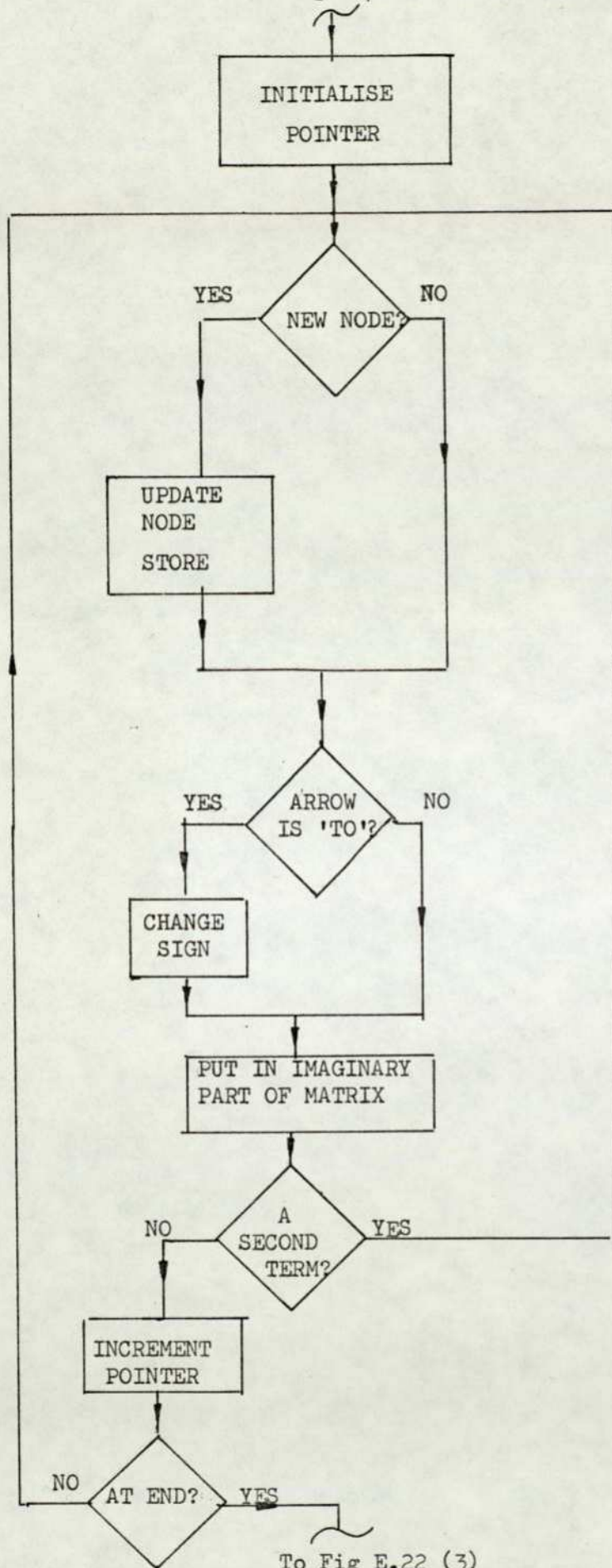


To Fig E.22 (2)

FLOWCHART FOR INSERTION OF 'TF' OR 'GY' ELEMENTS

Figure E.24

From Fig E.22 (3)



To Fig E.22 (3)

FORMING FINAL INCIDENCE MATRIX

Figure E.25

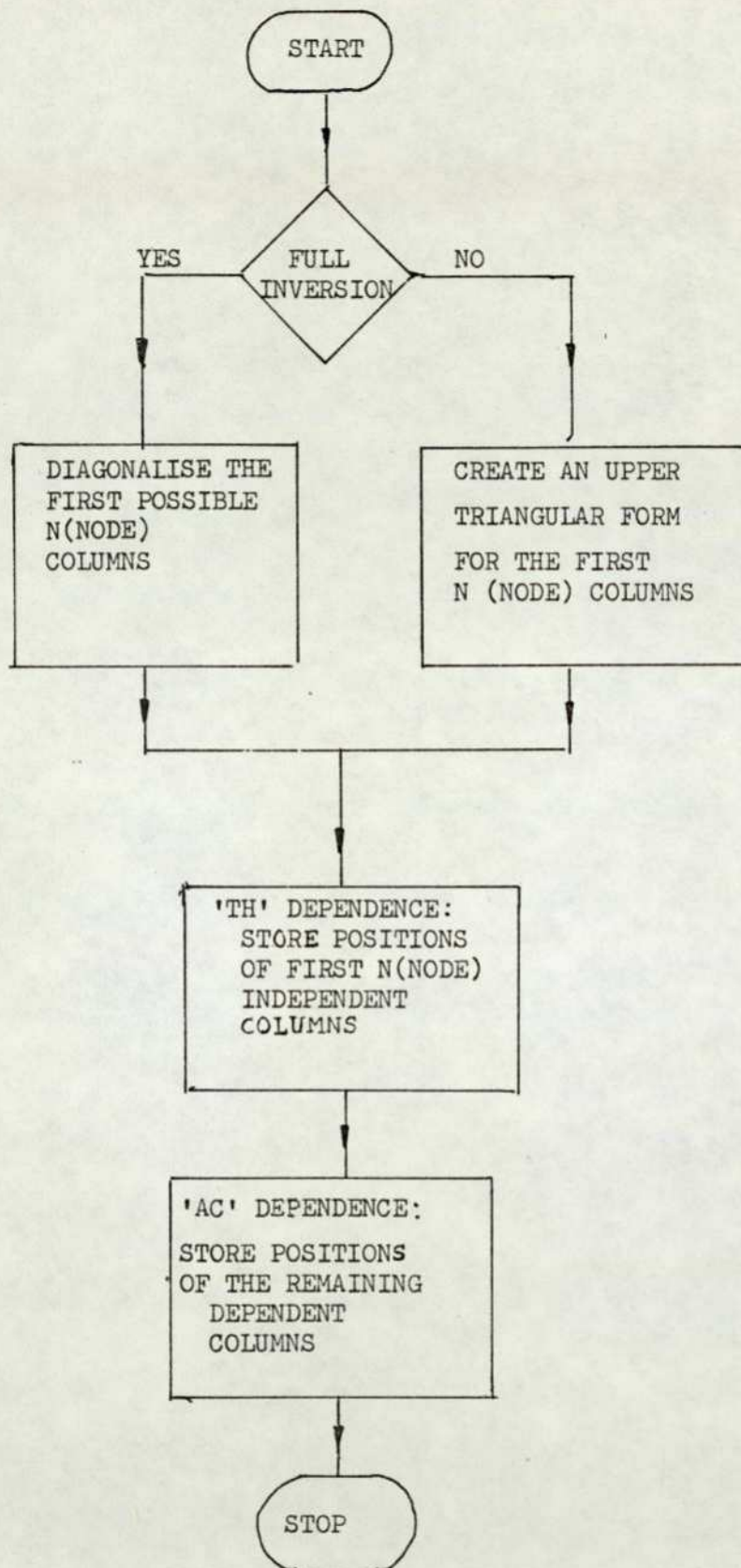
process is simply to feed in the final fundamental set of elements, (changing sign if the arrow is towards the node). As both nodes and elements are checked for each entry, the process is completely general and no ordering (except that elements of the same number must appear consecutively) is necessary.

In order to save space, the incidence matrix is formed in the imaginary part of the global matrix. The scheme is to ascertain the various cutset terms and then enter these on the corresponding real part of the matrix. Then the imaginary terms can be made zero - as they are no longer needed. This reduces considerably the amount of storage necessary.

In Fig E.26, the subroutine TREE carries out section Fig E.22(4). (In fact this routine was also used for placing the 'TF' and 'GY' elements. However it is shown here, as no 'TF' or 'GY' terms may appear in the structure). The process used is Gaussian elimination. However as the system uses sparse matrices the manipulation necessary becomes considerably more complex.

Essentially there are two ways to proceed:-

- a) Use special calling routines for adding, subtracting, multiplying, zeroing, etc. matrices. Then a Gaussian elimination uses these routines.



TREE:TO DETERMINE FINAL CAUSALITY

Figure E.26

- b) Use some addressing system so that a Gaussian elimination can identify the required element in an indirect function.

For the mini computer used it was found that a good set of routines to implement a) used approx 0.3 of a disc storage system. This was found to be unacceptable, as approx 1.1 discs were available for programs, the rest being the operating system and the compiled program itself.

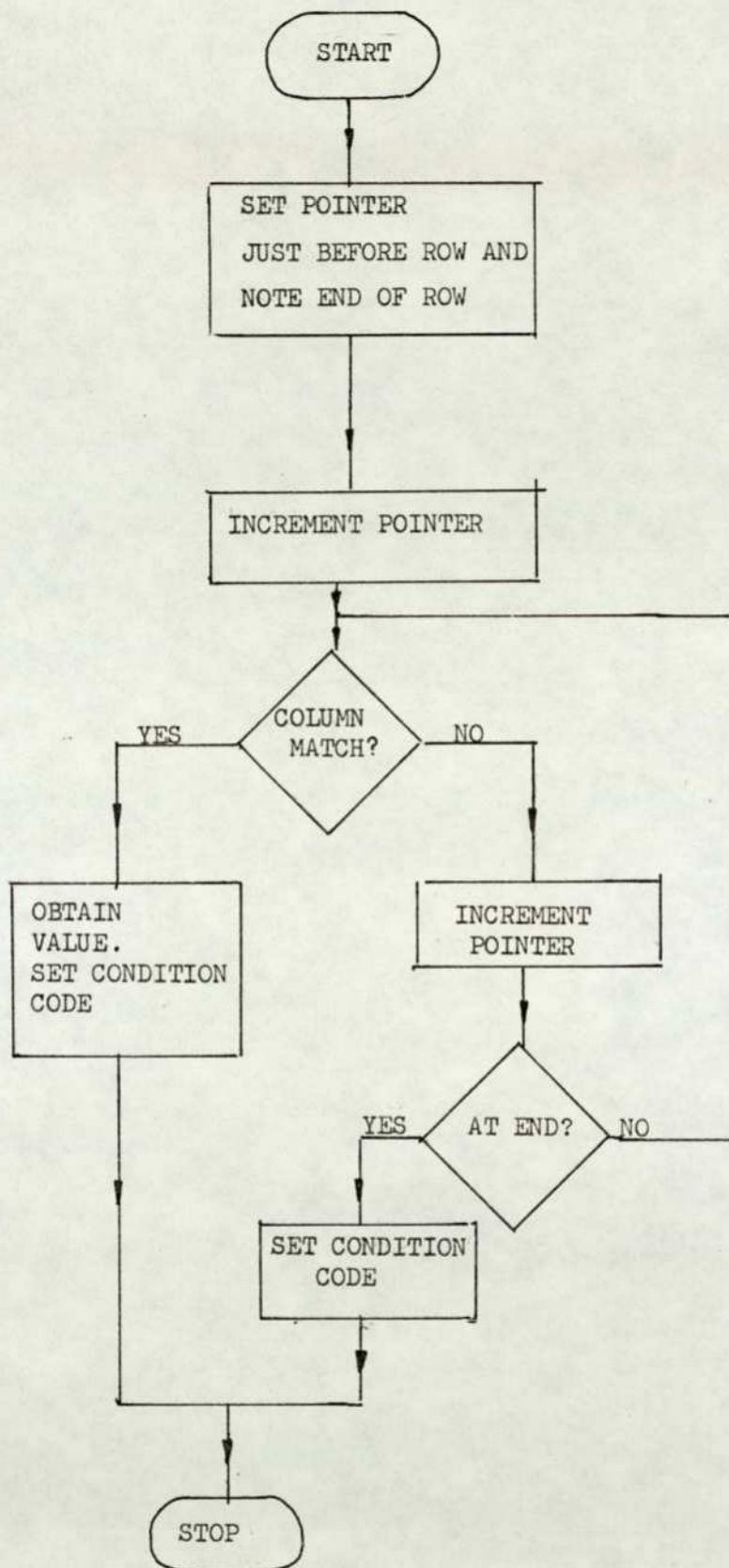
For b) only two routines need be considered. These are to 'get' a value from the matrix and 'put' a value into the machine. Because of storage considerations this latter method was used. Fig E.27 and Fig E.28 show the GET routine, and PUT routine respectively. These are now explained.

In storing a value in the matrix, it is of course necessary to also store the addresses. Normally this is inherent so that to find the value at I, J, for a two dimensional matrix we have:

$$\text{VALUE} = \text{MATRIX} (\text{I}, \text{J})$$

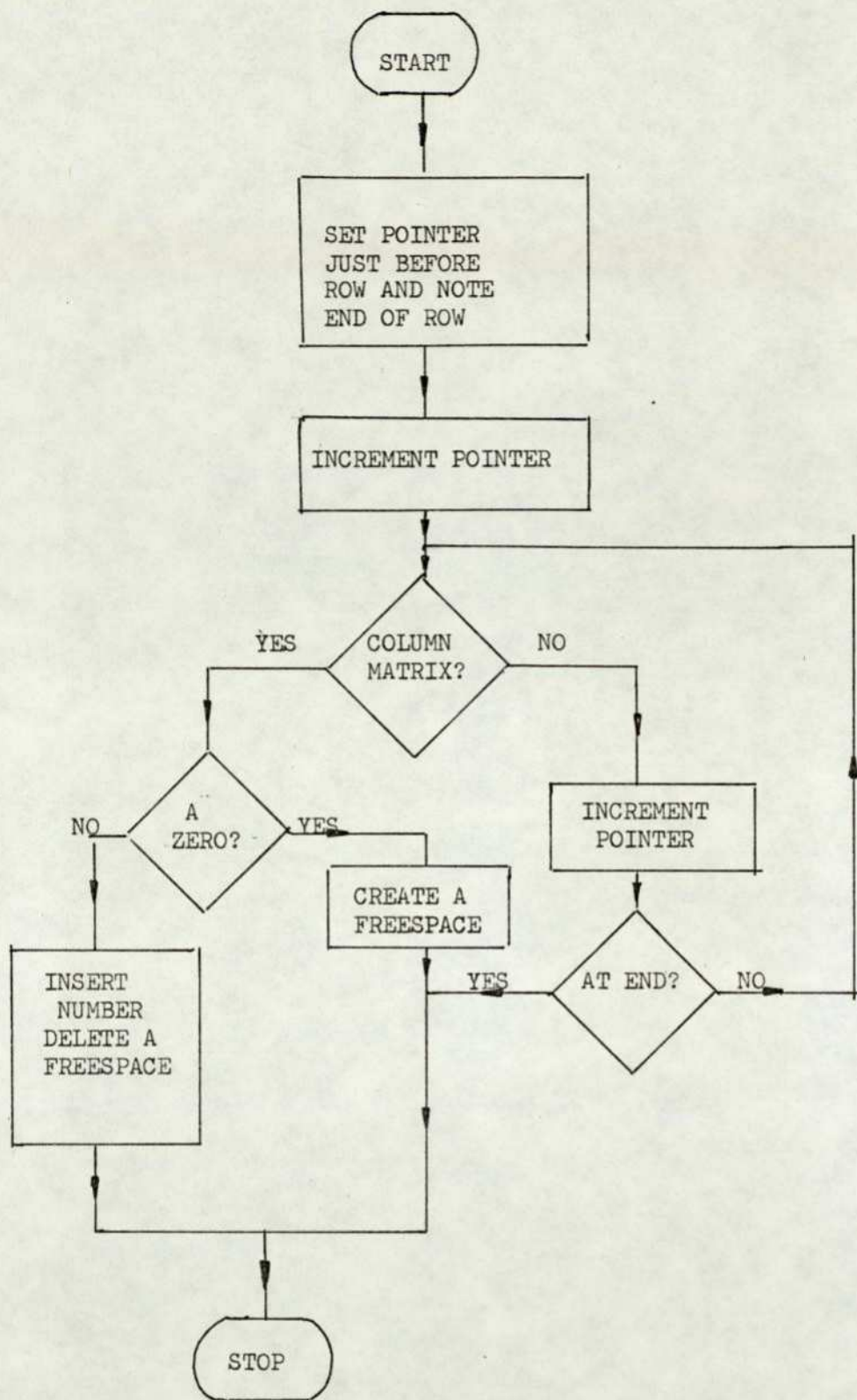
using only two dimensional form.

For the sparse matrix case one approach is to use three separate arrays so that if the value is stored in locations N



GET: TO OBTAIN A VALUE FROM THE SPARSE MATRIX

Figure E.27



PUT: STORE A VALUE IN THE SPARSE MATRIX

Figure E.28

```

I   =   ARRAYI (N)
J   =   ARRAYJ (N)
VALUE = MATRIX (N)

```

where now MATRIX is a one dimensional array.

For less than 30% full this form begins to save considerable space,⁽⁵¹⁾ especially as the arrays for I and J are integer. The main problem within this approach is the time taken to access a value. It is necessary to run through checking off ARRAYI and ARRAYJ until they match. Within a gaussian elimination routine this time would accumulate to become excessive.

Another idea is to have ARRAYI pointing to the first term of a row. Then ARRAYJ would again be the column as well as providing access to a value. So for

```

I   1 1 1 1 2 2 2 2 3
J   1 2 3 4 2 3 5 9 2
VALUES 1 2 1 3 2 4 5 1 2

```

This gives the row terms

```

ARRAYI (1) = 1
ARRAYI (2) = 5
ARRAYI (3) = 9

```


then to access element 2, 5 would require starting at position 5 and finding the relevant column. This naturally provides faster access time.

This is essentially the technique employed for both GET and PUT. However as the pointer can only move forward it has to access the previous element so that an insert into the first column position for a row can always be made. The method is particularly suitable for very sparse matrices (although it is necessary to have at least one value for each row), as there will be cases when only one term need be accessed, providing a near optimum access time. If a value does or does not exist a condition code specifies the next non-zero value so that the next column is immediately available.

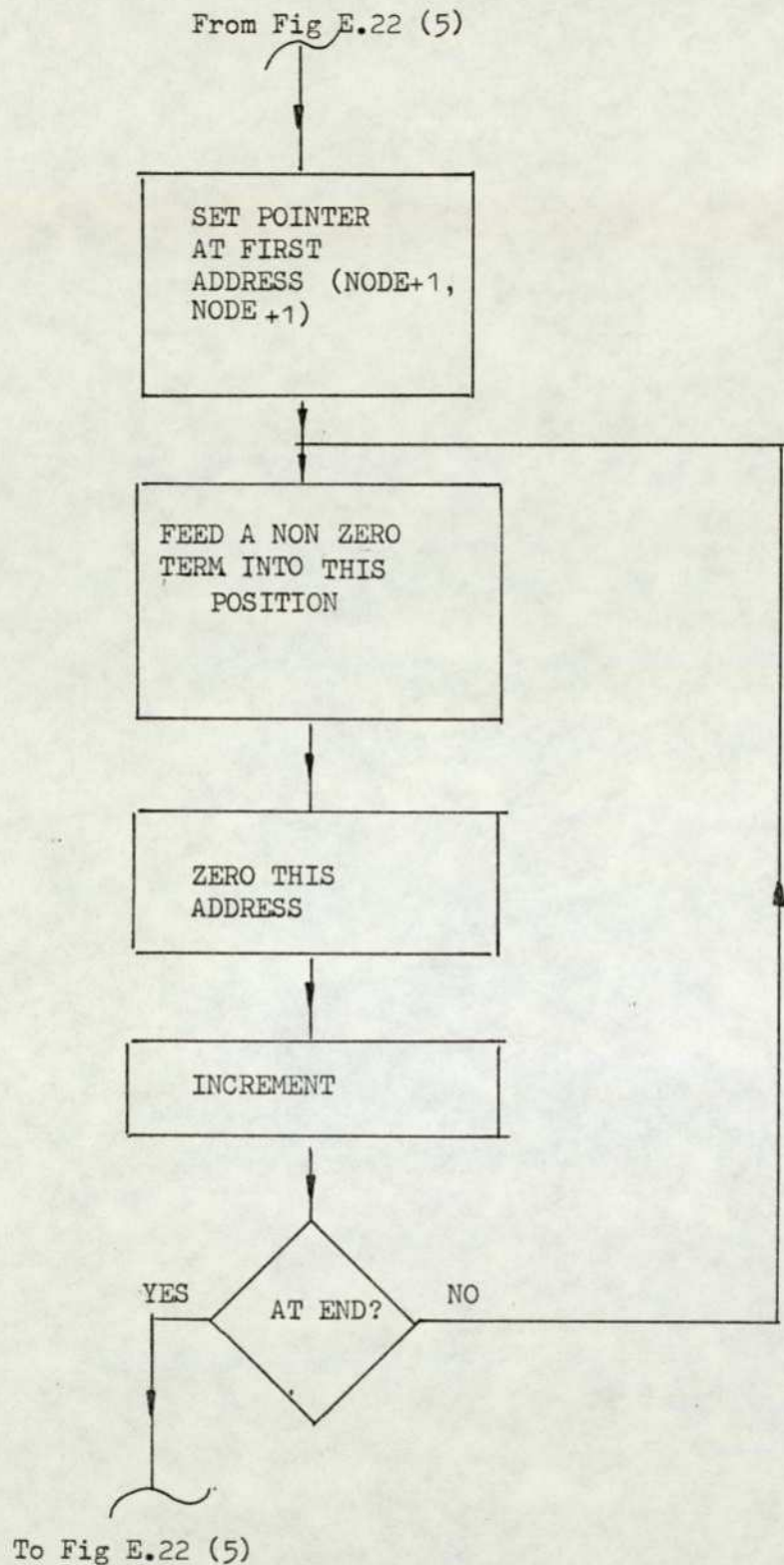
The advantage with link processes is the ease which elements may be inserted or deleted. If a non-zero value is to be inserted where there is no term at this location, then freespace is found (if possible), and if a zero value is to be placed where before a non-zero value existed then a freespace is created. As both freespace is used and then re-used, it is hoped that the process will not overflow. This depends a good deal on the 'fills' that may be created⁽⁵²⁾. However it would appear from experimentation that 'fills' are not excessively created on the global matrix.

Returning to Fig E.26, the 'TH' dependences can be very easily gathered as can the 'AC' dependences. These terms are used to set up the partitioning necessary to transfer to the real part of the global matrix.

Finally for INCID, some extra work must be done with the data structure in use to allow the matrix to handle the fully-expanded model. The precise size will be a total of Node rows and Elements + Sources columns. (This is a necessary routine as each row must have at least one entry before the next row is created). (See Fig E.29).

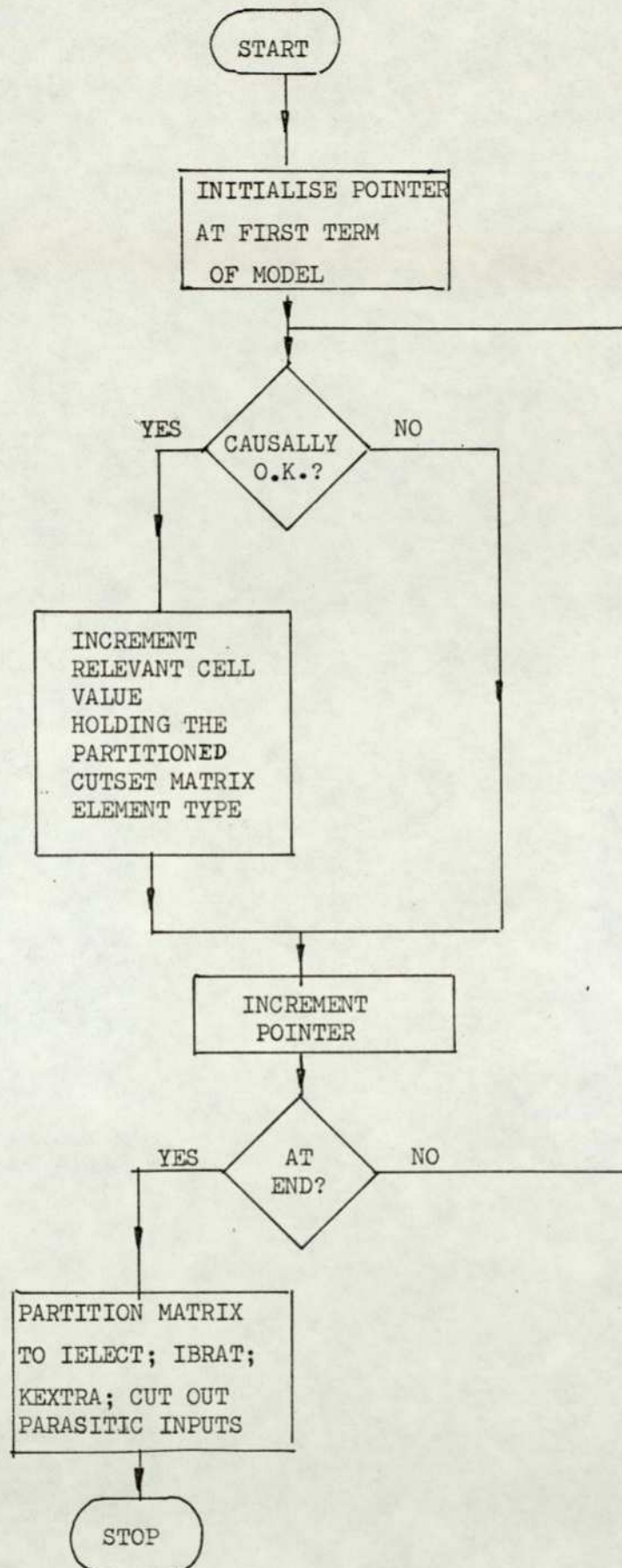
The next few routines to be considered puts the partitioned matrices from INCID onto the global matrix, and then proceeds in a fairly liberal manner to add in the relevant parameters. PUT1 (Fig E.30) starts this off by partitioning the INCID matrix as well as selectively separating out the actual to the parasitic inputs. Note that the outputs are themselves through or across independent step sources.

PUT2A (Fig E.31) now transfers these partitioned matrices in a row by row mapping. The process is predetermined as the matrix formed is of a symbolic nature and the placement is thereby precisely defined. All that is necessary is an initial starting point or co-ordinate setting at which to unload the partitioned matrix. Of great important here is to make sure that any relevant sections left unfilled, i.e. no dependent capacitors or inductors,



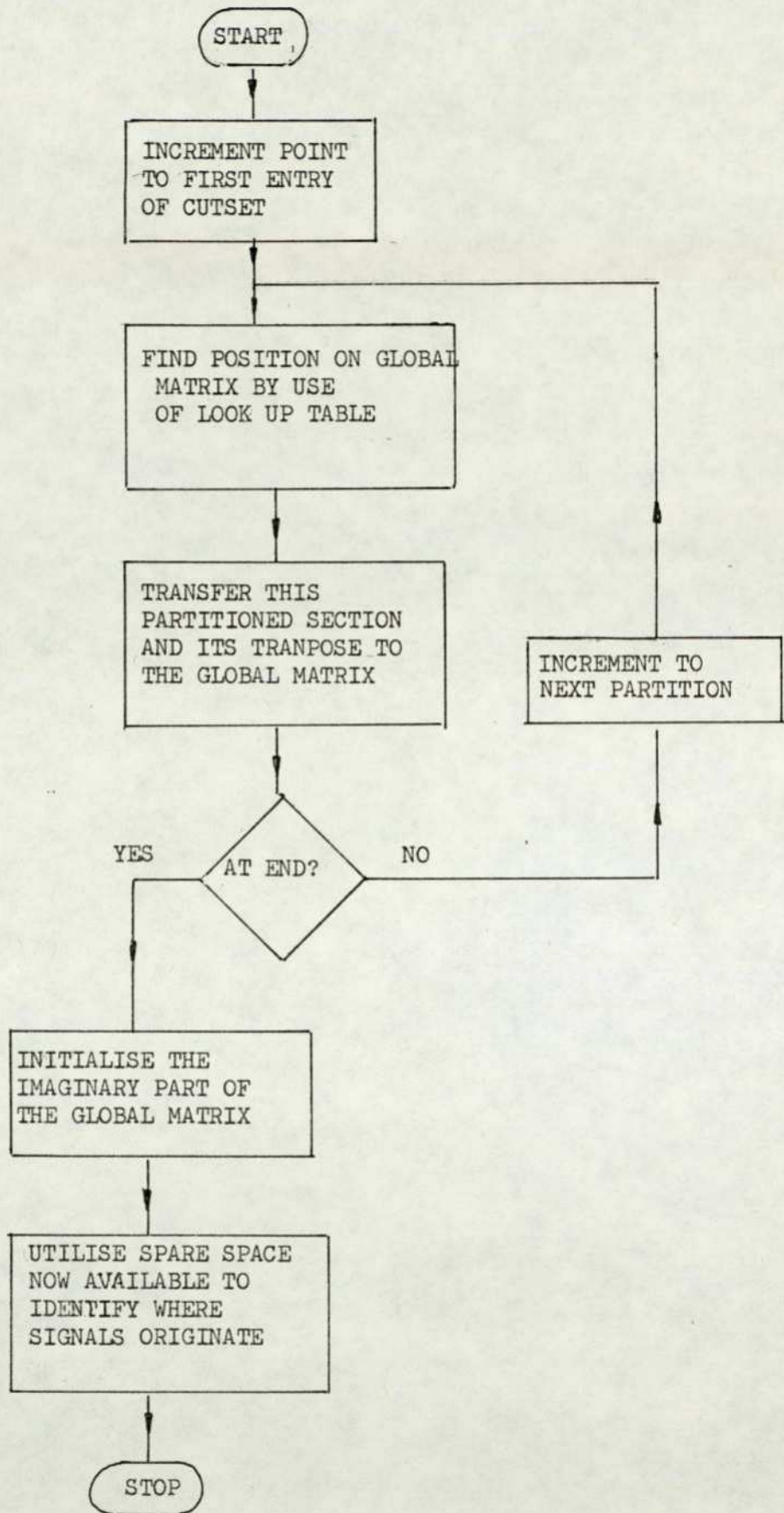
SET UP GLOBAL MATRIX TO HANDLE EXPANDED MODEL

Figure E.29



PUT1: DIRECT THE CUTSET MATRIX

Figure E.30



PUT2A: TRANSFER PARTITIONED MATRIX TO GLOBAL MATRIX

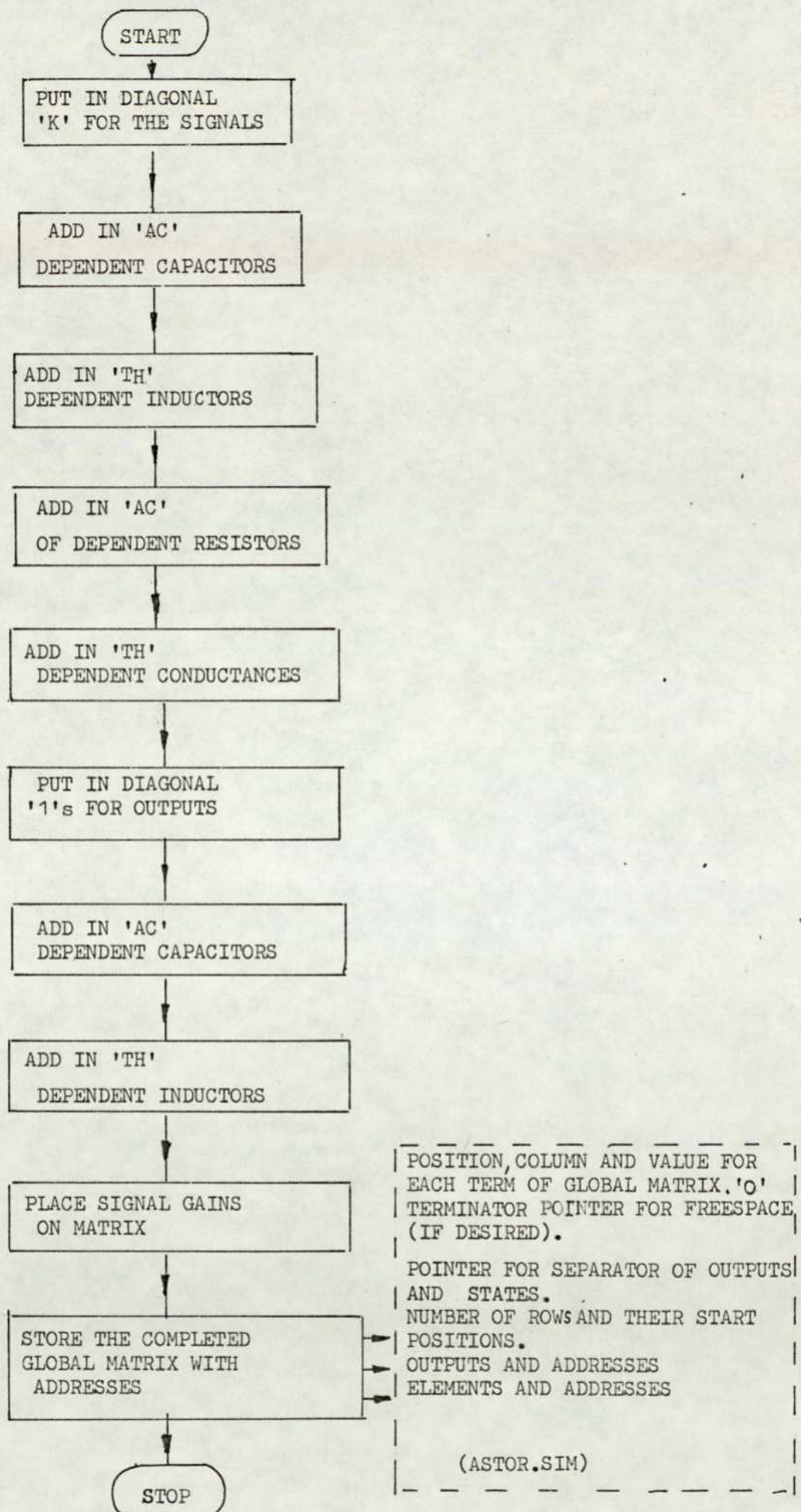
Figure E.31

will automatically be accounted for in offsets generated. All of this section is entered onto the real part of the global matrix.

Once the partitioned matrices have been transferred then the imaginary area used for INCID is free to be cleared. This is essential as parameter values may also be stored in these locations. Naturally with unlimited storage this would be unnecessary, and in fact the slower speed in utilising real numbers (in FORTRAN) to evaluate the incidence matrix would also be avoided⁽³⁹⁾.

PUT2B (Fig E.32) now proceeds to enter the relevant parameter terms. As these are entered the addresses are also stored for later use. The approach is to work through the global matrix in a deliberate function. Both the dependent capacitors and inductors and independent capacitors and inductors are stored in the imaginary part of the global matrix. This becomes equivalent to storing the relevant derivative (providing that the derivative is never greater than order one). At the end of this routine the whole global matrix is put onto a file (called ASTOR SIM). (This is to enable work to be carried out using other packages).

Essentially, a convenient storage process should be constructed. In this case the relevant addresses and values for both the real and imaginary parts are put onto FILE(3) of the P.D.P. FORTRAN IV language.



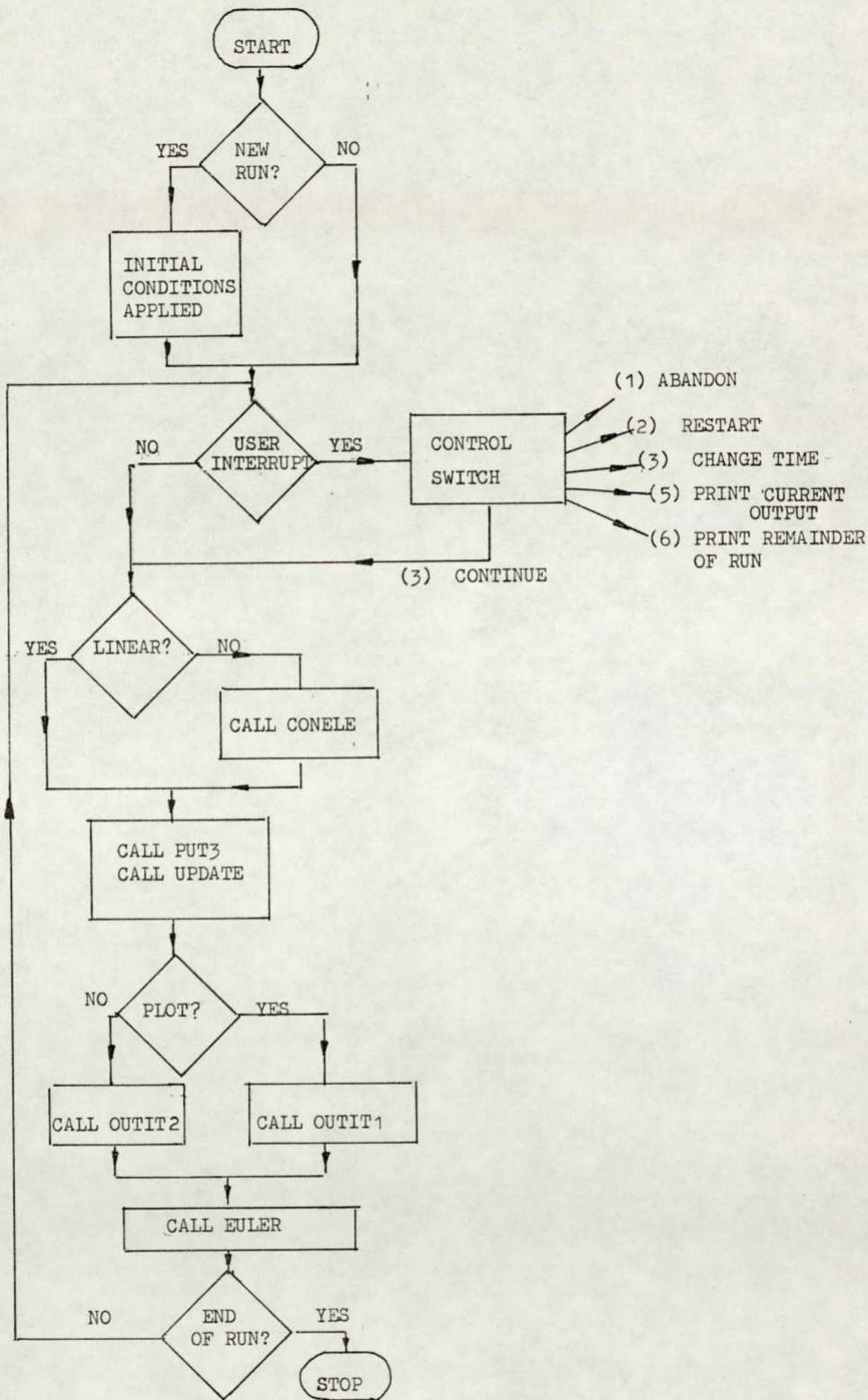
PUT2B: PLACING ELEMENT VALUES ONTO GLOBAL MATRIX

Figure E.32

Up to this point an overlap occurs between the linear and nonlinear response. This now branches slightly with a routine to control both types of problem (the linear and nonlinear solution). CHEOUT (CHECKOUT) shown in Fig E.33 in fact controls the complete evaluation phase.

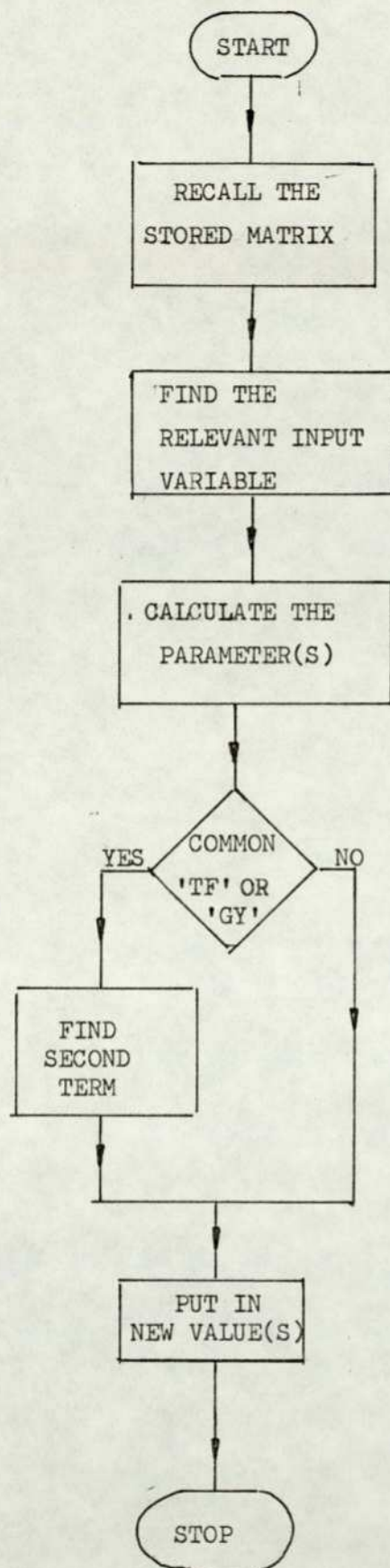
For a new problem the initial conditions need to be applied. This simply puts in the relevant initial value for each state. A user break (IBREAK) is then tested. (This routine gives the engineer control over a simulation run and would in any interactive system be essential). Unfortunately FORTRAN read statements wait for user input &(CR). Therefore this routine had to be coded in assembler language. In general, if a user interrupt occurs any possible list of command operations can be selected. For the package, six different commands are possible. The precise interaction with TIM and CHEOUT is not shown as the cases are fairly trivial.

At this point the program checks whether the model is linear or nonlinear and if nonlinear routine CONELE is called. This is shown in Fig E.34. Fundamentally the original global matrix is restored and the new parameters calculated using linear regression are positioned at their respective entry points in the global matrix. The only difficult case is the common modulation term of 'GY' and 'TF'. In this case a second term must be found and also updated.



CHEOUT: CONTROL OF TIME RESPONSE

Figure E.33



CONELE: TO FIND AND INSERT VALUES FOR NONLINEAR TERMS

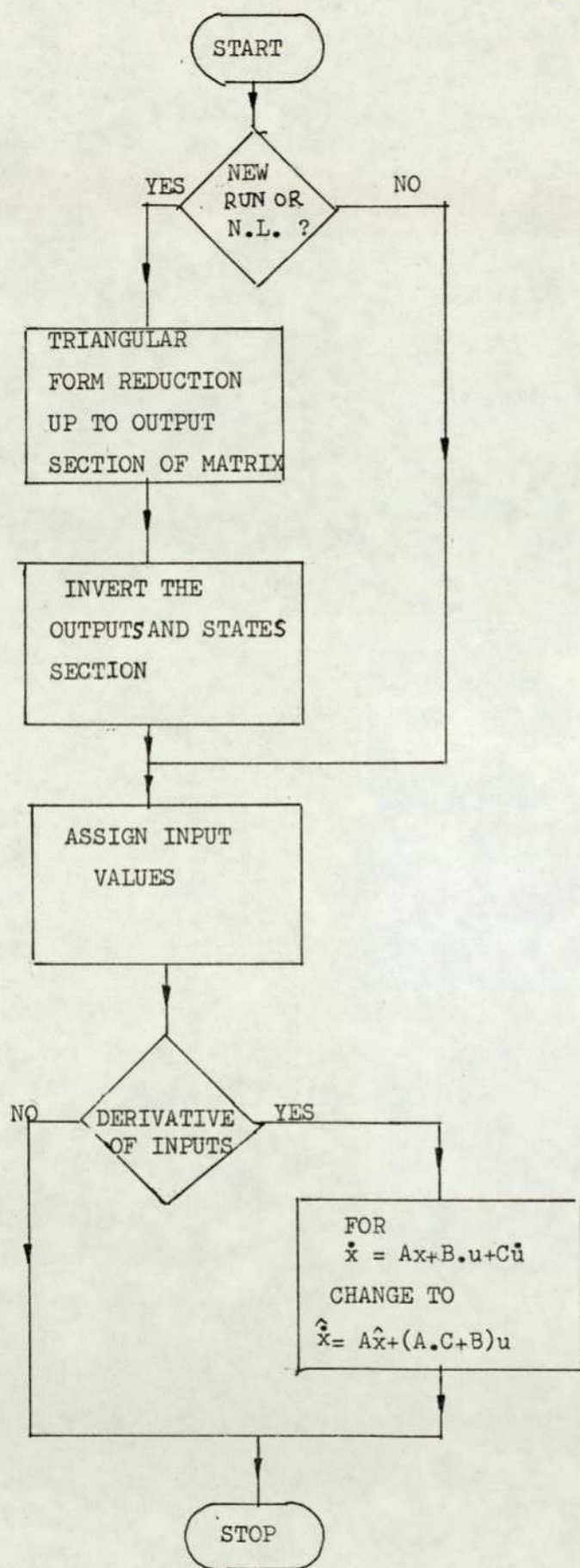
Figure E.34

After this CHEOUT then calls the routines to precisely determine the states and outputs. These are PUT3 and UPDATE. PUT3 is shown in Fig E.35. This uses a gaussian elimination procedure to produce the required states. The only area to be noted here is the check for derivatives of the input which occur because of dependent capacitors or inductors⁽²⁷⁾. In this case some matrix multiplication is necessary, adding to the time necessary to produce the overall states. The input terms that are time dependent (i.e. ramps etc) are also updated at this stage.

UPDATE is shown in Fig E.36. This provides the output quantities for both the linear and nonlinear analysis. Some extra manipulation is again necessary if there are derivatives input terms.

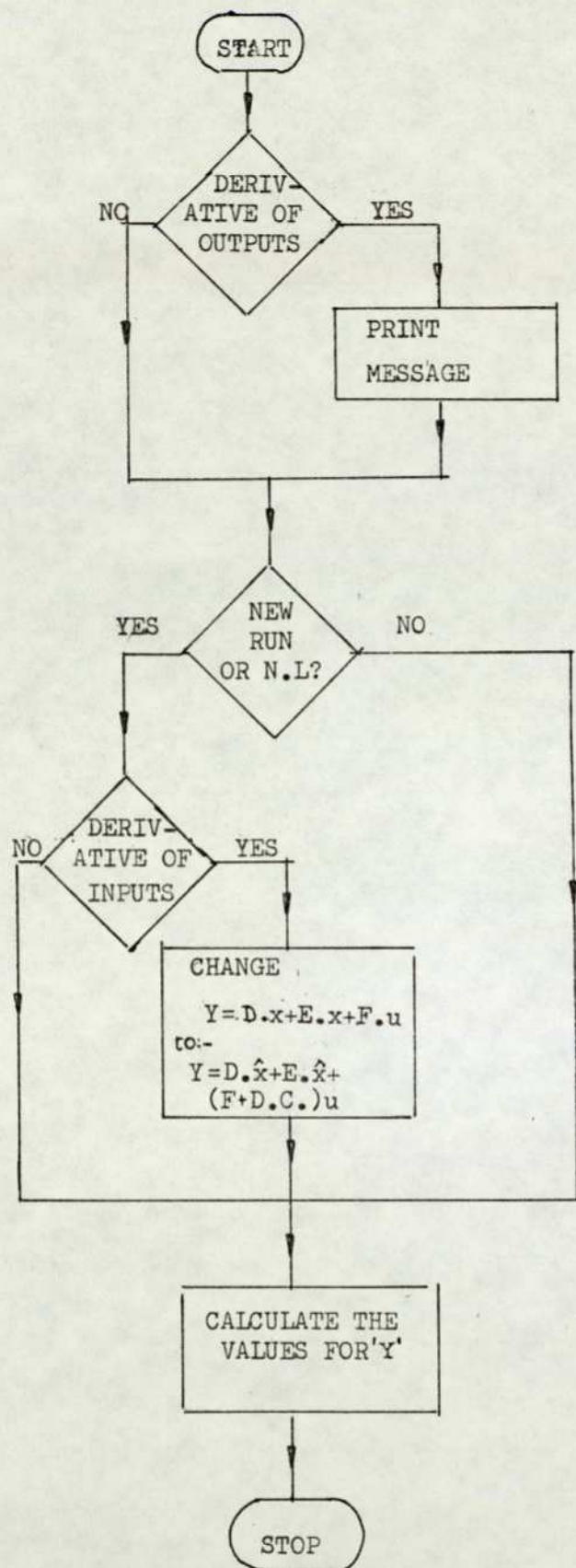
It is convenient here to consider the derivatives of the states (x) in the solution as well, simply because of the internal representation used. The outputs are then plotted. This is a separate section in Fig E.1 and will not be discussed further here.

After the value or values which represent outputs of interest have been plotted, it only remains to find new values for the states. Due to space limitations only one integration routine has been included. The one chosen however has been taken from an article specifically describing integration routines for C.A.D. work using minicomputers⁽⁴¹⁾. The advantages are long term stability



PUT3: START OF FORMULATION OF SYSTEM OUTPUT

Figure E.35



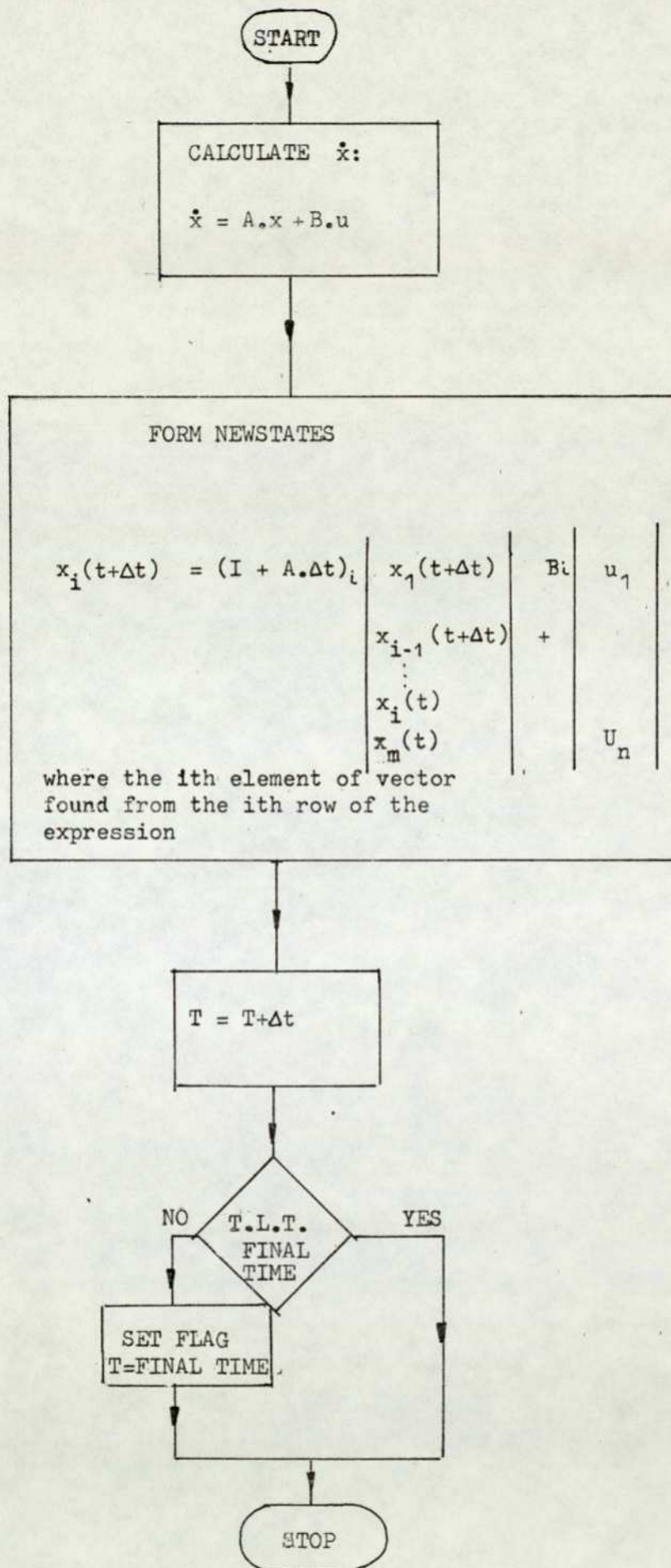
UPDATE: TO PRODUCE DESIRED OUTPUTS

Figure E.36

(useful if small time steps are used); simplicity in implementation (it is even easier to implement than simple euler); suitable for both linear and nonlinear models; semi-implicit giving a higher order accuracy and stability than trapezoidal. It is not as accurate as a fourth order Runge-Kutta, but it is much faster, and when they are compared on this basis, quite favourable performance is possible.

The subroutine is shown in Fig E.37. The routine also includes other computations as it is convenient for overlay reasons to have them here. This is rather unfortunate as these areas are independent of the integration formula used. The derivatives of the states are also obtained, and this speeds up the computation in UPDATE. Newstates then uses this modified form of euler (called sequential euler) to generate the new states. Some time comparison, and time updating is also performed. Because the time internal may have rounding-off errors, it is possible that there will be an overshoot of one integration step internal. Normally this would not matter on a graph, but it can be inconvenient on a tabulated response. The normal way to avoid this is to choose an error margin much smaller than ΔT .

Once EULER is complete, then CHEOUT allows exits back to TIM. This then describes a complete cycle for KDIR=3 shown in Fig E.10. Naturally many of the routines here are also called by other sections and in fact most of the remaining flowcharts are simply manipulating those already



EULER: INTEGRATION ROUTINE

Figure E.37

described. The steady state condition is explained in STEADY in the Frequency Section.

Section 4

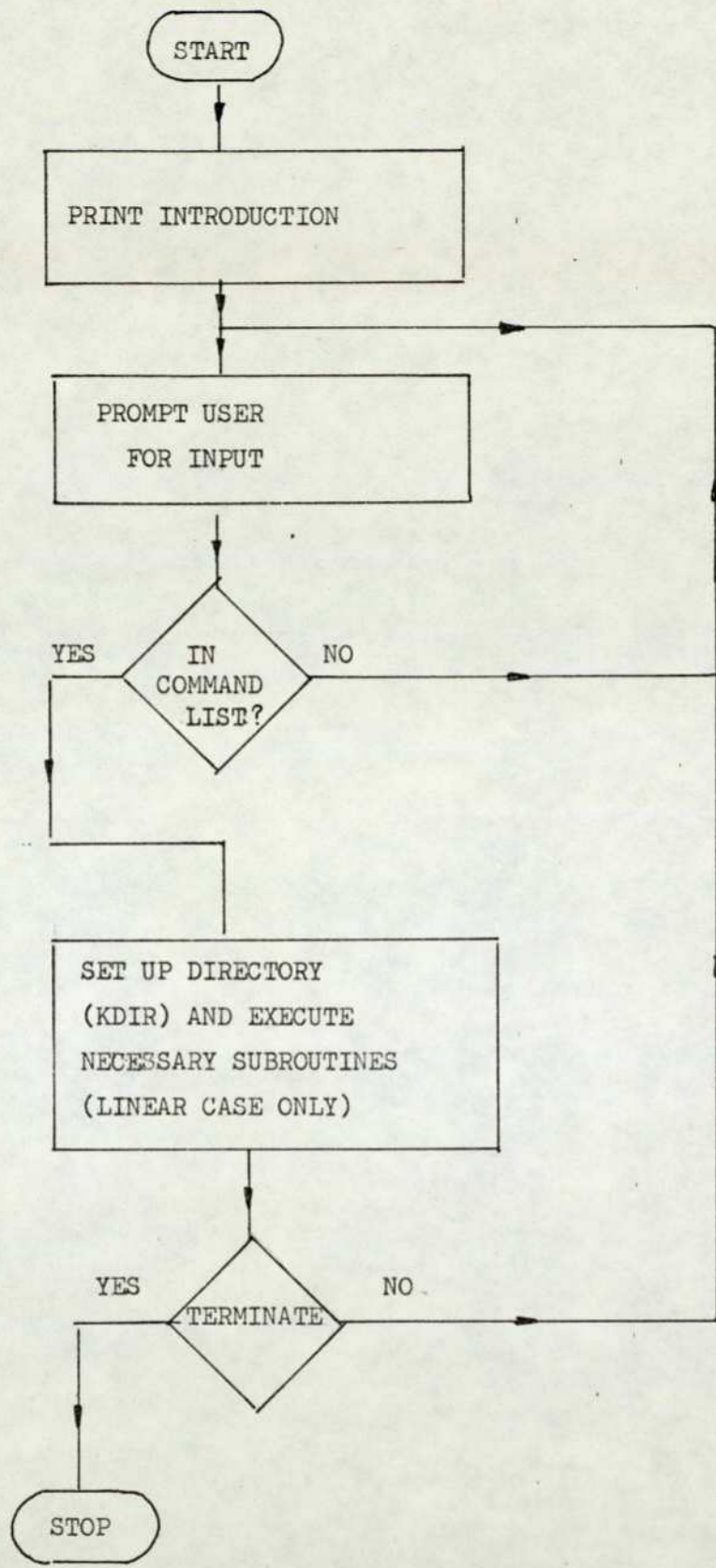
In Section 4 shown in Fig E.1 the outputs can be either tabulated or plotted. the possible combinations are, at the moment,

- a) Tabulate on the GT42 screen
- b) Plot on Tektronix
- c) Tabulate on Line Printer
- d) Plot on Line Printer.

Although these routines have been written for the package they are fairly standard of their type and so no flowcharts are given. In fact the only part that cannot be accommodated in standard FORTRAN is the plotting of points and lines on the Tektronix. However some assembler routines are available to do this job. These can simply be called as normal subroutines with arguments. For a lineprinter plot 80 divisions are possible for the Y axis and the first 10 are taken to represent time.

Section 5

Fig E.38 shows the command level structure once FREQ is entered. This is very similar to TIM, and indeed it is designed to be so!



FREQ: FREQUENCY / DOMAIN SOLUTION

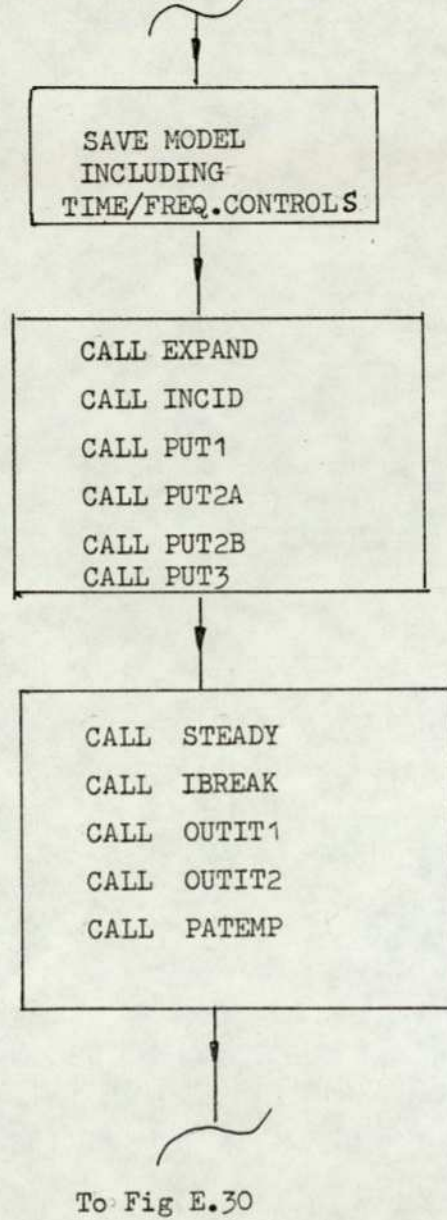
Figure E.38

For Frequency responses only the linear case is considered. An appropriate error message will occur if any data tables (specifying controlled parameters) are present.

Fig E.39 gives an illustration of the routines called in evaluating the frequency response. KDIR=3 provides the condition where a maximum number of the subroutines that can be called. Again there is a similarity between this and Fig E.10. In fact only two routines are different STEADY and PATEMP. These will now be explained. (STEADY shown in Fig E.40).

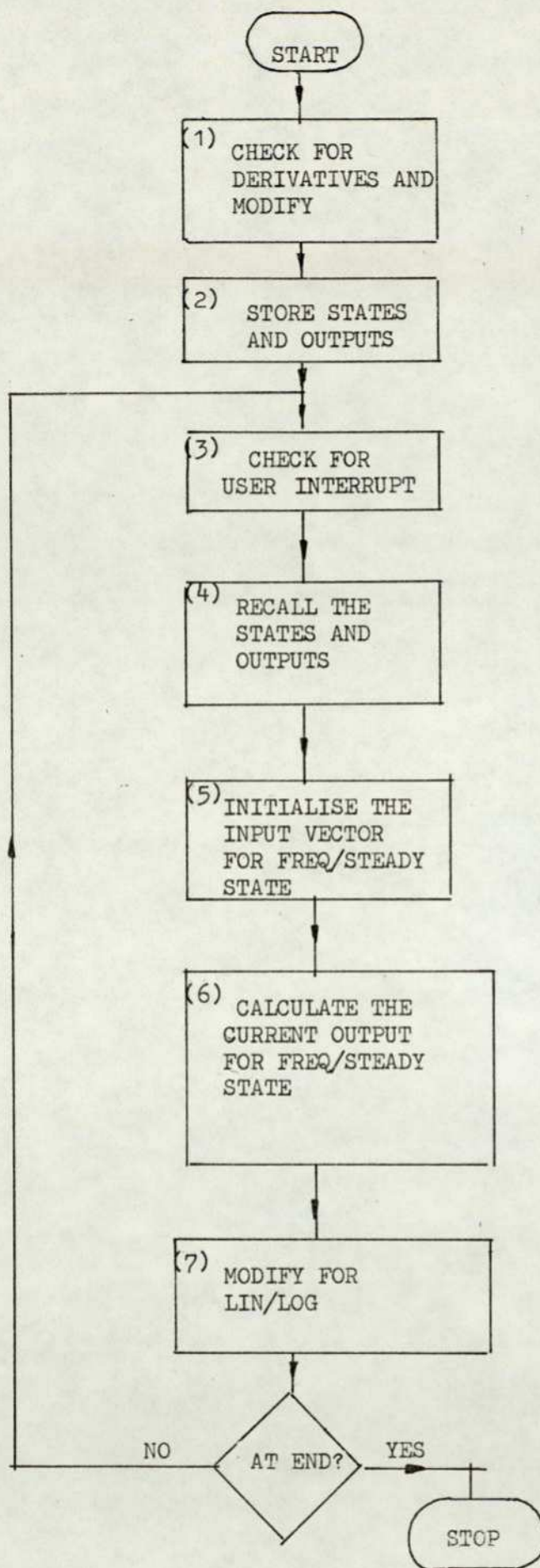
STEADY has a dual function of analysing both the frequency and steady state. This is another rather complicated routine and is split up in seven sections. Fig E.41 gives the first two sections, which modify the output equations for derivative terms and stores the corresponding state and output equations produced. (The reason for storing these equations is so that various frequencies of interest can now be analysed by simply recalling the equations and substituting the appropriate value of frequency). This is described, in slightly more detail in Fig E.42. The control of the frequency evaluation is initially checked for user interrupt, giving as for the time response, six possible choices. Then after the states and output equations have been re-linked, the output matrices are multiplied by:-

From Fig E.38 KDIR=3



SEQUENCE OF CALLS FOR SOLUTION WITH KDIR=3

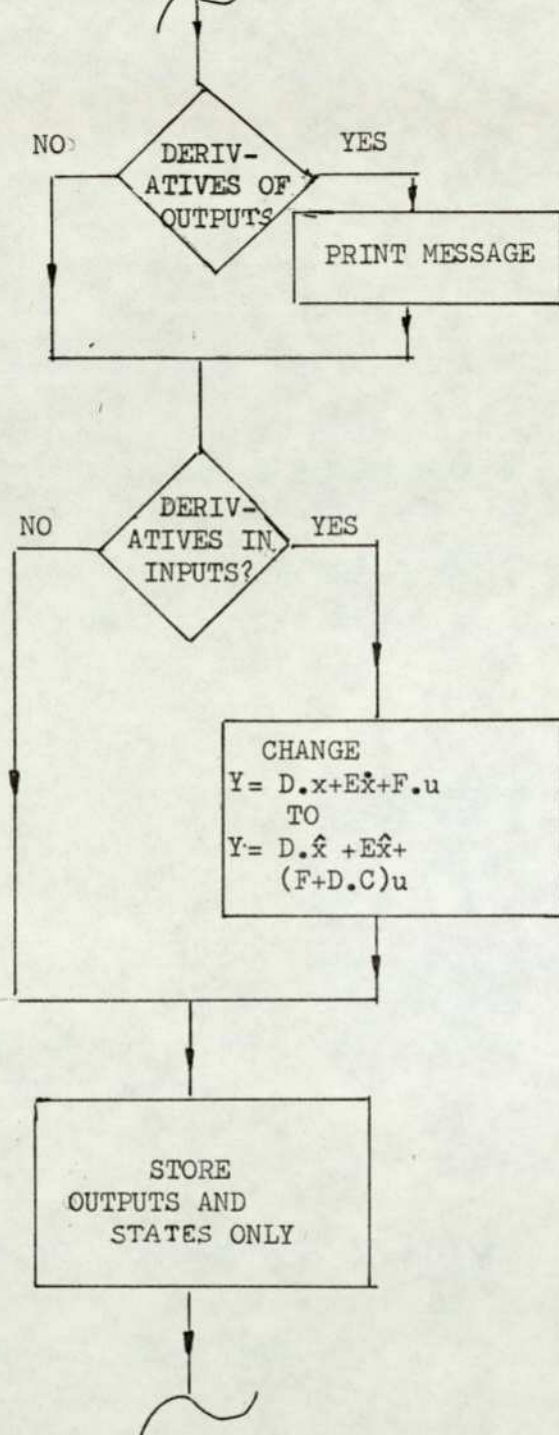
Figure E.39



STEADY: TO CALCULATE STEADY STATE FREQ. RESPONSE

Figure E.40

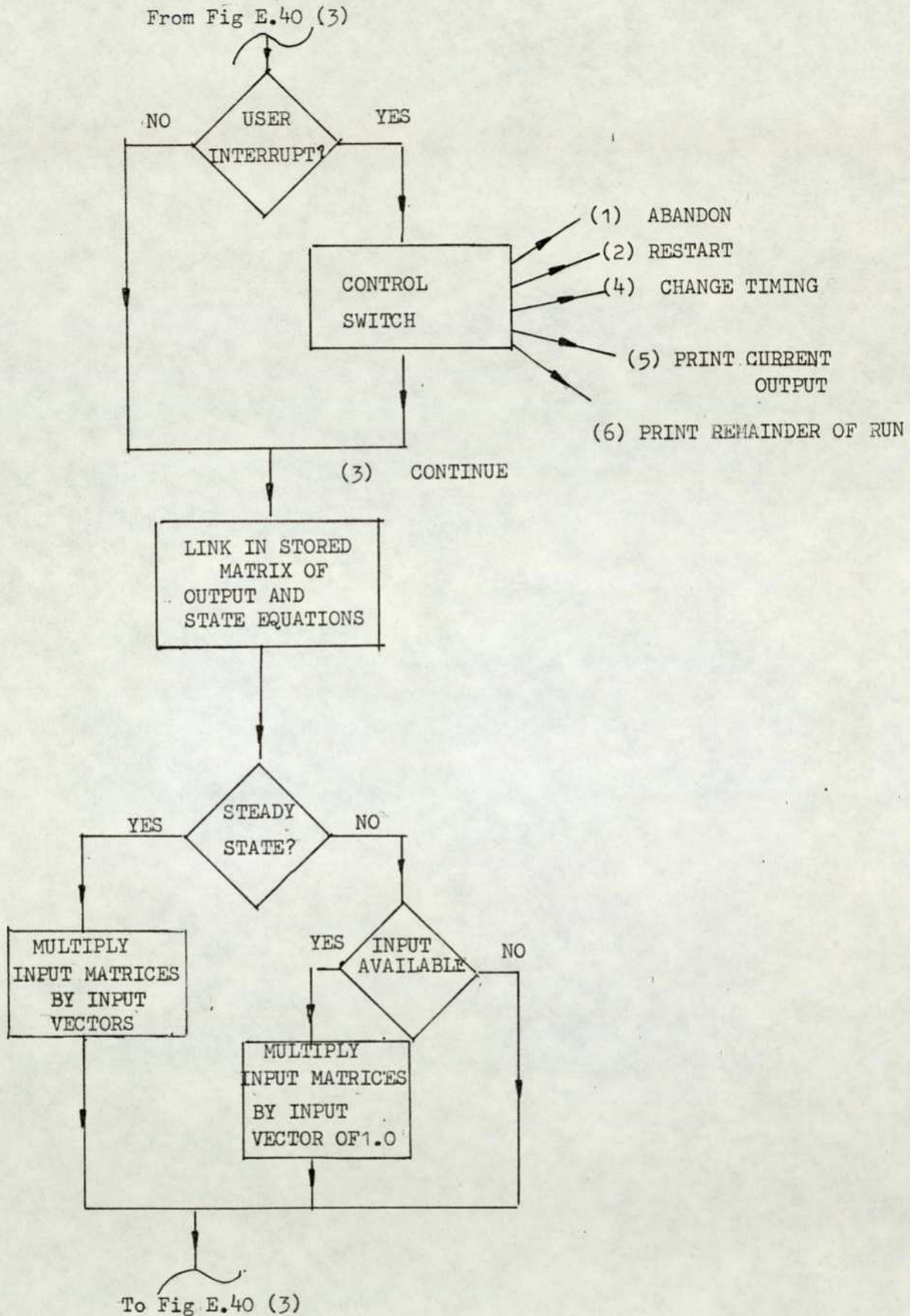
From Fig E.40 (3)



To Fig E.40(3)

FLOWCHART OF SECTION (1) AND SECTION (2) OF STEADY ROUTINE

Figure E.41



SECTION (3) (4) AND (5) OF STEADY STATE

Figure E.42

- a) A unit vector for the particular input of interest, or
- b) The input vector,

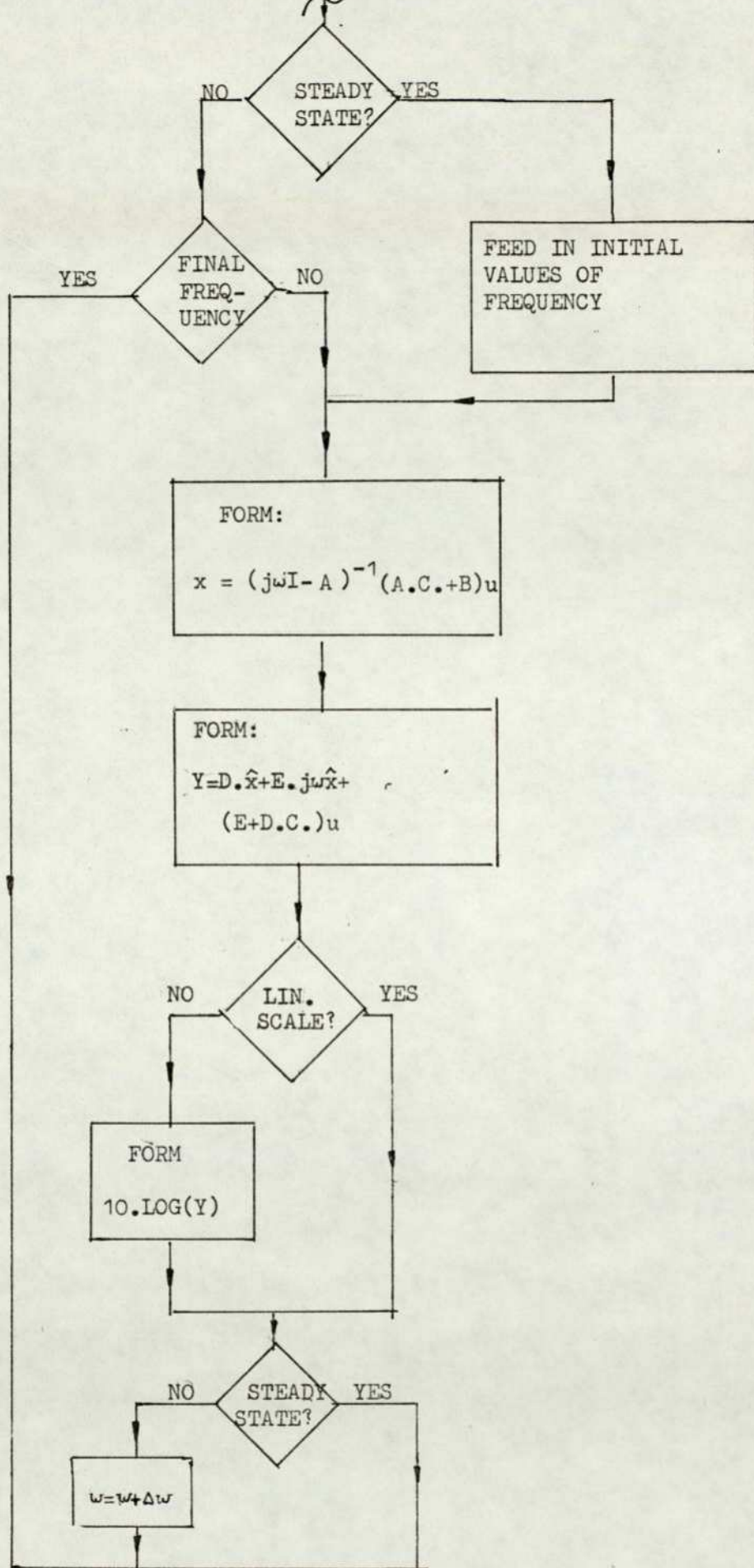
whether the frequency or steady state response is required respectively.

Fig E.43 describes the mathematical formulation and evaluation of the desired frequency or steady state response. The state equations are inserted with the trace (i.e. the diagonal) containing a value of frequency. For steady state this is ideally zero. However there are cases where the A matrix will not have an inversion, and yet there is a steady state! Under these conditions a very small value will suffice. This can be estimated quite quickly from the frequency response.

Section 6

Local changes are accomplished using PATEMP (parameter temporary changes). A flowchart of this is shown in Fig E.44. The same matrix as that used for updating the nonlinearity in TIM can be used. As it was found convenient to be able to give a listing of these changes, a tabulation function is also included. When exiting from this routine the necessary value of KDIR must be modified so that one further reduction of the global matrix can be made producing the new states and outputs.

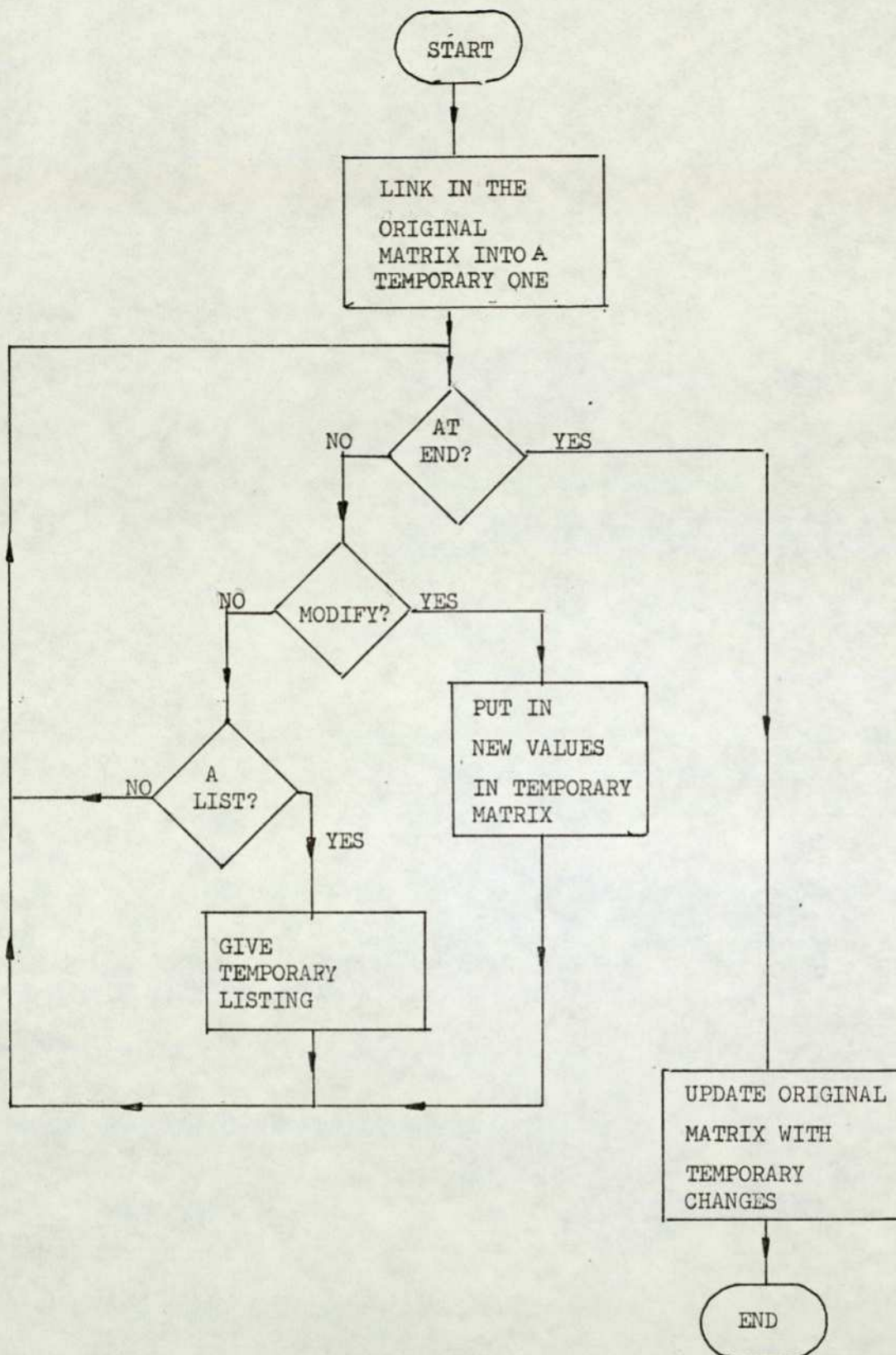
From Fig E.40 (3)



TO FIG E.40 (7)

SECTION (6) & SECTION (7) OF ROUTINE STEADY

Fig E.43



PATEMP: TO HANDLE TEMPORARY CHANGES

Figure E.44

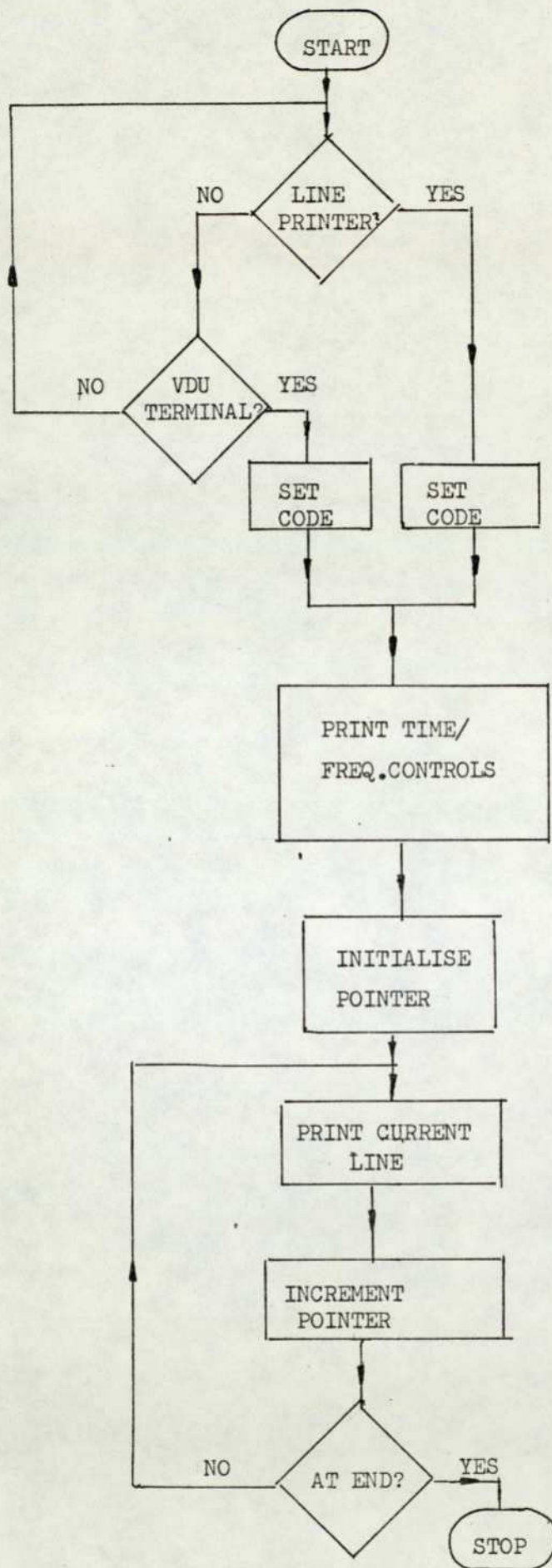
Section 7

This is the same as Section 6.

Section 8

Fig E.45 gives the flowchart for listing a structure. This is the only direct method of checking whether the entered structure is correct. If elements are of the same number or conjoined like 'TF' and 'GY' terms then they are grouped for convenience. Ideally a graphical plot of the model would be desirable here (although it would still be necessary to give the data of time and frequency correctly, as well as the element parameter values).

Two other routines for saving files and restoring them are also used. Because of the operating system on the PDP 11 machine, it is necessary to call these in the main segment. Therefore these are not themselves separate subprograms. To speed up the process these are unformatted, and full advantage of block storage is taken i.e. storing an array composed of several separate entities in consecutive locations.



LISTX: TO PRINT OUT THE STRUCTURE
AND PARAMETERS

Figure E.45

ALPHABETICAL LIST OF ROUTINES

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CHEOUT	352
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