

AN ABSTRACT OF THE THESIS OF

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PARAMETER SEARCH ALGORITHM

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An interactive man-hybrid computer algorithm is presented for searching a set of dynamic system parameters which effect a compromise between performance characteristics and give satisfactory system sensitivity without any analytical calculations or a priori indices of performance. The parameter search is conducted in a real time design situation in which the computer algorithm provides interfacing functions between the man and the hybrid computer. The interfacing functions include the interpretation and translation of preferential cues into appropriate parameter changes, visual presentation of time response information, operational messages alerting the man of system events, and data outputs. The preferential cues are given by the man in response to his critical examination and judgment of the visual time response information.

Experimental results for both linear and nonlinear systems are given along with a discussion of experimental findings on the judgments a man can make with consistency about time response characteristics.

An Interactive Man-Hybrid Computer  
Parameter Search Algorithm

by

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# AN INTERACTIVE MAN-HYBRID COMPUTER PARAMETER SEARCH ALGORITHM<sup>1</sup>

## CHAPTER I

### INTRODUCTION

Techniques used today in the design of dynamic systems range from analysis to synthesis and from trial-and-error to automatic adjustment based on measurements of functions of the system variables (5, 8, 17, 20). Few of the techniques select parameters in the time domain where the system actually operates and many rely on a single scalar quantity to measure overall system performance (8). Even though a system has optimum performance for a given scalar quantity, the quality of the system has to be measured by its time behavior and its sensitivity to parameter changes. In fact, reliance on a rigid a priori index of performance forces either the acceptance of the resulting time behavior and sensitivity to parameter changes or the search for a more acceptable solution using a different index of performance.

Parameter selection for a system involves the consideration of many different interdependent performance characteristics. For

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<sup>1</sup>Two papers based on the material in this thesis have been accepted for presentation and publication (15, 16).

instance the parameter selection for a linear servomechanism with a step input requires consideration of risetime, overshoot, final value error, and settling time which are interdependent in most systems (3). In the final analysis the interdependence of the time response characteristics leads to a compromise dependent on human experience and judgment.

The role of the computer in the selection of parameters for system design has changed from a passive tool to an active tool. Even though the man can act more decisively in the selection of parameters when the computer is an active design tool, the man is occupied with many operator and data recording duties. These duties reduce the full-time attention of the man to the judgment and evaluation of the all important time behavior of the system.

The computer algorithm presented in this thesis is the result of efforts to increase the interaction between the man and the hybrid computer in a way that not only frees the man from his operator and data recording duties, but also directly augments the man in the selection of the parameters which effect a compromise between performance characteristics and give satisfactory system sensitivity without any analytical calculations or a priori indices of performance.

### The Problem Statement and Results

The problem considered in this thesis is the selection of a set

of parameters so that a dynamic system can accomplish a given task<sup>2</sup> with reasonable sensitivity to parameter variations. The degree to which the task can be accomplished and the limits of parameter sensitivity are assumed to be known initially. Some statement of the physical realizable constraints is assumed to be known so that the initial size of the parameter space to be considered can be estimated. The dynamic system is represented by a set of ordinary differential or difference equations subjected to meaningful inputs. The task is assumed to be expressible in terms of the time behavior of the system variables.

The most significant result of the thesis is the interactive parameter search algorithm which makes it possible for the computer to augment the man in a real time design situation. The algorithm is discussed in detail in Chapter II along with the requirements for the computer system used to implement the algorithm.

The second result is a set of experimentally determined meaningful judgments that a man can make with consistency about his visual evaluation of time responses of a dynamic system. Both the parameter search algorithm and the method of implementing the computer algorithm were influenced by this set of meaningful

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<sup>2</sup> Examples of a given task for a dynamic system are tracking changes in position with no final value error for a positional servomechanism and the matching of computer model time responses to measured data.

judgments. The discussion of this result is given in Chapter III.

A final result of the thesis is several design examples representing a variety of dynamic systems. These examples include systems in which two, three, and four parameters are searched. Linear and nonlinear systems are considered along with a model matching example and a multivariable system. The examples appear in Chapter III.

### Background

Analytical methods of parameter selection for the design of dynamic systems date back as far as the classical methods of solving differential equations. The use of Laplace transforms made the solution of the differential equations more routine simplifying the design process. In 1932 Nyquist published his paper which greatly assisted in the design of feedback amplifiers (18). Nyquist's work was extended by Black and Bode (1, 2), and Hall and Harris applied the same methods to feedback control systems (10, 11). In 1948 Evans published his paper on the root locus method of system analysis which was a significant contribution to the design process (6).

In these analytical methods the man spends a great deal of time on arithmetic and graphical details eventually leading to a set of parameters and "improved" system performance. After all the system parameters are set, the designer obtains by hand calculation

an estimate or the entire time response to see if the performance of the system is actually improved. If the time response is unacceptable, the designer repeats the analytical method again making adjustments based on the time response and his experience gained over the years. Often the time between when the designer selects the parameters and when he determines the time response is considerable, but to the designer his job is not complete until he inspects the proposed final time response.

If, in addition, the designer desires information about parameter sensitivity, he has to manipulate the parameters with involved mathematical techniques which use linearizing approximations (19, 20), or he can calculate a set of time responses for parameter changes around his design values. In either case the information is not quickly obtained with ease.

Not only are the previously mentioned methods time consuming, but also there are other problems. If the system to be designed possesses a nonlinearity, the designer either has to linearize the nonlinearity or else abandon the use of any of the previously mentioned methods. Also, as the systems became more complex with multiple feedback loops, inputs, and outputs, the calculations became extremely involved, if not intractable. An additional complaint from many designers is the lack of "feel" for the physical process when only analytical methods are used.

The problem with nonlinearities and the lack of "system feel" led to the development of electrical circuits which respond in an analogous manner to the dynamic system (4, 13). The electrical circuits were improved and eventually evolved into the present analog computer (14). The analog computer allows the dynamic system to be simulated in a manner closely associated with the physical layout of the system. Also nonlinearities can be simulated with nonlinear circuit elements, so that the simulation of the dynamic system yields more realistic results than most analytical methods.

Another important use of the analog computer in the design process is the convenient way in which the designer can vary the parameters of the system and observe the effect of the variation on the time response of the system (12). When the solution time is reduced and repeated in a periodic manner so that a steady image can be displayed to the designer (repetitive operation), the analog computer provides the designer with an active design tool which allows him to design by trial-and-error and to conduct parameter sensitivity studies.

There are certain disadvantages and problems in using the analog computer as an active design tool. The designer must obtain an initial estimate of the parameter values using either an analytical method or intuition. Then he can make adjustments by hand around the initial estimate. If he attempts a parameter search with



arbitrarily chosen parameter values, he must start with a global search which can be very difficult due to overloading of computer components in regions of intolerable time response.

If there is more than one region of tolerable time response, the designer must find the regions, keep track of the regions and examine each region separately. As he searches the regions of tolerable time response, the designer must carefully change the parameters by a prescribed amount so that he can accurately detect the effect the parameter change has had on the time response. In fact as the number of parameters increases, the designer may be unable to keep track of what effect a certain parameter change has had because of all the operational duties he must perform and data he must record.

Initially the digital computer was used as a passive design tool to carry out the tedious arithmetic calculations used in the mathematical algorithms. As the speed of the digital computer was increased and improved electronic hardware made more parallel operations feasible, the digital computer became a more active tool for the designer. However due to the inadequacies of the digital input-output devices, the digital computer was unable to perform in the same interactive man-computer process as the analog computer.

Interfacing the digital and analog computer into a hybrid computing system has opened many new and unexplored avenues for

application of the computer in the design process. The hybrid system offers good man-computer interaction and has a capability for parallel implementation of large sets of differential equations. In addition it has a capability for storing information and carrying out involved logical operations and numerous input-output devices to accommodate digital and analog information.

The computing systems of today are a definite part of the design process (11). They assist the designer in nearly all phases of the design process and are being included more often as an integral part of the controller for the dynamic system. In the future computing systems will be more actively involved in the design process as the present research into completely automated design procedures indicates (11). However, it is doubtful that the man will ever be totally eliminated from the design process.

## CHAPTER II

### THE INTERACTIVE MAN-HYBRID COMPUTER ALGORITHM

There are three distinct computational systems which interact in the design situation considered here: a man, an analog computer, and a digital computer. Figure 2.1 shows the interactions between the three systems. Due to their computational differences the three systems must be properly interfaced to operate effectively. An existing hardware data interface is provided between the analog and digital computer. The computer algorithm developed in this thesis provides the interfacing functions between the man and the hybrid computer so that they can interact in a real time parameter search.

The algorithm serves as the interpreter between the designer<sup>3</sup> and the computer model of the physical system so that they can interact in a real time design situation, void of special indices of performance. As Figure 2.1 illustrates, the inputs to the algorithm are the preferential cues from the designer. The algorithm interprets the cues and translates them into computer actions, such as changing the system parameters and recording data about the design process. The algorithm also acts as the supervisor to the model of

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<sup>3</sup> The words "man" and "designer" are used interchangeably depending on which seems appropriate.

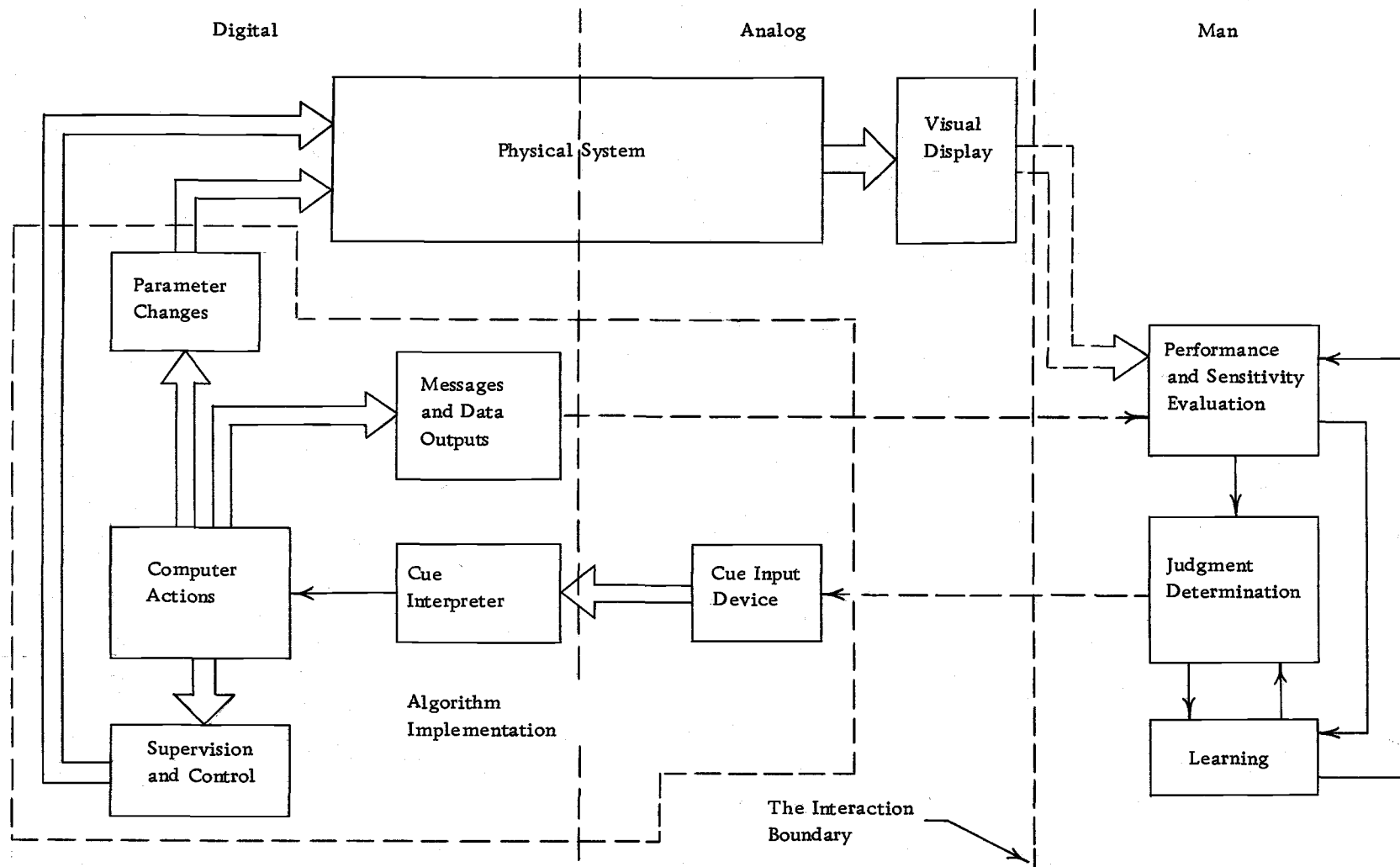


Figure 2. 1. The interaction between the man, the physical system, and the implementation of the algorithm.

the physical system based on the designer's preferential cues, data recording requirements, and operational requirements for proper visual display to the designer and timing of sequences of computer actions.

In the following sections the discussion of the algorithm is divided into the following two parts:

1. The man-hybrid computer interaction and its implementation.
2. The parameter search algorithm.

The first part discusses the general description of the man-computer system. The second part describes in detail the phases of the algorithm, the cues the designer can use and their effect on the search process, and the data recording aspects of the algorithm. Simplified flow charts are included in the second part. Detailed flow charts are found in Appendix B.

### The Man-Hybrid Computer Interaction and Its Implementation

As shown in Figure 2.1, the physical system can be modelled by analog or digital means. The outputs of the physical system are displayed to the man for his visual inspection and represent the first point of interaction between the man and the computer. For the interaction to have its maximum effectiveness the man should receive immediate visual reinforcement to his preferential cues.

Delays in outputting the effect of his cues and interruptions in the visual information being received by the man tend to confuse his judgments about the qualities of the time responses of the physical system.

An example of an effective computer-visual display combination and the one used in this thesis is a fast repetitive analog computer for modelling the physical system with a multichanneled oscilloscope for the visual display. With the physical system scaled properly a steady visual image can be projected to the man at all times, using the external synchronizing capability of the oscilloscope. This computing system has the additional advantage of allowing the man to make adjustment in the solution time through the manual control of the repetitive timer within his easy reach at all times. Also the man can make adjustments for amplitude and time axis presentation on the oscilloscope to please his visual comfort and interest.

However oversimplified the representation of the man in Figure 2.1 is, it indicates some of the decision and learning processes that occur within the man. Not only is there a definite performance and sensitivity evaluation process occurring, but also a learning process where the man accumulates qualitative and quantitative information about the time behavior of the system. As a result, the man's final judgment about a particular time response

is based on a weighting function whose terms represent his evaluation of the characteristics of the present response he is observing, his experience with the system to date, and his concept of an acceptable time response.

Additional factors influence the terms of the man's weighting function, such as earlier training, both in system design and use of the parameter search algorithm. Unfortunately, distractions, discomfort, and fatigue influence the man's weighting function. However the man is able to make certain definitive judgments about the time responses as they are presented to him. The judgments he can make consistently are discussed in the next section.

Once the man has made a judgment about the present time response, he signals the computer system to take certain actions. The signals are referred to as preferential cues and are the second point of interaction between the man and the hybrid computer. If the interaction is to be effective, the cues should be easy and quick to give and the man should not have to interrupt his observation of the visual display. As shown in Figure 2. 2, the preferential cue input device for the system used in this thesis is a remote panel of push-buttons which can be easily positioned near the visual display. When the man wishes to cue the computer, he merely pushes the corresponding pushbutton to the cue he desires to give.

Upon receipt of the preferential cue, the computer interprets

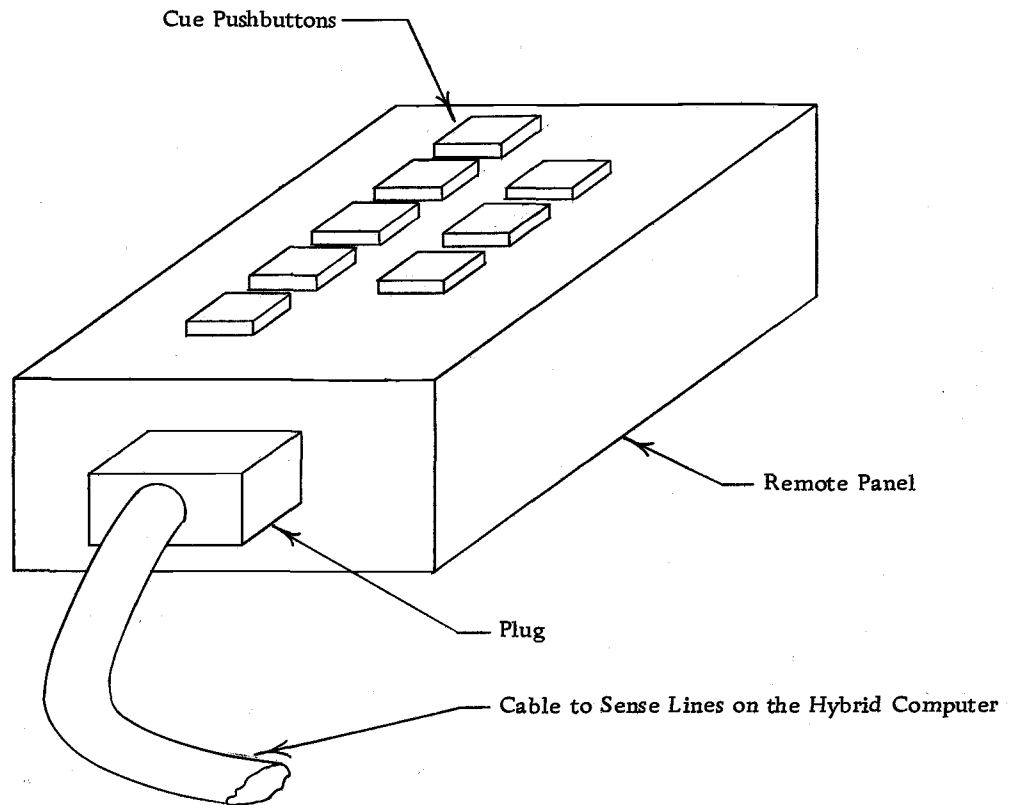


Figure 2. 2. A sketch of the remote panel of pushbuttons.



which cue has been given and instigates the corresponding action. The types of actions the computer takes are parameter changes, deletion of intolerable and unnecessary time responses, recording data, changes in inputs to the physical system, resetting to initial settings, and notification of the occurrence of certain events in the algorithm.

Since the basic goal of the computer algorithm is to augment the man in his search of the parameter space, the primary type of computer action is parameter changes. Not only does the computer change the parameters of the physical system in a manner indicated by the man, but also the computer makes parameter changes in the physical system which reinforces the judgment process of the man. Around each starting point in parameter space, the computer automatically places a grid of parameter points whose corresponding time responses are presented to the man for his evaluation. The number of points in the grid is determined by whether the grid is used in a global or a regional search of the parameter space. The amount of change of the parameters between grid points is called the grid spacing.

The grid around the starting point makes the searching process somewhat like a gradient hill climber in that the man selects a time response from one of the family produced by the grid which gives a distance and direction to move in the parameter space.

The final point of interaction between the man and the computer is the messages and data outputs from the computer to the man. The messages take the form of notifications to the man about events in the computer algorithm and the physical system and actions the man should take due to events in the physical system. Data outputs are comprised of parameter values and recordings of the time responses of the physical system.

### The Parameter Search Algorithm

The parameter search algorithm consists of four distinct phases:

1. A global search of the parameter space.
2. The selection of starting points in each tolerable region of system time response.
3. A regional search of each tolerable region of system time response.
4. A final comparison of the most acceptable time response from each of the tolerable regions.

Phases two and three are repeated until all the tolerable regions are considered. Then phase four concludes the search. Figure 2.3 illustrates a simplified flow chart of the computer algorithm. In the following sections the phases of the algorithm are discussed separately along with their relation to each other.

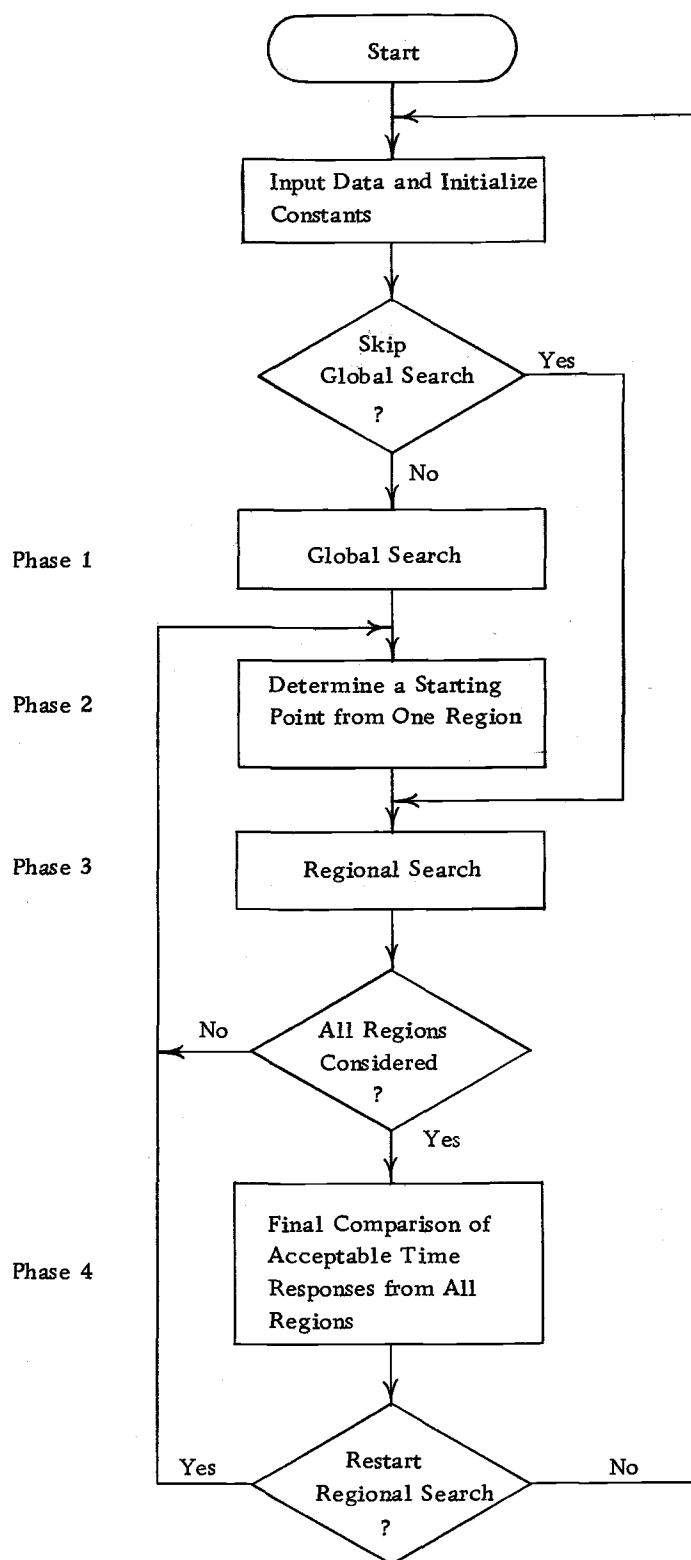


Figure 2. 3 The simplified flow chart of the computer algorithm.

### Phase One: The Global Search

Generally speaking, the parameter space contains regions of parameter values, such as shown in Figure 2.4, which yield tolerable and intolerable time responses. The definition of tolerable and intolerable time responses is determined solely by the designer. One of the primary considerations in his definition is the basic task that the system is to accomplish. If the time response of the system is such that the basic task is not accomplished, then the designer is definitely not interested in the set of parameters which yields that time response. There may be other considerations in the designer's definition of tolerable, but during the global search, they are not important.

In order to determine the regions of tolerable and intolerable time response in a global manner, the time responses for a large grid of coarsely spaced parameter values are evaluated by the designer or by the computer if the definition of a tolerable time response can be appropriately implemented. The global grid of points is shown in Figure 2.4. If there is more than one input to the system, the designer or the computer must evaluate the time response for the system for every input as well as for every grid point. If any of the time responses of the grid points are judged intolerable for any one of the inputs to the system, then those grid points are

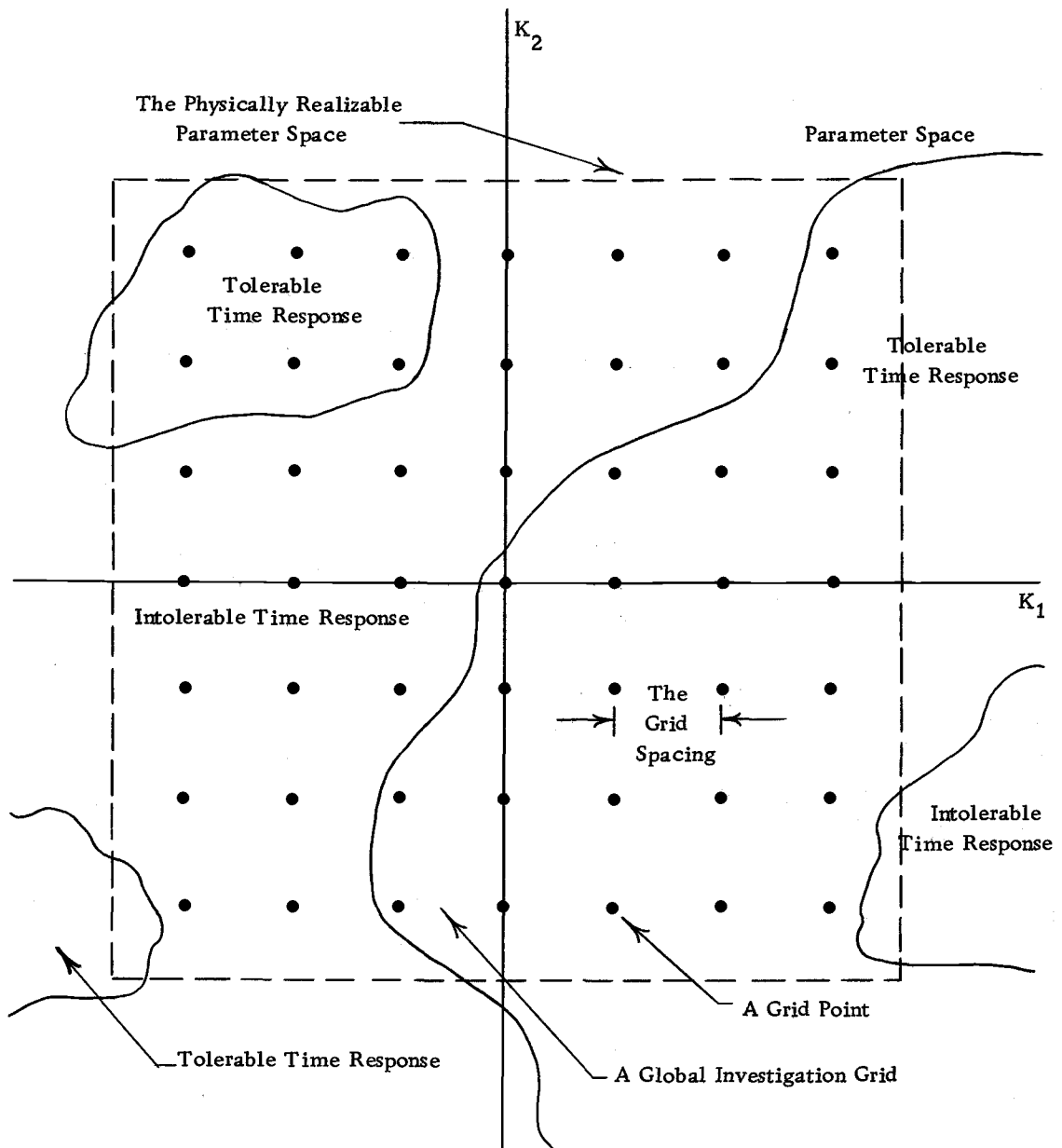


Figure 2. 4. A two dimensional global investigation grid centered at the origin.

deleted from further consideration.

The size and location of the global investigation grid are determined by the physical realizability of the parameters. The realizability of the parameters relates to the physical devices used to implement the parameters in the physical system. As shown in Figure 2.4 the physically realizable parameter space is not necessarily as large as the entire parameter space.

The spacing of the global grid is dependent on the memory capacity of the computer, any a priori knowledge about the system, and a posteriori subjective evaluation of the success of the global search by the designer. These latter two considerations also influence the size and location of the global grid.

Another trade-off results in selecting the grid size and the grid spacing because of the primary goal of the global search. The primary goal of the global search is not to find all the parameter values which yield tolerable time responses, but to establish starting points in the various regions of tolerable time response so that a regional search can be conducted in each region. Therefore, not only does the designer necessarily select the number of grid points and the grid spacing before the global search begins, but also he may be required to start the global search again after he gains some experience with the time behavior of the system.

As shown in Figure 2.4 there may be more than one region

of tolerable time response. If there is more than one region of tolerable time response, a regional search must be made of each region because the intermediary intolerable region isolates the tolerable regions during the regional search and there is the possibility that the most desirable time response would be completely overlooked. Therefore, after the global search is conducted and each global grid point is rated as tolerable or intolerable, the digital computer analyzes the global grid, separating and numbering the distinct regions of tolerable time response. The criteria used by the computer algorithm to determine if two tolerable grid points belong to the same region is simply that the two grid points are no greater than one grid spacing apart in all the dimensions of the parameter space. Figure 2.5 illustrates a simplified flow chart of the global search.

#### Phase Two: The Selection of Starting Points

Following the numbering of the tolerable regions of time response, the next phase of parameter search is the selection of a starting point from the first region of tolerable time response. The selection is accomplished by the designer cueing the digital computer to sequence through the grid points in the first tolerable region and all the possible input levels so that he can compare and judge the various time responses. As the designer cues the computer to

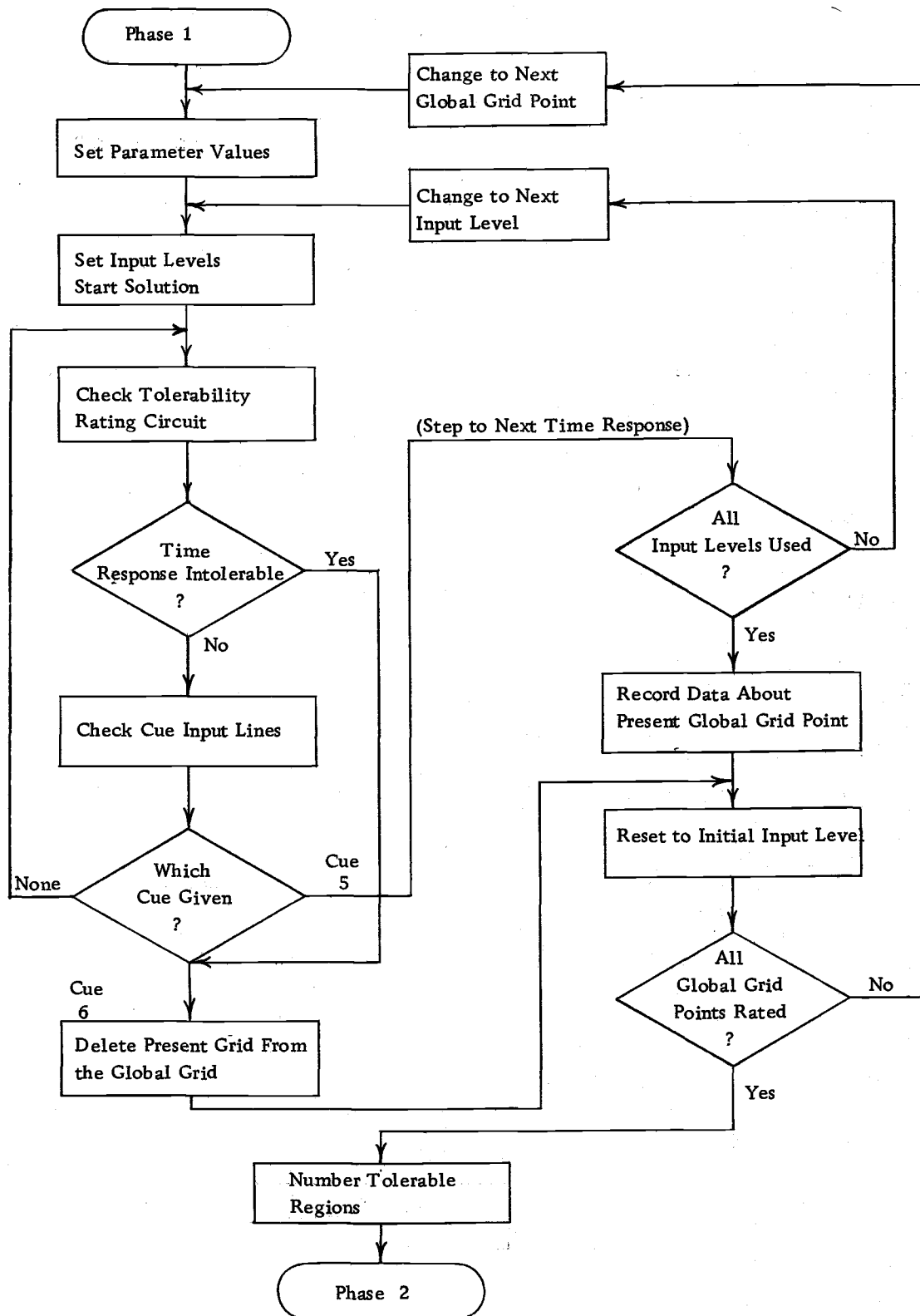


Figure 2. 5. A simplified flow chart of the global search phase.



sequence through the time responses, the designer can also cue the digital computer to delete the present global grid point from consideration on a restorable basis. The deletion capability allows the designer to reduce the number of time responses that he must examine and judge, thus making his starting point selection easier and more positive.

If the designer decided that he has erroneously deleted a grid point or if there is a malfunction in the computer system that detects intolerable responses, the designer can cue the digital computer to reset all the grid points of the region that had been deleted during the starting point selection.

An additional feature of the algorithm is that the designer can cue the computer to obtain a strip chart recording of the present time response he is observing. Upon receipt of the cue the computer records the grid spacing and the parameter values of the time response and makes a note that a time recording is to be made. Then the computer automatically records the time response of all the variables patched to the strip chart recorder by the designer. The designer must adjust the amplitude and time settings of the recorder previous to requesting the recording.

Finally when the designer has selected one of the time responses from the first tolerable region, he cues the computer to transfer to the next phase of the parameter search, the regional

search. A recording of the parameter values, the grid spacing, and the region number is made before the transfer is completed. Figure 2.6 illustrates a simplified flow chart of the selection phase of the algorithm.

### Phase Three: The Regional Search

Once a starting point is selected in a region of tolerable time response, a regional search is begun. The investigation grid used in the regional search is shown in Figure 2.7. The grid spacing for the regional grid is initially much smaller than the global grid.

The regional search begins with the computer setting the system parameters equal to the parameter values of one of the regional grid points. Then the designer observes the resulting time response of the appropriate system output until he can make one of the following judgments:

1. No opinion can be made at the present time; more information is needed.
2. The time response is totally unsatisfactory.

Based on which judgment the designer makes, he can cue the computer to either transfer to the next regional grid point or delete the present grid point from the present regional grid and transfer to the next regional grid point, respectively. At the first grid point other cues by the designer are not meaningful because of his lack of

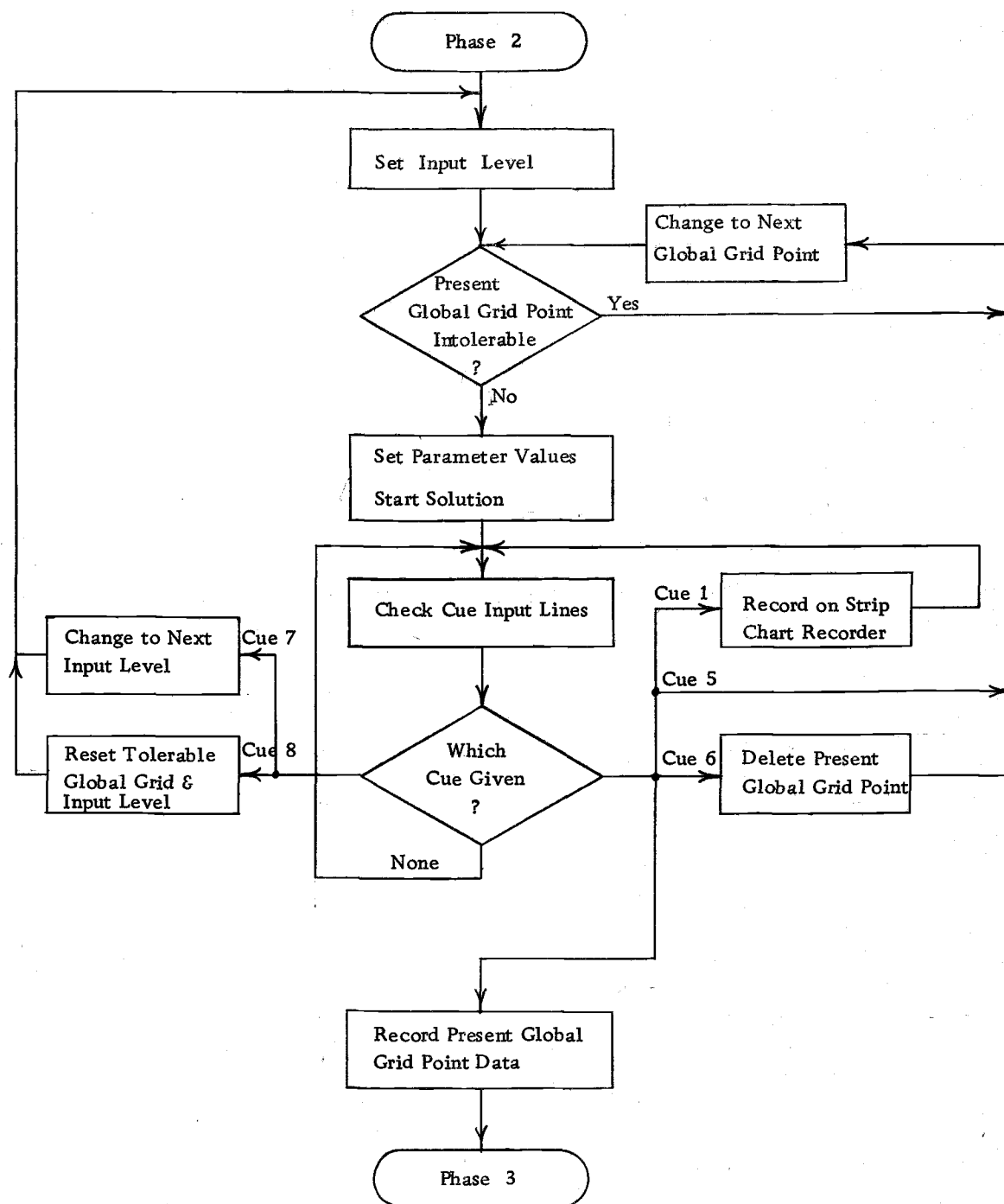


Figure 2.6. A simplified flow chart of the selection a starting point phase.

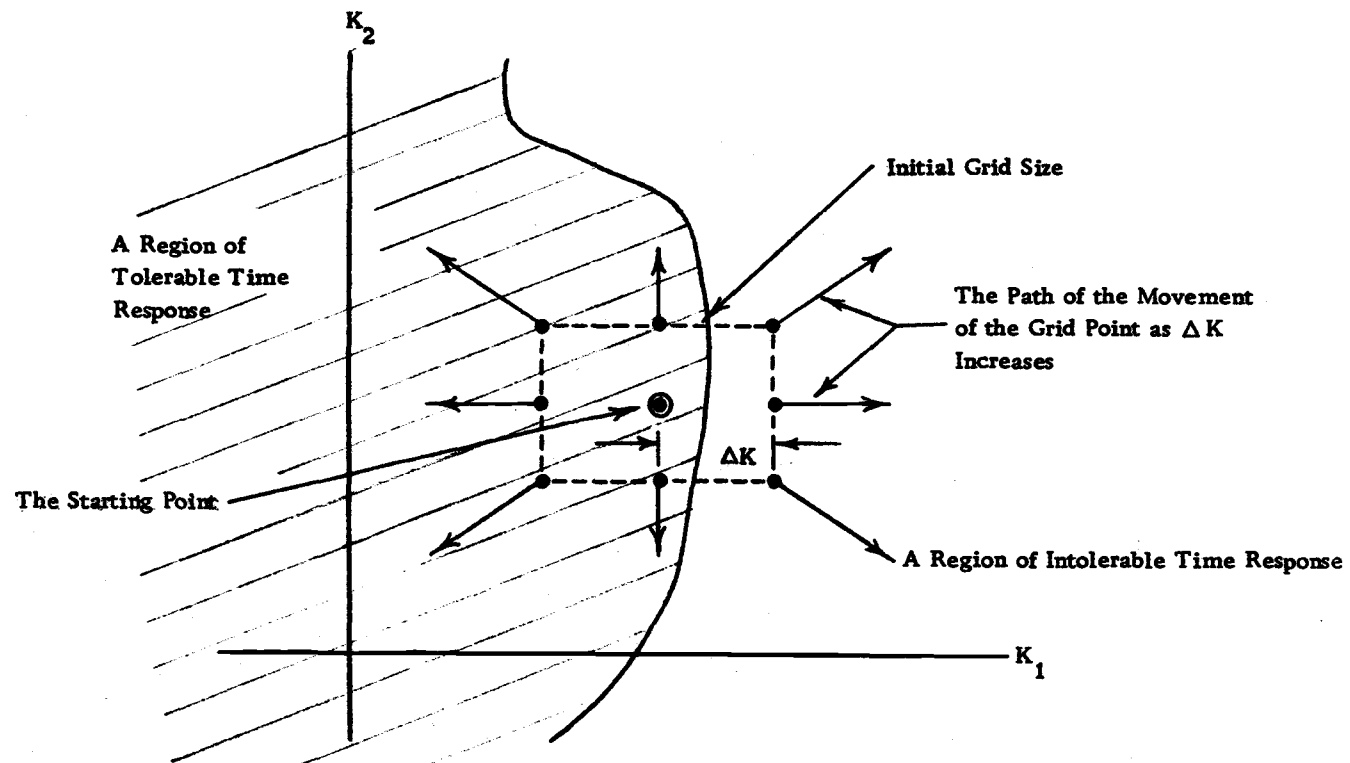


Figure 2. 7. The two dimensional regional investigation grid.

comparative data.

As the search progresses sequentially through the grid points, the designer is able to expand the number of judgments to include the following:

1. No opinion can be made about the comparison between the present time response and other time responses in the regional grid at the present time.
2. The present time response is inferior in comparison with other responses being considered or is totally unsatisfactory.
3. The present time response is preferred in comparison to the other responses being considered.
4. A previous error in judgment or operation of the cueing system has resulted in an improper deletion of grid points.

The reasons for the increase in the number of judgments that the designer can make are his increased experience with the time domain behavior of the system and his accumulation of comparative information regarding the effect of changing parameters on the time responses of the system, i. e., his feel for system sensitivity.

The increase in the number of judgements that the designer can make leads to a correspondingly larger number of cues the designer can give that have meaning. The following is a list of the meaningful cues that the designer can give:

1. Increase the grid spacing.
2. Decrease the grid spacing.
3. Reset the grid spacing to its initial value.
4. Transfer to the next regional grid point.
5. Transfer to the next input level.
6. Delete the present grid point from the present regional grid and transfer to the next grid point.
7. Obtain a time recording of the system outputs on the strip chart recorder.
8. Transfer to a new regional grid.
9. Terminate the regional search with the present grid point.
10. Reset all the deleted grid points for the present regional grid.

The first five cues are used in connection with the first judgment. Their purpose is to instigate computer actions which furnish new information to the designer about the present time response so that he can eventually decide which time response in the grid he prefers. The type of information the designer obtains from these cues is not only comparative information with respect to other time responses in the grid, but also information about the changes of the time response characteristics as the present grid point moves in the parameter space.

Increasing the grid spacing in small increments moves the grid

points outward from the starting point as shown in Figure 2. 7. The basic effect of the outward movement of a grid point is to increase the differences between the time responses corresponding to the various grid points.

When used in conjunction with other cues, the "increase the grid spacing " cue can achieve different results. For instance if the designer is having difficulty distinguishing between the time responses of the grid, which is very often the case, he can increase the grid spacing. Then using the fourth cue, the designer can sequence through the grid points to compare the members of the new set of time responses. If the designer still cannot make a judgment of preference or dislike, he can continue to increase the grid spacing until a judgment is possible.

If the designer wishes to explore the effect on the time response of moving a particular grid point outward from the starting point, he can continue to give the "increase the grid spacing" cue and observe the progressive changes in the time response characteristics. Then to illustrate dramatically the effects of the increase in the grid spacing and to prevent unfair judging of the time response of other grid points, the designer can cue the computer to reset the grid spacing to its initial value.

The first two cues can be used together to move the grid point outward until the time responses go beyond a preferred form and

then to return to the preferred response. This probing action contributes greatly to the designer's experience about the time domain behavior of the system and the system sensitivity to parameter change.

Besides being useful with the "increase the grid spacing" cue, the "decrease the grid spacing" cue is useful to decrease the initial grid size if the responses at some of the grid points are too widely different or if some of the grid points are not in the tolerable region as shown in Figure 2. 7. Repeated reductions of the initial grid size indicate a poor choice of the initial grid spacing and should be avoided because of the possible misjudging of the time responses of certain grid points. Also if the second cue is initially necessary when the regional grid starting point is approximately zero, in any one dimension, rescaling the computer model of the system is useful.

If the system has multiple inputs or if the design specification calls for consideration of several types or combinations of inputs, the designer can cue the computer to step through the different combinations or types of inputs at any regional grid point. Earlier before starting the global search, the designer must input to the computer the number of inputs and the number of levels in the inputs and properly implement the computer model to receive the input from the computer algorithm.

As the designer sequences through the regional grid with or



without changing the grid spacing, he is able to judge certain of the time responses as inferior to the other time responses of the grid and they are of no further interest to him. In fact, the inferior time responses tend to confuse the designer's judgment about the time responses he prefers because he must cycle through the less desirable responses to compare desirable ones. As a result the designer can cue the computer to delete on a restorable basis any of the grid points from the present regional grid. Then the designer can sequence immediately from one time response of interest to him to another, making his comparison much more definitive and his judgment much more positive.

A resetting cue is also available in the regional search as it is in the selection of the starting point. The reason that it is needed is because the designer may change his mind about the qualities of one of the deleted time responses or he may accidentally delete a grid point by giving the wrong cue. If the computer is implementing the automatic deletion of intolerable time response, occasionally a malfunction in the computer mechanism deletes a grid point which the designer preferred.

If during the search of the regional grid the designer wants a permanent record of some of the time responses he observes, he can cue the computer to automatically record all the system variables that he has previously patched to the strip chart recorder.

The designer's cue causes the computer to pause to record that a strip chart recording is being made, the grid spacing, and present grid point coordinates and then to start and stop the strip chart recorder automatically after one computer cycle of the computer model.

After the process of deletion and probing the parameter space about the initial starting point of the global search, the designer eventually singles out one time response from the regional grid he prefers. The preferred time response, however, is rarely the time response he is willing to accept as the final design time response. So he is ready to transfer to a new regional grid and continue the search. The transfer is accomplished very simply by the designer cueing the computer that he is ready for a new grid. Then the computer records the grid spacing and the parameters of the present grid point and makes the present grid point the starting point of the next regional grid. Figure 2.8 illustrates a possible sequence of several transfers from one regional grid to another.

Figure 2.8 also illustrates the process of expanding the grid size, deleting certain grid points and continuing to expand the grid spacing until a preferable time response is selected. Then once the new regional starting point is selected and the regional search is resumed, the designer can go back into the region he was just in due to the overlap of the old and new regional grids. The "doubling-back" feature is particularly useful if the designer changes his mind

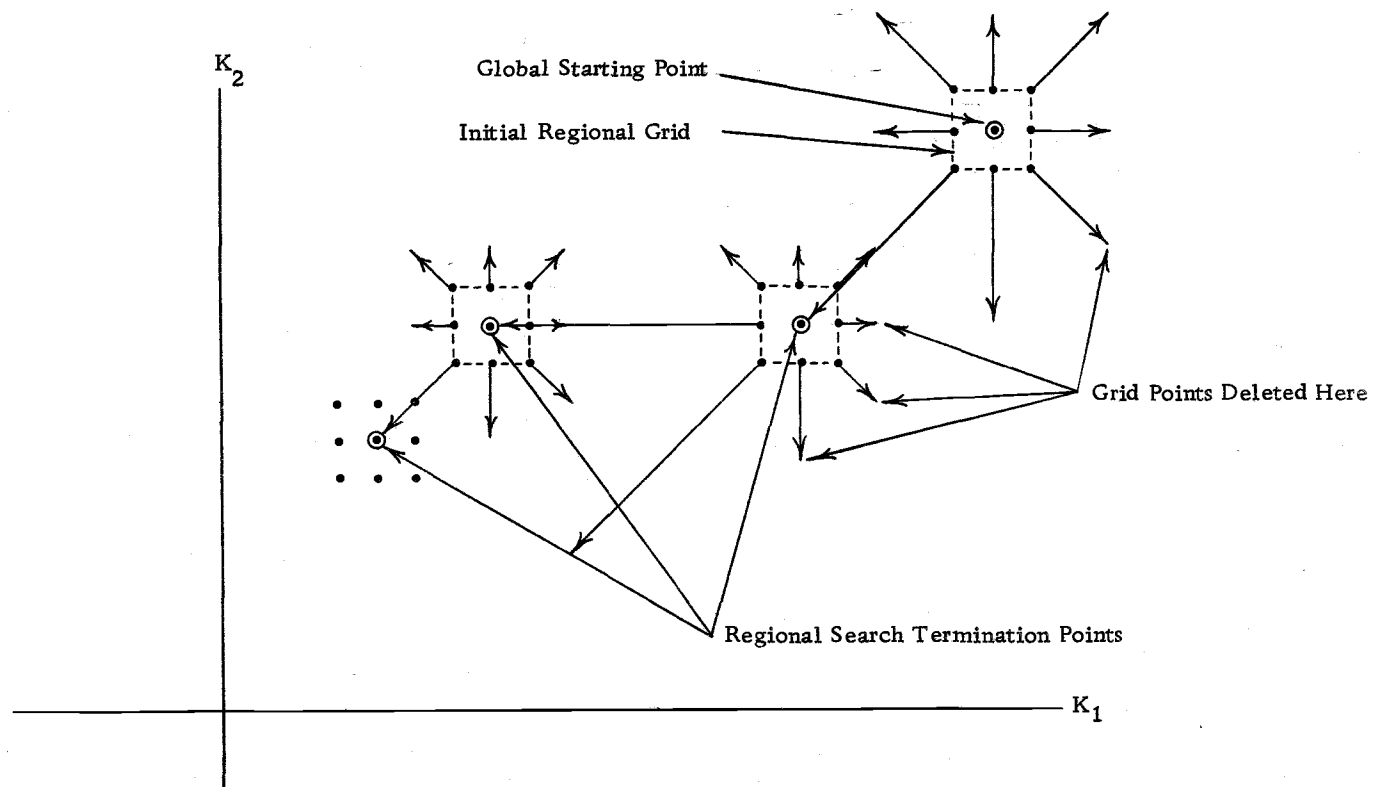


Figure 2.8 An illustration of the transfer from one regional search to another.

about a previous time response due to the additional information he has obtained from the new grid. Also the "doubling-back" feature is necessary from the standpoint that only the global starting points and present regional starting point are stored in the computer memory and recorded on the data output from the digital computer.

After searching a region of tolerable time response, the designer finally decides he has an acceptable time response for the region he is considering. He then cues the computer to terminate the search. The computer records that the search is terminated for the present region and records and stores the final grid point's parameter coordinates.

If there are any additional regions of tolerable response, the computer cycles back to the starting point selection phase for the next region. If there are no other regions of tolerable response, the computer proceeds to the final phase of the parameter search, the comparison of the most acceptable time response from each region. A simplified flow chart of the complete regional search is shown in Figure 2.9.

#### Phase Four: The Comparison of the Final Regional Time Responses

Upon entering the final phase of the algorithm the computer sets the system parameters equal to the first stored values of acceptable parameters. Then the designer can either cue the

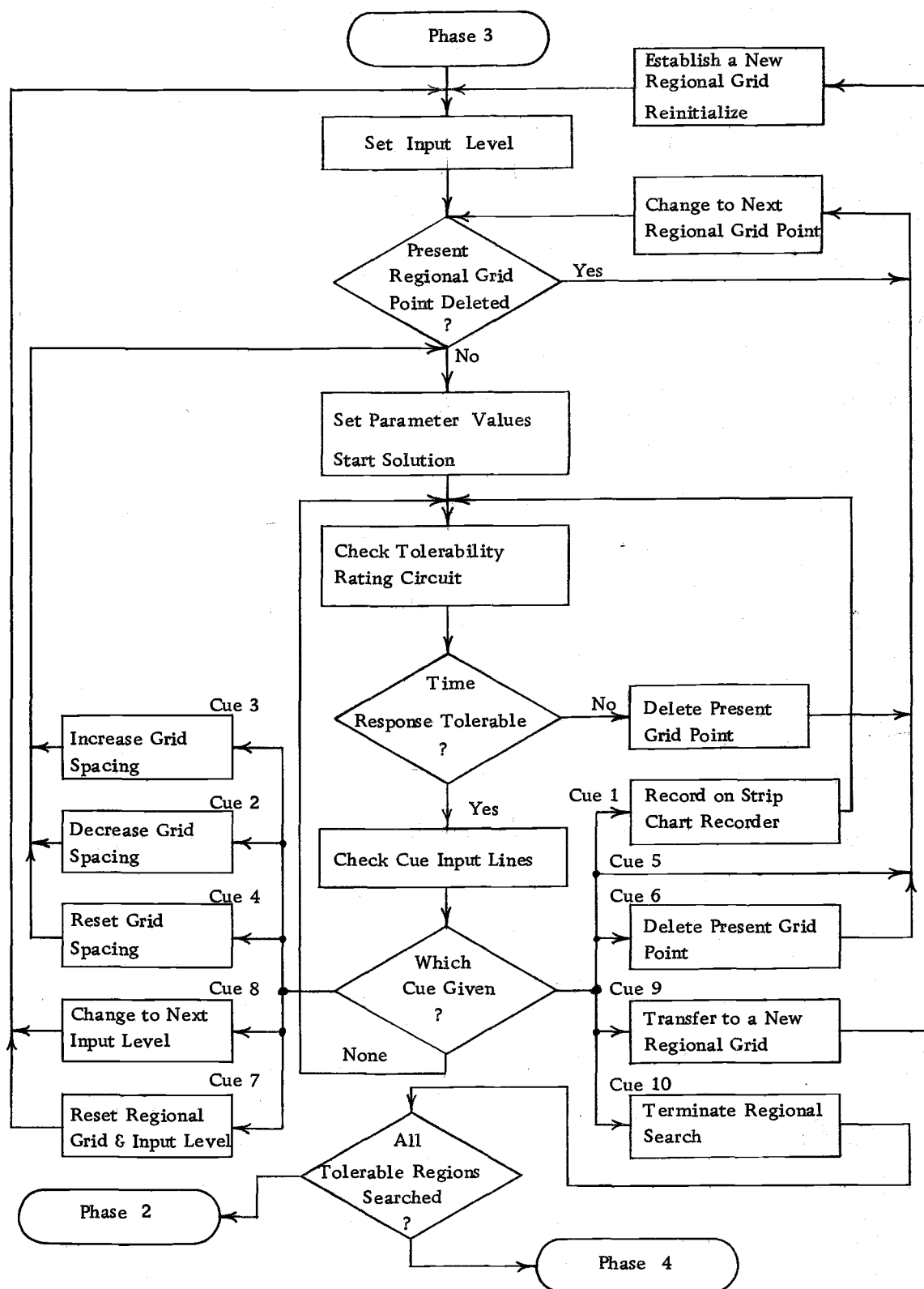


Figure 2.9. A simplified flow chart of the regional search phase.

computer to sequence through the different time responses for the various regions or to sequence through the various input combinations.

A time recording of any of the final time responses can be cued. Also, if the designer wishes to begin the selection of a starting point phase again, he can cue the computer to recycle to that point in the algorithm. Finally the designer can terminate the entire search process by cueing the computer to do so. The computer records that the search is terminated and records the final region selected.

Figure 2.10 illustrates a simplified flow chart of the final phase of the algorithm.

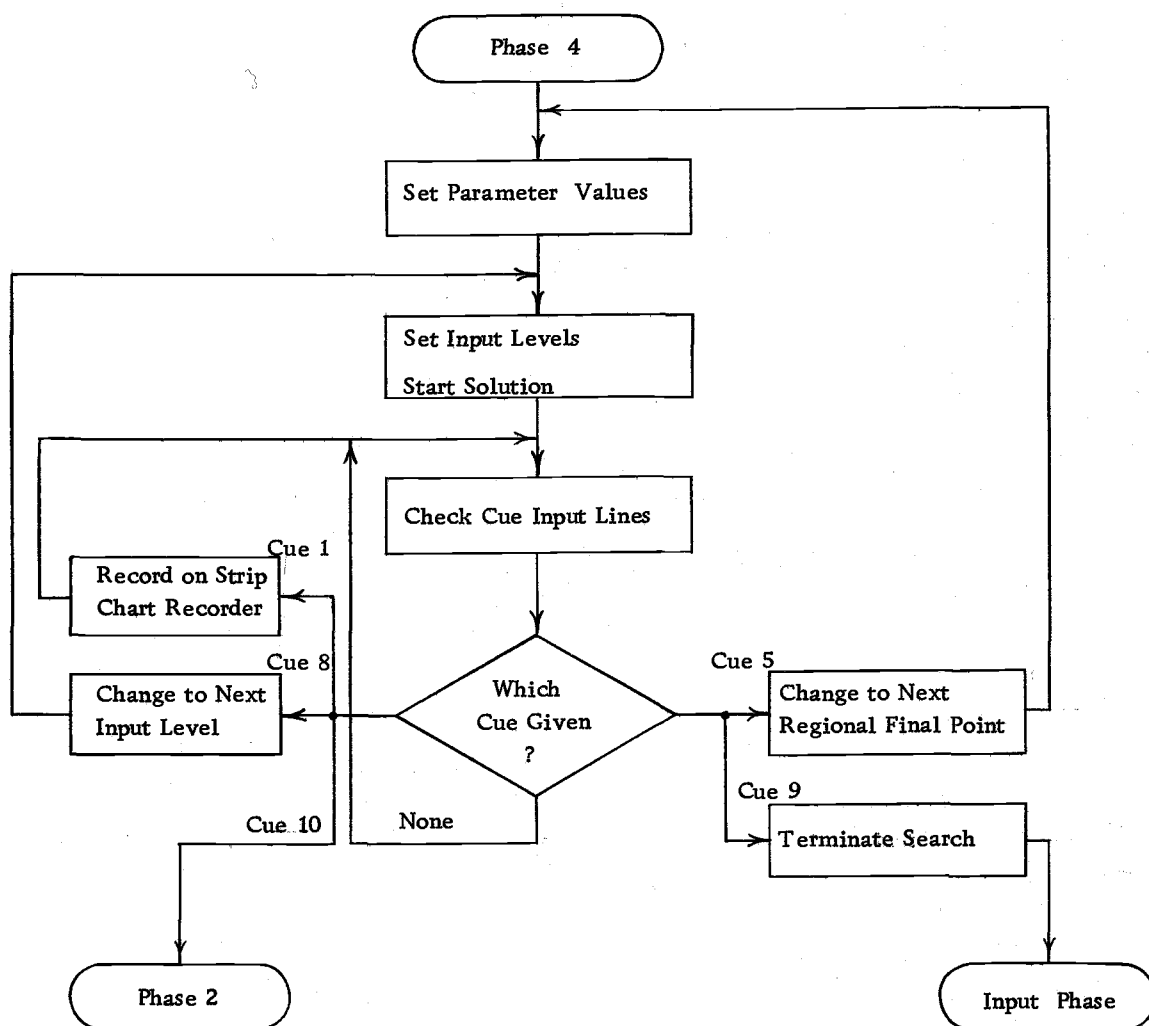


Figure 2. 10. A simplified flow chart of the final comparison phase.

## CHAPTER III

### EXPERIMENTAL RESULTS

Experimental work was conducted in two chronologically separated parts:

1. The human evaluation of time response characteristics was investigated.
2. The computer algorithm was applied to actual design problems.

The main result of the first part is the set of judgments a man can make with consistency about the time response characteristics of a dynamic system. The result of the first part was used to develop the computer algorithm. The second part was conducted after the computer algorithm was developed to investigate the usefulness of the computer algorithm.

#### Investigation of the Human Evaluation of Time Response Characteristics

Before the development of the parameter search algorithm, an experiment was conducted with the following objectives:

1. To determine the judgments that a man can make about time response characteristics
2. To evaluate the feasibility of interpreting the rating of



system performance by a man for use in a hill-climbing  
parameter adjustment scheme

During the experiment, time responses from the linear feedback system shown in Figure 3.1 were presented to the man for his rating. The adjustable parameters,  $K_1$  and  $K_2$ , were set automatically in a predetermined pattern by a digital computer in the scheme illustrated in Figure 3.2. The man was asked to rate the output response of the perturbed system in comparison to the output response of a reference system to a step function input.

The reference system was the same system as shown in Figure 3.1 except the parameters were held constant over one comparison cycle. A comparison cycle included a comparison of output responses for a grid of nine points centered on the reference point. The grid spacing was varied to assess the effect of larger differences between the time responses.

The rating scale used by the man was a five number scale where the general meaning of each number was as follows:

<u>Rating Number</u>	<u>Meaning</u>
+2	The perturbed response is greatly preferred to the reference response.
+1	The perturbed response is preferred to the reference response.
0	No preference

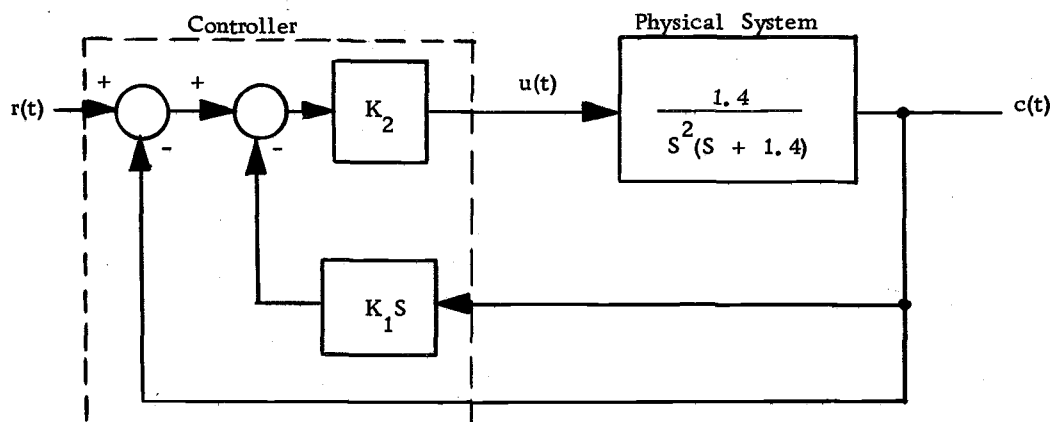


Figure 3.1. The system used to investigate the human evaluation of time response characteristics.

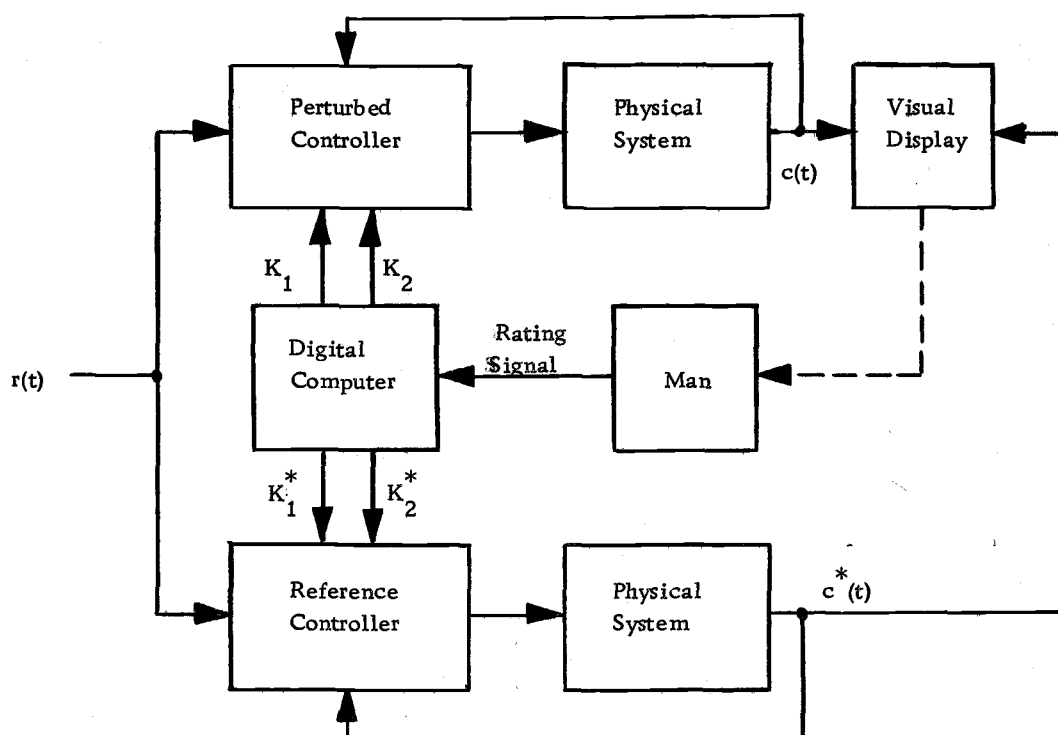


Figure 3.2. The computer scheme used to investigate the human evaluation of time response characteristics.

Rating NumberMeaning

- |    |  |
|----|--|
| -1 | The reference response is preferred to the perturbed response.         |
| -2 | The reference response is greatly preferred to the perturbed response. |

In the experiment the man was given no a priori performance criteria for the system's performance. He was asked to rate the comparison on the basis of his definition of a "good" time response. The background of the men tested included sufficient control theory for them to be familiar with the accepted definitions of time response characteristics and to be aware of the generally accepted composition of a "good" time response.

Although the experiment was simple, certain results about the human evaluation process became obvious and ultimately influenced the computer design algorithm. The following results were observed:

1. A man can make a quick clearcut decision about stability and the degree of stability from the time response of the system.
2. A minimum difference between the reference and perturbed outputs is necessary for a decision to be made by the man.
3. The weighting function of the performance criteria used by the man in his evaluation of the time domain

performance changes as he gains experience about the system performance.

4. The meaning of the rating numbers changes as the man gains more experience about the system.
5. A hill-climbing parameter adjustment scheme does not appear feasible.
6. A more general rating scheme is suggested.

The first result did not necessarily depend on a comparison between the perturbed and the reference system. If either of the systems was stable and the other system was unstable, the man quickly rated the comparison strongly in favor of the stable system. Even if both systems were unstable, the man tended to rate the comparison strongly negative, where in fact he should have rated the comparison as no preference. Also lightly damped responses with many overshoots were rated strongly negative, especially if the reference system was not as lightly damped. Responses which resulted when the forward gain was zero were rated negatively, but not as quickly or definitely as the unstable responses.

In all other cases when both systems exhibited stable responses, the man required more time to make his decision, and he agreed with other men less frequently than in the unstable case. In fact, as the second result states, a minimum difference between the reference and output time responses was necessary for the man to make a

judgment. If the grid spacing was increased, eventually the man could make a reliable judgment.

The region in parameter space enclosed by the investigation grid where the man was unable to make a rating is referred to as the region of indifference. The size and shape of the region of indifference is dependent on the system and the location of the region in parameter space. Although the region of indifference is not useful in comparing the reference and perturbed system, it is useful in the investigation of the sensitivity of the system to parameter changes because within the region of indifference no appreciable change in the response of the system can be detected.

Generally, including a man in any process not only makes the process nonlinear but also makes the process a learning adaptive process. The experiment being discussed is no exception as the third and fourth results indicate. If the reference and perturbed system were stable and the investigation grid was larger than the region of indifference, the man did not rate the same comparison of time responses consistently, indicating a changing weighting function of time domain performance criteria. Also interviewing the man at various points of the experiment about the meaning he attached to the rating factors showed definite changes, further indicating a changing weighting function.

The fifth and sixth results are conclusions based on the other

results. Due to the changing of the meaning of the rating factors and the variations in the size of the region of indifference, the interpretation of the rating of system performance by man for purposes of a hill-climbing parameter adjustment system does not appear feasible. Also due to the changing meaning of the rating factors a simpler rating system is suggested, based only on the following judgments which the human can make with consistency:

1. No opinion can be made at the present time; more information is needed.
2. The time response is totally unsatisfactory or is inferior in comparison with other responses being considered.
3. The time response is preferred in comparison to the other responses being considered.

Each of these judgments is incorporated into one of the cues used in the computer algorithm.

### Design Examples

In order to demonstrate the usefulness of the computer algorithm, several design examples are considered:

1. The step function response for a third-order linear system with two and three parameter controllers.
2. The step function response for a third-order linear system with a three parameter nonlinear controller.

3. The step function response for a multivariable linear system with a four parameter controller and two inputs.
4. The determination of a three parameter dynamic model of a batch reactor reaction from measured data.

The basic task in the first three examples is for the output of each system to follow a step function input with no final value error. In the fourth example the basic task is to match the dynamic model response to the measured data with the "best fit" possible.

The inputs used in the examples were adjusted so that a meaningful basis for judging a time response as tolerable was that the system accomplished the basic task without overloading any of the amplifiers in the analog model. With the computing system used in this thesis the overloading requirement was implemented automatically (see Appendix A).

For each example a global search of the parameter space was conducted first. The initial size of this parameter space considered in the global search was arbitrarily selected. If the global search yielded a set of tolerable responses, the selection of size of the global space was considered successful.

After the global search several regional searches were conducted, starting at different global grid points which were initially judged as tolerable. Normally this procedure is not necessary, but in order to demonstrate the tendency for the designer to converge to

the same time response characteristics from different starting points, several starting points were considered.

The criteria used to select the final time response is given with each example. No a priori set of time response specifications was assumed. Also, the limits on the sensitivity requirements were only determined on a qualitative basis and the influence of parameter sensitivity on the final design was subjective.

Unfortunately none of the examples have multiple regions of tolerable time response; so the overall effectiveness of the algorithm is not demonstrated. Figure 3.3 and 3.4 show the results of test examples for the region numbering subprogram. The input to the subprogram was a set of positive and negative ones where a positive one represented the rating number for the tolerable grid point. Referring to Figure 3.3 and 3.4, the dotted lines show the assumed tolerable region due to a grid point being positive. The actual shape of the region is unknown and there may be gaps between the parts of one region which can only be found by more grid points or a shift of the present points.

### Implementation of the Design Examples

The design examples were implemented on a hybrid computer consisting of an analog computer, a digital computer, and a data



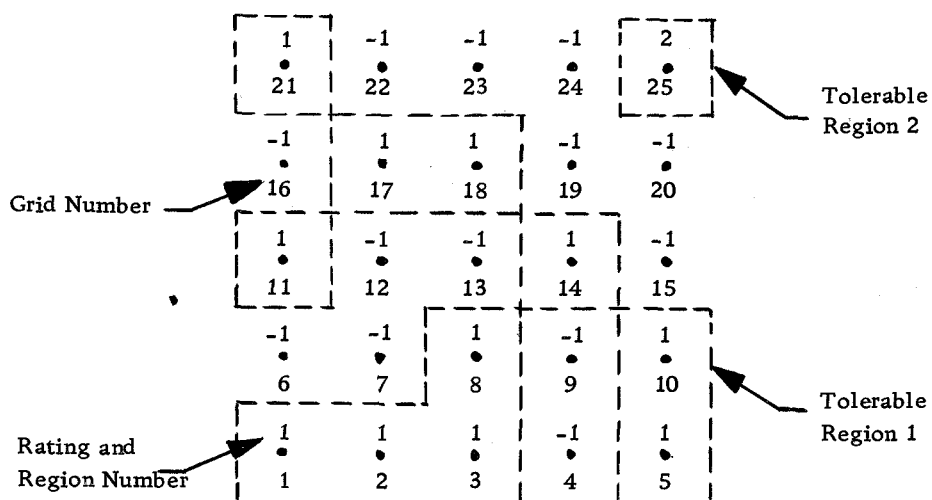


Figure 3.3. The results from the two dimensional regional numbering subprogram.

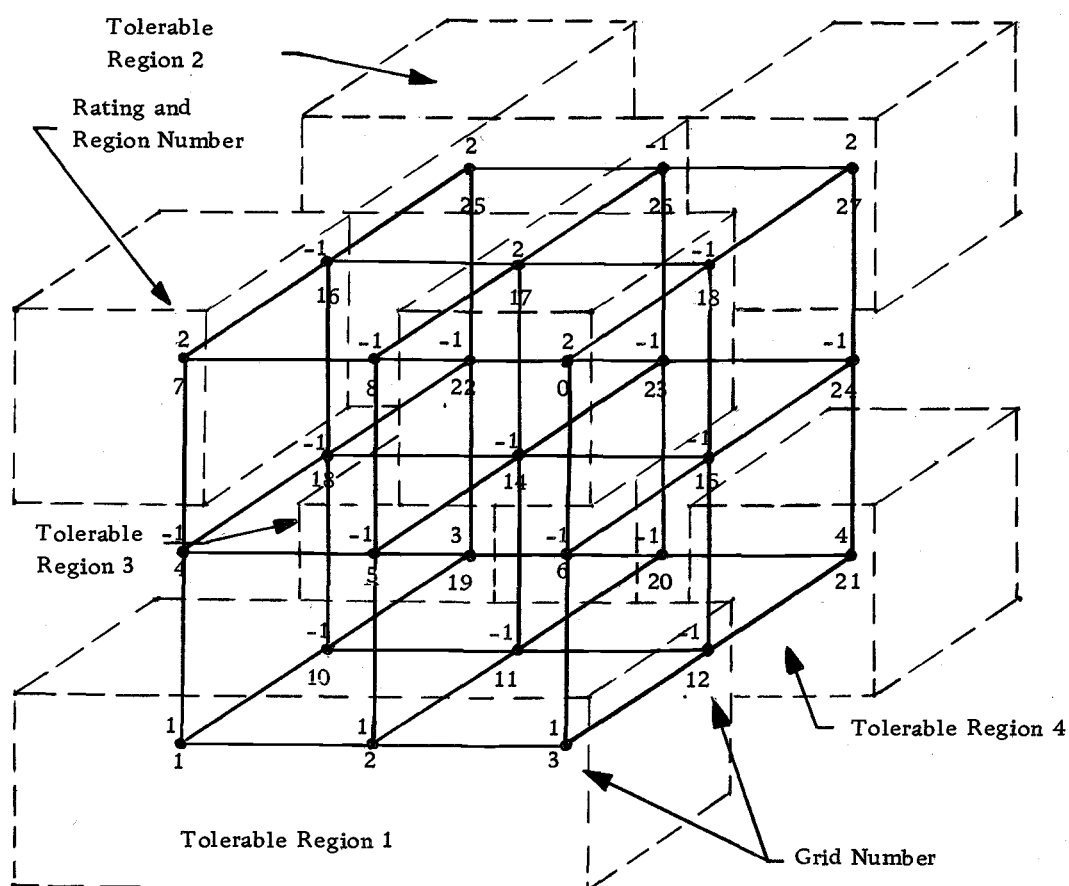


Figure 3.4. The results from the three dimensional regional numbering subprogram.

interface.<sup>4</sup> The following characteristics of the computing system are necessary and useful for the examples:

1. Direct communication lines (sense lines) for inputting the preferential cues of the man
2. Rapid parameter changing devices which do not interrupt the visual display of output information from the computer to the man
3. A general purpose digital computer for the stored program used to implement the algorithm and with a memory sufficient to store the required program variables and sub-programs used with the algorithm
4. Output devices to present the visual information, the program messages, and output data to the man for his evaluation
5. A simulation capability which computes the time behavior of the system sufficiently fast after receiving a preferential cue so that the man receives reinforcement to his cue with no significant delay.

A multichanneled oscilloscope was used as a visual display. The preferential cues of the designer were connected to the logic

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<sup>4</sup> Further discussion of the implementation of the computer algorithm and the digital computer program appears in Appendix A.

devices and sense lines on the analog computer using the remote panel of pushbuttons and cable assembly shown in Figure 2. 2.

The logic devices are necessary with the cues because the digital computer carries out operations many times faster than the response time of a man. In fact in the time that a man takes to give cue (to press and release a pushbutton), the digital computer can carry out the operation directed by the cue many times. In most cases the man requires a time interval between when he gives a cue and when he can evaluate the effect of the cue on the time responses. So once a cue is received by the digital computer, the cue must be disconnected from the digital computer long enough for the man to release the pushbutton so that only one operation occurs for each cue.

With the exception of the parameters being searched, the physical systems were simulated on the analog computer. The parameters being searched were set by the digital computer and transferred to the analog computer by digital-to-analog converters. Then either quarter-square multipliers or digital-analog multipliers<sup>5</sup> were used to implement the parameters in the analog computer simulation.

The physical layout of the computing system during the design examples allowed the designer to have ready access and good visual

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<sup>5</sup> A digital-analog multiplier forms the product of an analog variable and a digital number from the digital computer directly and yields the product as an analog variable.

contact with the visual display, the strip chart recorder, and the analog computer. However, so that he would not be influenced by the parameter values during the search, the designer was unable to see the printout from the digital computer.

### Two and Three Parameter Linear Controller

Figure 3.5 illustrates the controller and the physical system used in the two and three parameter examples. The only difference between the two controllers is the feedback from the phase variable,  $x_3(t)$ . In the two parameter case  $K_2$  in Figure 3.5 is equal to zero. The basic task in both cases is for the output to follow a step function input with no final value error. Therefore, the controller contains a direct comparison between the output and the input. The remainder of the controller is composed of state variable feedback information. Obviously there are other controller configurations, such as a cascade compensator, but there is no comparison made between types of controllers because this is not the purpose of these examples.

In the two parameter case the global search used a grid of 25 points centered at the origin. The bounds on the global region were  $|K_1| \leq 8$  and  $|K_3| \leq 0.8$ . The grid points which gave tolerable time responses were for  $K_1$  and  $K_3$  greater than zero, indicating only one region of tolerable response. Figure 3.6 illustrates the tolerable responses obtained from the global search.

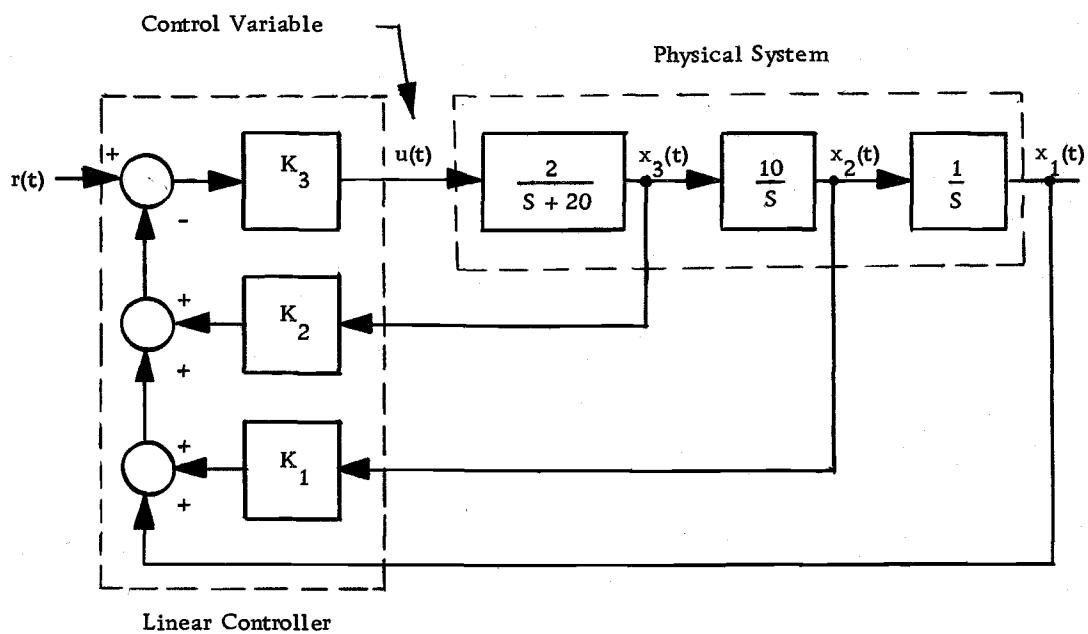


Figure 3.5. The two and three parameter controller for the third-order linear feedback system.

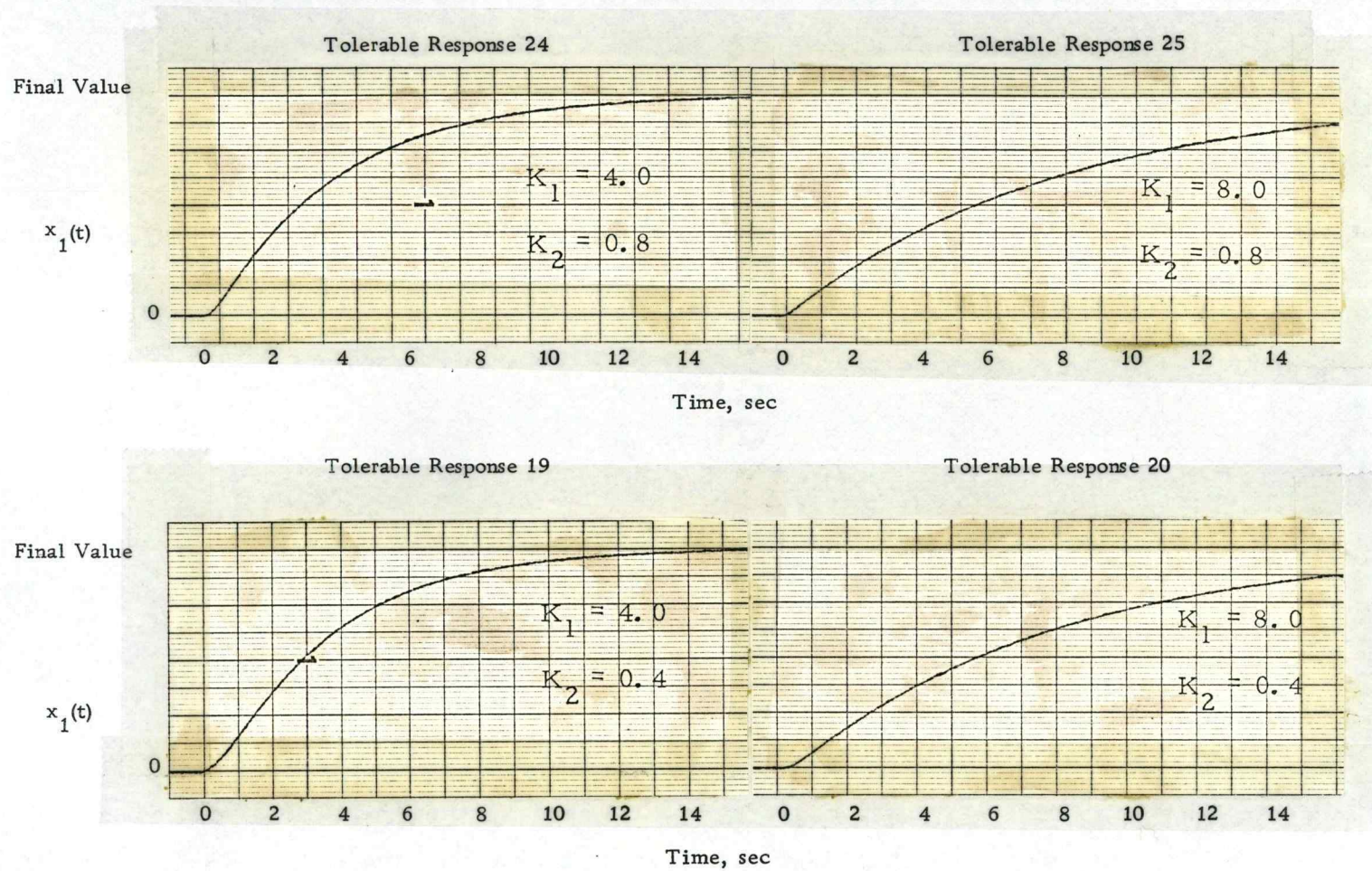


Figure 3.6. The tolerable global search time responses for the two parameter case.

The criteria used to select the final time response for  $x_1(t)$  were a maximum overshoot of ten percent, a risetime and settling time as short as possible under the constraint of  $K_3 \leq 4$ , and reasonable response characteristics for the other observable state variables and the control variable of the system.

In order to evaluate the other system state variables the designer displayed them on the visual display and recorded them on the strip chart recorder as shown in Figure 3.7. The attention given the other system variables was not as great as the output variable. However, the final design was not reached without the designer considering the response characteristics of all the observable system variables.

Figure 3.7 shows a regional search sequence starting at  $K_1 = 4$  and  $K_3 = 0.8$  and ending at  $K_1 = 0.7$  and  $K_3 = 3.54$ . The time responses shown in Figure 3.7 correspond to the terminating points for each regional search conducted during this design sequence. Not shown in Figure 3.7 are all the time responses considered by the designer between regional search termination points. Figure 2.8 illustrates a regional search sequence in the parameter space and indicates how many additional time responses the designer considers between regional search termination points.

The design sequence shown in Figure 3.7 gives insight into the technique of regional searching employed by the designer. Since the



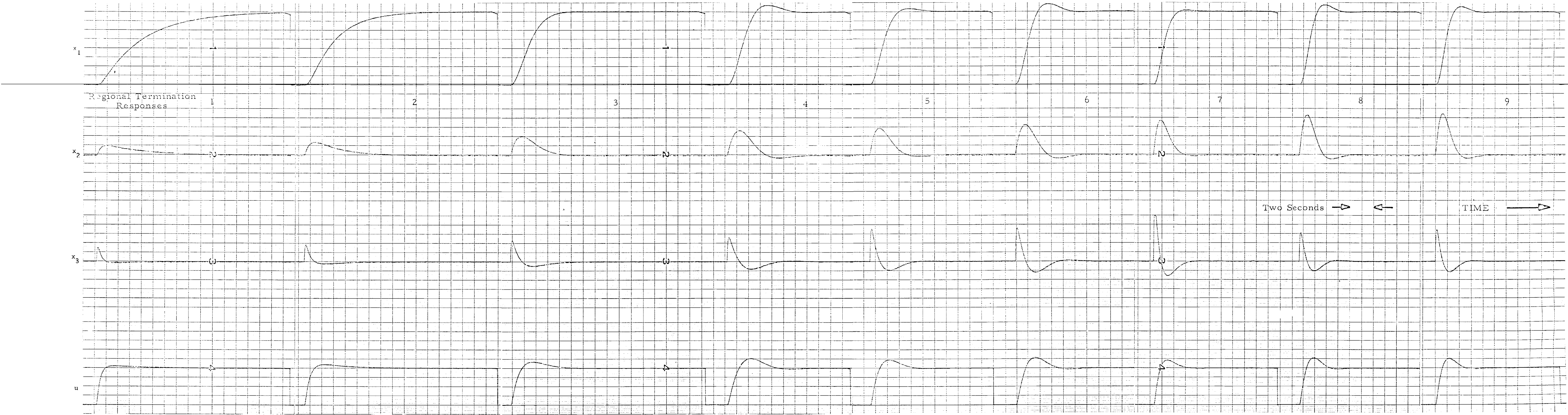


Figure 3.7. A regional search sequence for the two parameter case starting at grid point 24.



time responses for the starting point are overdamped, the designer first improves the risetime as shown by Responses 1-4 of Figure 3. 7. Once he obtains a response with overshoot (Response 4 in Figure 3. 7), the designer has to give consideration to overshoot, risetime, and settling time characteristics, making more difficult his selection of the terminating responses for each regional search.

Another factor contributing to the difficulty of the design process is the paths of the regional grid points relative to the final design point. As shown in Figure 3. 8 none of the grid points from an arbitrary starting point move in the direction of the final design point. Therefore the designer must weave a zigzag path through the parameter space to reach the final design point in a manner similar to that shown in Figure 3. 8. The actual path taken by the designer is not unique and is dependent upon not only the time response characteristics encountered along the paths of the regional grid points, but also upon the time varying performance weighting function of the designer.

In Figure 3. 9 several actual design sequences in the parameter space are shown, demonstrating the zigzag path just described. The time domain reflection of the zigzag path can be seen in Figure 3. 7 with alternating increases and decreases in overshoot.

In order to show that approximately the same time response is obtained starting from different points in the parameter space, four initial starting points were considered. Table 3. 1 shows a tabulation

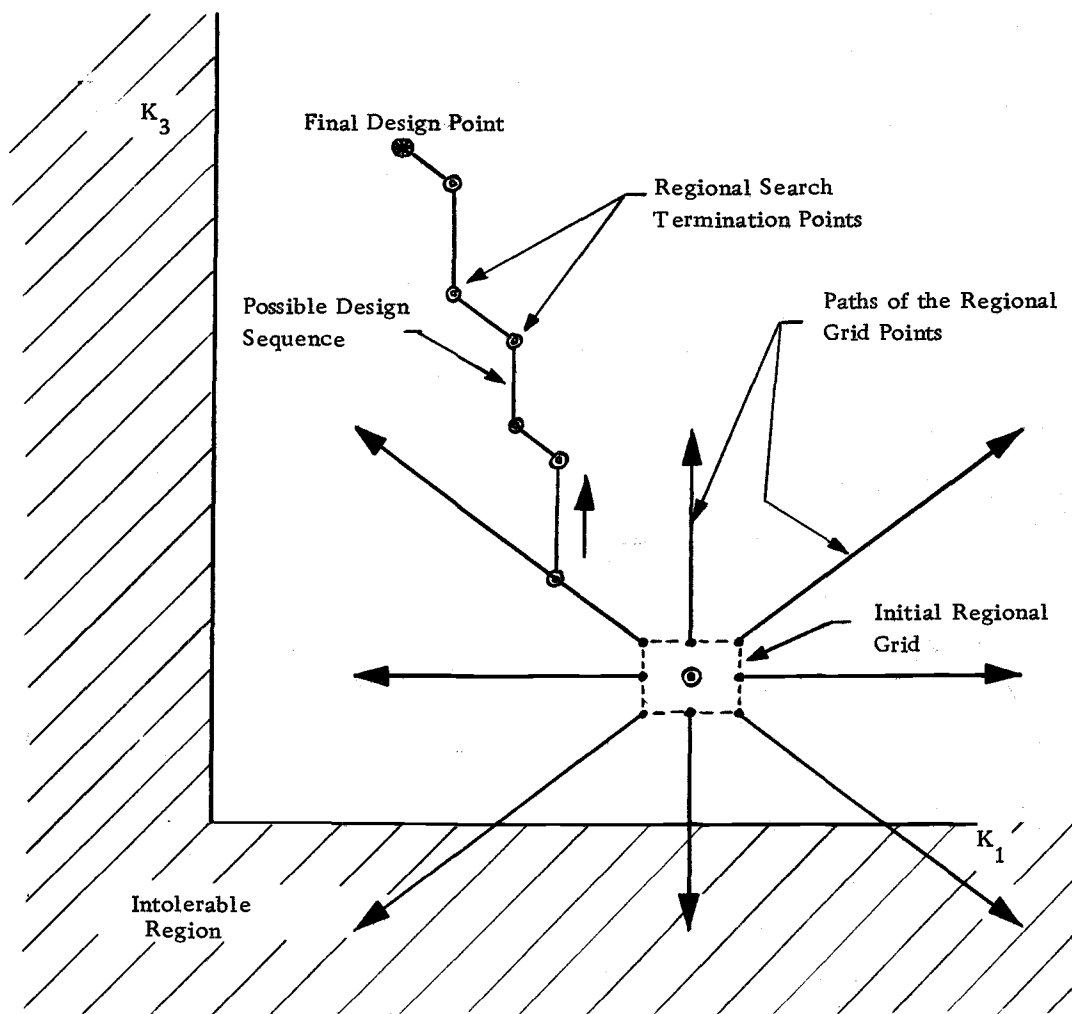


Figure 3.8. The paths of the regional grid points relative to the final design point.

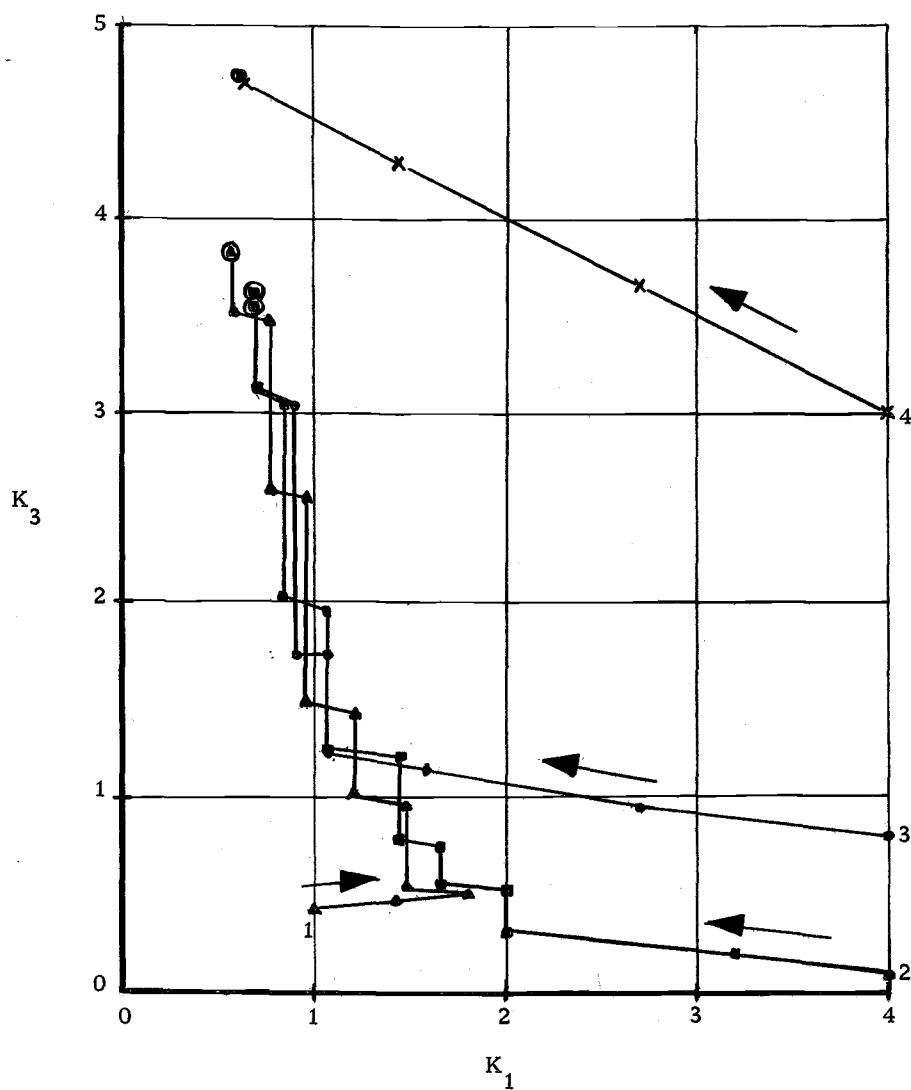


Figure 3.9. The variation of the parameters as the design process from an initial point in the tolerable region to an acceptable final response.

of the final output time response characteristics for the four starting points which are very nearly equal. Figure 3.9 shows the paths from the starting to the final points in parameter space for the four cases. Even though there are differences in the final parameters, the time responses are nearly equal, indicating the tendency of the designer to achieve the same time response characteristics.

Table 3. 1. The final time response characteristics for the two parameter case.

Starting Pt. No.	Risetime, in sec	Overshoot %	Settling time, sec	$K_1$	$K_3$
1	.0. 9	7. 5	2. 5	0. 7	3. 54
2	0. 9	8. 75	2. 6	0. 65	3. 83
3	0. 9	7. 5	2. 6	0. 7	3. 65
4	0. 85	7. 5	2. 4	0. 6	4. 7

For the fourth starting point the gain limit on  $K_3$  was five instead of four as was the case for the other three starting points. As a result, the final value of  $K_3$  was higher than for the other starting points; however, the first three search paths were headed toward the final point of the fourth path when they encountered their gain limit as shown in Figure 3. 9.

Two additional items of interest are shown by the results of Table 3. 1. The first item is that the choice of the starting point in the tolerable region of the parameter space is not critical in terms

of the final design. However the starting point selection influences the number of regional searches required to reach the final design point as demonstrated in Figure 3. 9.

The second item of interest is that the final design response characteristics are more sensitive to changes in  $K_1$  than  $K_3$ . During the experiment the designer was not aware of this fact, but he was able to obtain the responses he preferred, with nearly the same value of  $K_1$ , indicating a qualitative awareness of the sensitivity to  $K_1$ .

The global search for the three parameter case covered the region shown in Figure 3. 10 and included an inspection of 125 global grid points of which 20 points yielded tolerable time responses. From the 20 global grid points two were selected as starting points for regional searches. The starting points are widely separated in parameter space as Figure 3. 10 shows.

At first the overshoot requirement was tentatively set at 10% or less, but as the design process progressed it was apparent that the overshoot requirement could be made more stringent without sacrificing the risetime and settling time. The final time response characteristics used to judge the final waveforms was 5% overshoot or less with as short a risetime and settling time as appeared possible.

The manner in which the parameters changed during the two regional searches is given in Figure 3. 11. Although only  $K_1$  is the

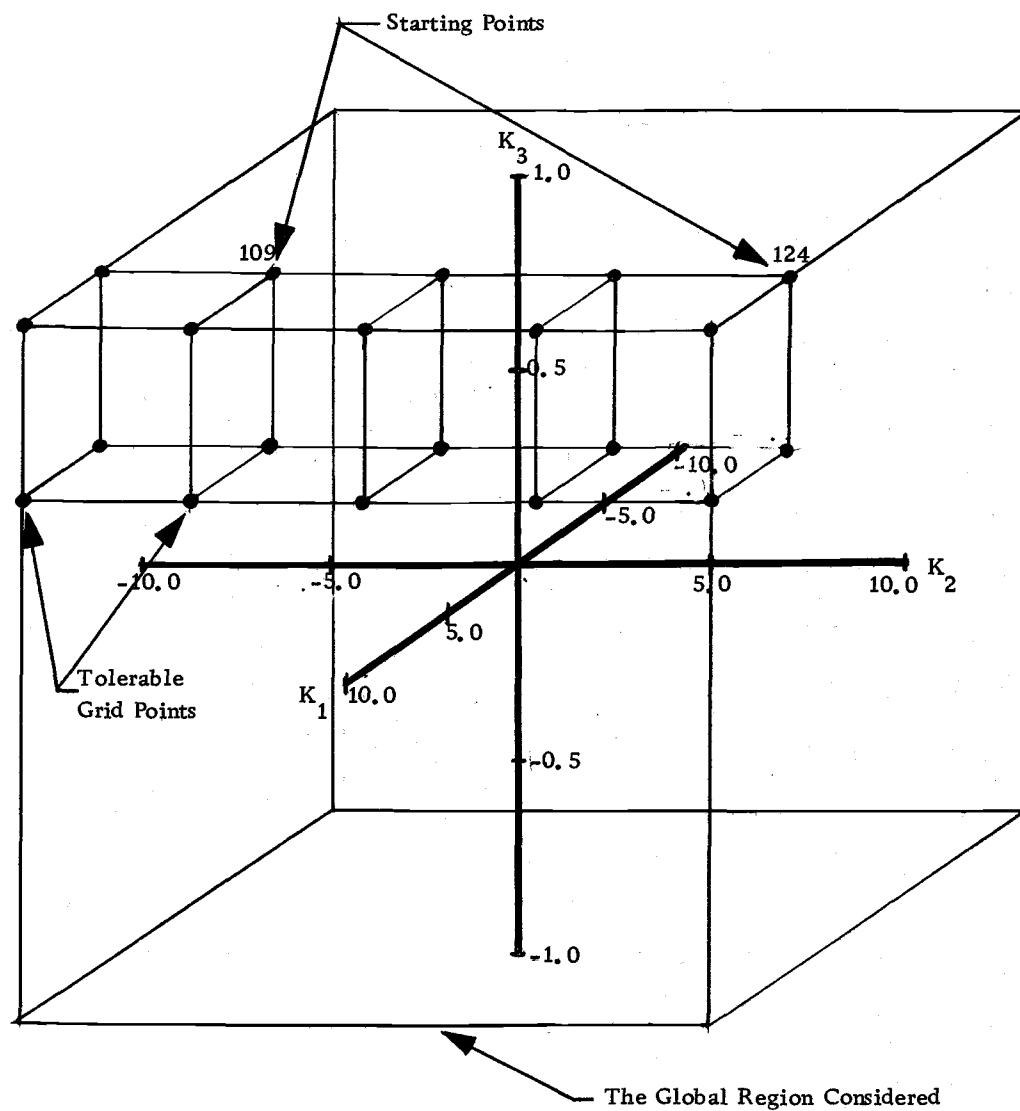


Figure 3.10. The tolerable grid points for the three parameter case.

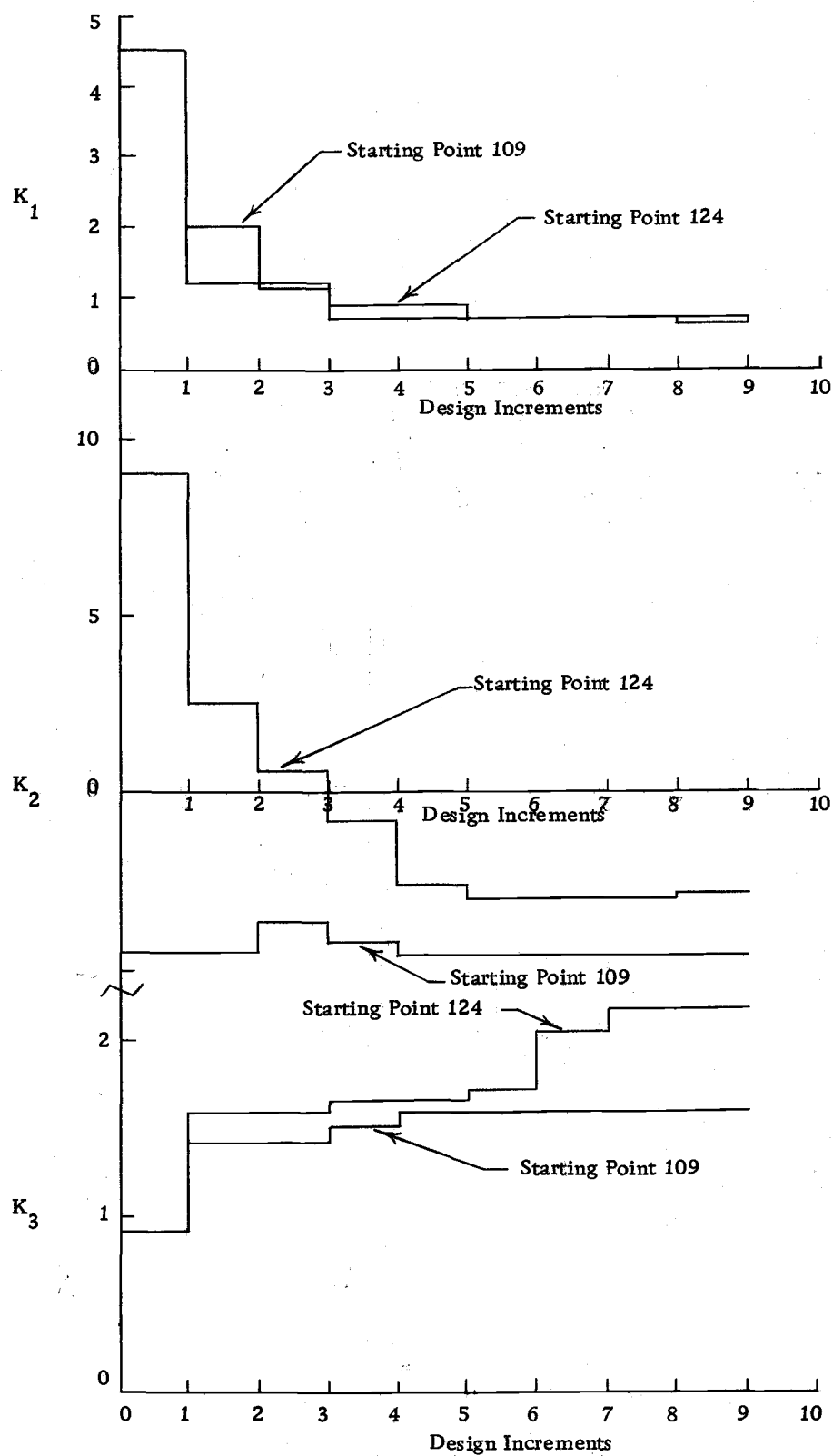


Figure 3.11. The variation of the parameters as the three parameter search progressed.

same for both design sequences, a definite convergence to the same final value is indicated in the parameter values. The final time responses for the two regional searches are shown in Figure 3.12 and are significantly similar even though all their parameters are not equal.

In Figure 3.13 a complete regional search sequence is shown starting at global grid point 109. Since the starting point response is overdamped, the initial goal of the designer is to improve the risetime. Once he has a time response with overshoot, the designer selects responses from the regional grid which not only improve the risetime, but also maintain the overshoot requirement. The selection process may be complicated because of the paths of the regional grid points in parameter space relative to the final design point. During the searching process the designer gains a qualitative measure of the system sensitivity to certain parameters (he may not know which parameters they are). He demonstrates this qualitative measure by obtaining consistently close agreement for the final value of the sensitive parameter,  $K_1$ .

#### A Three Parameter Nonlinear Controller with a Third-Order Linear Plant

The nonlinear controller and linear plant used in this example are shown in Figure 3.14. The plant and controller are exactly the



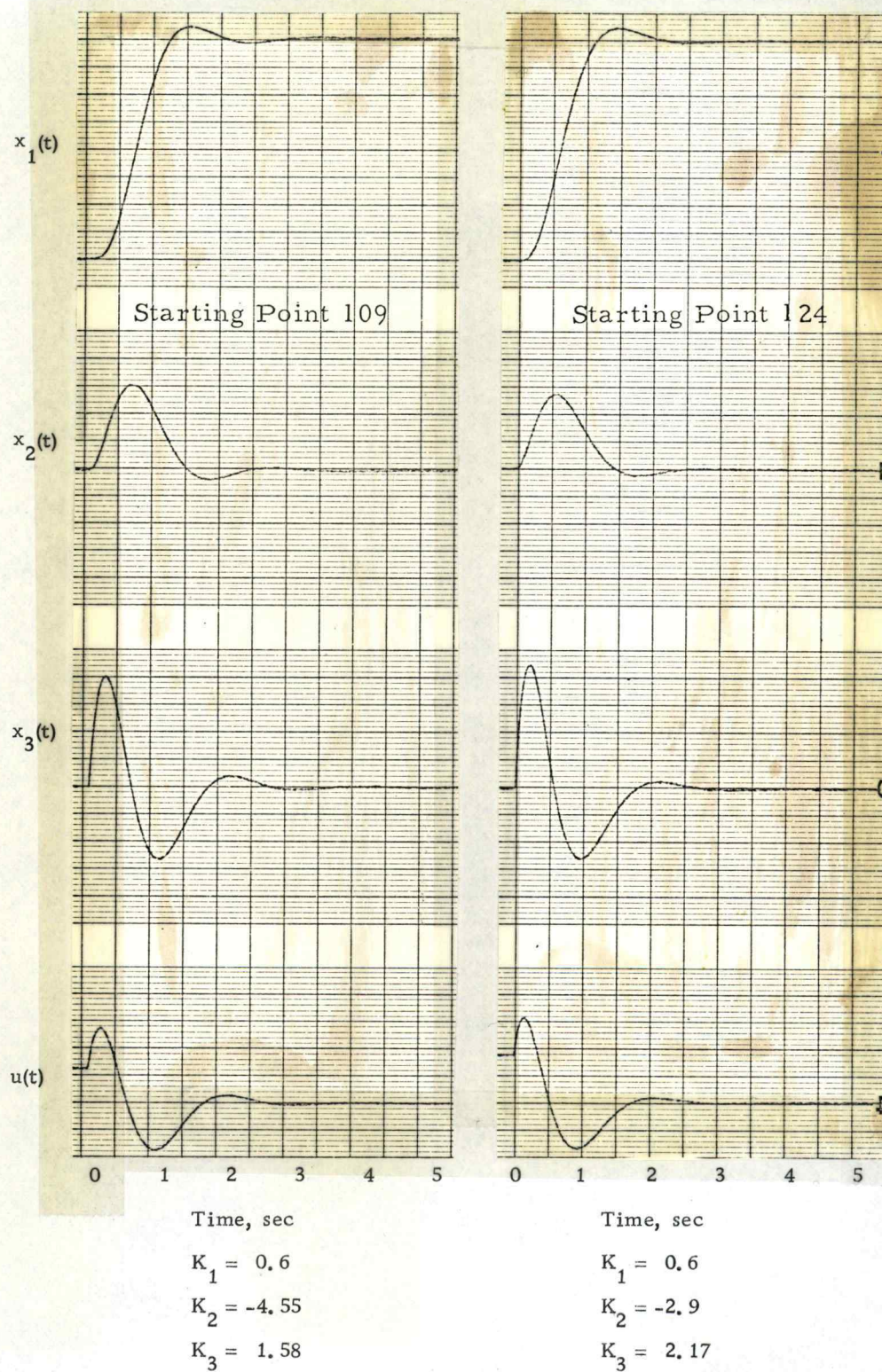


Figure 3.12. The final time responses for starting points 109 and 124.



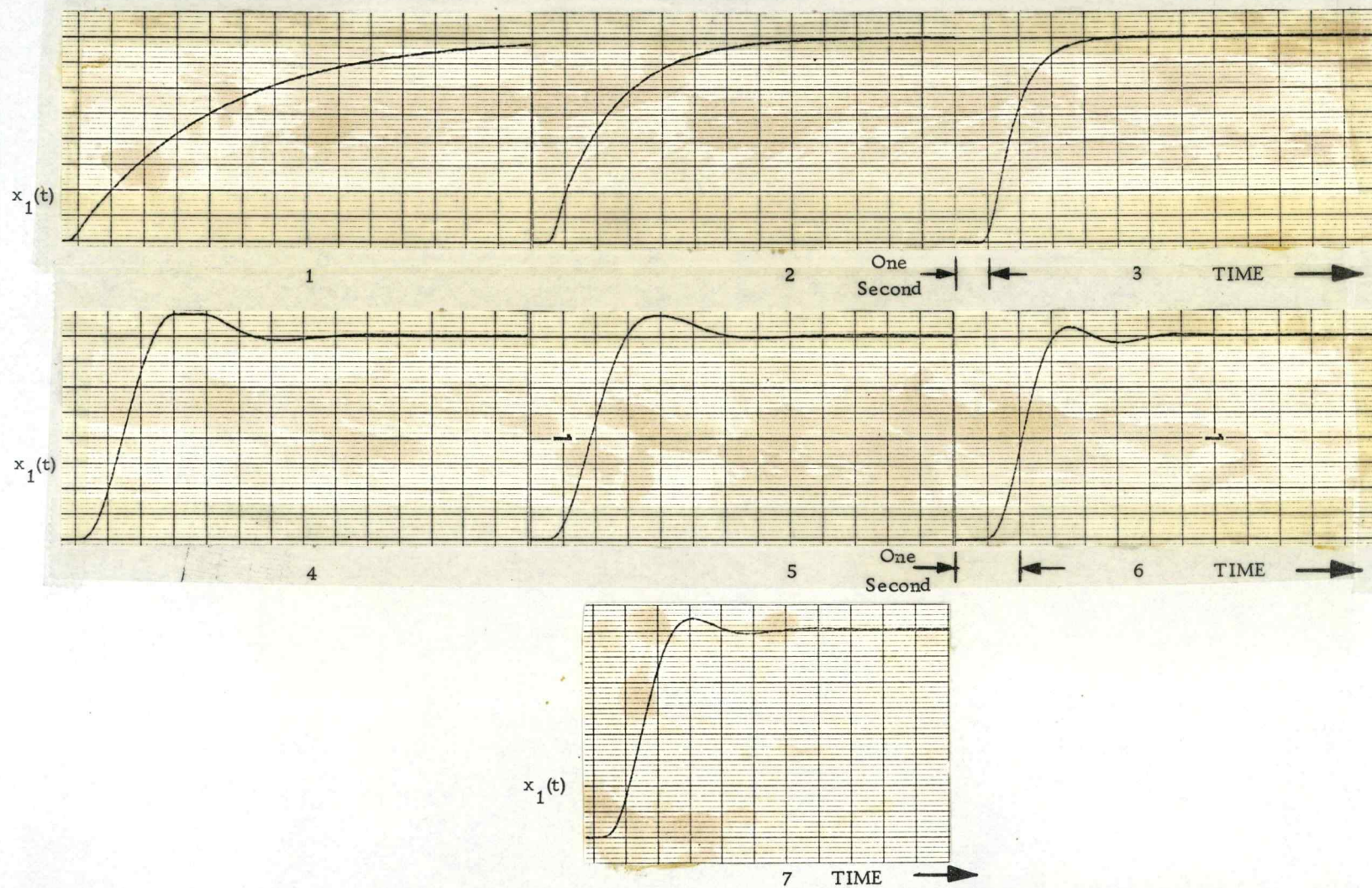


Figure 3.13. The design sequence for starting point 109 for the three parameter example.

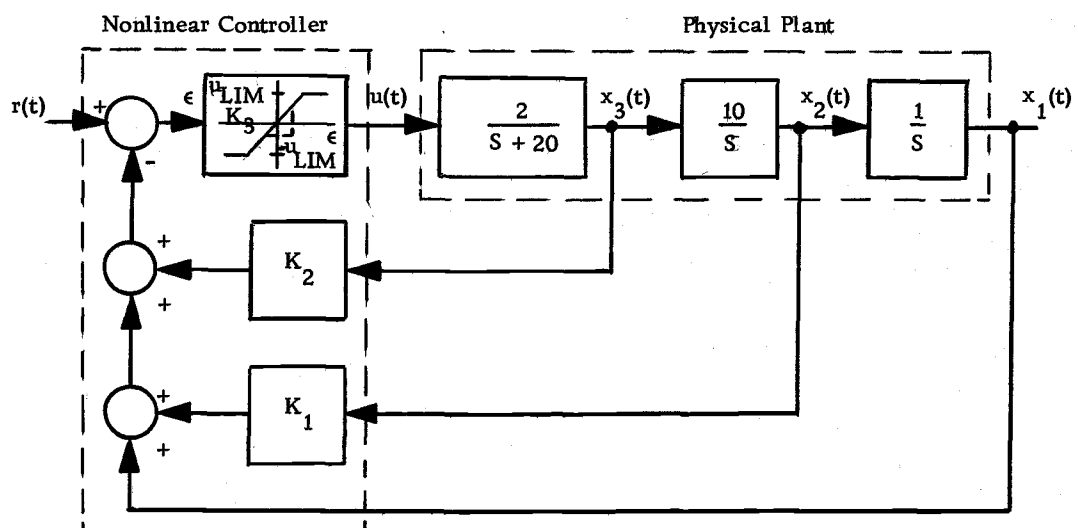


Figure 3.14. The nonlinear controller with a linear physical plant.

same as used in the previous example except the output of the controller saturates. The basic task is the same as for the previous example. To properly design the controller, several input amplitudes must be considered because of the amplitude sensitivity of the controller. The input amplitudes considered in this example are 0.5, 1.0, and 1.5 times the maximum output from the controller so that there is definite limiting in the output of the controller.

Figure 3.15 illustrates the time responses of the system for the three input levels. There is limiting in the first two sets of time responses, but the third set of time responses appears to be linear.

The global search in this example considered the same region of parameter space as shown in Figure 3.10 with the same number of grid points. However, at each grid point the final judgment of the tolerability of the time responses depended on consideration of all three input levels. Therefore, the designer had to evaluate many more time responses than he did in the linear controller example.

In Figure 3.16 a regional search sequence is shown with its starting point at global grid point 124 (see Figure 3.10). The final design parameters are  $K_1 = 0.7$ ,  $K_2 = -3.45$ , and  $K_3 = 0.93$ . Limiting of the control variable for all three input levels is shown in Figure 3.16 for the final time responses, regional termination responses 12-14. A comparison of the final time responses for the linear and nonlinear controllers shown in Figure 3.12 and 3.16,



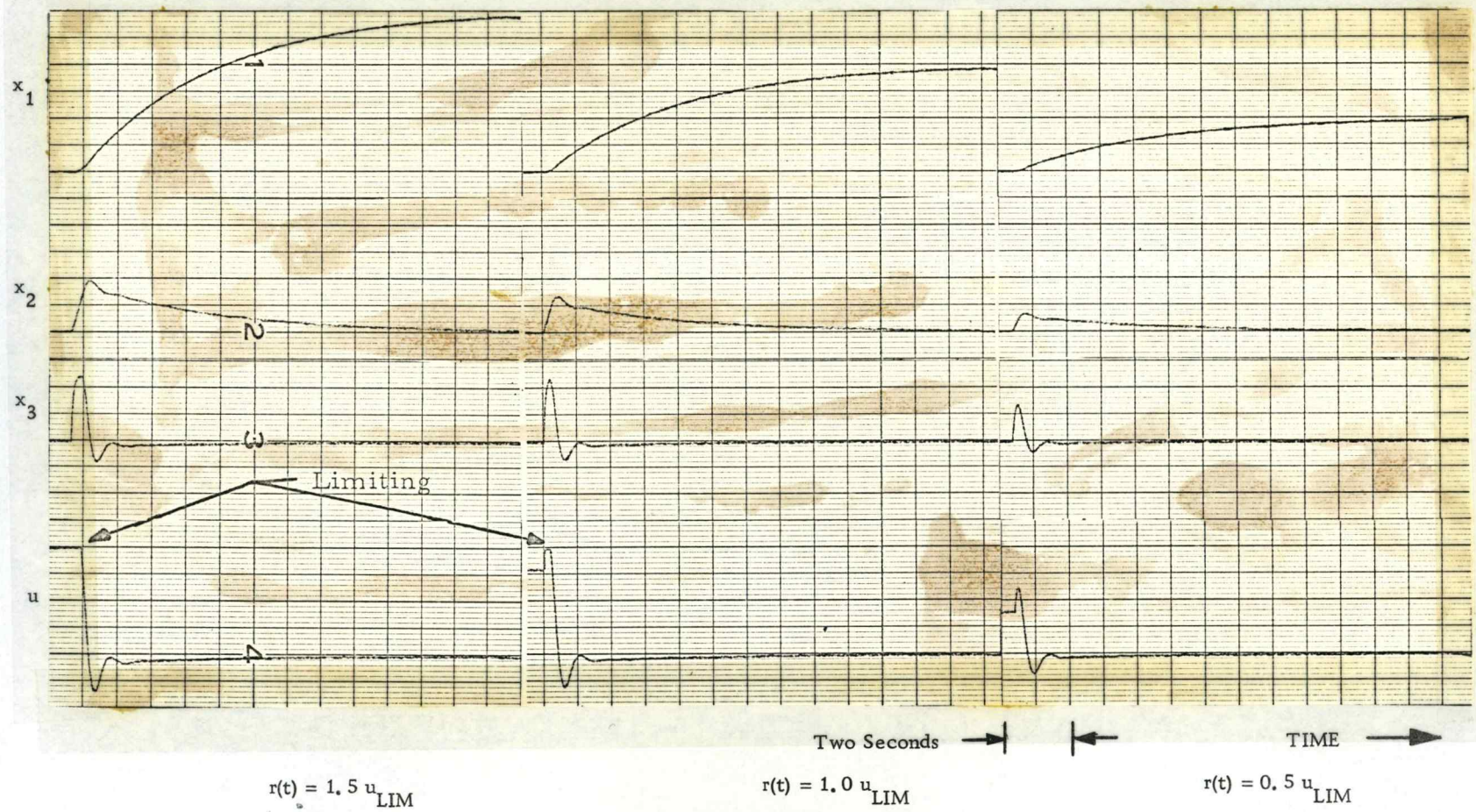


Figure 3.15. The time responses for three input levels for the nonlinear controller and linear physical plant example.



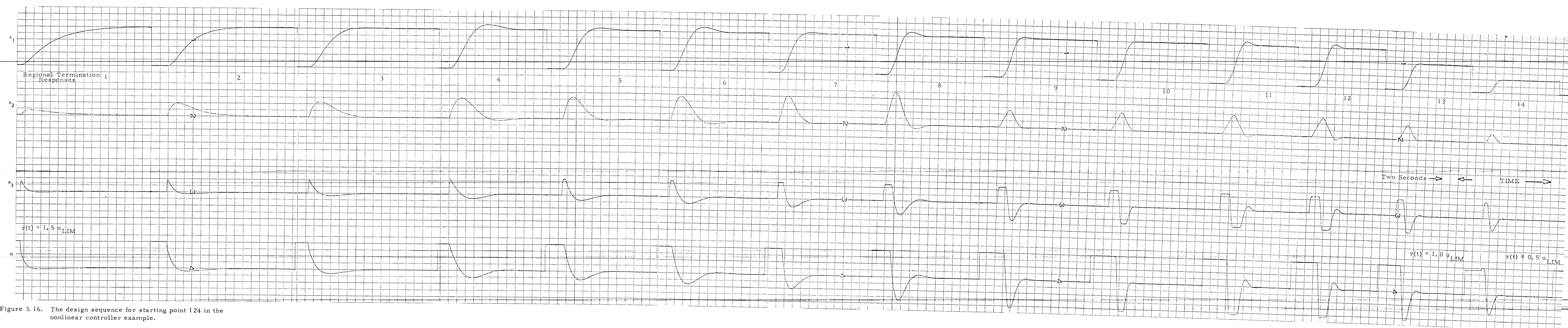


Figure 3.16. The design sequence for starting point 124 in the nonlinear controller example.

respectively, shows that the designer has had to compromise his requirements on the system time responses to cope with the nonlinear effects in the controller.

#### A Four Parameter Multivariable Controller with a Linear Plant

In order to see if a designer could carry out a higher dimensional search successfully and to evaluate the problems he would have, a four parameter two input-two output linear system was studied. The multivariable system is shown in Figure 3.17. The physical system has considerable cross-coupling in parameters A and B. The basic task given the physical system is for the outputs to follow a step function input applied to the respective inputs with no final value error. No initial statement about the amount of cross-coupling is assumed, but cross-coupling is assumed to be detrimental to the time response of the system. Also, no a priori requirements are established on the final time response characteristics.

In this example the number of responses in each grid which the designer must examine reflects the extent of the difficulty with higher dimensionality. The number of responses in the smallest grid is given by the following expression:

$$\text{Number of Responses} = 3^n \quad (3.1)$$

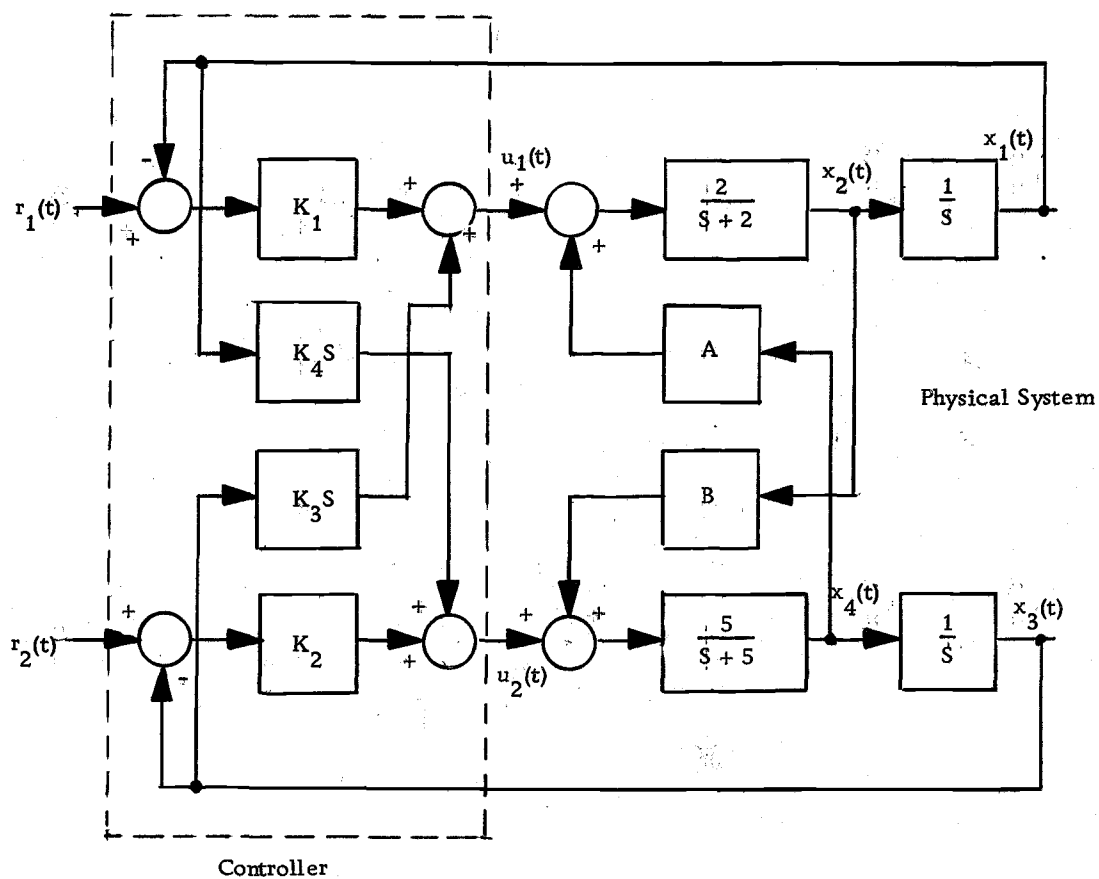


Figure 3.17. The four parameter multivariable controller.



where  $n$  equals the number of parameters being searched. So as the number of parameters increases, the number of responses the designer must consider increases exponentially. For example, a two parameter problem has nine responses and a four parameter problem has 81 responses. As a result, the designer has a large increase in the number of comparisons and evaluations he must make in order to make a selection. Also, the amount of information about the time response characteristics and sensitivity has increased immensely.

In addition the designer must consider the two inputs in combinations to investigate the possible effects of cross-coupling. The combinations include an input to each input separately and then an input to both inputs simultaneously. Thus the designer has not only a regional grid of 81 points to consider, but also three input levels to consider at each grid point (243 evaluations per regional grid).

The global grid used in this example included only 81 points and yielded a total of six grid points with tolerable time responses. Table 3.2 gives the coordinates of the global grid points which yielded tolerable time responses.

Table 3. 2. The parameter values of the tolerable grid points for the four parameter case.

Grid Number	$K_1$	$K_2$	$K_3$	$K_4$
9	5	5	-5	-5
18	5	5	0	-5
36	5	5	-5	0
45	5	5	0	0
63	5	5	-5	5
72	5	5	0	5

Figure 3. 18 illustrates the time responses for global point 9. There is obviously a great deal of cross-coupling and the responses are not well damped. The final time responses of the regional search sequence are shown in Figure 3. 19 and have the characteristics of no cross-coupling and 10% overshoot or less. However, the intermediate responses of the sequence demonstrate both undesirable time response characteristics and cross-coupling, indicating that the designer bases his regional judgments on a relative improvement and must accept less than desirable time responses before he reaches his final choice. The final parameter values are  $K_1 = 1.45$ ,  $K_2 = 3.15$ ,  $K_3 = 2.0$ , and  $K_4 = -7.0$ .

As Figure 3. 19 indicates, the designer was able to eliminate all the cross-coupling effects. Examining Figure 3. 17 shows that  $K_3$  must equal  $-A$  and  $K_4$  must equal  $-B$  for no cross-coupling.

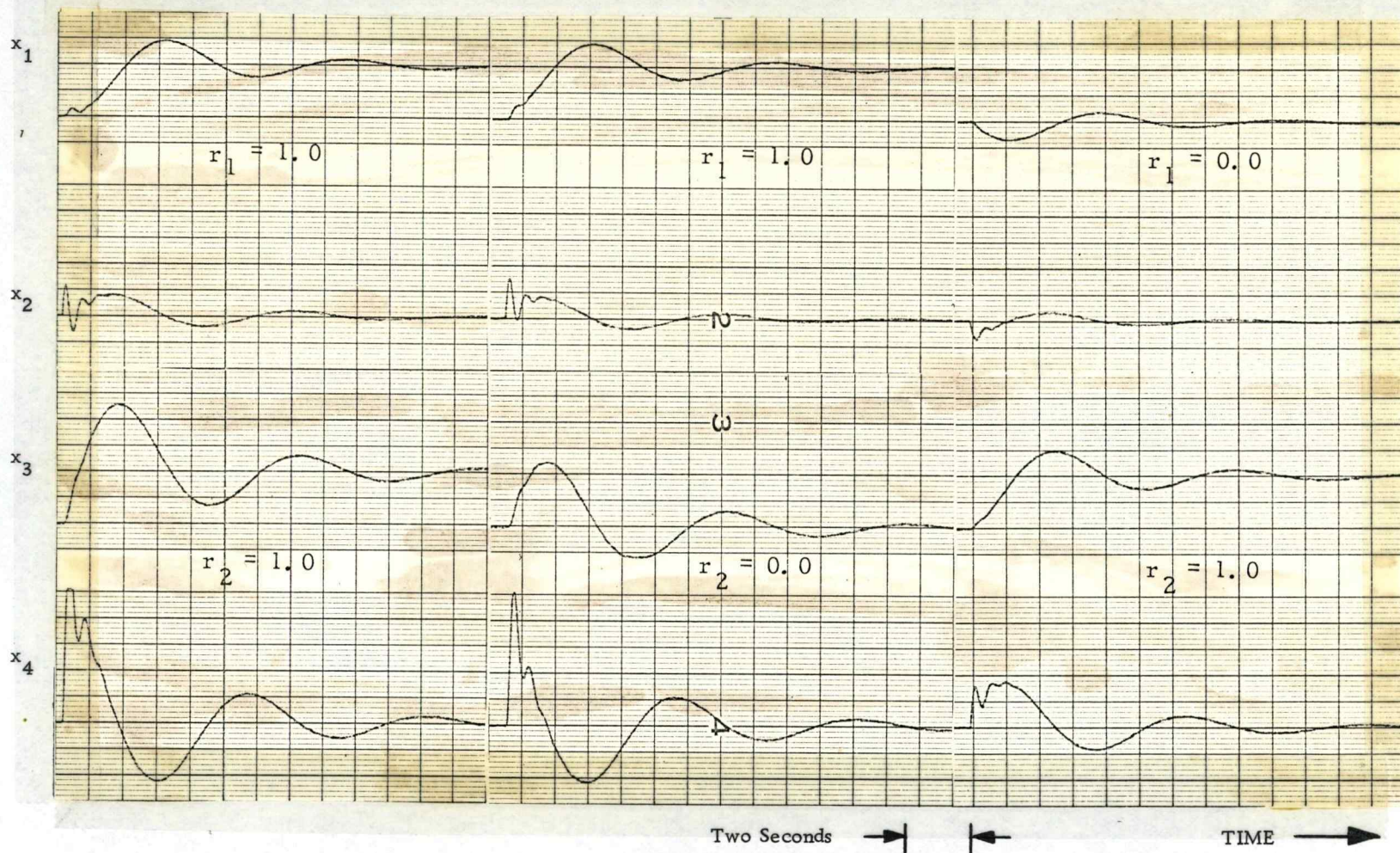


Figure 3.18. The time responses for global grid point 9 for the four parameter case.



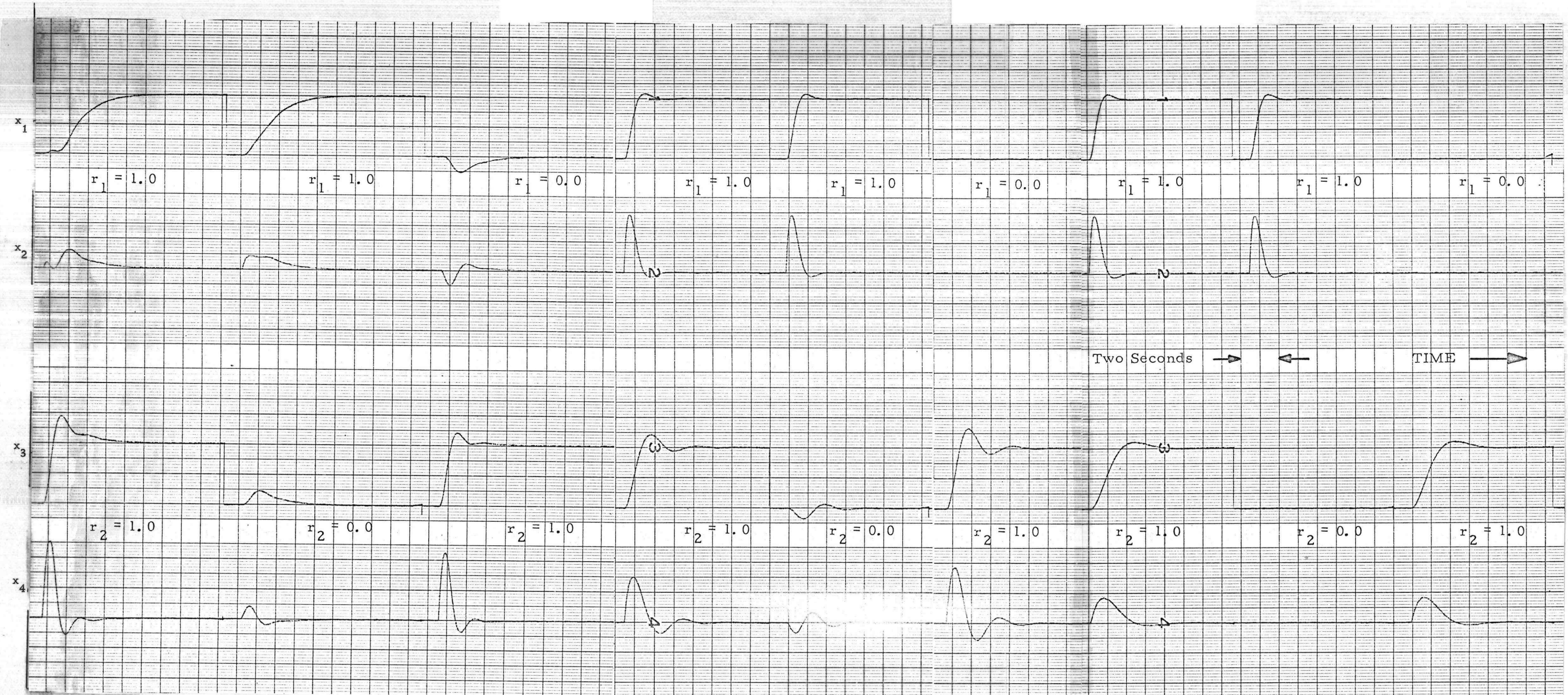
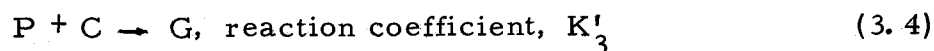
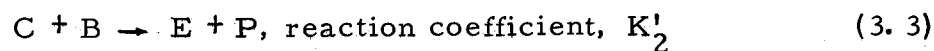
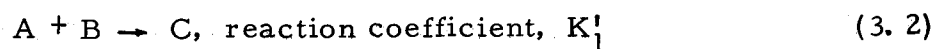


Figure 3.19. A regional search sequence beginning at global grid point 9.

Even though the designer was unaware of the values of the parameters during the design process the final result was  $K_3 = -A$  and  $K_4 = -B$ .

### The Adjustment of Three Parameters for Matching a Model Response with Actual Data for a Batch Reactor Reaction

As a final example, a slightly different design problem was considered in which the three reaction coefficients for a proposed chemical reaction mechanism are to be adjusted so that the model response matches measured data for the actual chemical reaction. The proposed chemical equations for the model (21, 22) are:



The proposed differential equations (21, 22) governing the reaction mechanism are as follows:

$$\frac{dA}{dt} = -K'_1 AB \quad (3.5)$$

$$\frac{dB}{dt} = -K'_1 AB - K'_2 BC \quad (3.6)$$

$$\frac{dC}{dt} = K'_1 \frac{M_C}{M_A} AB - K'_2 \frac{M_C}{M_B} BC - K'_3 CP \quad (3.7)$$

$$\frac{dE}{dt} = K'_2 \frac{M_E}{M_B} BC \quad (3.8)$$

$$\frac{dP}{dt} = K'_2 \frac{M_P}{M_B} BC - K'_3 \frac{M_P}{M_C} PC \quad (3.9)$$

$$\frac{dG}{dt} = K'_3 \frac{M_G}{M_C} PC \quad (3.10)$$

where  $M_A = M_B = M_P = 100$ ,  $M_C = M_E = 200$ , and  $M_G = 300$ .

There are two auxiliary equations which are given as:

$$C' = 2(A(t_0) - A) \quad (3.11)$$

$$P' = P + \frac{1}{3} G \quad (3.12)$$

where  $A(t_0)$  is the initial value of  $A$ . Then if the equations are time scaled so that machine time is equal 100 times real time, the following set of equations can be used to simulate the physical model:

$$\frac{dA}{d\tau} = -K_1 AB \quad (3.13)$$

$$\frac{dB}{d\tau} = -K_1 AB - K_2 BC \quad (3.14)$$

$$\frac{dC}{d\tau} = 2K_1 AB - 2K_2 BC - K_3 CP \quad (3.15)$$

$$\frac{dE}{d\tau} = 2K_2 BC \quad (3.16)$$

$$\frac{dP}{d\tau} = K_2 BC - 0.5 K_3 PC \quad (3.17)$$

$$\frac{dG}{d\tau} = 1.5 K_3 CP \quad (3.18)$$

$$C' = 2(A(t_0) - A) \quad (3.19)$$

$$P' = P + \frac{1}{3}G \quad (3.20)$$

where

$$K'_1 = 100 K_1$$

$$K'_2 = 100 K_2$$

$$K'_3 = 100 K_3$$

In order to make a comparison between the measured data and model response convenient and reasonably accurate, the measured data (22) was copied onto a clear overlay and attached to the face of the visual display, the oscilloscope. Then the designer could align the proper output from the model with the proper measured data curve for direct comparison.

The global search of the parameter space included 125 grid points and yielded the tolerable grid points shown in Figure 3.20. A regional parameter search was conducted starting at grid point 124 in Figure 3.20. The resulting time response of the search in comparison to the measured data (22) is shown in Figure 3.21. Not shown in Figure 3.21 are the final values of the time response of the

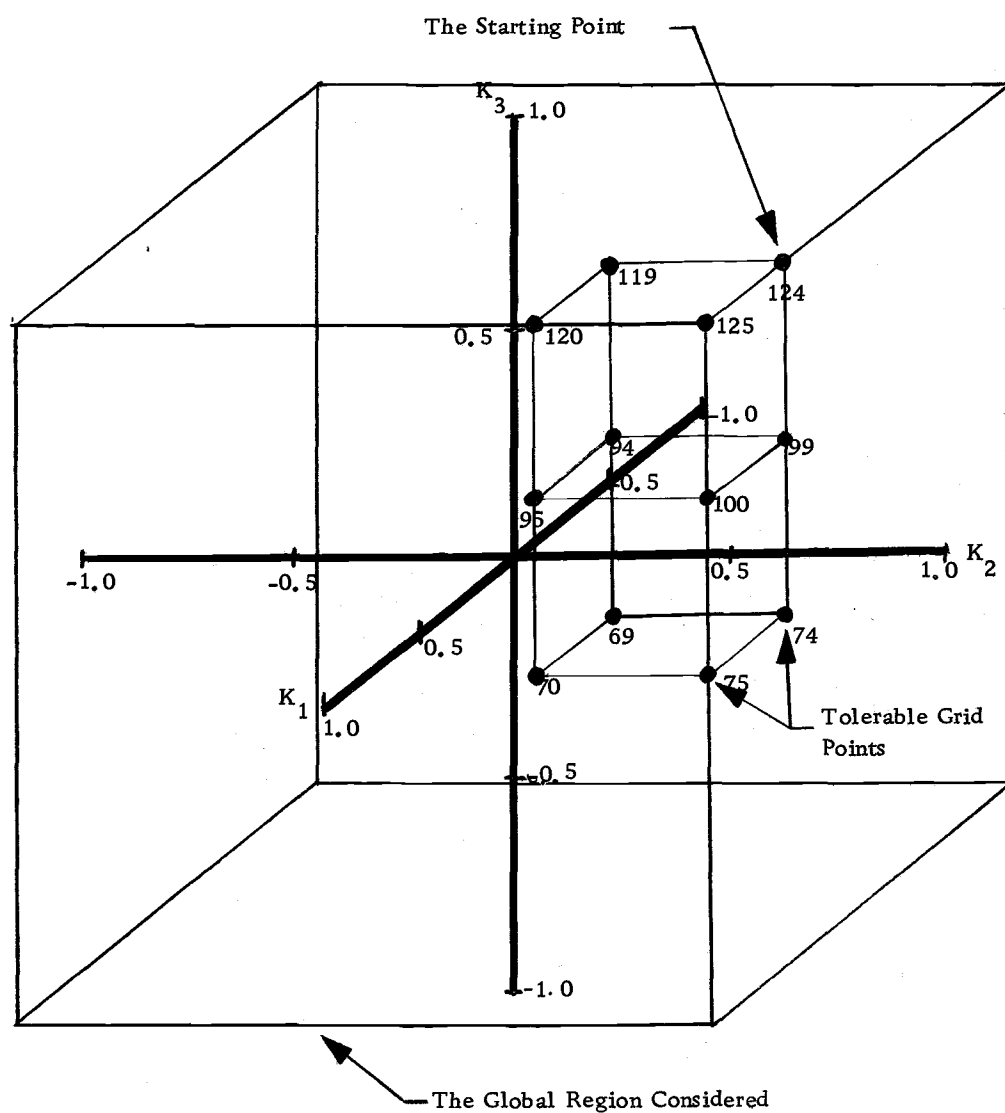


Figure 3. 20. The parameter space for the batch reactor reaction.



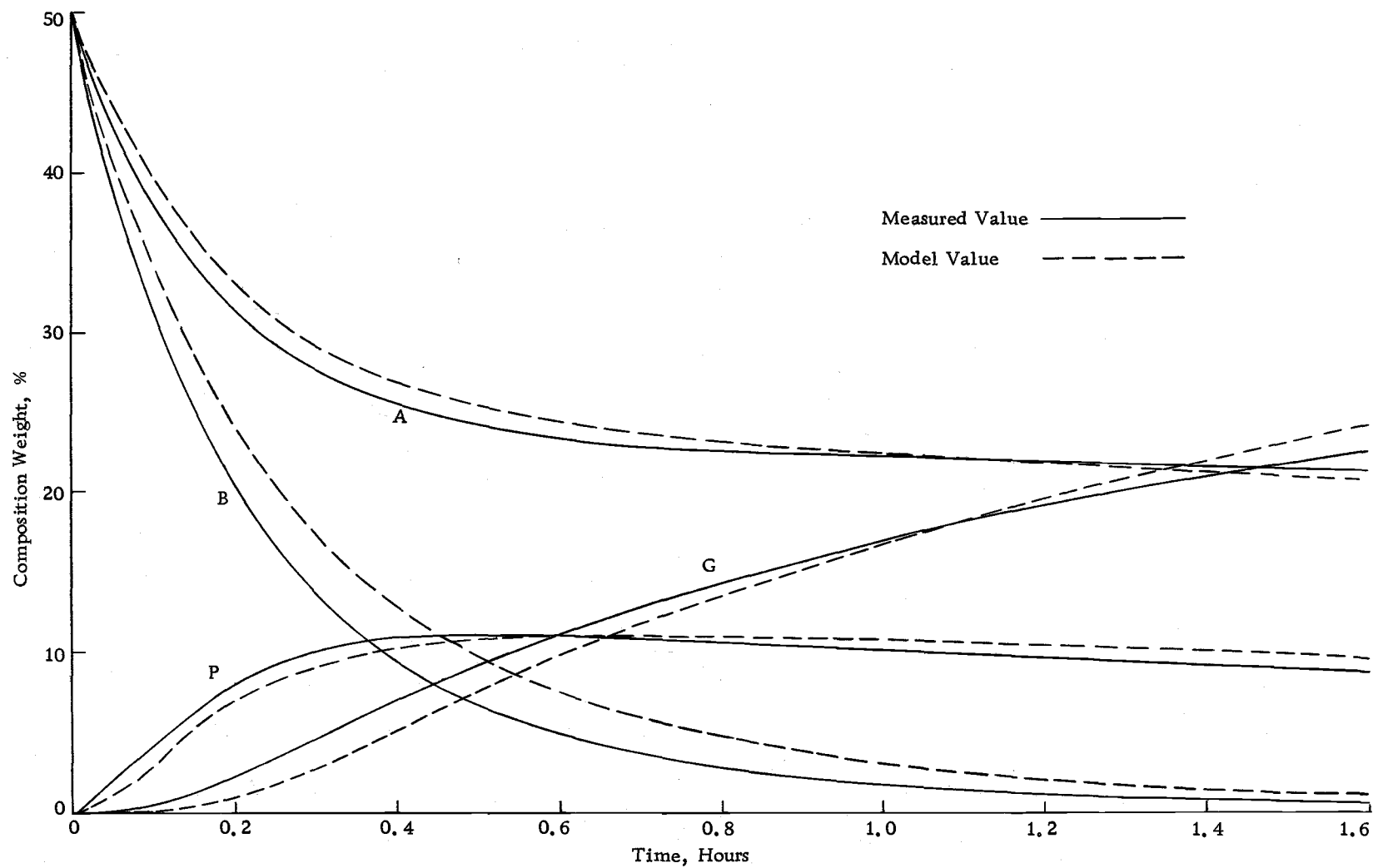


Figure 3. 21. A comparison between the measured data and the model response.

model. For A, B, and G the final value match between the measured data and the model response was satisfactory, but for P there was a 40% error.

Referring to Figure 3. 21, the indicated inability of the designer to achieve a perfect match between the measured data and the time response of the model is due to the lack of a priori knowledge about the accuracy of the proposed model. In fact the three parameter model shown here is not sufficient to model the batch reactor reaction (22). Actually a five parameter model is needed (22). However, as Figure 3. 21 shows, the designer was able to obtain an adequate match. If he would have been willing to sacrifice the final value comparisons a greater amount, the designer could have obtained a better transient match.

#### Comments on the Design Examples

The length of time required by the designer to carry out a complete design example using the parameter search algorithm varied from 15 to 30 minutes of computer time. However, during much of this time the digital computer was waiting for the man to respond to the visual information and messages from the computer. A time-sharing computer scheme could release the digital computer for other uses during the waiting time.

Many factors influence the time required by the designer to

carry out a complete design. The following is a partial list of these factors:

1. Differences between the mental awareness of the men and their familiarity with design techniques.
2. The designer's experience in using the computer algorithm.
3. The number of parameters being searched.
4. The choice of the starting point from the global grid points (the initial parameter choice).
5. The number of global grid points and their separation in parameter space.
6. The size and number of tolerable regions in the parameter space.
7. The capability of the system to accomplish the basic task.
8. The a priori specifications on the system performance.
9. The constraints on the parameters being searched.

With the possible exception of the fifth factor, all the factors influence all design algorithms in varying degrees.

Accidentally the fourth example provided additional insight into the evaluation process of time responses by the man and the requirements of the computing system. Normally quarter-square multipliers or digital analog multipliers are used to set the parameters, but for this example the model required more multipliers than were

available. Therefore, a potentiometer was used to set  $K_3$ .

Each time  $K_3$  was changed, the operation of the analog computer was interrupted by the potentiometer changing value. As a result, the visual presentation of the effect of parameter changes on the time response of the model was significantly interrupted. The interruption greatly frustrated the designer to the point that he was nearly unable to obtain a final match between the measured data and the time response of the model.

Apparently in the evaluation process the man relies heavily on visual information about trends in time response characteristics and on visual comparisons before and after a parameter changes. Therefore, the visual display of time domain information is a crucial portion of the computing system and the manner in which the visual information is projected to the man is a critical part of the computer algorithm.

## CHAPTER IV

### CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

#### Conclusions

The system design procedure presented in this thesis directly utilizes the time domain where ultimately the performance of a system must be judged. The procedure allows the designer a great deal of flexibility in his final choice of time response characteristics. During his visual inspection the performance measures used by the designer to judge the time responses change due to experience and qualitative sensitivity information gained. Using this algorithm the designer is able to devote his full attention to the task of evaluating the time behavior of the system.

The results of this thesis also demonstrate a successful interactive process between a man and a computing system illustrating the changing role of the computer in the design process. The extent of the interaction is the visual inspection of time responses by the designer and his preferential cues directing the computer to carry out certain actions. The cues are based on the three basic judgments the designer is capable of making consistently:

1. No opinion can be made at the present time; more information is needed.

2. The time response is totally unsatisfactory or is inferior in comparison with other responses being considered.
3. The time response is preferred in comparison to the other responses being considered.

Data taken prior to the development of the algorithm showed that a more complicated interactive process involving a hill-climbing scheme based on performance ratings from the man appeared unfeasible. However, the same experiment indicated that the man can make the three basic judgments listed previously.

A designer can obtain good time responses from the system using the algorithm for linear and nonlinear systems. The number of parameters he can effectively cope with does seem to be limited to about four for this algorithm because of the immense number of grid points he must consider.

Lastly the hybrid computer offers an effective and flexible tool for the study of interactive man-machine problems.

#### Recommendations for Future Study

The following subprograms can be added to the present computer algorithm to make it more useful:

1. A subprogram to convert component values into system parameters in compliance with physical constraints.
2. A subprogram to measure changes in the time response

characteristics due to changes in parameter value so that quantitative sensitivity measures can be outputted to the man.

A storage scope can be substituted for the multichanneled oscilloscope to increase the comparative information available to the man. A subprogram to accomplish the writing and erasing of images at the proper time is necessary.

The physical layout of the computing system can be modified to improve the interaction between the man and the computer. The man should be as close as possible to all the output devices which influence him directly.

Finally, in order to make this type of design tool useful for systems with more than four parameters, work must be done to reduce the number of regional time responses the man must consider before he can make an accurate judgment. A possible approach involves computer-measured time response characteristics and correlation of these characteristics to the judgments of the man so that the computer can eliminate grid points automatically.

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## APPENDICES

## APPENDIX A

THE COMPUTER ALGORITHM IMPLEMENTATION AND  
THE DIGITAL COMPUTER PROGRAM

The computer algorithm was implemented using an Electronic Associates, Inc. 690 hybrid computer system in the Simulation Laboratory of the School of Engineering. This system is composed of an EAI 680 analog computer, an EAI 693 data interface, and an EAI 640 digital computer. A digital program controls the computer system for implementation of the computer algorithm and is written in FORTRAN IV language. The program is composed of a main program and ten subprograms which are named along with their purpose in Table A. 1. The detailed flow charts for the main program and the ten subprograms are given in Appendix B.

During the global search each grid point is rated as tolerable or intolerable by either the man or the computer. If the man does the rating, he uses one of the cue pushbuttons (see Figure 2. 2). If the computer does the rating, a digital subprogram checks the output of an analog comparator. If the comparator is "on", the digital subprogram gives the grid point an intolerable rating and waits until the comparator goes "off".

The comparator is triggered "on" by the overload signal which occurs whenever the output of any amplifier in the analog computer

Table A. 1. List of subroutines.

Mnemonic	Description/Purpose
PTSET	To enable the designer to set the system pots which are invariant during the search from the typer; a record of the system pot settings is obtained at the typer.
RESET	To initialize the grid point locator numbers and the input locator numbers; to initialize the grid point and input level number; to initialize the grid spacing; to initialize the grid point rating vector for each region separately.
STBCK	To conduct a global search of the parameter space.
SETKS	To set all the analog parameters and inputs which are under the control of the computer algorithm.
UNSTB	To detect intolerable time responses automatically in the analog model (specifically overloads).
COMCK	To detect the cue given by the designer.
CHNNK	To change to the next grid point locator number and sequence to the next grid point number.
CHLVL	To change to the next input locator number and sequence to the next input level number.
REGNB	To number the regions of tolerable response as determined by the global search.
TRCDG	To obtain a time response of several analog variables on the strip chart recorder on cue from the designer automatically.

saturates. The overload signal remains "on" until all the amplifiers come out of saturation. To provide time for the analog amplifiers to fully recover,<sup>6</sup> the digital subprogram is further delayed for a couple of seconds by either the means shown in Figure A. 1 or a delaying subprogram.

A convenient rating scheme is positive numbers for tolerable points and negative numbers for intolerable points. Then during the region numbering phase, the tolerable points of one region can be assigned to the same positive number for convenient sorting during the starting point selection phase. Also, the regional grid points for a tolerable region can be initially assigned the same positive numbers as the tolerable region number so that sorting is easier and data recording is complete.

When grid points are deleted during the regional search phase and the starting point selection phase, the sign of the grid point rating numbers is set negative. Then to sort through the grid to find out which grid points the designer wishes to consider, the computer need only check the sign of the rating numbers.

Both the global and current regional grid rating numbers are stored in memory. The way in which the rating numbers are stored is to form an ordered set of rating numbers for each grid. The

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<sup>6</sup> After an amplifier comes out of saturation, a few seconds are required for the amplifier to fully recover.

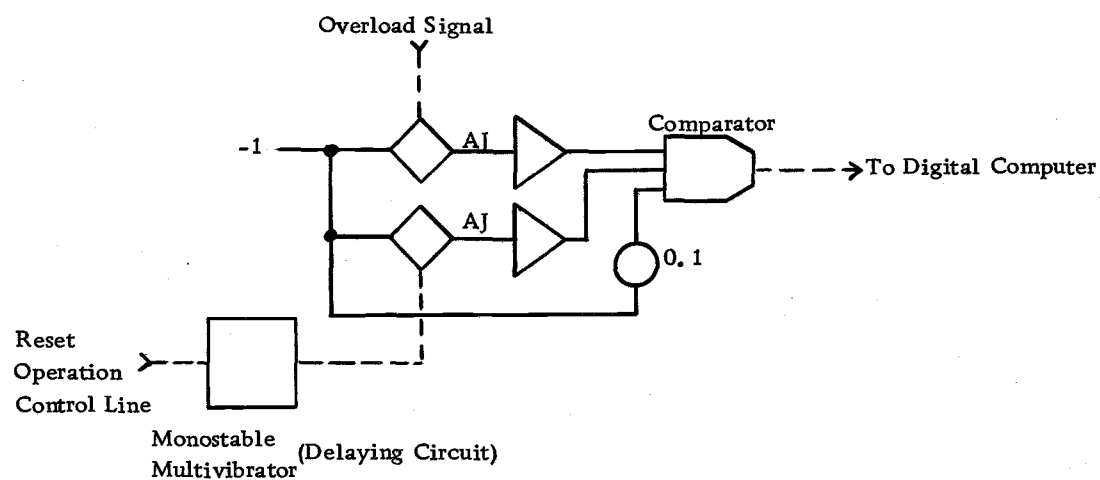
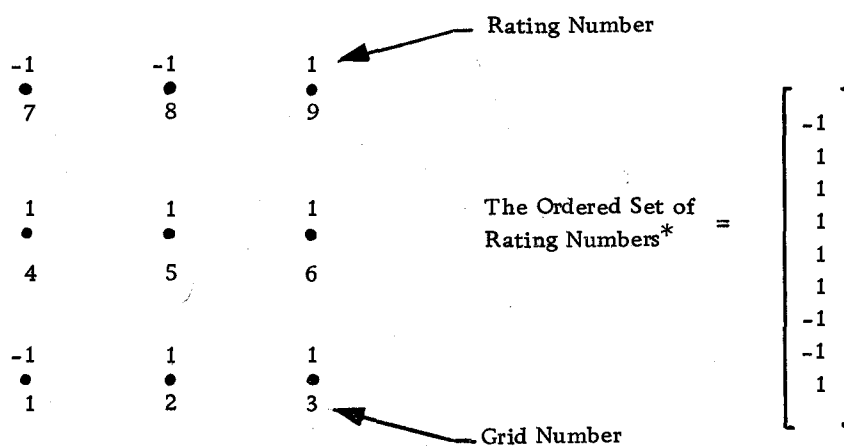


Figure A. 1. The comparator used to signal the digital computer of overloads in the analog computer.



\* Referred to as the rating vector in Appendix B.

Figure A. 2. A grid showing the grid numbers and the rating numbers.

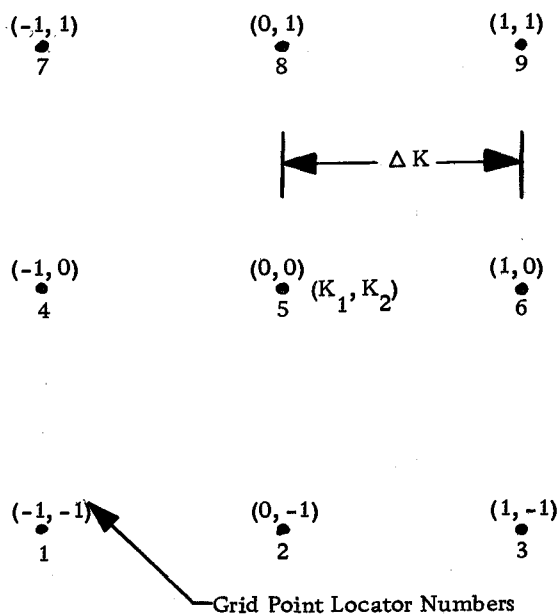
ordering is accomplished by numbering each grid point in order.

Figure A. 2 illustrates the rating numbers and grid point numbering scheme for a nine point grid and the ordered set of rating numbers.

To avoid storing all the parameter values for an entire grid, each grid point has a set of associated integers which when combined with the grid spacing, locates the grid point relative to the center point of the grid. The only parameter values that need to be stored are those of the center point. Also the only grid point locator numbers that are stored are those of the current grid point.

A subprogram, using only the grid point number (see Figure A. 2), sequences to the proper set of locator numbers associated with the grid point. Then another subprogram uses the grid locator numbers, the grid spacing, and the center point parameter values to calculate the parameter values of the current grid point. Figure A. 3 shows a regional grid with center parameter values,  $K_1$  and  $K_2$ , grid point locator numbers, and a table of parameter values for each grid point.

To avoid multiple cue actions for each cue given by a man, the cue is disconnected from the digital computer upon its receipt. To accomplish the disconnecting action, the inverted output of a monostable multivibrator is combined with the cue in an "and" gate. Then once the cue is received by the digital computer, the digital computer triggers the multivibrator with an operation control line which



<u>Grid Point Number</u>	<u>Parameter Values</u>
1	$K_1 - \Delta K, K_2 - \Delta K$
2	$K_1, K_2 - \Delta K$
3	$K_1 + \Delta K, K_2 - \Delta K$
4	$K_1 - \Delta K, K_2$
5	$K_1, K_2$
6	$K_1 + \Delta K, K_2$
7	$K_1 - \Delta K, K_2 + \Delta K$
8	$K_1, K_2 + \Delta K$
9	$K_1 + \Delta K, K_2 + \Delta K$

Figure A. 3. A grid showing the relation between grid point locator numbers and the parameter values of the grid.



disables the "and" gate for the period of the multivibrator. Figure A. 4 illustrates the cues and their connections to the logic and the sense lines.

The cues which do not need to be disconnected with logic either are not harmful if repeated several times, i. e., reset cues, or cause a delay in the digital program due to a message output from the digital typer. Cues, 1, 4, 7, 9, and 10, in Table A. 2 are examples of this type of cue.

Since there are only eight sense lines on the EAI 680 and ten preferential cues in the algorithm (see Table A. 2 for a list of the preferential cues), two additional lines to the digital computer had to be furnished for inputting the two cues. The comparators on the analog computer have a direct logic input to the digital computer. So the reset pushbutton of a comparator substitutes for a cue pushbutton and a sense line. Figure A. 4 shows the implementation of the last two cues.

The outputs of the digital-to-analog converters (DAC) used to set the parameters from the digital computer are limited to 1.0 per unit. If the parameter search leads to one of the DAC limits, the gain in the analog model can be increased to enlarge the size of the of the parameter space.<sup>7</sup>

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<sup>7</sup> The actual parameter value is equal to the product of the DAC output and the associated analog simulation gain.

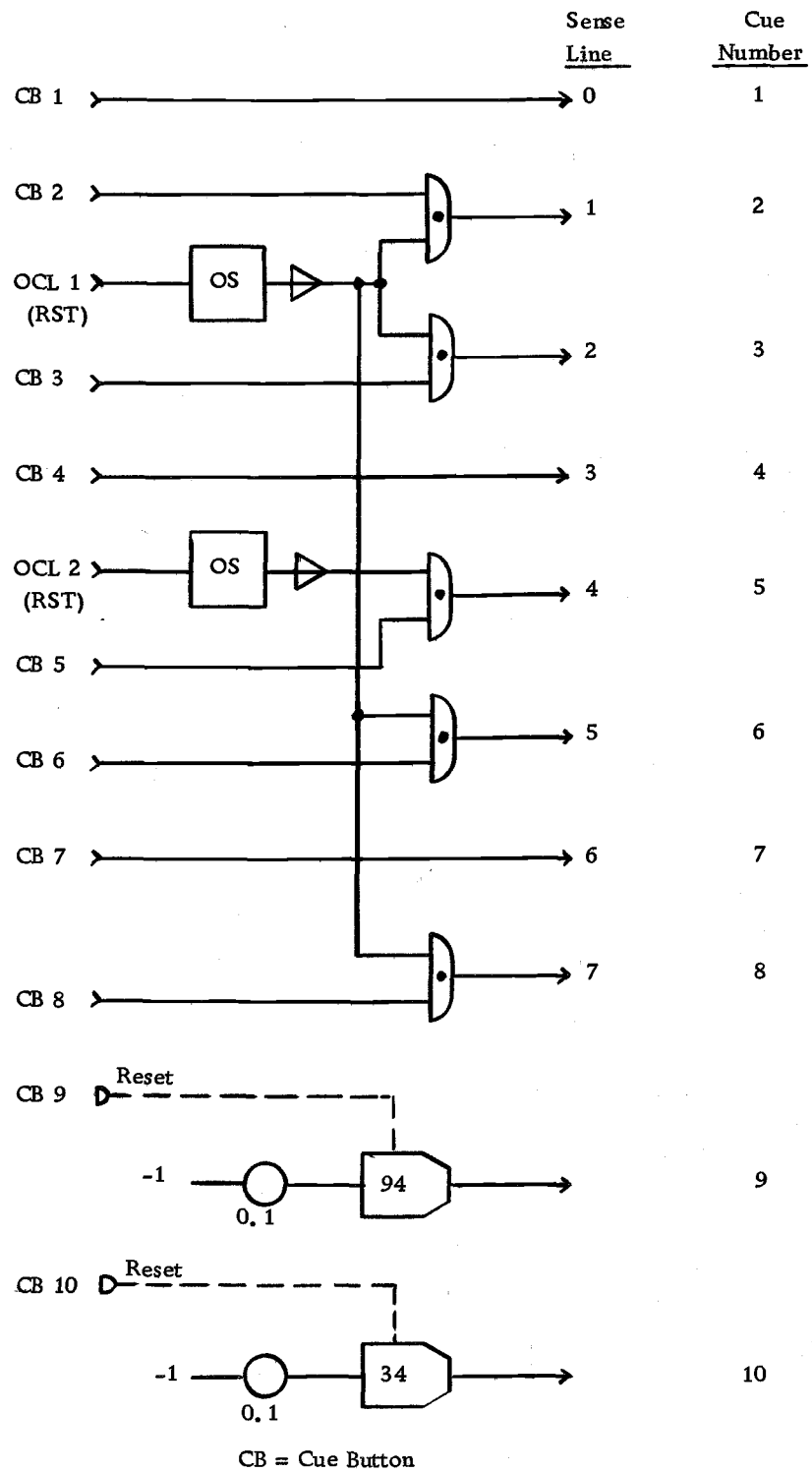


Figure A. 4. The implementation of the input of the preferential cues.

Table A. 2. A list of the preferential cues.

Cue No.	Purpose	Input Location
1	To list the parameters for the present grid point and to start and stop the strip chart recorder so that a time response recording can be obtained automatically.	Cue Button #1 on the Cue Board
2	To decrease the grid spacing.	Cue Button #2 on the Cue Board
3	To increase the grid spacing.	Cue Button #3 on the Cue Board
4	To reset the grid spacing to its initial value.	Cue Button #4 on the Cue Board
5	To step the system parameters to the next grid point.	Cue Button #5 on the Cue Board
6	To delete the present grid point from the investigation grid.	Cue Button #6 on the Cue Board
7	To reset all quantities pertaining to the present investigation grid to their initial values.	Cue Button #7 on the Cue Board
8	To step to the next input level.	Cue Button #8 on the Cue Board
9	To transfer to a new grid during the regional search or after termination of the search, to restart the starting point search.	Comparator Reset Button #94 on the Analog Computer
10	To terminate the search at the present grid point.	Comparator Reset Button #34 on the Analog Computer

To avoid problems with the analog computer overloading as the gain of one of the amplifiers is changed, the subprogram which sets the parameters on the DACs senses when a digital parameter to be set is beyond the DACs numerical limit, types a message to the designer, and causes the digital computer to pause. Then the designer can increase the analog gain for the indicated parameter. When the designer restarts the digital computer, he enters the increase factor and the digital computer automatically recalculates and sets the parameter.

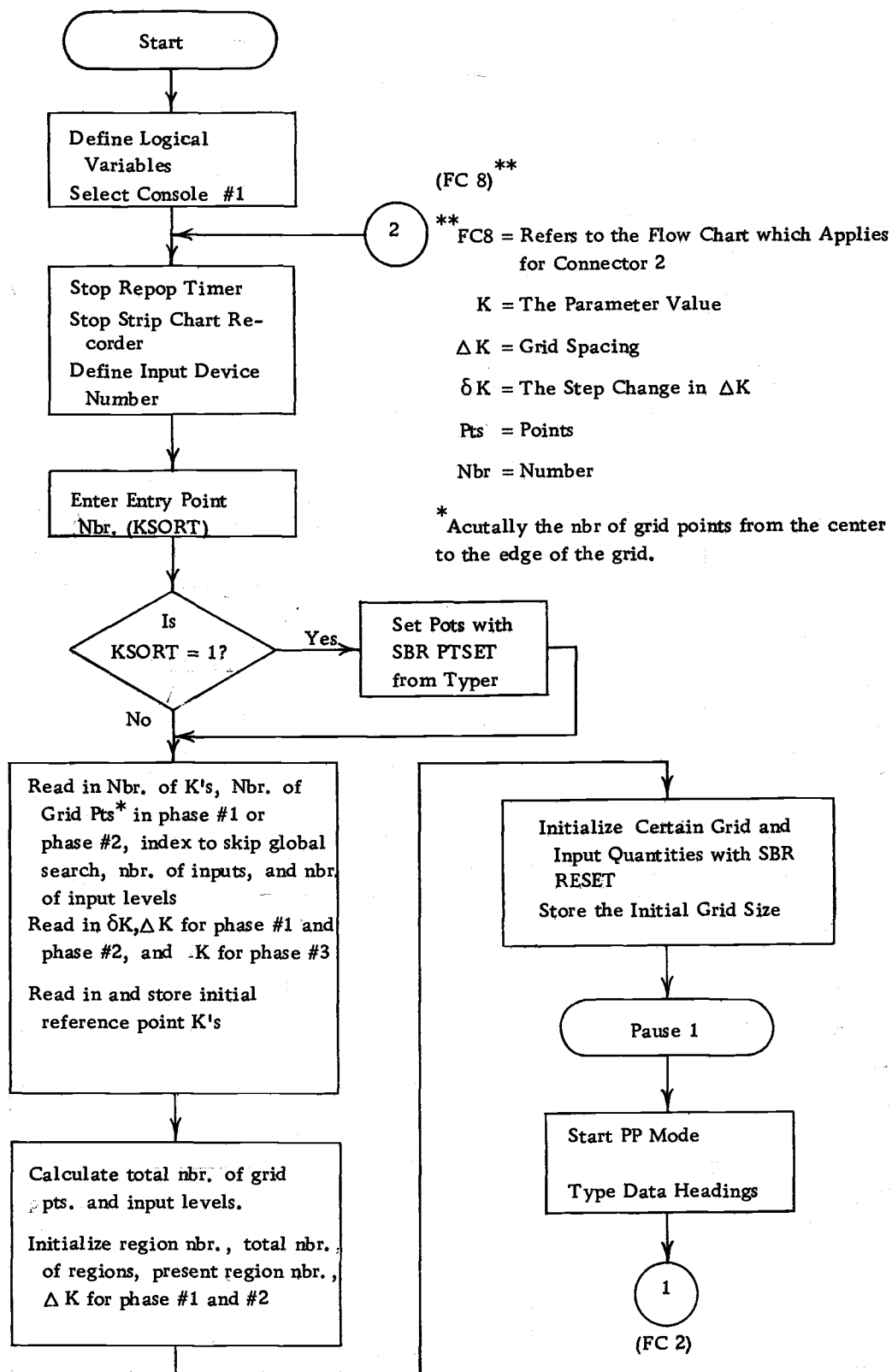
In some cases the search reaches a limit even though the designer is not interested in an extended parameter space. The subprogram detects that a limit has been exceeded and causes the computer to pause. Since the designer does not wish to increase the analog gain, he has the option of entering a negative number for an increase factor. Then the computer resets the grid spacing and continues the program.

Once a gain change has been made in a tolerable region, a record is kept so that if the starting point phase is entered again the analog gain can be changed properly. Also the record can be used during the final comparison phase to change the analog gain properly in the case of multiple tolerable regions.

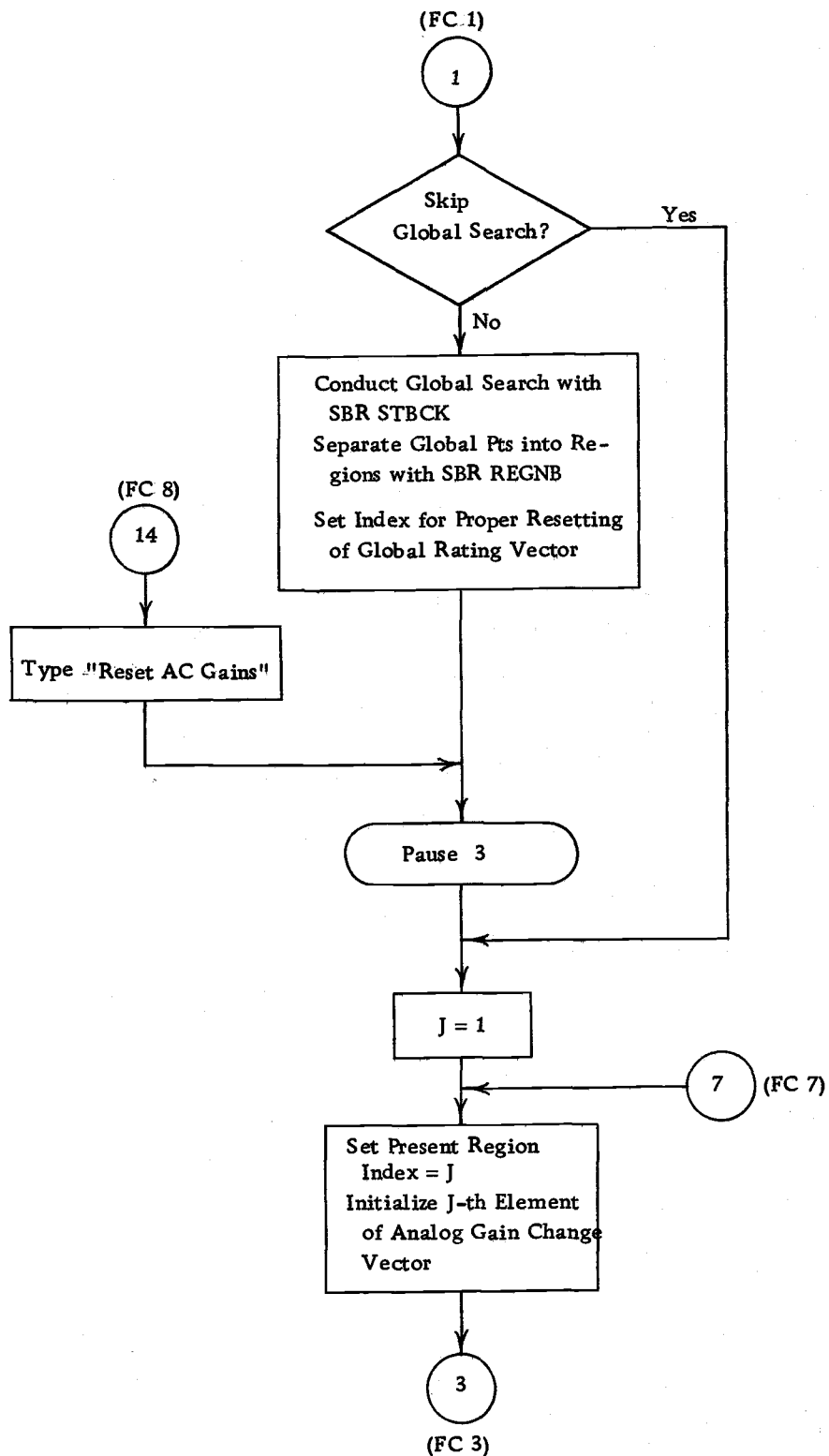
## APPENDIX B

## DETAILED FLOW CHARTS OF THE COMPUTER ALGORITHM

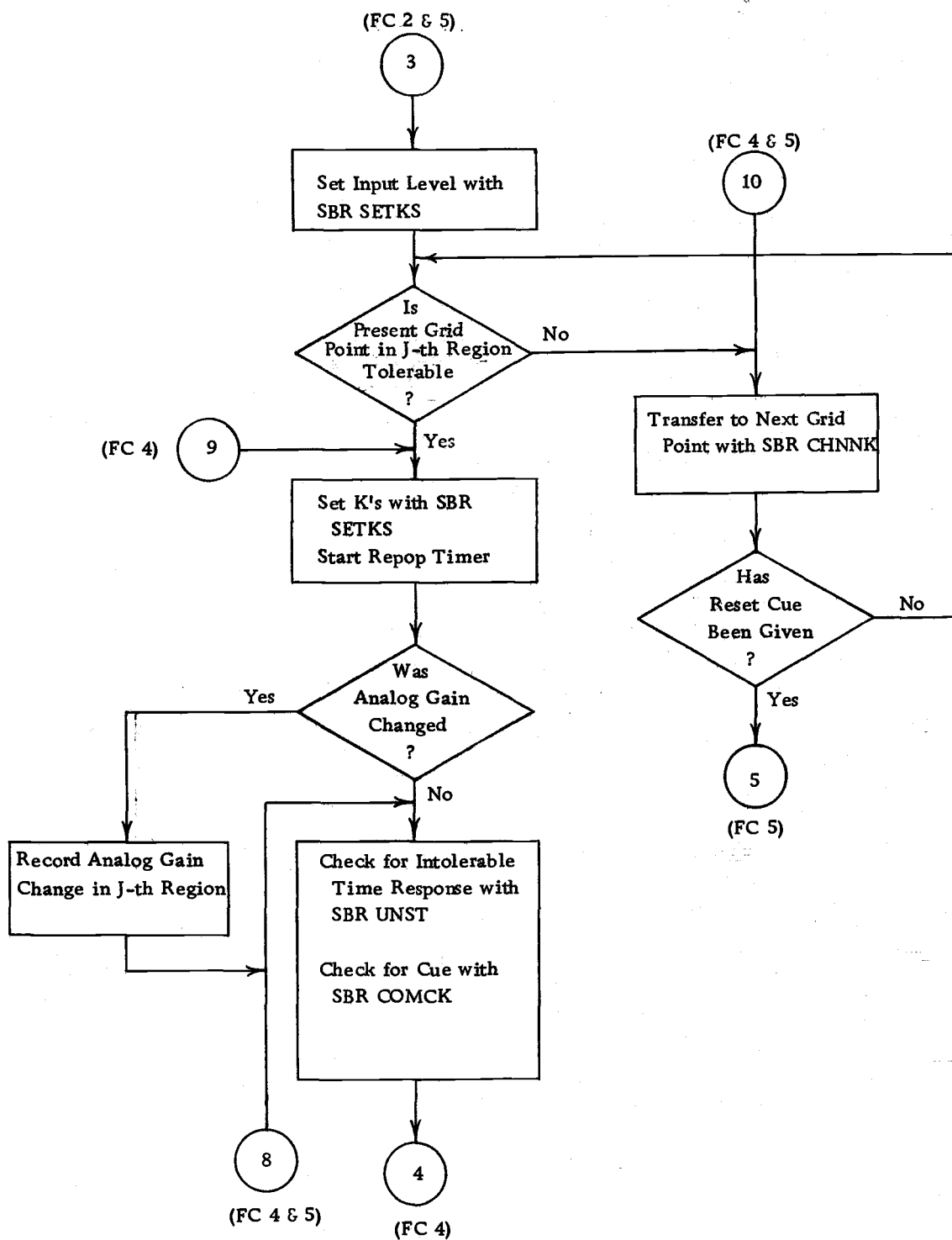
The program listings for the following flow charts are available in the Simulation Laboratory of the School of Engineering under the title of "Interactive Man-Hybrid Computer Parameter Search Algorithm for Dynamic System Design" dated September 20, 1968. The mnemonic for the algorithm on the hybrid computing system tape is CASD (Computer Augmented System Design).



Flow Chart 1. The main program.

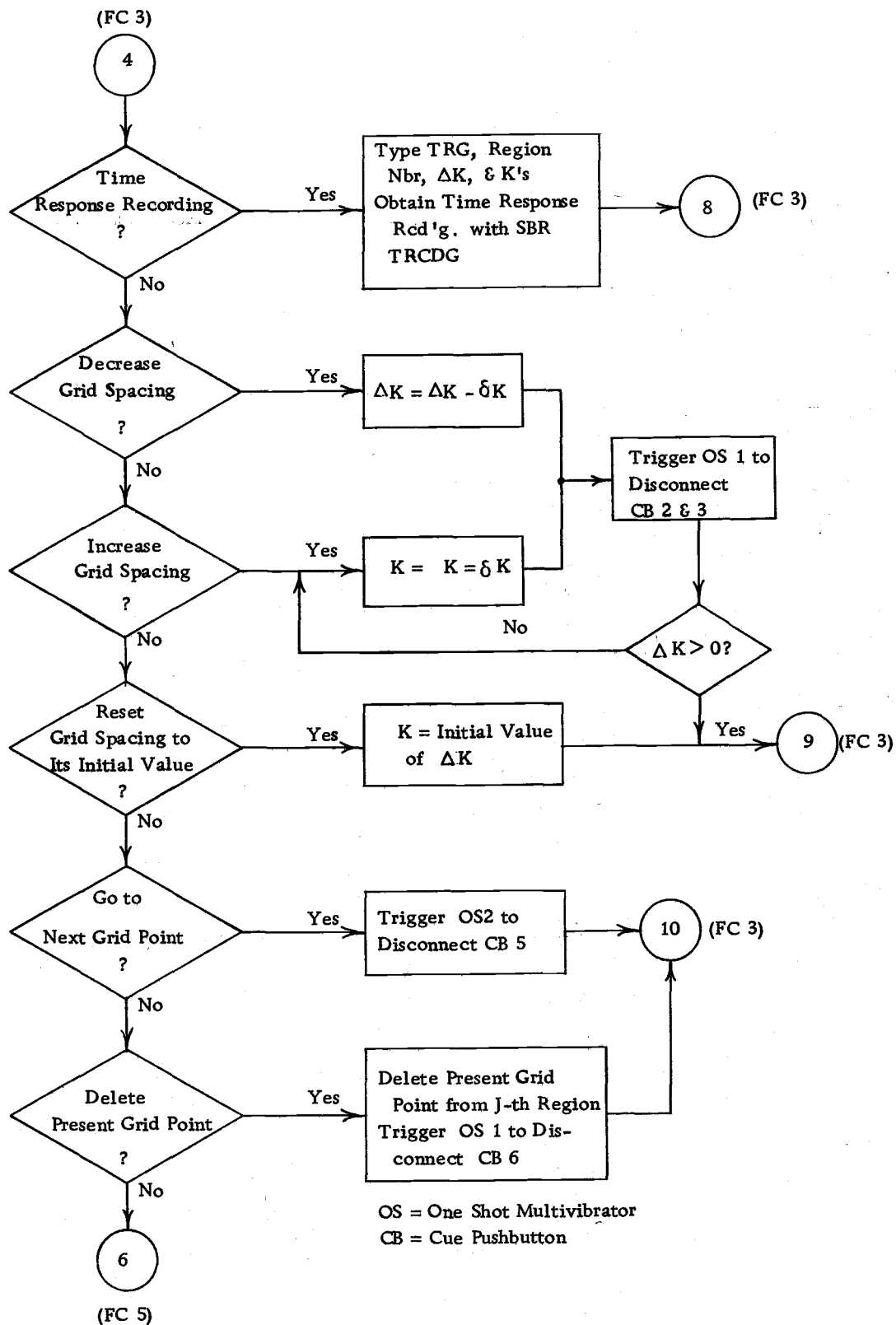


Flow Chart 2. The main program.

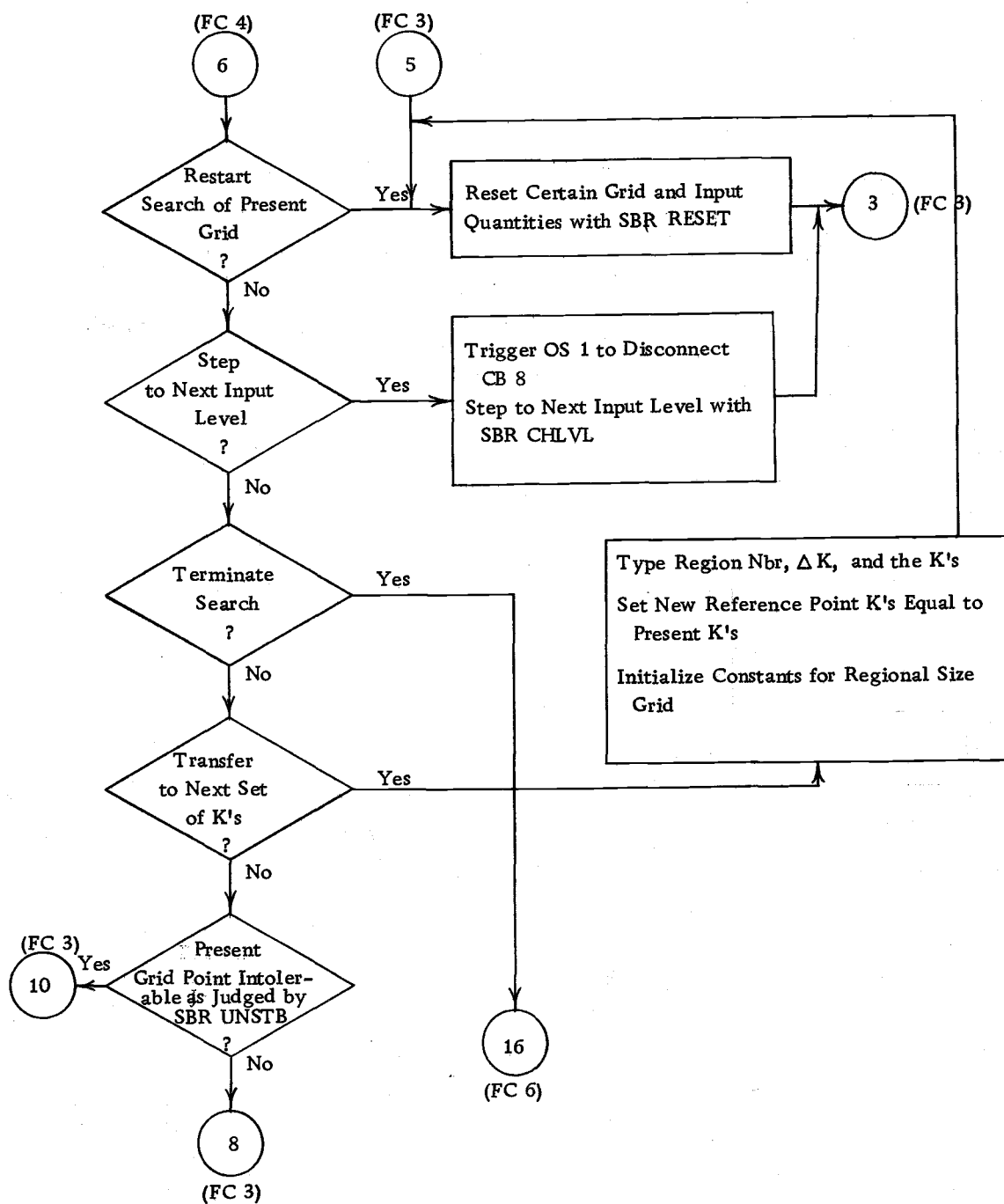


Flow Chart 3. The main program.

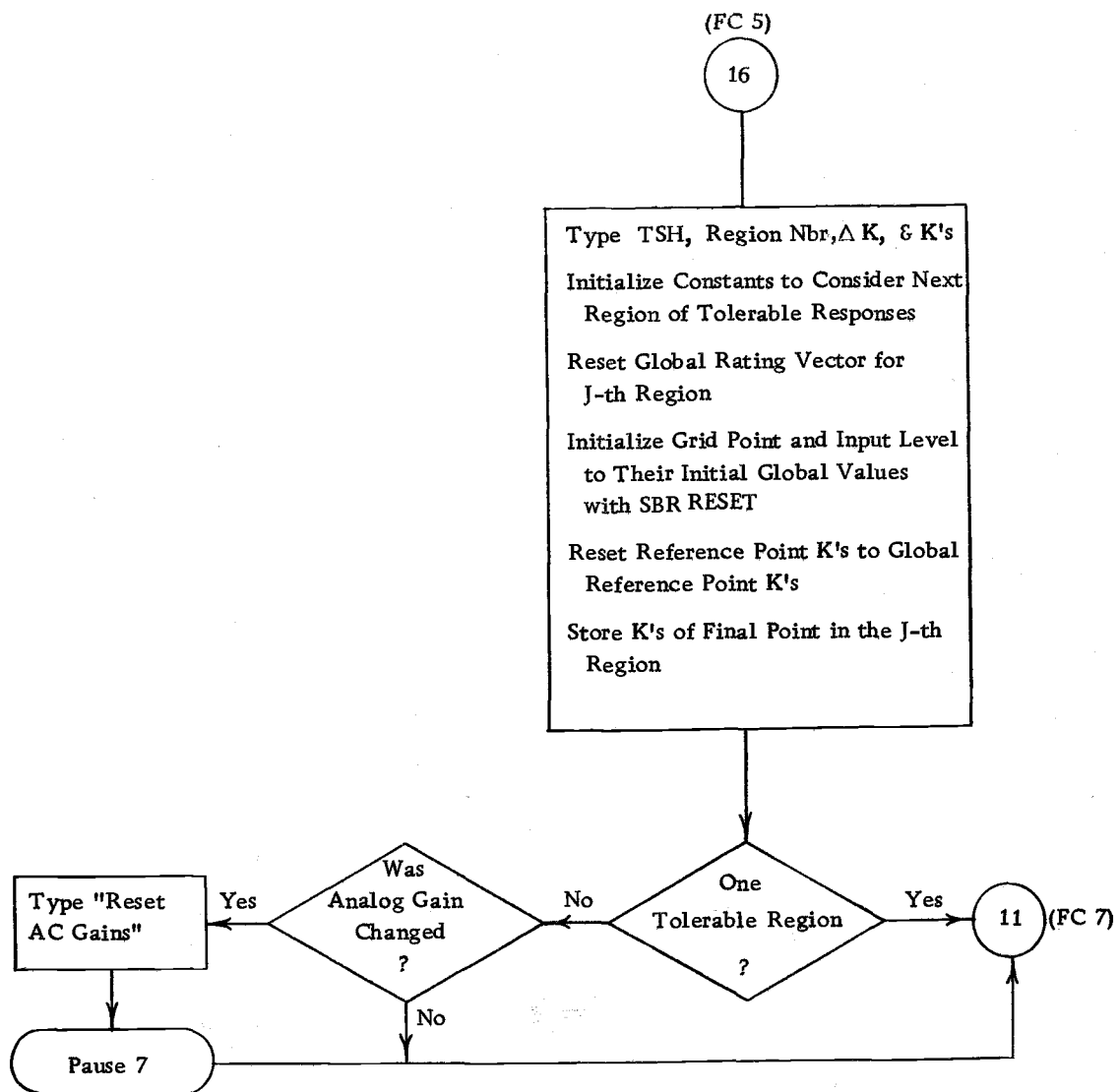




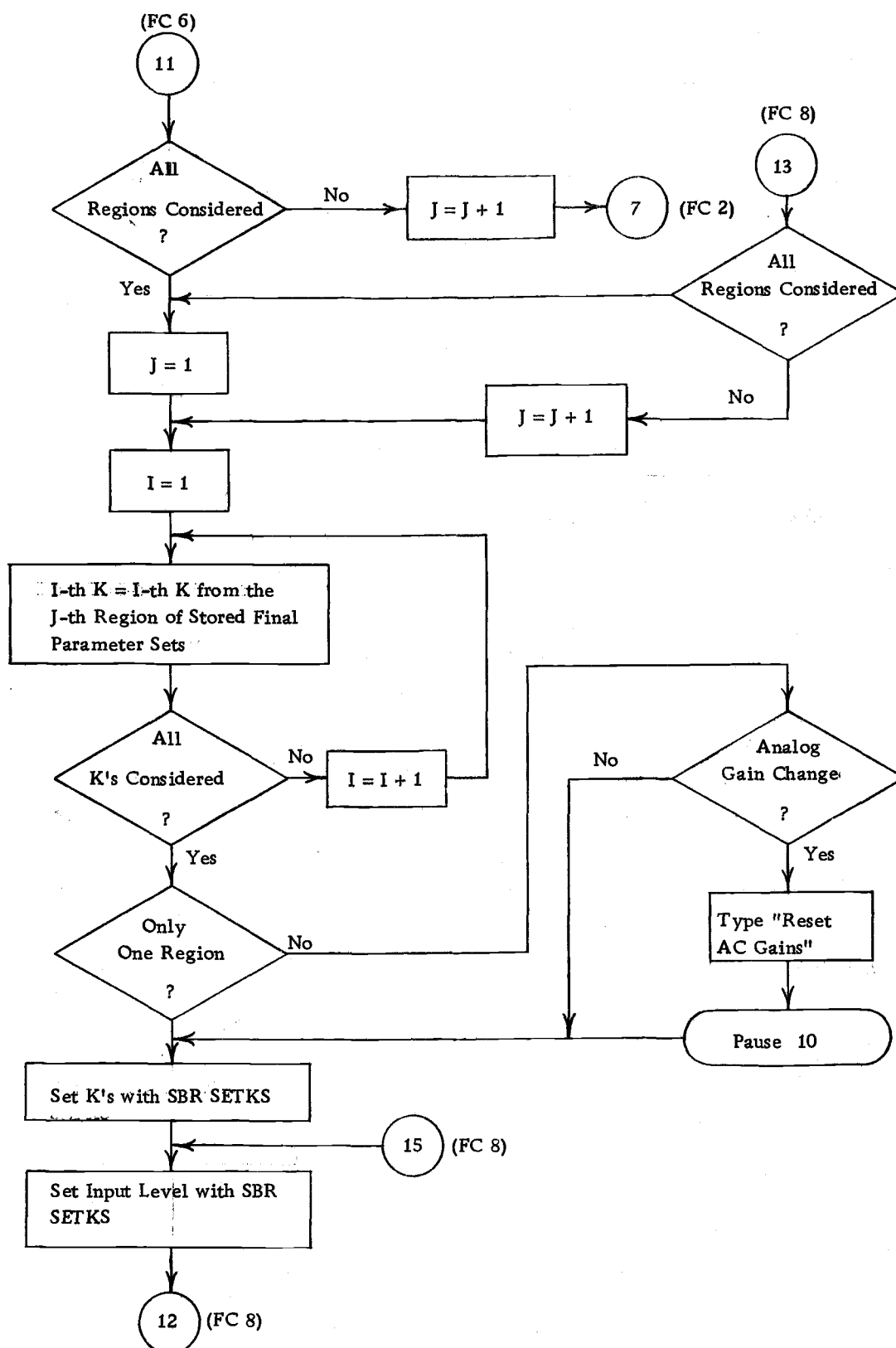
Flow Chart 4. The main program.



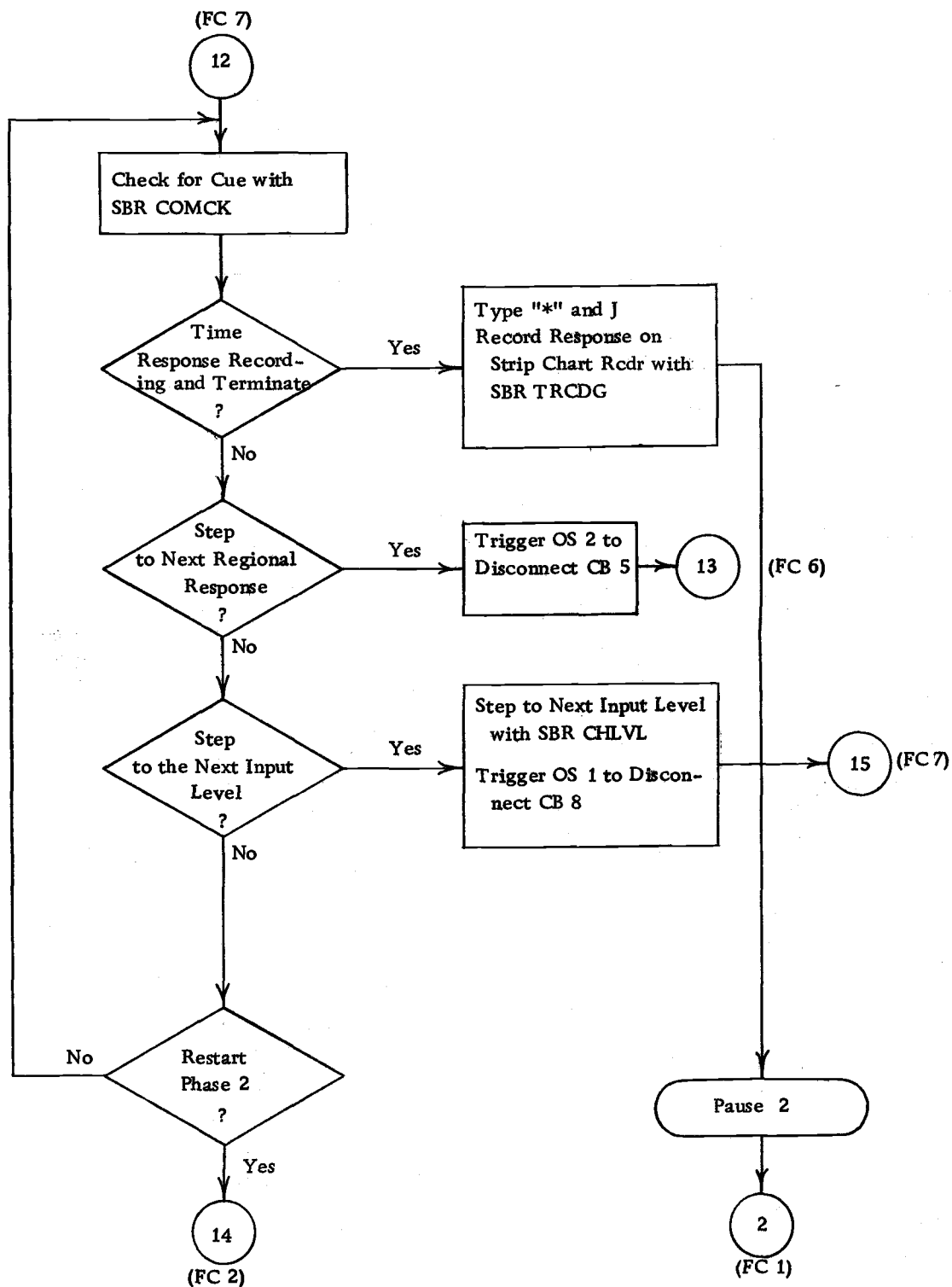
Flow Chart 5. The main program.



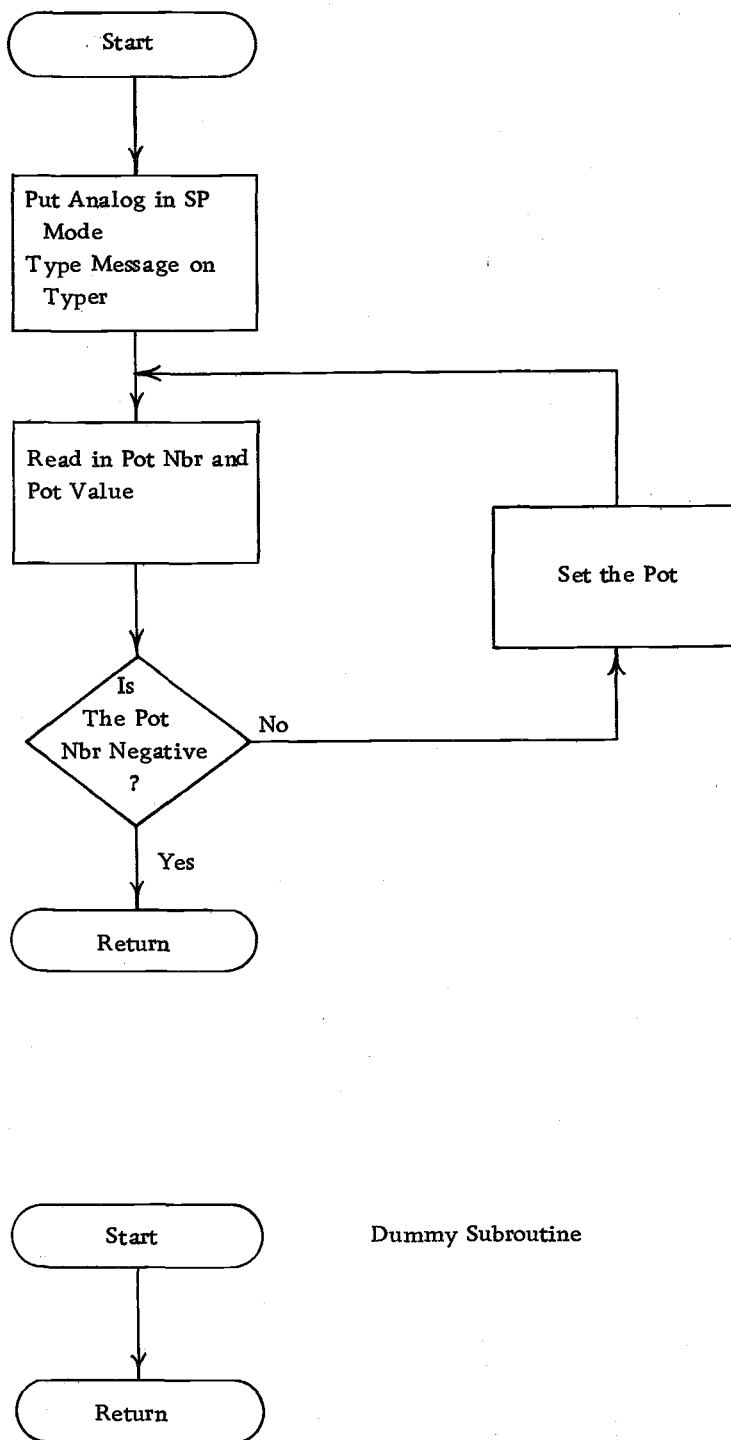
Flow Chart 6. The main program.



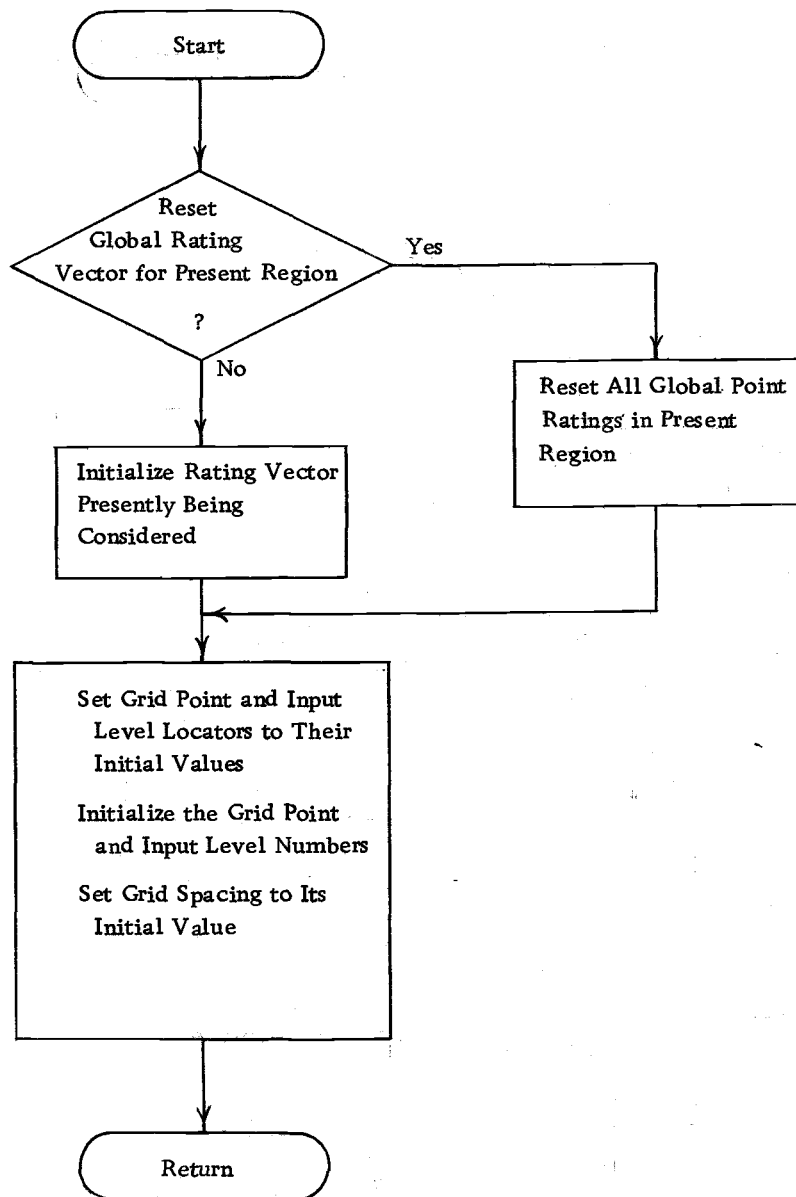
Flow Chart 7. The main program.



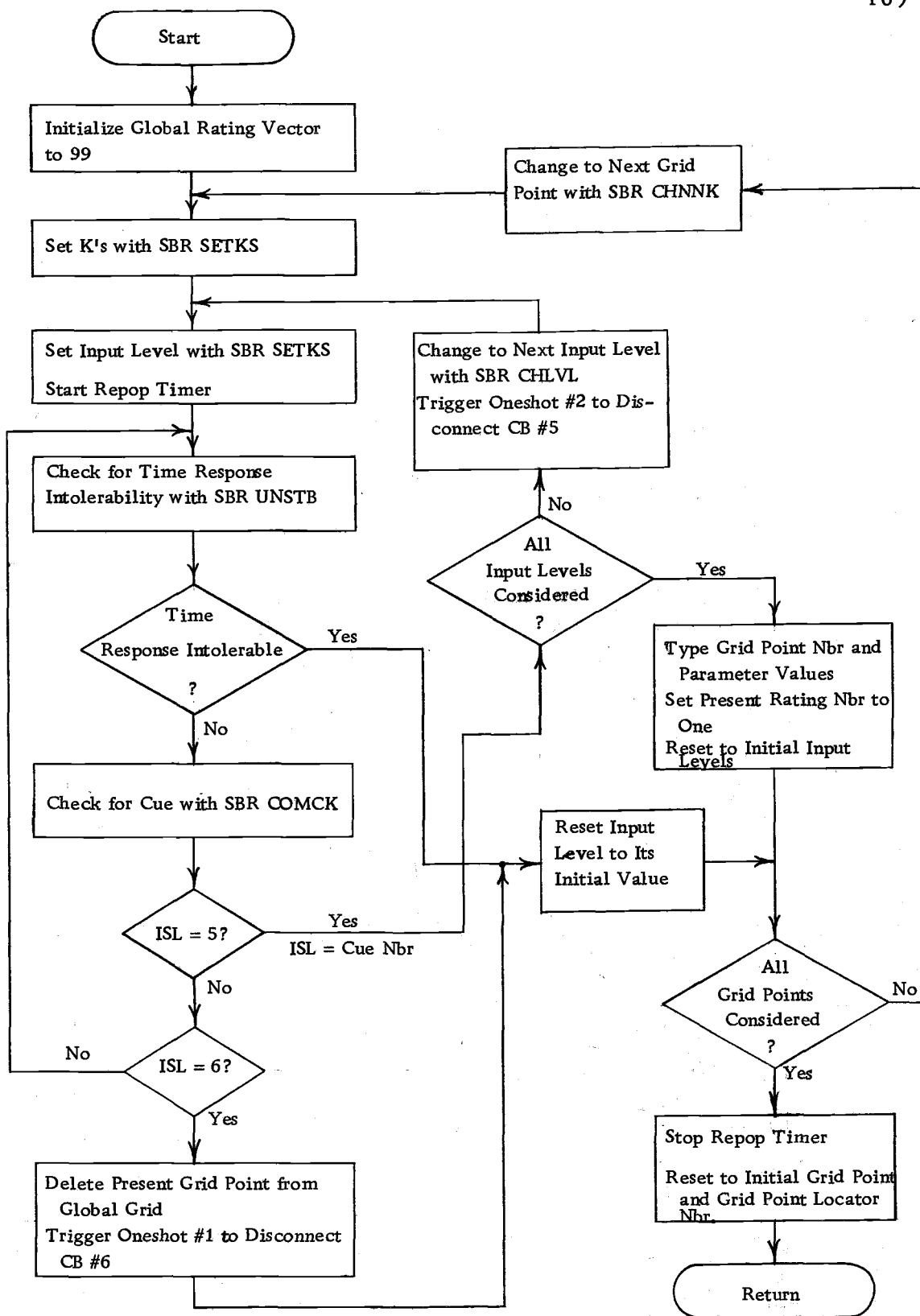
Flow Chart 8. The main program.



Flow Chart 9. Subroutine PTSET.

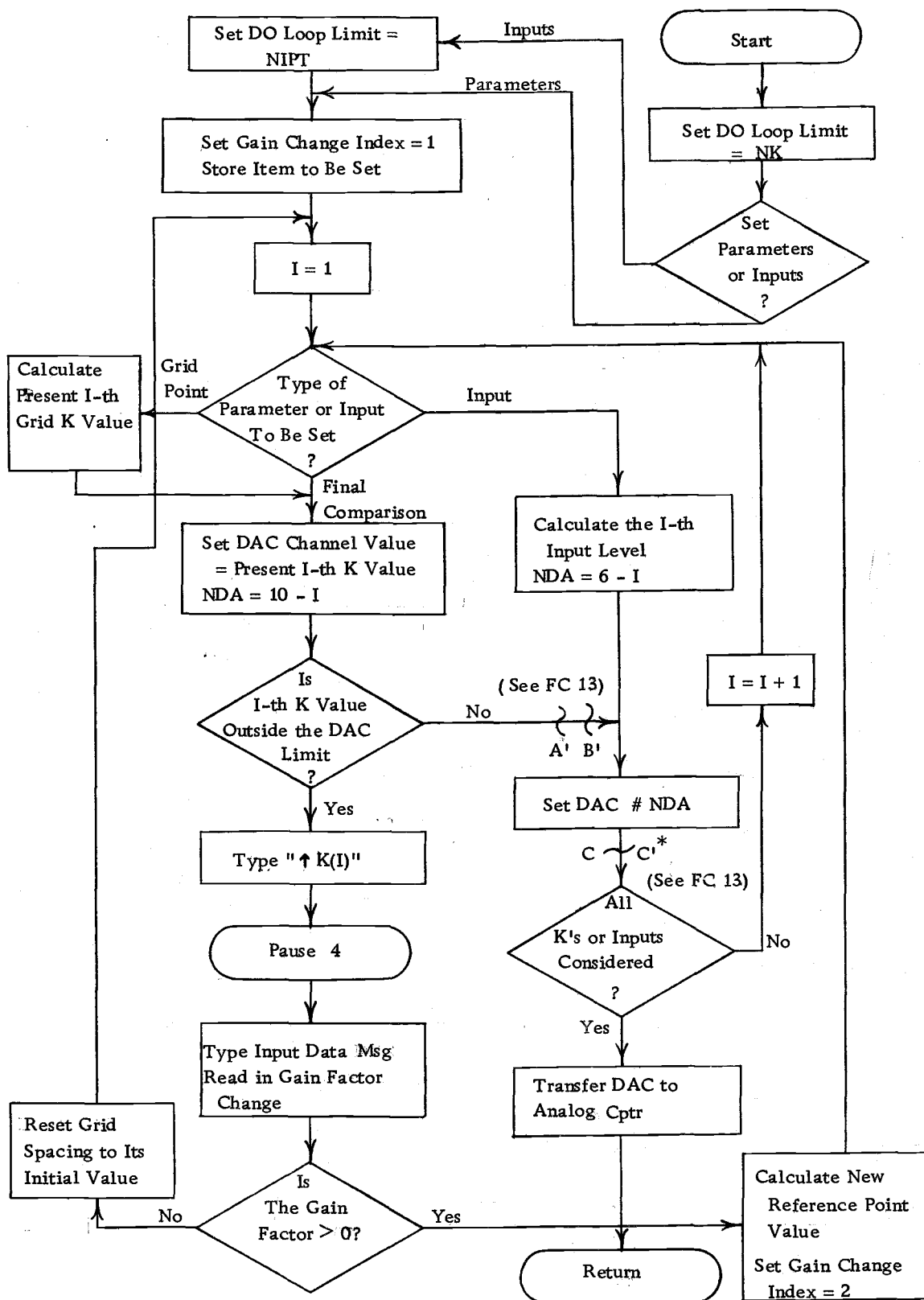


Flow Chart 10. Subroutine RESET.

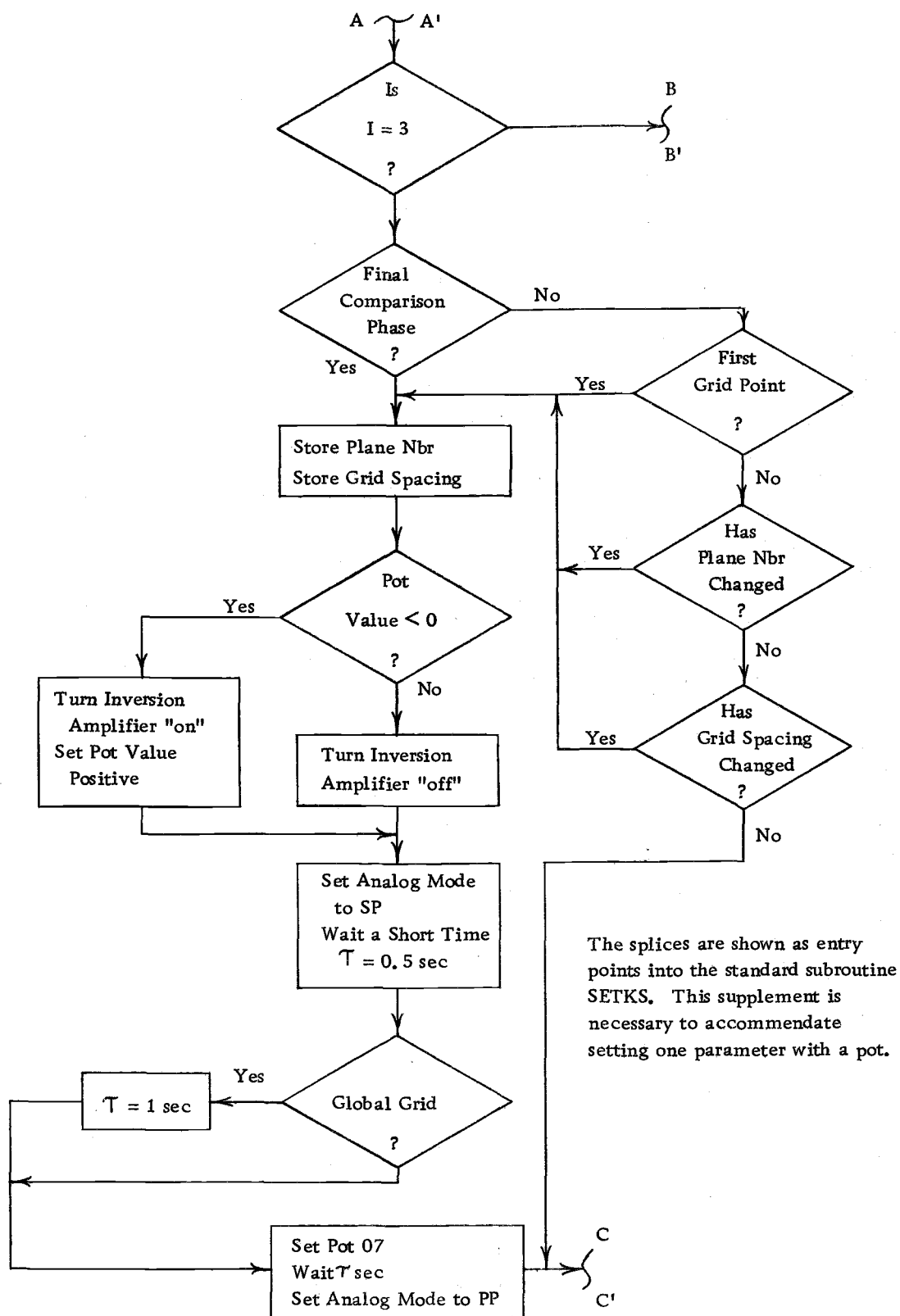


Flow Chart 11. Subroutine STBCK.

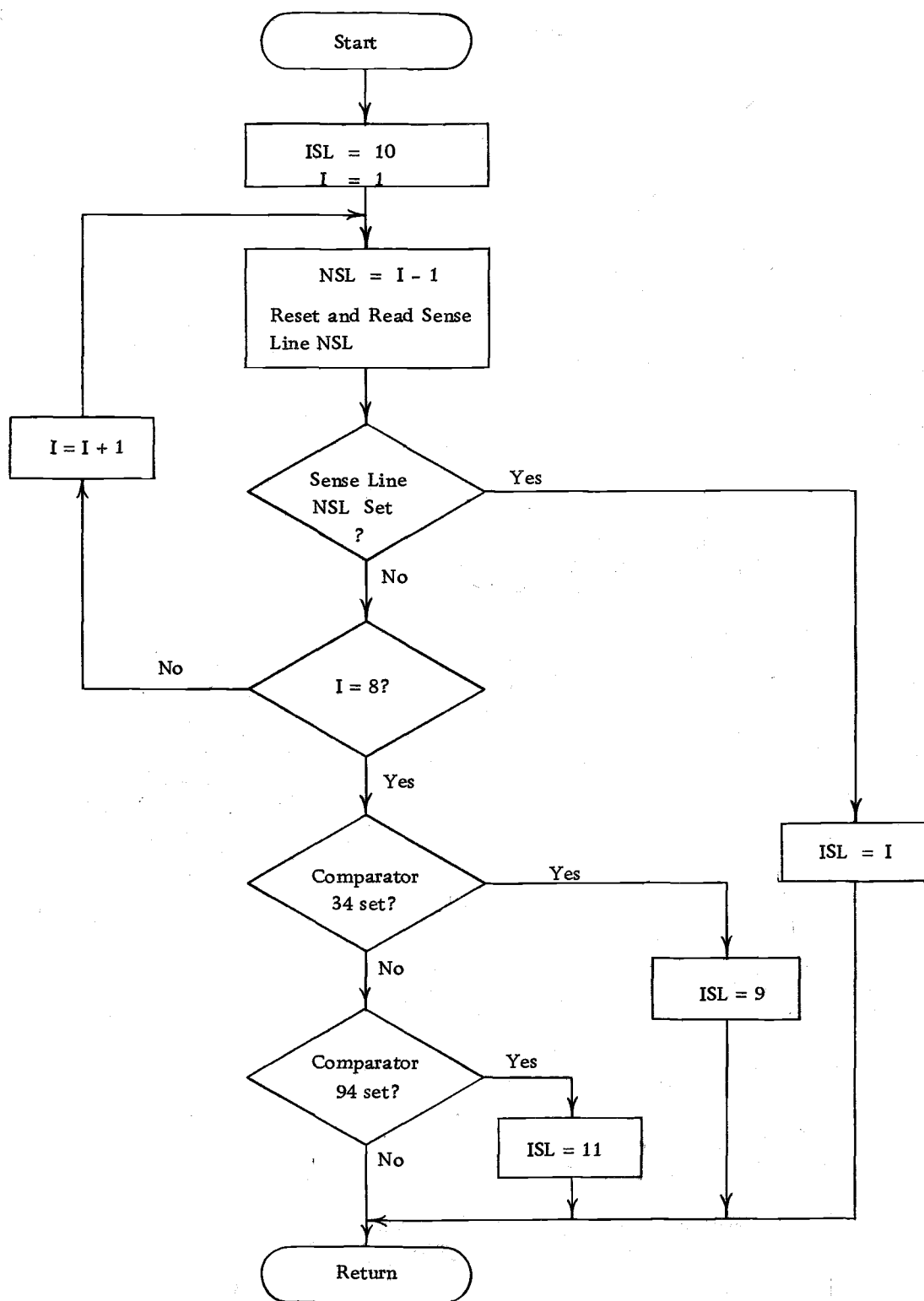




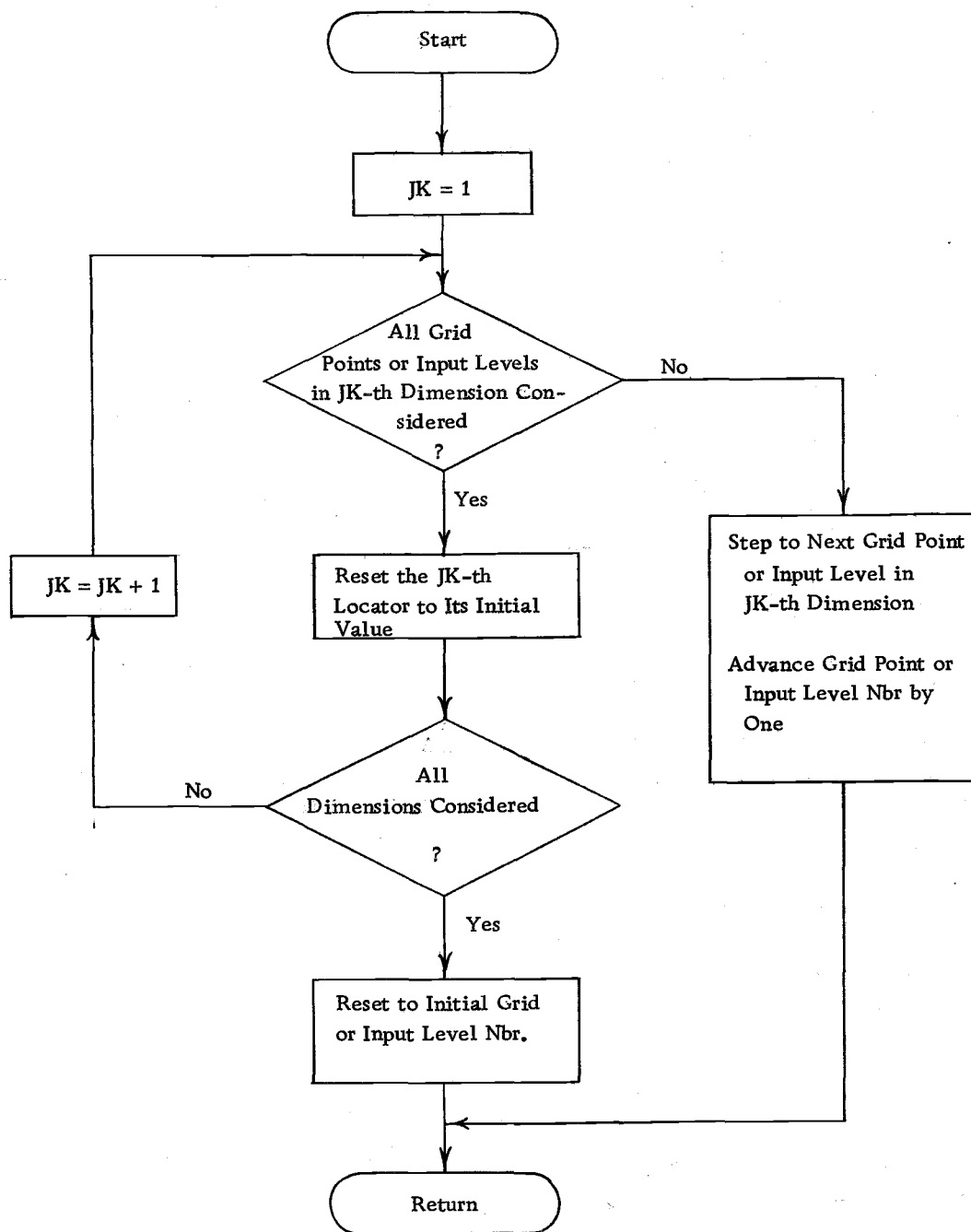
Flow Chart 12. Subroutine SETKS.



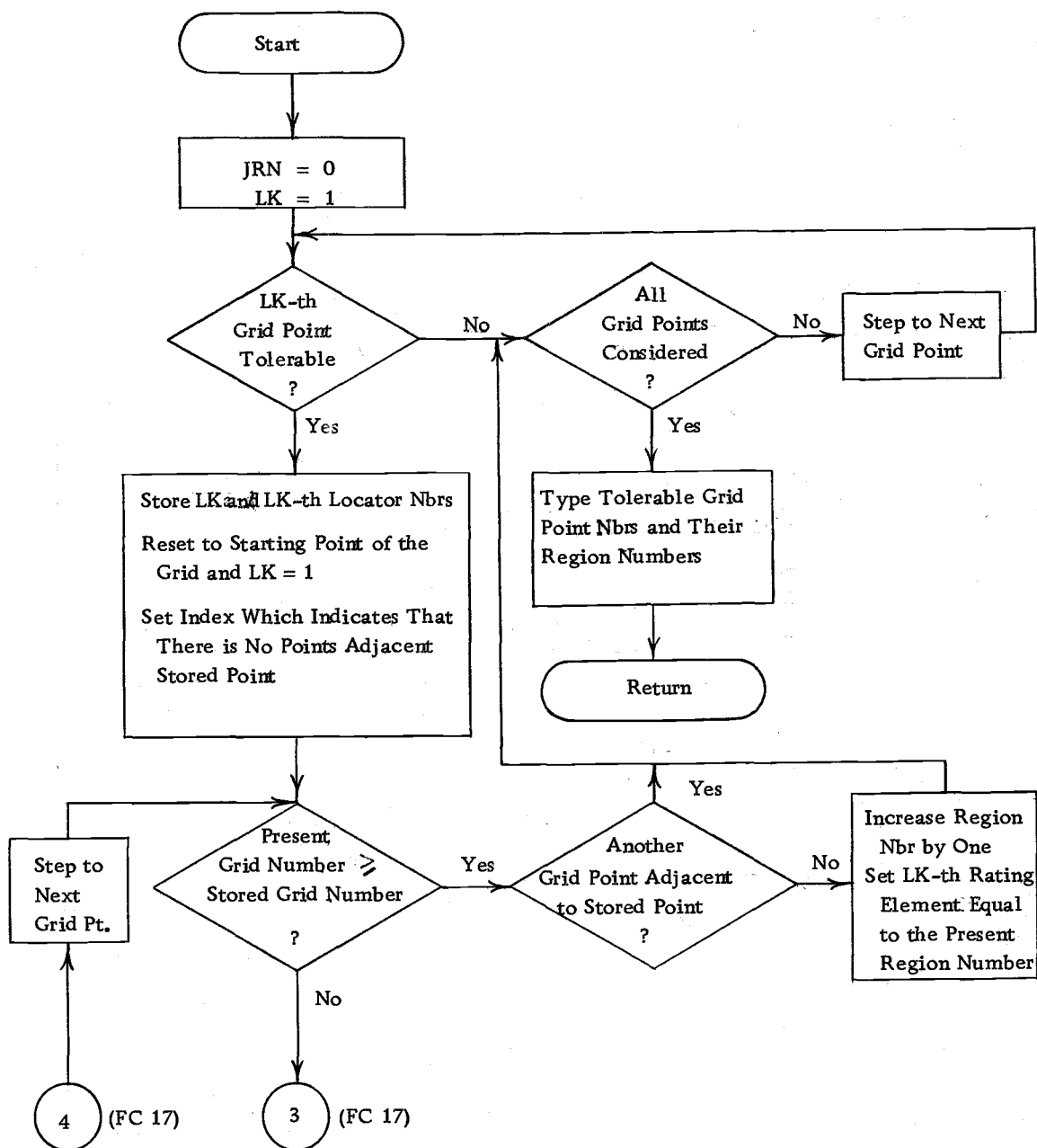
Flow Chart 13. Supplement to subroutine SETKS.



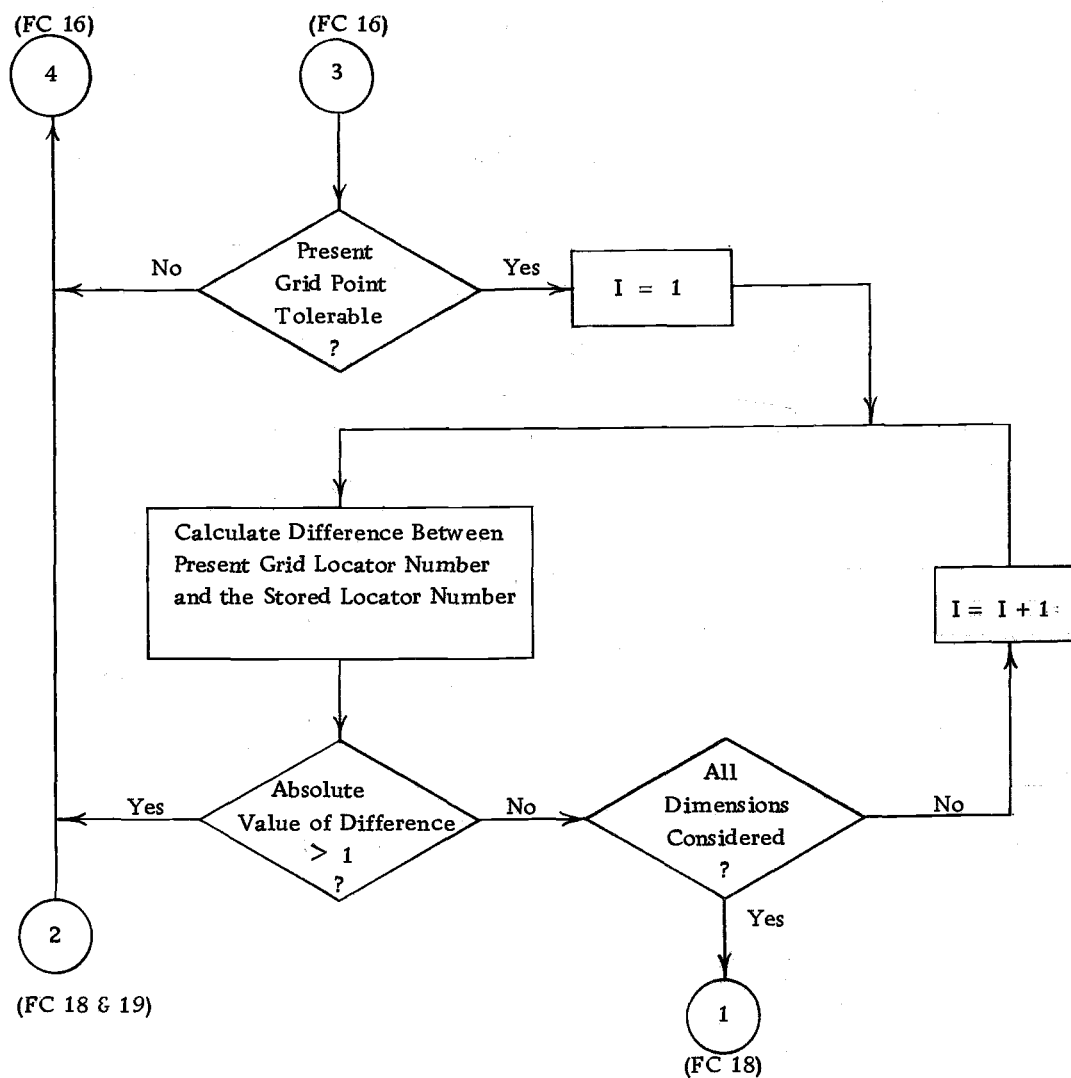
Flow Chart 14. Subroutine COMCK.



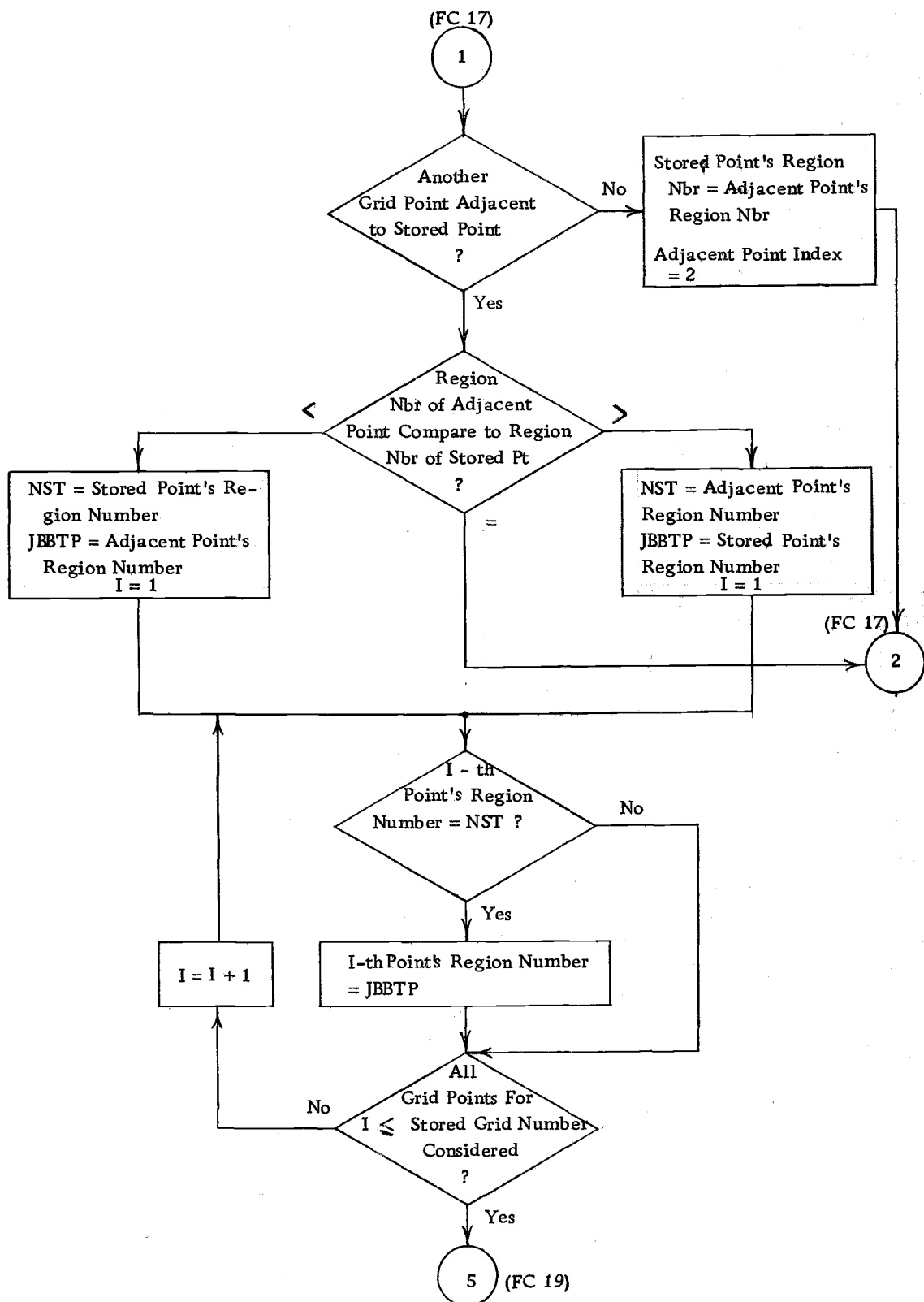
Flow Chart 15. Subroutines CHLV L and CHNNK.



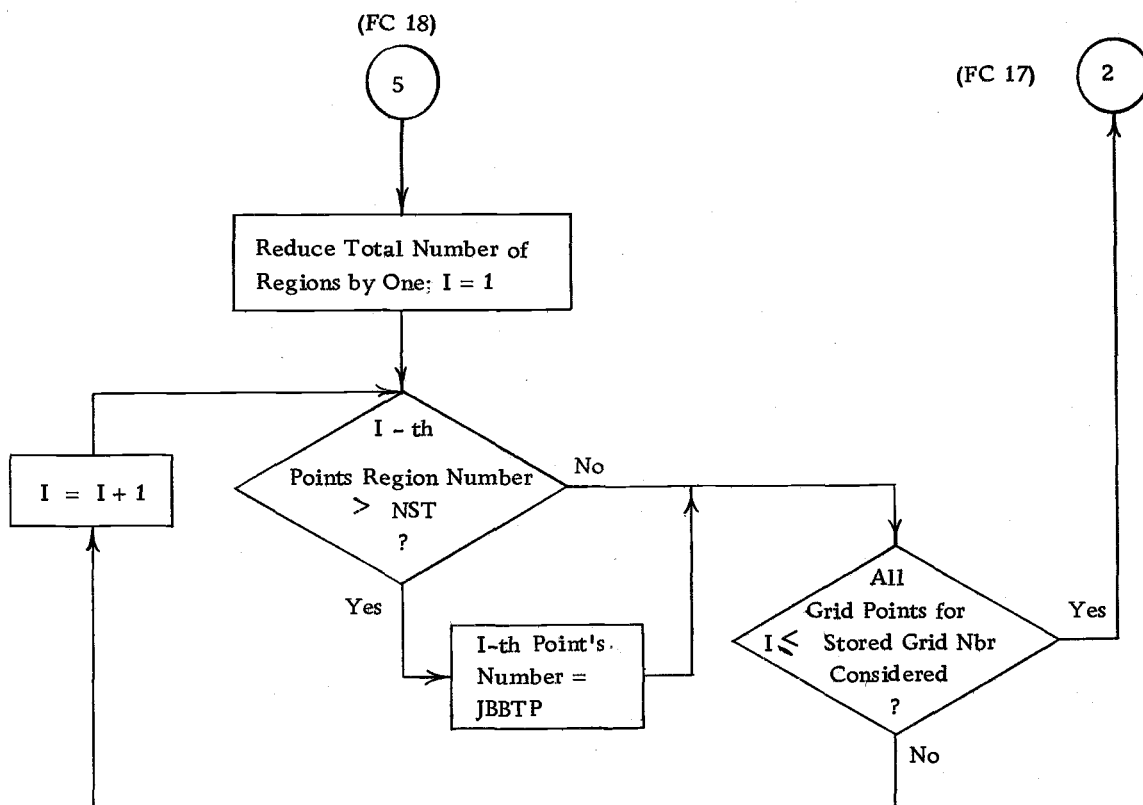
Flow Chart 16. Subroutine REGNB.



Flow Chart 17. Subroutine REGNB.

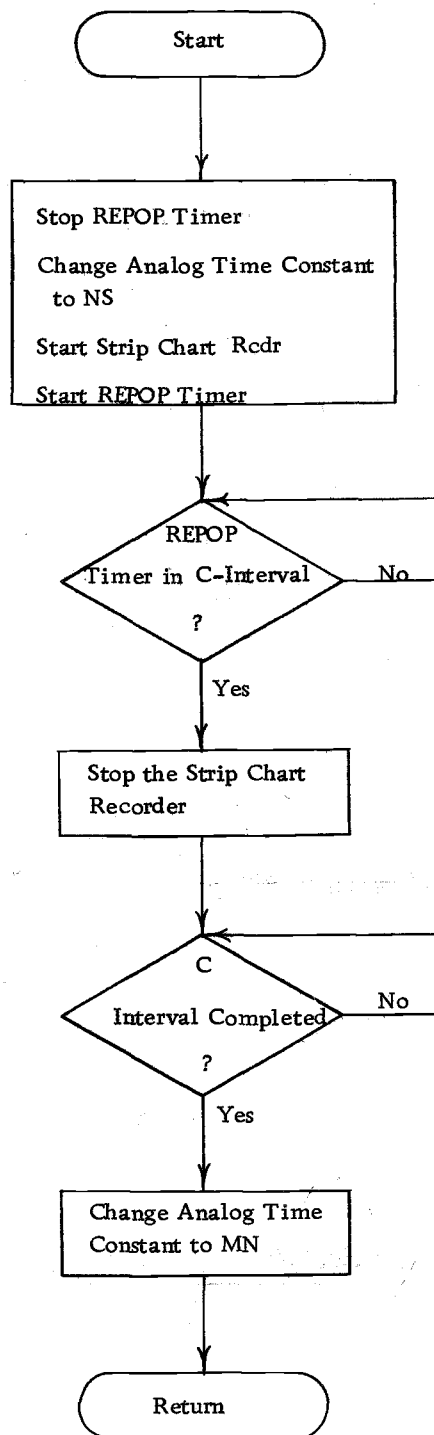


Flow Chart 18. Subroutine REGNB.

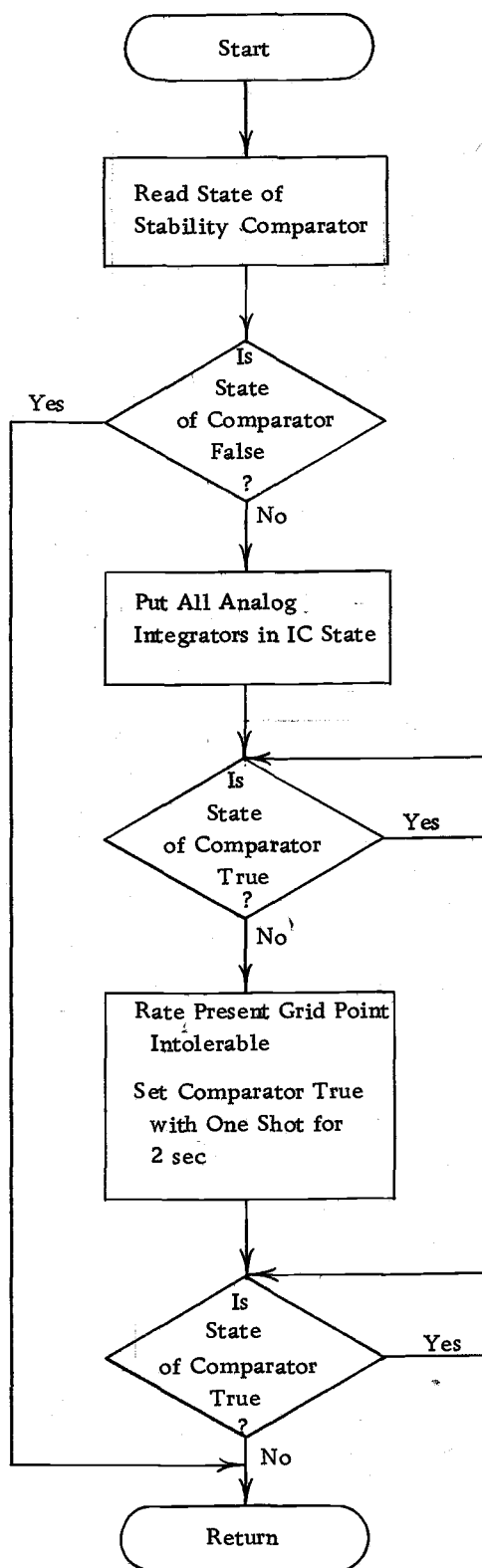


Flow Chart 19. Subroutine REGNB.





Flow Chart 20. Subroutine TRCDG.



Flow Chart 21. Subroutine UNSTB.