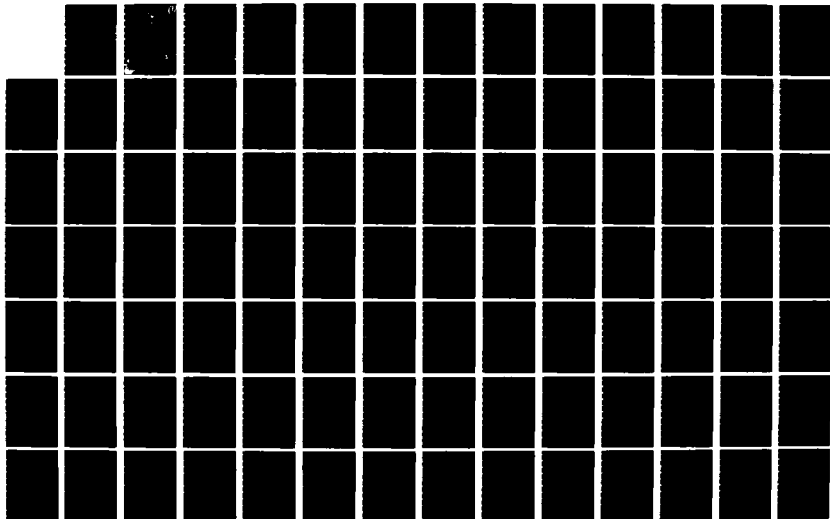
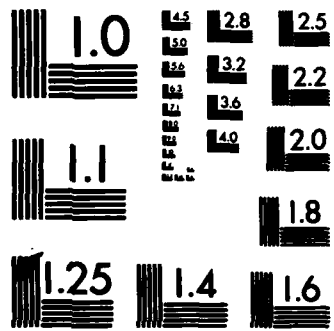


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COMMAND GENERATOR TRACKER SYNTHESIS  
 METHODS USING AN LQG-DERIVED  
 PROPORTIONAL PLUS INTEGRAL CONTROLLER  
 BASED ON THE INTEGRAL  
 OF THE REGULATION ERROR

THESIS

AFIT/GE/EE/83D-46 James P. McMillian  
 1st Lt USAF

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## Acknowledgments

I wish to express my deepest appreciation to Professor Peter S. Maybeck for his guidance throughout the duration of this work. I would also like to thank Captain Richard M. Floyd, whose invaluable experience and assistance made possible the successful completion of this project. Finally, I wish to extend a warm thank you to my wife Susan and daughters, JoAnne, Stefanie, and Jamie for their understanding and patience during the past many months.

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Abstract

This study develops a computer program for interactive execution to aid in the design of Command Generator Tracker control systems employing Proportional Plus Integral inner loop controllers based on the integral of the regulation error and Kalman Filters for state estimation (CGT/PI/KF controllers). Sampled-data controller designs are based upon the Linear system model, Quadratic cost, and Gaussian noise process (LQG) assumptions of optimal control theory.

The report develops the CGT/PI/KF controller theory with the PI controller portion based upon the integral of the regulation error. Following a brief description of the computer program developed, results of applying it to an example aircraft-related controller design problem is presented. The CGT/PI/KF controller is found to be a technique particularly well suited to the aircraft control design problem but is a technique that may be applied to any general controller problem fitting the design criteria.

Use of the computer program is fully documented in the appendices of the report. Included are a brief Programmer's Manual, a complete User's Manual, and a program listing. These pertain to the computer program as implemented on a CDC CYBER computer system.

COMMAND GENERATOR TRACKER SYNTHESIS METHODS  
USING AN LQG-DERIVED  
PROPORTIONAL PLUS INTEGRAL CONTROLLER  
BASED ON THE INTEGRAL OF THE REGULATION ERROR

I. Introduction

1.1 Background

The earliest flight control designs served exclusively as a pilot relief function. It was much later before control systems were designed to improve aircraft stability, but these still had limited control authority. Furthermore, such systems were designed in a trial and error evolutionary fashion.

Current and future aircraft designs require increasingly complex controls. These newer aircraft employ digital flight control systems in order to meet complex performance specifications. The typical aircraft control design problem is one in which measurement data from many sensors are input, and signals to multiple control surfaces and actuators are output. These multiple-input/multiple-output control systems are required to respond to commanded inputs while simultaneously rejecting disturbances.

There are typically two general approaches to solving the problems of flight control. The oldest and most widely used and accepted is the classical design technique. The other technique is the "modern control" design. Despite

the systematic nature and performance potential of the modern control design technique, this method has not supplanted, or even complemented to the degree originally anticipated, the classical control methodology. This is due in part to numerous deficiencies in initial applications of modern control design techniques. These deficiencies include: (1) traditional design criteria were not readily specified directly in the performance index, (2) it was difficult to select appropriate weighting matrices for the cost functionals to ensure desired response, (3) the resulting controllers required full-state feedback, but direct perfect measurements of all states are never available--thus requiring approximations or insertion of filters or observers before implementation, and (4) the original formulation of the optimal controller solved only the regulator problem and not the required tracking response to the command inputs.

To make modern control design techniques more applicable, a synthesis method known as model following, including implicit and explicit model following, has been used. Recent developments in modern control theory have been unified into a new synthesis technique known as command generator tracking (CGT) (Refs 2; 3; 4; and 18:151-166). In this methodology, one requires a system to respond to command inputs while rejecting disturbances, so that the states of the system maintain desired trajectories in real time. Both the desired trajectories and the disturbances are formulated as the outputs of linear system models. The

first of these, the command generator model, can produce a time history of variables that the actual system is to follow or mimic, thereby incorporating handling qualities into the controller design (Refs 10 and 16).

In an open loop format, the problem is to determine appropriate gains, from the states of both the command generator model and the disturbance model or shaping filter (Ref 17:180-186) to the system control inputs (also to determine appropriate inputs to those models), that will yield command generator tracking; i.e. replication by the actual system of the desired output responses despite any modelled disturbances. If the original system is unstable or marginally stable, or affected by unmodelled disturbances and uncertainties, the addition of stabilizing feedback is required. The feedback controller should produce a system with a type-1 property to ensure the system will respond with zero steady-state error to a step input, since a more complex input can be approximated by a series of step inputs. Thus the consideration of a proportional plus integral (PI) design is appropriate for the feedback controller, since it can provide this type-1 property (Refs 5; 6; and 18:132-151). PI design based on augmenting the original state equations with difference equations for control variables, treating control pseudorates as driving functions, has already been exploited (Refs 9; 19; and 21). It has also been shown that analogous PI controllers can be obtained by augmenting the original system states with the integrals of regulation error (Ref 18:135-141). Finally,

since perfect access to all system state variables is rarely available, sensor outputs must be processed by a Kalman filter (KF) or observer to generate estimates of the state variables (Ref 17:203-406). The resulting controller is known as a CGT/PI/KF controller.

To date, two efficient interactive computer software programs have been developed for the design and performance analysis of CGT/PI/KF controllers. The first software program, known as "CGTPIF" developed by Capt. Floyd (Ref 9) and later modified by Lt. Moseley (Ref 21), specifically aids the user in conducting the synthesis and analysis of the components of the CGT/PI/KF controller. The second, "PFEVAL" developed by Lt. Moseley, conducts a statistical performance analysis of the resulting composite controllers (Ref 21). "CGTPIF" currently bases the design of the PI controller only on the difference equations for control variables, but since some designers may be more familiar with, or have a better feel for, designing the PI controller based on the integral of the regulation error, the need for this type analysis tool exists.

## 1.2 Problem and Scope

The primary objectives of this thesis are:

1. To develop an interactive, user-oriented computer program similar to "CGTPIF", which will also interface with "PFEVAL", to aid in the design of CGT/PI/KF controllers, basing the design of the PI controller on the integral of the regulation error.

2. To apply the design program to an aircraft flight control problem to evaluate characteristics of this CGT/PI/KF controller design and to compare the designs.

### 1.3 Sequence of Presentation

The results of this effort are fully documented in the body of the thesis and in the appendices. Chapter II contains a short overview of the existing work performed in the previous two theses (Refs 9 and 21), with the theoretical aspects of the alternate PI controller design techniques presented in Chapter III. Chapter IV presents a description of the computer program developed for the alternate PI controller designs as well as summarizing the pertinent information from the existing "CGTPIF" program. Chapter V discusses and compares the PI controller designs through use of the program. A final chapter offers conclusions and recommendations for further research.

There are four appendices to this thesis. The first is a brief description of the computer program subroutines that were changed in going from "CGTPIF" to the alternate program called "CGTPIQ". For a complete program analysis, the reader of this thesis must also read Floyd's and Moseley's theses (Refs 9 and 21), especially if the plan is to understand all the computer program subroutines with the idea of modifying the program in any way. The second is a complete user's guide for "CGTPIQ". The third is a full source listing of the computer code and the fourth is a summary of the CGT/PI/KF design evaluation for CGTPIQ.

## II. EXISTING CGT/PI/KF Design

### 2.1 Introduction

The control philosophy employed in the CGT/PI/KF controller is not new. While it is clearly in the class of model-following controllers and has characteristics closely related to those typical of the earlier model-following designs, the theory from which it is derived is distinctly not in a linear path with earlier work. In one consistent development it incorporates all the capabilities of earlier model-following designs, provides new capabilities, and does so in a single unified controller/filter structure.

The basic structure of this controller is as depicted in Fig. II-1. It accepts command inputs and generates a feedforward control through the command generator model and CGT controller; it incorporates a PI controller as an inner loop feedback controller to drive the system to follow the CGT inputs; and it uses a Kalman filter to provide estimates of both the system and disturbance states needed by the controllers.

Before presenting the theoretical development of the alternate PI controller (Chapter III), the rest of this chapter will introduce the CGT/PI/KF controller concept by briefly summarizing what is currently implemented in the interactive computer programs "CGTPIF" and "PFEVAL". This chapter is taken in part from a paper by Maybeck, Floyd, and



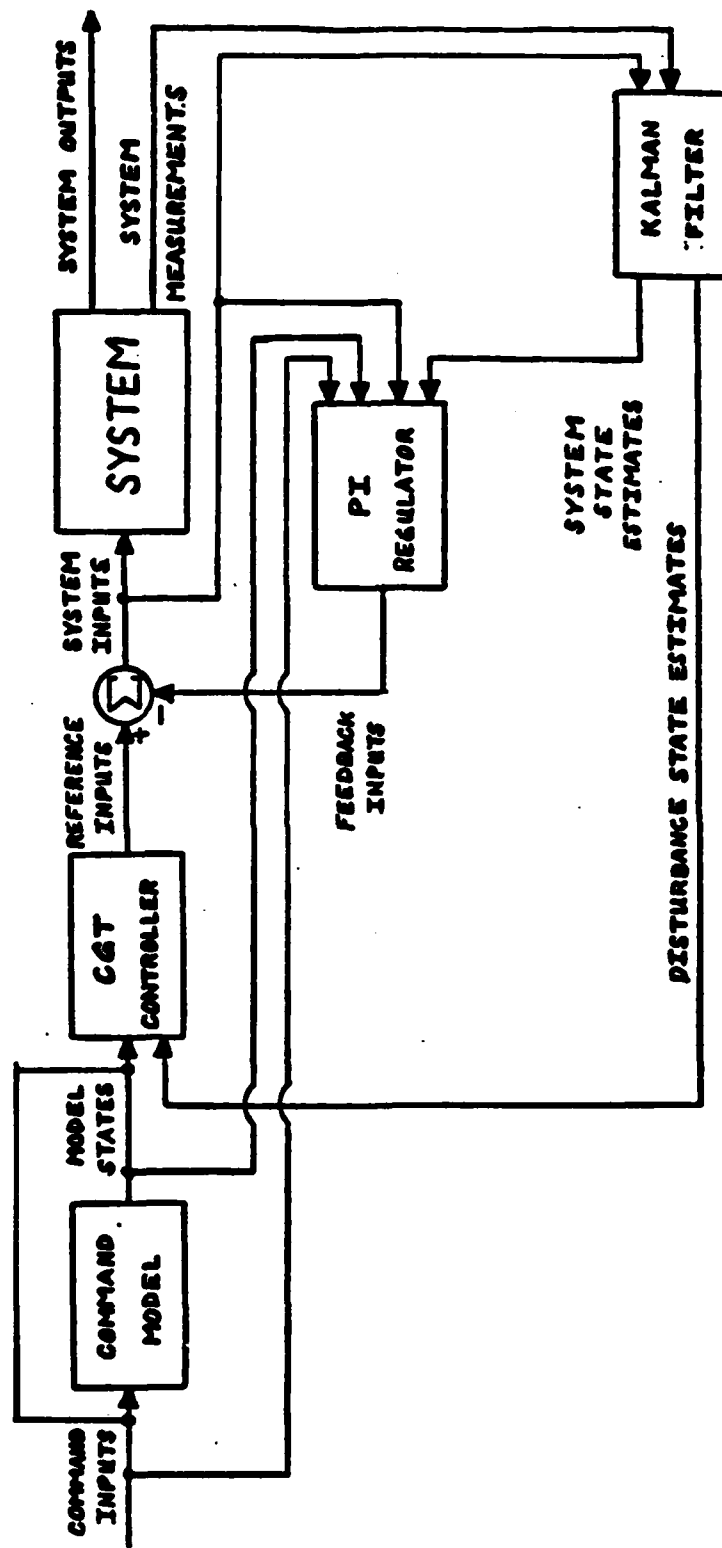


Fig. II-1. CGT/PI/KF General Block Diagram

Moseley (Ref 19) which presents this concept in a tutorial manner. The development presented in Chapter III will be constructed in a linear path with "CGTPIF" and will interface directly with "PFEVAL". It is recommended that the reader of this thesis also read the preceding theses (Refs 9 and 21) to obtain a more thorough overall picture of the problem.

## 2.2 Command Generator Tracking

Consider a system described by the linear time invariant discrete time model

$$\underline{x}(t_{i+1}) = \underline{A}\underline{x}(t_i) + \underline{B}_d\underline{u}(t_i) + \underline{E}_x\underline{n}_d(t_i) + \underline{w}(t_i) \quad (\text{II-1})$$

$$\underline{y}_c(t_i) = \underline{C}\underline{x}(t_i) + \underline{D}_y\underline{u}(t_i) + \underline{E}_y\underline{n}_d(t_i) \quad (\text{II-2})$$

where  $\underline{x}(t_i)$  is the state at sample time  $t_i$ ,  $\underline{u}(t_i)$  is the control applied to the system at time  $t_i$ ,  $\underline{n}_d(t_i)$  is a vector of time correlated noises and disturbances,  $\underline{w}(t_i)$  is zero-mean white Gaussian dynamics driving noise of covariance  $\underline{Q}$ , and  $\underline{y}_c(t_i)$  is a vector of output controlled variables over which we want to exert influence and to cause to behave in a desirable manner. Such a model can be established by writing the continuous time linear perturbation equations for a system (such as an aircraft) and then generating the equivalent discrete time model at a chosen sample rate (Refs 17 and 18). This model is assumed to be stabilizable and detectable (Ref 18). In Equations (II-1) and (II-2)

$\underline{n}_d(t_i)$  is a vector of disturbances whose effects on the system we specifically want to reject, and it is modelled as the output of a shaping filter of the form

$$\underline{n}_d(t_{i+1}) = \underline{G}_n \underline{n}_d(t_i) + \underline{G}_n \underline{w}_{dn}(t_i) \quad (\text{II-3})$$

where  $\underline{w}_{dn}(t_i)$  is a zero-mean white Gaussian noise of covariance  $\underline{Q}_n$  that is independent of  $\underline{w}(t_i)$  in Equation (II-1). It is desired that the system described by these equations duplicate as closely as possible the output of a command generator model

$$\underline{x}_m(t_{i+1}) = \underline{G}_m \underline{x}_m(t_i) + \underline{B}_m \underline{u}_m(t_i) \quad (\text{II-4})$$

$$\underline{y}_m(t_i) = \underline{C}_m \underline{x}_m(t_i) + \underline{D}_m \underline{u}_m(t_i) \quad (\text{II-5})$$

where the model input  $\underline{u}_m(t_i)$  can be viewed as the desired input (such as provided by the pilot stick), and this model specifies the system's desired dynamic characteristics. Although  $\underline{x}_m(t_i)$  and  $\underline{u}_m(t_i)$  need not be of the same dimension as  $\underline{x}(t_i)$  and  $\underline{u}(t_i)$  of Equation (II-1),  $\underline{y}_m(t_i)$  is of the same dimension as  $\underline{y}_c(t_i)$  of Equation (II-2). For controller development, it is assumed that  $\underline{u}_m(t_i)$  is a constant,  $\underline{u}_m$ . In actual applications it typically varies very slowly relative to the chosen sample period, and  $\underline{u}_m$  can thus be considered piecewise constant with long intervals of essentially constant value. Since  $\underline{u}_m$  is generally nonzero, a PI controller will be more desirable

than a simple regulator for feedback, to enable achieving the desired values with zero steady state mean error. This will be pursued in the next section.

Mathematically, the objective of the CGT is to force the error between the actual system output,  $\underline{y}_c$ , and the desired (model) output,  $\underline{y}_m$ , to zero:

$$\underline{e}(t_i) = \underline{y}_c(t_i) - \underline{y}_m(t_i) = \underline{0} \quad (\text{II-6})$$

Assume initially that  $\underline{x}(t_i)$ ,  $\underline{n}_d(t_i)$ , and  $\underline{y}_c(t_i)$  are all perfectly accessible, to be replaced later by Kalman filter estimates. Thus, the ideal state and control trajectories,  $\underline{x}_I(t_i)$  and  $\underline{u}_I(t_i)$  for all  $t_i$ , are defined as the time histories the system states and controls must follow so that the true system output perfectly matches the model output, as in Equation (II-6); while the system is being affected by modelled disturbances:

$$\underline{x}_I(t_{i+1}) = \underline{A}\underline{x}_I(t_i) + \underline{B}\underline{u}_I(t_i) + \underline{E}_x\underline{n}_d(t_i) \quad (\text{II-7})$$

Another requirement levied on the ideal trajectories is that they must be linear functions of  $\underline{x}_m(t_i)$ ,  $\underline{u}_m(t_i)$  and  $\underline{n}_d(t_i)$ :

$$\begin{bmatrix} \underline{x}_I(t_i) \\ \underline{u}_I(t_i) \end{bmatrix} = \begin{bmatrix} \underline{A}_{11} & \underline{A}_{12} & \underline{A}_{13} \\ \underline{A}_{21} & \underline{A}_{22} & \underline{A}_{23} \end{bmatrix} \begin{bmatrix} \underline{x}_m(t_i) \\ \underline{u}_m(t_i) \\ \underline{n}_d(t_i) \end{bmatrix} \quad (\text{II-8})$$

The CGT problem is then to solve for the matrix partitions in Equation (II-8) such that Equations (II-6), (II-7), and (II-8) are all satisfied. This will be shown in Chapter III (Section 3.3.1). Once these evaluations are accomplished, the CGT control law is implemented simply as the lower partition of Equation (II-8):

$$u_I(t_i) = A_{21}x_m(t_i) + A_{22}u_m(t_i) + A_{23}n_d(t_i) \quad (\text{II-9})$$

### 2.3 PI Controller

Now consider the PI controller of Fig. II-1. One seeks a controller structure that includes accepting the sensed error between  $y_m(t_i)$  and achieved  $y_c(t_i)$ , and generating the appropriate control to feed back into the system to keep this difference small. To keep the system in a nonzero equilibrium condition such that steady state error is zero, the controller fed by the regulation error  $[y_m(t_i) - y_c(t_i)]$  must be able to deliver the appropriate nonzero steady state control when its own input is zero. This cannot be achieved by a simple proportional feedback regulator, and so a PI controller is motivated. This form of controller will also be able to reject the effect of unmodelled constant disturbances (as due to generating controller designs based on linear perturbation models expanded about a particular point in the operational envelope of the vehicle, while the vehicle is actually operating at a somewhat different

point), which is also highly desirable in this application.

In this section, perfect access to all states and pertinent variables is again assumed, and the Linear system, Quadratic cost, Gaussian noise (LQG) synthesis technique will be used. This methodology provides a systematic synthesis procedure to generate a controller with desired stability properties ensured, in which the appropriate cross feeds in this multiple input/multiple output controller (whose evaluation may not be very apparent from other design techniques) are dictated by system and cost descriptions, and in which tradeoffs between state and control amplitudes can be readily accomplished in the design process.

### 2.3.1 PI Controller Based on Control Difference Equations

One means of developing a PI controller for this application is to consider the perturbation variables

$$\delta \underline{x}(t_i) = \underline{x}(t_i) - \underline{x}_I(t_i) \quad (\text{II-10a})$$

$$\delta \underline{u}(t_i) = \underline{u}(t_i) - \underline{u}_I(t_i) \quad (\text{II-10b})$$

$$\delta \underline{y}_C(t_i) = \underline{y}_C(t_i) - \underline{y}_m(t_i) \quad (\text{II-10c})$$

In terms of these variables, perturbations about the ideal trajectories can be described by the augmented perturbation state equation

$$\begin{bmatrix} \delta \underline{x}(t_{i+1}) \\ \delta \underline{u}(t_{i+1}) \end{bmatrix} = \begin{bmatrix} \underline{A} & \underline{B}_d \\ \underline{0} & \underline{I} \end{bmatrix} \begin{bmatrix} \delta \underline{x}(t_i) \\ \delta \underline{u}(t_i) \end{bmatrix} + \begin{bmatrix} \underline{0} \\ \underline{I} \end{bmatrix} \Delta \underline{u}(t_i) \quad (\text{II-11})$$

where the upper partition is the perturbation equation associated with the system and the lower partition treats  $f_u(t_i)$  as additional states by considering them as the output of a summation (pseudointegration) process

$$f_u(t_{i+1}) = f_u(t_i) + \Delta u(t_i) \quad (\text{II-12})$$

in terms of control differences or "pseudorates". For this augmented perturbation system description, an optimal constant gain controller to minimize the quadratic cost

$$J = \sum_{i=0}^{\infty} \begin{bmatrix} f_x(t_i) \\ f_u(t_i) \\ \Delta u(t_i) \end{bmatrix}^T \begin{bmatrix} X_{11} & X_{12} & S_1 \\ X_{12}^T & X_{22} & S_2 \\ S_1^T & S_2^T & U \end{bmatrix} \begin{bmatrix} f_x(t_i) \\ f_u(t_i) \\ \Delta u(t_i) \end{bmatrix} \quad (\text{II-13})$$

can be efficiently generated via solution to steady state (algebraic) Riccati difference equations (Ref 13).  $X_{11}$  specifies the cost weighting on state magnitudes,  $X_{22}$  on control magnitudes, and  $U$  on control differences. The solution form for this controller problem is

$$\Delta u^*(t_i) = - [G_{c1}^* \quad G_{c2}^*] \begin{bmatrix} f_x(t_i) \\ f_u(t_i) \end{bmatrix} \quad (\text{II-14})$$

In terms of the controller gains  $G_{c1}^*$  and  $G_{c2}^*$ , the final incremental PI control law can be written as (Ref 18:145)

$$\begin{aligned} u(t_i) = & u(t_{i-1}) - K_x [x(t_i) - x(t_{i-1})] \\ & + K_z [y_m(t_i) - y_c(t_{i-1})] \end{aligned} \quad (\text{II-15})$$

where  $K_x$  and  $K_z$  are given by

$$K_x = G_{c1} \pi_{11}^* + G_{c2} \pi_{21}^* \quad (\text{II-16a})$$

$$K_z = G_{c1} \pi_{12}^* + G_{c2} \pi_{22}^* \quad (\text{II-16b})$$

with

$$\begin{bmatrix} \pi_{11} & \pi_{12} \\ \pi_{21} & \pi_{22} \end{bmatrix} = \begin{bmatrix} (\Phi - I) & B_d \\ C & D_y \end{bmatrix}^{-1} \quad (\text{II-17})$$

which will be developed further in Chapter III.

### 2.3.2 Closed Loop CGT/PI Controller Based on Control Difference Equations

Without going into any detail as to its development, the incremental closed loop CGT/PI controller equation based on the control difference (as currently implemented in "CGTPIF") will be shown here. After reading Chapter III, the reader should refer back to this section to see the similarities in the two CGT/PI control laws. The law is



$$\begin{aligned}
\underline{u}(t_i) = & \underline{u}(t_{i-1}) - \underline{K}_x [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\
& + \underline{K}_z \left\{ \begin{bmatrix} \underline{C}_m & \underline{D}_m \end{bmatrix} \begin{bmatrix} \underline{x}_m(t_{i-1}) \\ \underline{u}_m(t_i) \end{bmatrix} - \begin{bmatrix} \underline{C} & \underline{D}_y \end{bmatrix} \begin{bmatrix} \underline{x}(t_{i-1}) \\ \underline{u}(t_{i-1}) \end{bmatrix} \right\} \\
& + [\underline{K}_x \underline{A}_{11} + \underline{A}_{21}] [\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\
& + [\underline{K}_x \underline{A}_{12} + \underline{A}_{22}] [\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\
& + [\underline{K}_x \underline{A}_{13} + \underline{A}_{23}] [\underline{n}_d(t_i) - \underline{n}_d(t_{i-1})] \quad (\text{II-18})
\end{aligned}$$

Issues such as speedup and initial conditions will be addressed in Chapter III and are applicable to Equation (II-18). (The full development is presented in Refs 9 and 18:135-147).

#### 2.4 Kalman Filter

The previous sections developed controllers under assumption that perfect access to all states is available at each sample time. Since this is generally not the case, a Kalman Filter is used to generate optimal estimates of these states from the incomplete noise corrupted outputs of physical sensors. Certainty equivalence (Ref 18) under the LQG assumptions yields the optimal controller as the controllers presented previously, but with  $\underline{x}(t_i)$  and  $\underline{n}_d(t_i)$  replaced by the estimates provided by the filter.

The dynamics model upon which the filter is based is generated by augmenting Equations (II-1) and (II-3) to get

$$\begin{bmatrix} \underline{x}(t_{i+1}) \\ \underline{n}_d(t_{i+1}) \end{bmatrix} = \begin{bmatrix} \underline{\Phi} & \underline{E}_x \\ \underline{0} & \underline{E}_n \end{bmatrix} \begin{bmatrix} \underline{x}(t_i) \\ \underline{n}_d(t_i) \end{bmatrix} + \begin{bmatrix} \underline{B} \\ \underline{0} \end{bmatrix} \underline{u}(t_i) + \begin{bmatrix} \underline{I} & \underline{0} \\ \underline{0} & \underline{G}_n \end{bmatrix} \begin{bmatrix} \underline{w}(t_i) \\ \underline{w}_n(t_i) \end{bmatrix} \quad (\text{II-19})$$

and the measurement devices are modelled by

$$\underline{z}(t_i) = \begin{bmatrix} \underline{H} & \underline{H}_n \end{bmatrix} \begin{bmatrix} \underline{x}(t_i) \\ \underline{n}_d(t_i) \end{bmatrix} + \underline{v}(t_i) \quad (\text{II-20})$$

where  $\underline{v}$  is zero mean white Gaussian noise of covariance  $\underline{R}$ , independent of  $\underline{w}$  and  $\underline{w}_n$ . From these models, a standard Kalman filter (or observer) can be derived and implemented in the constant-gain steady state form to accept measurements  $\underline{z}(t_i)$  and produce  $\hat{\underline{x}}(t_i^+)$  and  $\hat{\underline{n}}_d(t_i^+)$ , as shown in Fig. II-1. In the CGT/PI control law,  $\underline{y}_c(t_i)$  is replaced by  $\hat{\underline{y}}_c(t_i^+)$  in Equation (II-16) where from Equation (II-2)

$$\hat{\underline{y}}_c(t_i^+) = \underline{C}\hat{\underline{x}}(t_i^+) + \underline{D}_y \underline{u}(t_i) + \underline{E}_y \hat{\underline{n}}_d(t_i^+) \quad (\text{II-21})$$

#### 2.4.1 CGT/PI/KF Control Law Based on Control Difference Equations

The Kalman filter outputs can be combined with the CGT/PI control law to produce a CGT/PI/KF control law. The development of this law is thoroughly documented in Lt. Moseley's thesis as part of "PFEVAL" and is

$$\begin{aligned}
\underline{u}(t_i) = & - \underline{K}_x (I - KH) \hat{\underline{x}}(t_i^-) - \underline{K} \underline{H}_n \hat{\underline{n}}_d(t_i^-) + \underline{K} \underline{z}(t_i) \\
& + [\underline{K}_x \underline{A}_{11} + \underline{A}_{21}] \underline{x}_m(t_i) \\
& + [\underline{K}_x \underline{A}_{13} + \underline{A}_{23}] [-\underline{K}_n \underline{H} \hat{\underline{x}}(t_i^-) + (I - \underline{K}_n \underline{H}_n) \hat{\underline{n}}_d(t_i^-)] \\
& + \underline{K}_n \underline{z}(t_i) + \underline{K}_f \underline{f}(t_i)
\end{aligned} \tag{II-22a}$$

where

$$\underline{K}_f(t_i) = \underline{K}_f(t_{i-1}) + \begin{bmatrix} \underline{C}_m & \underline{D}_m \end{bmatrix} \begin{bmatrix} \underline{x}_m(t_{i-1}) \\ \underline{u}_m(t_i) \end{bmatrix} - \begin{bmatrix} \underline{C} & \underline{D}_y \end{bmatrix} \begin{bmatrix} \underline{x}(t_{i-1}) \\ \underline{u}(t_{i-1}) \end{bmatrix} \tag{II-22b}$$

and where the Kalman filter gains are given by

$$\begin{bmatrix} \underline{K} \\ \underline{K}_n \end{bmatrix} = \begin{bmatrix} \underline{P}_{xx} & \underline{P}_{xn} \\ \underline{P}_{xn}^T & \underline{P}_{nn} \end{bmatrix} \begin{bmatrix} \underline{H}^T \\ \underline{H}_n^T \end{bmatrix} \left\{ \begin{bmatrix} \underline{H} & \underline{H}_n \end{bmatrix} \begin{bmatrix} \underline{P}_{xx} & \underline{P}_{xn} \\ \underline{P}_{xn}^T & \underline{P}_{nn} \end{bmatrix} \begin{bmatrix} \underline{H}^T \\ \underline{H}_n^T \end{bmatrix} + \underline{R} \right\}^{-1} \tag{II-23}$$

#### 2.4.2 Implicit and Explicit Model Following Based on Control Difference Equations

A modification performed by Lt. Moseley and documented in his thesis was to add implicit model following to the explicit model following of the "CGTPIF" program. In implicit model following, the model is incorporated into the performance index and thus helps determine appropriate feedback gains so that deviations in achieved transient response from the desired model response are penalized mathematically, and thus minimized operationally. In

explicit model following, the model is used not only to determine appropriate feedback gains, but also feedforward gains on the model states themselves, thereby requiring an explicit simulation of the model dynamics in the controller itself. (For a thorough explanation of implicit and explicit model refer to Capt. Floyd's thesis (Ref 9), which very adequately summarizes the available literature on the subject.)

The result of adding implicit model following was to change the weighting on the  $\underline{x}$  vector, with  $\underline{x}$  defined as in Equation (II-11) as

$$\underline{x} = \begin{bmatrix} \int \underline{x} \\ \int \underline{u} \end{bmatrix} \quad (\text{II-24})$$

from weights

$$\underline{X} = \begin{bmatrix} X_{11} & X_{12} \\ X_{12}^T & X_{22} \end{bmatrix} \quad (\text{II-25})$$

as in Equation (II-13), to

$$\underline{X} = \begin{bmatrix} X_{11} + \hat{X}_I & X_{12} + \hat{S}_I \\ X_{12}^T + \hat{S}_I^T & X_{22} + \hat{U}_I \end{bmatrix} \quad (\text{II-26})$$

where (Ref 18:68-82)

$$\underline{X}_{11} = \underline{C}^T \underline{Y} \underline{C} \quad (\text{II-27a})$$

$$\underline{X}_{22} = \underline{U}_y + \underline{D}_y^T \underline{Y} \underline{D}_y \quad (\text{II-27b})$$

$$\underline{X}_{12} = \underline{C}^T \underline{Y} \underline{D}_y \quad (\text{II-27c})$$

in terms of a quadratic weighting matrix  $\underline{Y}$  on  $\int \underline{y}_c$  and a weighting matrix  $\underline{U}_y$  on  $\int \underline{u}$  in an original cost function definition convenient for a designer's use, and (Ref 9 and 21)

$$\hat{\underline{X}}_I = (\underline{C}\underline{A} - \underline{A}_m\underline{C})^T \underline{X}_I (\underline{C}\underline{A} - \underline{A}_m\underline{C}) \quad (\text{II-28a})$$

$$\hat{\underline{S}}_I^T = \underline{B}^T \underline{C}^T \underline{X}_I (\underline{C}\underline{A} - \underline{A}_m\underline{C}) \quad (\text{II-28b})$$

$$\hat{\underline{U}}_I = \underline{U}_I + \underline{B}^T \underline{C}^T \underline{X}_I \underline{C}\underline{B} \quad (\text{II-28c})$$

(These same relations for  $\underline{X}_{11}$ ,  $\underline{X}_{22}$ ,  $\underline{X}_{12}$ ,  $\hat{\underline{X}}_I$ ,  $\hat{\underline{S}}_I$ ,  $\hat{\underline{U}}_I$  will appear in Chapter III for the alternate derivation of the PI controller based on the integral of the regulation error but the placement within the overall matrix will change. The reader may wish to refer back to this section after reading Chapter III.)

## 2.5 Performance Evaluation

It is desired to use the previous systematic controller design method for realistic applications in which online computer limitations such as speed and memory size are important constraints on the design. Thus, the system models used for controller design are purposely reduced order, reduced complexity models. A number of prospective CGT/PI/KF controllers can be developed, differing in state dimension, choice of states, complexity of defining

matrices, performance index weighting matrices, and filter tuning parameters.

For these CGT/PI/KF controllers, or any other digital controllers, it is desirable to conduct a performance analysis as depicted in Fig. II-2. The truth model portrays the actual system to be controlled and the effects of the external environment upon the system, as well as can be modelled, regardless of complexity or computational loading. Therefore, the dimension of the truth model state  $\underline{x}_t$  is typically much higher than that of the models used for controller design. For the most useful form of performance evaluation algorithm, one desires the ability to specify a continuous-time description of the truth model, and a discrete-time description of the digital controller with a sample frequency that is a variable design parameter. For performance evaluation purposes, it is important to portray the characteristics of the truth model state  $\underline{x}_t$  and the commanded controls  $\underline{u}$ , as shown as outputs in Fig. II-2. It is the truth model state, depicting actual system characteristics, and not the state of the model that the controller assumes to be an adequate description, that is at issue. Furthermore, it is desired to evaluate the level of commanded controls, as to verify that they do not exceed certain physical limits or design specifications.

In a stochastic model setting, the mean and rms time histories of these variables could be generated via Monte Carlo analysis in the most general case. However, if the

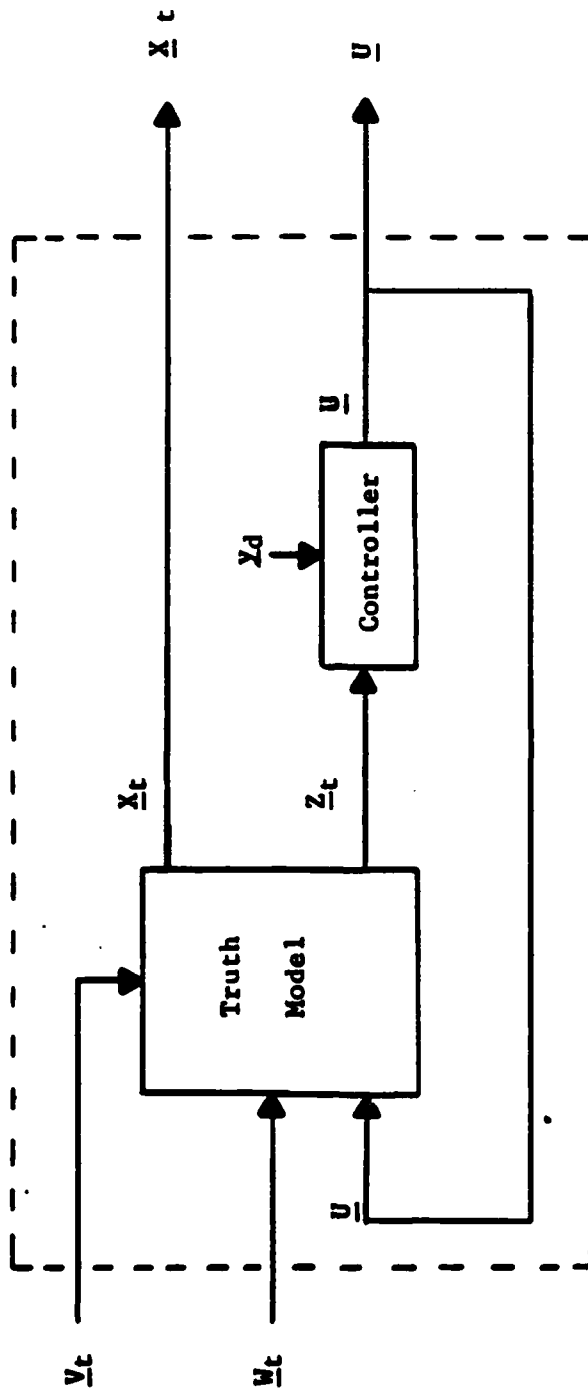


Fig. II-2. Performance Evaluation of Sampled Data Controller

truth model is itself linear, then such statistical time histories can be calculated explicitly, without requiring a Monte Carlo analysis of many simulation runs. This is what is accomplished in "PFEVAL".

## 2.6 Software Tools

Two efficient interactive computer software tools have been developed for the design and performance analysis of CGT/PI/KF controllers (Refs 9 and 21). Although one very important application is for the design of advanced digital flight controllers, these tools are in fact general purpose and can address a wide variety of control design problems.

The first software tool, known as "CGTPIF", specifically aids the user in conducting the synthesis of the components of the CGT/PI/KF controller and some analysis of characteristics of each of these components, as discussed in Sections 2.2-2.4. The second, "PFEVAL", conducts a statistical performance analysis of the resulting composite controllers, as discussed in Section 2.5. Some of their useful attributes for a user-friendly environment are:

- 1) each executes interactively;
- 2) each utilizes efficient array allocation;
- 3) various modes of entry are possible for the dynamics models for the design, command generator, and truth systems;
- 4) prespecified design paths are automatically followed, with user prompts at necessary decision points;
- 5) requests for inputs include informative prompts;
- 6) copious program output is provided; and



7) error checking is performed, and messages are given as appropriate.

Because of a significant usage of matrix manipulations, these programs employ an efficient library of routines (Ref 13). Aside from this library, "CGTPIF" contains about 2900 lines of source code and "PFEVAL" has about 1800. For ease of use, they are:

- 1) written in ANSI Standard Fortran IV;
- 2) highly portable;
- 3) implemented on a Control Data Corp. CYBER machine; and
- 4) segmented to achieve the necessary load size for interactive use without impacting the source code.

"CGTPIF" has three basic design paths: (1) design of a PI controller (using explicit and/or implicit quadratic weights), (2) design of either an open loop CGT or closed loop CGT/PI controller, and (3) design of a Kalman filter. As each of these components is generated, its performance is automatically evaluated: either controller path is automatically followed by deterministic analyses such as pole placement computations and step response plots (against a system described by either the design model or a truth model) while the filter generation is automatically followed by a covariance analysis of filter estimation accuracy in a truth model environment.

Initially, the user establishes the continuous time design model upon which to base the controller and filter, and also the desired sample period (the software generates all needed discretized models). Any of the three design

paths can then be chosen, typically in the numerical order as listed previously. If the PI controller design is pursued prior to the CGT design path, then the subsequent CGT design will automatically be of the CGT/PI controller. If the PI is not yet determined during the current execution of the program, the designer may elect to design either a CGT or a CGT/PI controller. The CGT design is not pursued if the open loop design model is unstable. When any of these design paths are completed, the user is given the opportunity to loop on the design path, to choose a different design path, or to terminate program execution. Each traversal of a design path yields a proposed component for use in Fig. II-1, and all pertinent information is saved in a file for processing by "PFEVAL".

"PFEVAL" specifically combines proposed CGT/PI and Kalman filter designs (as mentioned in Section 2.4.1) to generate an entire composite controller as in Fig. II-1, and then subjects these composite controllers to a covariance performance analysis of the closed loop system, as shown in Fig. II-2. Immediately after each such CGT/PI/KF controller is evaluated, the corresponding full state feedback CGT/PI is also tested against the same truth model, specifically to indicate the impact of the filter on closed loop system properties. By repeatedly testing the same controller against varied truth models, the important impact of the filter on robustness (Ref 18:102-114) can be portrayed explicitly.

Together, the two tools described provide a

user-friendly environment for efficient and systematic design and performance evaluation of CGT/PI/KF controllers. Applicability of the design approach and software tools to the following objectives has been demonstrated (Refs 9 and 21):

- 1) design of a conventional pitch rate controller for a modern fighter aircraft (AFTI/F-16);
- 2) decoupled pitch pointing control for the same aircraft;
- 3) effect of design model order reduction on closed loop system performance;
- 4) effect of parameter variations in the truth model upon closed loop system performance, and the impact of the filter upon controller robustness;
- 5) incorporation of implicit model following as well as explicit model following;
- 6) handling slowly changing disturbances via PI controller action versus direct rejection of modelled disturbances; and
- 7) incorporation of additional rolloff into the controller to address the inadequacy of linearized system models at higher frequencies due to neglected modes and other causes.

## 2.7 Summary

This chapter has introduced the CGT/PI/KF controller concept by briefly summarizing what is currently implemented in the interactive computer programs "CGTPIF" and "PFEVAL". Chapter III will now present the theoretical development of the alternate PI controller.

### III. PI and CGT/PI Development

#### 3.1 Introduction

The CGT/PI/KF design presented in Chapter II is currently incorporated into the two software packages previously discussed. Since the purpose of this thesis effort is to design a computer program that is similar to "CGTPIF" but bases the PI controller design on the integral of the regulation error, this chapter will develop only the equations pertinent to this effort. Also, any material contained in the previous theses which is needed or which will add continuity of thought to this effort will be repeated and incorporated into this development. This will prevent the reader from having to read Floyd's and Moseley's theses (Refs 9 and 21) to understand this development fully.

#### 3.2 PI Controller Based on the Integral of the Regulation Error

The design goal in employing a PI controller is to generate a feedback controller which will maintain the deterministic system output at a nonzero commanded value with zero mean steady state error, despite unmodeled constant disturbances which may also drive the system. Invoking the "Certainty Equivalence" property (Ref 18), let the deterministic system be described by the time-invariant model

$$\underline{x}(t_{i+1}) = \underline{A}\underline{x}(t_i) + \underline{B}_d u(t_i) + \underline{d}; \quad \underline{x}(t_0) = \text{given(III-1)}$$

$$\underline{y}_c(t_i) = \underline{C}\underline{x}(t_i) + \underline{D}_y u(t_i) \quad (\text{III-2})$$

Therefore, it is desired to generate a controller that will maintain the vector of controlled variables  $\underline{y}_c(t_i)$  at a nonzero desired value  $\underline{y}_d$  despite unknown disturbance  $\underline{d}$ . This is known as achieving a "type-one" property (Ref 18). One seeks a controller structure that includes accepting a sensed error between desired  $\underline{y}_d$  and the achieved  $\underline{y}_c(t_i)$ , and generating the appropriate control to keep this small. To keep the system at a nonzero equilibrium condition such that the steady-state error is zero, the controller fed by this regulation error signal  $[\underline{y}_d - \underline{y}_c(t_i)]$  must be able to deliver the appropriate nonzero steady state control when its own input is zero. This motivates the integral action to form a proportional plus integral or PI controller, accomplished by introducing an additional set of dynamic variables, with defining difference equations, which are then augmented to the original states. For Linear Quadratic Gaussian design of the PI controller, these additional variables can correspond to either (1) the "pseudointegral", or summation, of the (negative) regulation error

$$\begin{aligned} \underline{q}(t_i) &= \underline{q}(t_0) + \sum_{j=0}^{i-1} [\underline{y}_c(t_j) - \underline{y}_d] \\ &= \underline{q}(t_{i-1}) + [\underline{y}_c(t_{i-1}) - \underline{y}_d] \end{aligned} \quad (\text{III-3})$$

or (2) the control difference  $\Delta u(t_i)$ , such that

$$\underline{u}(t_{i+1}) = \underline{u}(t_i) + \Delta \underline{u}(t_i)$$

where  $\Delta \underline{u}(t_i)$  can be interpreted as a desired control rate times the sample period

$$\Delta \underline{u}(t_i) \cong [\dot{\underline{u}}(t_i)\Delta t]$$

and thus its alternate name of control "pseudorate". The second method was the method developed by Floyd in his thesis and currently implemented in the program "CGTPIF", and thus will not be discussed further. The method to be developed in this thesis is method 1, the "pseudointegral" of the regulation error.

The PI controller may be formulated for implementation in either of two forms, the "position form" or the "incremental form". The position form represents the current input in its entirety and does so in terms of the total values of the feedback variables. In the incremental form only the change in control input from its previous value is computed, and it is in terms of changes in the values of the feedback variables since the preceding sample period. The incremental form for the controller has certain advantages over the position form, such as less concern about proper initialization of augmented states, and is the method to be used for final implementation (Ref 18).

The optimal PI controller is first developed from a discrete-time problem formulation. Subsequently, the technique for translating a continuous-time quadratic cost

formulation, which is the formulation with which most designers will work, to the appropriate discrete-time cost function is demonstrated.

### 3.2.1 PI Mathematical Development

Following the development of Ref (18), define a "pseudointegral" state  $\underline{q}(t_i)$  as in Equation (III-3) where

$$[\underline{y}_c(t_i) - \underline{y}_d] = [\underline{C}\underline{x}(t_i) + \underline{D}_y\underline{u}(t_i) - \underline{y}_d] \quad (\text{III-4})$$

is the (negative) regulation error at time  $t_i$ . The system is assumed to be in equilibrium before  $t_0$ , so  $\underline{q}(t_0)$  is equal to the equilibrium value attained up to that time,  $\underline{q}_{old}$ , of value to be specified (which will be done later at the same time  $\underline{q}_0$  is established).

Thus, this state satisfies Equation (III-3). The augmented system description then becomes (after shifting time arguments on  $\underline{q}$ , combining Equation (III-2) and (III-3), and setting  $\underline{d}=\underline{0}$  in Equation (III-1), since  $\underline{d}$  is not to be modelled in the controller generation)

$$\begin{bmatrix} \underline{x}(t_{i+1}) \\ \underline{q}(t_{i+1}) \end{bmatrix} = \begin{bmatrix} \underline{A} & \underline{0} \\ \underline{C} & \underline{I} \end{bmatrix} \begin{bmatrix} \underline{x}(t_i) \\ \underline{q}(t_i) \end{bmatrix} + \begin{bmatrix} \underline{B}_d \\ \underline{D}_y \end{bmatrix} \underline{u}(t_i) - \begin{bmatrix} \underline{0} \\ \underline{I} \end{bmatrix} \underline{y}_d \quad (\text{III-5})$$

for  $t_i \geq t_0$ .

To satisfy the design goal in employing the PI controller, that of maintaining  $\underline{y}_c(t_i)$  at the

desired setpoint  $\underline{y}_d$ , an equilibrium solution must be found to yield  $\underline{x}(t_i) = \underline{x}_0$  for all  $t_i$ , such that  $\underline{y}_c(t_i) = \underline{y}_d$ . The nominal control  $\underline{u}_0$  to hold the system at that equilibrium point is found as the solution to

$$\underline{x}_0 = \underline{A}\underline{x}_0 + \underline{B}_d\underline{u}_0 \quad (\text{III-6})$$

$$\underline{y}_d = \underline{C}\underline{x}_0 + \underline{D}_y\underline{u}_0 \quad (\text{III-7})$$

or, rearranging,

$$\begin{bmatrix} (\underline{A}-\underline{I}) & \underline{B}_d \\ \underline{C} & \underline{D}_y \end{bmatrix} \begin{bmatrix} \underline{x}_0 \\ \underline{u}_0 \end{bmatrix} = \begin{bmatrix} \underline{0} \\ \underline{y}_d \end{bmatrix} \quad (\text{III-8})$$

If we assume that the composite matrix in Equation (III-8) is square and invertible, then for any given  $\underline{y}_d$ ,  $\underline{x}_0$  and  $\underline{u}_0$  can be found. If we let

$$\begin{bmatrix} (\underline{A}-\underline{I}) & \underline{B}_d \\ \underline{C} & \underline{D}_y \end{bmatrix}^{-1} = \begin{bmatrix} \pi_{11} & \pi_{12} \\ \pi_{21} & \pi_{22} \end{bmatrix} \quad (\text{II-18})$$

then

$$\begin{bmatrix} \underline{x}_0 \\ \underline{u}_0 \end{bmatrix} = \begin{bmatrix} (\underline{A}-\underline{I}) & \underline{B}_d \\ \underline{C} & \underline{D}_y \end{bmatrix}^{-1} \begin{bmatrix} \underline{0} \\ \underline{y}_d \end{bmatrix} \quad (\text{III-9a})$$

$$= \begin{bmatrix} \pi_{11} & \pi_{12} \\ \pi_{21} & \pi_{22} \end{bmatrix} \begin{bmatrix} \underline{0} \\ \underline{y}_d \end{bmatrix} \quad (\text{III-9b})$$



or

$$\underline{x}_0 = \underline{\pi}_{12} \underline{y}_d \quad (\text{III-10a})$$

$$\underline{u}_0 = \underline{\pi}_{22} \underline{y}_d \quad (\text{III-10b})$$

If the composite matrix in Equation (III-8) is not square, a solution can be found using the left or right inverses (Ref 18:124), but this will not be pursued here.

Having found  $\underline{x}_0$  and  $\underline{u}_0$ , perturbation variables can be defined as

$$\delta \underline{x}(t_i) = \underline{x}(t_i) - \underline{x}_0 = \underline{x}(t_i) - \underline{\pi}_{12} \underline{y}_d \quad (\text{III-11a})$$

$$\delta \underline{u}(t_i) = \underline{u}(t_i) - \underline{u}_0 = \underline{u}(t_i) - \underline{\pi}_{22} \underline{y}_d \quad (\text{III-11b})$$

$$\delta \underline{y}_c(t_i) = \underline{y}_c(t_i) - \underline{y}_d \quad (\text{III-11c})$$

$$\delta \underline{q}(t_i) = \underline{q}(t_i) - \underline{q}_0 \quad (\text{III-11d})$$

where  $\underline{q}_0$  is the new "pseudointegral" state steady state value, yet to be determined.

In terms of the perturbation variables, the augmented system perturbation model becomes (from Equation (III-5))

$$\begin{bmatrix} \delta \underline{x}(t_{i+1}) \\ \delta \underline{q}(t_{i+1}) \end{bmatrix} = \begin{bmatrix} \underline{A} & \underline{0} \\ \underline{C} & \underline{I} \end{bmatrix} \begin{bmatrix} \delta \underline{x}(t_i) \\ \delta \underline{q}(t_i) \end{bmatrix} + \begin{bmatrix} \underline{B}_d \\ \underline{D}_y \end{bmatrix} \delta \underline{u}(t_i) \quad (\text{III-12})$$

For the optimal regulator the quadratic cost criterion to be minimized is

$$\begin{aligned}
J = \sum_{i=0}^N & \left\{ \frac{1}{2} \begin{bmatrix} \delta \underline{x}(t_i) \\ \delta \underline{q}(t_i) \\ \delta \underline{u}(t_i) \end{bmatrix}^T \begin{bmatrix} \underline{X}_{11} & \underline{X}_{12} & \underline{S}_1 \\ \underline{X}_{12}^T & \underline{X}_{22} & \underline{S}_2 \\ \underline{S}_1^T & \underline{S}_2^T & \underline{U} \end{bmatrix} \begin{bmatrix} \delta \underline{x}(t_i) \\ \delta \underline{q}(t_i) \\ \delta \underline{u}(t_i) \end{bmatrix} \right\} \\
& + \begin{bmatrix} \delta \underline{x}(t_{N+1}) \\ \delta \underline{q}(t_{N+1}) \end{bmatrix}^T \begin{bmatrix} \underline{X}_{f11} & \underline{X}_{f12} \\ \underline{X}_{f12}^T & \underline{X}_{f22} \end{bmatrix} \begin{bmatrix} \delta \underline{x}(t_{N+1}) \\ \delta \underline{q}(t_{N+1}) \end{bmatrix} \quad (\text{III-13})
\end{aligned}$$

where  $\underline{X}_{11}$  weights state deviation from the nominal  $\underline{x}_0$ ,  $\underline{X}_{22}$  weights deviations from the nominal "pseudointegral" state  $\underline{q}_0$ , and  $\underline{U}$  weights control deviations from the nominal  $\underline{u}_0$ . The weights  $\underline{X}_f$  apply to the deviations at terminal time, and for an infinite time duration steady state controller problem (i.e.,  $N \rightarrow \infty$ ), these weights will not be used.

By letting  $N \rightarrow \infty$  in Equation (III-18), and solving for the steady-state control law, it was shown (Ref 18:1-60) that the solution is of the form

$$\underline{u}^*(t_i) = -[\underline{G}_{c1}^* \quad \underline{G}_{c2}^*] \begin{bmatrix} \delta \underline{x}(t_i) \\ \delta \underline{q}(t_i) \end{bmatrix} \quad (\text{III-14a})$$

$$= -\underline{G}_{c1}^* \delta \underline{x}(t_i) - \underline{G}_{c2}^* \delta \underline{q}(t_i) \quad (\text{III-14b})$$

Substituting Equations (III-11a), (III-11b), and (III-11d) into Equation (III-14b) yields

$$[\underline{u}^*(t_i) - \underline{u}_0] = -\underline{G}_{c1}^* [\underline{x}(t_i) - \underline{x}_0] - \underline{G}_{c2}^* [\underline{q}(t_i) - \underline{q}_0] \quad (\text{III-15})$$

or after multiplying and rearranging terms

$$\begin{aligned} \underline{u}^*(t_i) = & - \underline{G}_{c1}^* \underline{x}(t_i) - \underline{G}_{c2}^* \underline{q}(t_i) \\ & + [\underline{u}_0 + \underline{G}_{c1}^* \underline{x}_0 + \underline{G}_{c2}^* \underline{q}_0] \end{aligned} \quad (\text{III-16})$$

with  $\underline{q}(t_i)$  determined as in Equation (III-3).  
 $\underline{G}_{c1}^*$  and  $\underline{G}_{c2}^*$  are found by considering the  
 general form for  $\underline{G}_C^*$  in Equation (III-14a) (Ref  
 18:73)

$$\underline{G}_C^* = [\underline{U} + \underline{B}_d^T \underline{K}_C \underline{B}_d]^{-1} [\underline{B}_d^T \underline{K}_C \underline{x} + \underline{S}^T] \quad (\text{III-17})$$

where  $\underline{K}_C$  satisfies the backward Riccati equation

$$\underline{K}_C(t_i) = \underline{X} + \underline{x}^T \underline{K}_C(t_{i+1}) \underline{x} - [\underline{B}_d^T \underline{K}_C(t_{i+1}) \underline{x} + \underline{S}^T]^T \underline{G}_C^* \quad (\text{III-18a})$$

solved backwards from the terminal condition

$$\underline{K}_C(t_{n+1}) = \underline{X}_f \quad (\text{III-18b})$$

to its steady state value, or, equivalently, solving the  
 (algebraic) steady state version of Equation (III-18a) for  
 the constant  $\underline{K}_C = \underline{K}_C(t_i) = \underline{K}_C(t_{i+1})$ . If  
 we take our augmented system descriptions, Equations (III-5)  
 and (III-13), and partition them so that each segment  
 matches an entry in the general solution we have

$$[G_{c1}^* \quad G_{c2}^*] = \left\{ U + [B_d^T \quad D_y^T] \begin{bmatrix} K_{c11} & K_{c12} \\ K_{c12}^T & K_{c22} \end{bmatrix} \begin{bmatrix} B_d \\ D_y \end{bmatrix} \right\}^{-1} \\ \left\{ [B_d^T \quad D_y^T] \begin{bmatrix} K_{c11} & K_{c12} \\ K_{c12}^T & K_{c22} \end{bmatrix} \begin{bmatrix} \underline{x} & 0 \\ C & I \end{bmatrix} + [S_1^T \quad S_2^T] \right\} \quad (III-19)$$

Multiplying this out yields

$$[G_{c1}^* \quad G_{c2}^*] = \{ U + B_d^T K_{c11} B_d + D_y^T K_{c12} B_d \\ + B_d^T K_{c12} D_y + D_y^T K_{c22} D_y \}^{-1} \{ [B_d^T K_{c11} \underline{x} \\ + D_y^T K_{c12}^T \underline{x} + B_d^T K_{c12} C + D_y^T K_{c22} C + S_1^T] \\ [B_d^T K_{c12} + D_y^T K_{c22} + S_2^T] \} \quad (III-20)$$

Doing the same thing for  $K_c(t_i)$  yields

$$\begin{bmatrix} K_{c11} & K_{c12} \\ K_{c12}^T & K_{c22} \end{bmatrix} = \begin{bmatrix} X_{11} & X_{12} \\ X_{12}^T & X_{22} \end{bmatrix} + \begin{bmatrix} \underline{x}^T & C^T \\ 0 & I \end{bmatrix} \begin{bmatrix} K_{c11} & K_{c12} \\ K_{c12}^T & K_{c22} \end{bmatrix} \begin{bmatrix} \underline{x} & 0 \\ C & I \end{bmatrix} \\ - ([B_d^T \quad D_y^T] \begin{bmatrix} K_{c11} & K_{c12} \\ K_{c12}^T & K_{c22} \end{bmatrix} \begin{bmatrix} \underline{x} & 0 \\ C & I \end{bmatrix} \\ + [S_1^T \quad S_2^T])^T [G_{c1}^* \quad G_{c2}^*] \quad (III-21)$$

and multiplying this out yields

$$K_{c11}(t_i) = X_{11} + \underline{x}^T K_{c11} \underline{x} + C^T K_{c12}^T \underline{x} + \underline{x}^T K_{c12} C \\ + C^T K_{c22} C - [B_d^T K_{c11} \underline{x} + D_y^T K_{c12}^T \underline{x} \\ + B_d^T K_{c12} C + D_y^T K_{c22} C + S_1^T] G_{c1}^* \quad (III-22a)$$

$$\begin{aligned} \underline{K}_{c22}(t_i) &= \underline{X}_{22} + \underline{K}_{c22} - [\underline{B}_d^T \underline{K}_{c12} + \underline{D}_y^T \underline{K}_{c22} \\ &\quad + \underline{S}_2^T] \underline{G}_{c2} \end{aligned} \quad \text{(III-22b)}$$

$$\begin{aligned} \underline{K}_{c12}(t_i) &= \underline{X}_{12} + \underline{K}_{c12} + \underline{C}^T \underline{K}_{c22} - [\underline{B}_d^T \underline{K}_{c11} \underline{E} \\ &\quad + \underline{D}_y^T \underline{K}_{c12} \underline{E} + \underline{B}_d^T \underline{K}_{c12} \underline{C} + \underline{D}_y^T \underline{K}_{c22} \underline{C} \\ &\quad + \underline{S}_1^T] \underline{G}_{c2} \end{aligned} \quad \text{(III-22c)}$$

(all K's on the right are at time  $t_{i+1}$ )

Now comes the question of appropriately choosing  $\underline{q}_0$  so as to yield the best possible transient performance from Equation (III-16). We seek the equilibrium value  $\underline{q}_0$  that results in the lowest total cost to complete the process. It has been shown that this value of  $\underline{q}_0$  is found by minimizing (Ref 18:136-137)

$$J_{\min} = \frac{1}{2} \{ \underline{f}_x^T(t_0) \quad \underline{f}_q^T(t_0) \} \begin{bmatrix} \underline{K}_{c11} & \underline{K}_{c12} \\ \underline{K}_{c12}^T & \underline{K}_{c22} \end{bmatrix} \begin{bmatrix} \underline{f}_x(t_0) \\ \underline{f}_q(t_0) \end{bmatrix} \quad \text{(III-23)}$$

with respect to  $\underline{f}_q(t_0)$ :

$$\underline{Q} = \frac{\partial J_{\min}}{\partial \underline{f}_q(t_0)} = \underline{K}_{c22} \underline{f}_q(t_0) + \underline{K}_{c12}^T \underline{f}_x(t_0) \quad \text{(III-24)}$$

Solving for  $\underline{f}_q(t_0)$  yields

$$\begin{aligned} \underline{f}_q(t_0) &= \underline{q}_{old} - \underline{q}_0 = -\underline{K}_{c22}^{-1} \underline{K}_{c12}^T [\underline{x}_{old} - \underline{r}_{12} \underline{y}_d] \\ &= -\underline{K}_{c22}^{-1} \underline{K}_{c12}^T \underline{r}_{12} [\underline{y}_d^{old} - \underline{y}_d] \end{aligned} \quad \text{(III-25)}$$

or

$$\underline{q}_0 = -\underline{K}_{c22}^{-1} \underline{K}_{c12}^T \underline{\pi}_{12} \underline{y}_d \quad (\text{III-26a})$$

$$\underline{q}_{old} = -\underline{K}_{c22}^{-1} \underline{K}_{c12}^T \underline{\pi}_{12} \underline{y}_d \text{ old} \quad (\text{III-26b})$$

Substituting Equations (III-26b), (III-10a), and (III-10b) into Equation (III-16) yields the final control law in position form

$$\underline{u}^*(t_i) = -\underline{G}_{c1}^* \underline{x}(t_i) - \underline{G}_{c2}^* \underline{q}(t_i) + \underline{E} \underline{y}_d(t_i) \quad (\text{III-27a})$$

$$\begin{aligned} \underline{q}(t_{i+1}) &= \underline{q}(t_i) + [\underline{y}_c(t_i) - \underline{y}_d(t_i)] \\ &= \underline{q}(t_i) + [\underline{C}\underline{x}(t_i) + \underline{D}_y \underline{u}(t_i) - \underline{y}_d(t_i)] \end{aligned} \quad (\text{III-27b})$$

where

$$\underline{E} = [\underline{G}_{c1}^* - \underline{G}_{c2}^* \underline{K}_{c22}^{-1} \underline{K}_{c12}^T] \underline{\pi}_{12} + \underline{\pi}_{22} \quad (\text{III-28a})$$

$$\underline{q}(t_0) = \underline{q}_{old} \quad (\text{III-28b})$$

The position form control law as given by Equation (III-27) is diagrammed in Fig. III-1. The structure of this controller is seen to be composed of (1) full state feedback through  $\underline{G}_{c1}^*$ , (2) command feedforward through  $\underline{E}$ , and (3) "pseudointegration" of the regulation error in the forward path.

By writing Equation (III-27a) for both  $t_i$  and  $t_{i-1}$ , explicitly subtracting, rearranging and incorporating Equation (III-3), the incremental form of this

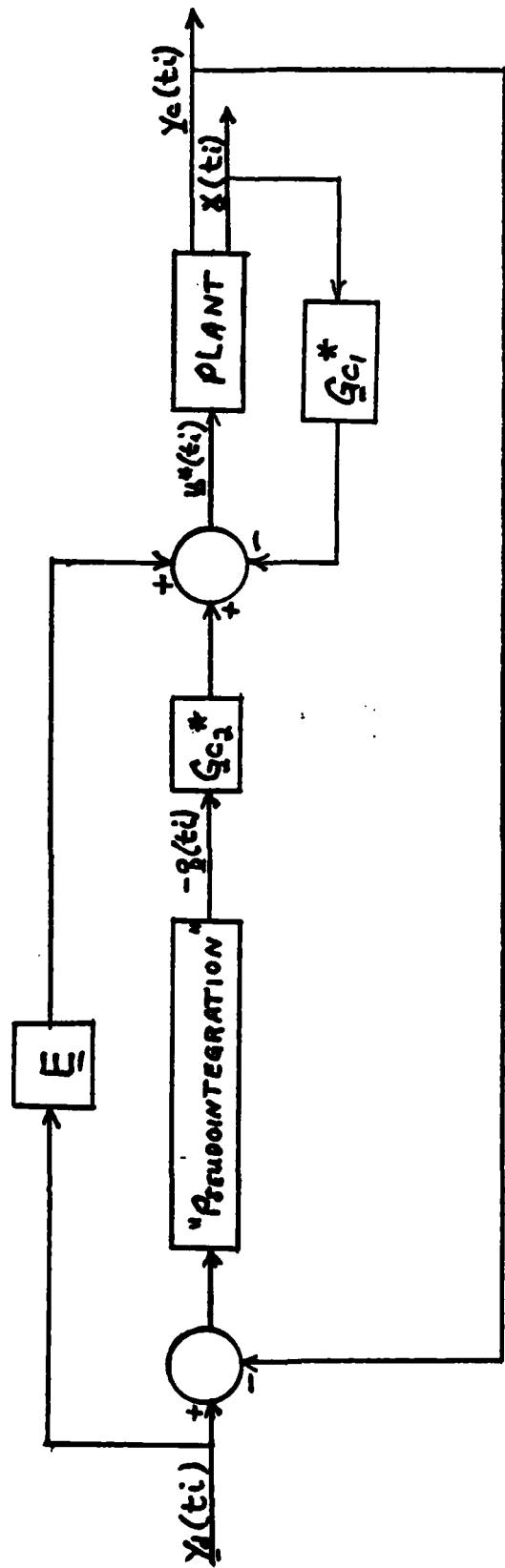


Fig. III-1. Position Form PI Control Law Based on the "Pseudointegration" of the Regulation Error

PI law is obtained as

$$\begin{aligned} \underline{u}^*(t_i) = & \underline{u}^*(t_{i-1}) - \underline{G}_{c1}^* [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\ & + \underline{G}_{c2}^* [\underline{y}_d(t_{i-1}) - \underline{y}_c(t_{i-1})] \\ & + E[\underline{y}_d(t_i) - \underline{y}_d(t_{i-1})] \end{aligned} \quad (\text{III-29})$$

There is no explicit "pseudointegral" state in this form, so we do not have to be concerned about proper initialization of augmented states as we do in position forms (Ref 18:139, 234-238). This is one reason why incremental forms are preferred (also see Ref 18:223-260). It has been shown that either form has the desired type-1 property if  $\det\{\underline{G}_{c2}^*\} \neq 0$ , and that  $\underline{y}_c(t_i)$  converges to  $\underline{y}_d$  in the limit as  $t \rightarrow \infty$ , despite the effect of unmodeled  $\underline{d}$  (Ref 18:139). If we compare Equation (III-29) with Equation (II-15) we can see the similarities between the two PI controller developments. The similarities are pointed out in Ref (18:148-150) and summarized in the following discussion.

The two PI controllers can be interrelated by the generic form of the PI controller which is

$$\underline{u}^*(t_i) = -\underline{G}\underline{x}(t_i) + \underline{K}_p[\underline{y}_d(t_i) - \underline{y}_c(t_i)] + \underline{K}_i \xi(t_i) \quad (\text{III-30a})$$

$$\xi(t_{i+1}) = \xi(t_i) + [\underline{y}_d(t_i) - \underline{y}_c(t_i)] \quad (\text{III-30b})$$

where the state feedback gain  $\underline{G}$  and regulation error proportional gain  $\underline{K}_p$  and integral gain  $\underline{K}_i$  are given



by

$$\underline{G} = (\underline{I} - \underline{E}\underline{D}_y)^{-1} (\underline{G}_{c1}^* - \underline{E}\underline{C}) \quad (\text{III-31a})$$

$$\underline{K}_p = (\underline{I} - \underline{E}\underline{D}_y)^{-1} \underline{E} \quad (\text{III-31b})$$

$$\underline{K}_i = (\underline{I} - \underline{E}\underline{D}_y)^{-1} \underline{G}_{c2}^* \quad (\text{III-31c})$$

for the PI controller based on the integral of the regulation error, and by

$$\underline{G} = (\underline{I} - \underline{K}_z \underline{D}_y)^{-1} (\underline{K}_x - \underline{K}_z \underline{C}) \quad (\text{III-32a})$$

$$\underline{K}_p = (\underline{I} - \underline{K}_z \underline{D}_y)^{-1} \underline{K}_z \quad (\text{III-32b})$$

$$\underline{K}_i = \underline{K}_p \quad (\text{III-32c})$$

for the PI controller based on control differences. Note that the proportional and integral gains are distinct in the PI controller based on the integral of the regulation error, whereas, they are the same in the PI controller based on control differences. This difference should allow the PI controller based on the integral of the regulation error to compensate better for applications in which the system is in fact nonlinear and linear techniques are being used to generate perturbation controls, i.e., for essentially all real applications of this synthesis technique. This should provide better compensation for an important phenomenon called windup (Ref 18).

### 3.2.2 Converting from Continuous Time Cost

Although the controller design determines a

discrete-time control law, the design itself proceeds from continuous-time specifications. The system to be controlled is generally a continuous-time process and so it is appropriately defined by a continuous-time model.

Since the system to be controlled is a continuous-time system, and since its behavior is important at all time and not merely at the controller sample times, the cost function appropriate to the controller design is

$$J_C = \frac{1}{2} \int_{t_0}^{t_{N+1}} \begin{bmatrix} \underline{x}(t) \\ \underline{u}(t) \end{bmatrix}^T \begin{bmatrix} \underline{X}_C & \underline{S}_C \\ \underline{S}_C^T & \underline{U}_C \end{bmatrix} \begin{bmatrix} \underline{x}(t) \\ \underline{u}(t) \end{bmatrix} dt \quad (\text{III-33})$$

(plus a terminal quadratic involving  $\underline{x}_f$  which is not used for an infinite time steady state controller problem, i.e. for  $t_{N+1} \rightarrow \infty$ ) and where

$$\underline{x} = \begin{bmatrix} \int \underline{x} \\ \int \underline{q} \end{bmatrix} \quad (\text{III-34a})$$

$$\underline{u} = \int \underline{u} \quad (\text{III-34b})$$

$$\underline{X}_C = \begin{bmatrix} \underline{X}_{C11} & \underline{X}_{C12} \\ \underline{X}_{C12}^T & \underline{X}_{C22} \end{bmatrix} \quad (\text{III-34c})$$

Furthermore, since the design objective is to drive the system so that its output tracks the desired output, it is appropriate that the quadratic weighting matrices specified should apply to the system outputs, Equation (III-2) but on a continuous-time basis, and inputs,  $\underline{u}$ . Thus, defining the weights on output deviations as  $\underline{Y}$ , on input magnitudes as

$\underline{U}_y$ , and on the "pseudointegral" state as  $\underline{U}_q$ , the components of the  $\underline{X}_c$  matrix are obtained as (Refs 9 and 21)

$$\underline{X}_{c11} = \underline{C}^T \underline{Y} \underline{C} \quad (\text{III-35a})$$

$$\underline{X}_{c22} = \underline{U}_q \quad (\text{III-35b})$$

$$\underline{X}_{c12} = \underline{0} \quad (\text{III-35c})$$

$\underline{U}_c$  becomes

$$\underline{U}_c = \underline{U}_y + \underline{D}_y^T \underline{Y} \underline{D}_y \quad (\text{III-36})$$

and  $\underline{S}_c$  becomes

$$\underline{S}_c = \begin{bmatrix} \underline{C}^T \underline{Y} \underline{D}_y \\ \underline{0} \end{bmatrix} \quad (\text{III-37})$$

where  $\underline{C}$  and  $\underline{D}_y$  are as defined in Equation (III-2) and  $\underline{Y}$ ,  $\underline{U}_y$  and  $\underline{U}_q$  are positive semidefinite, positive definite and positive definite, respectively.

In order to use the continuous-time cost function of Equation (III-33) for solution of the discrete-time optimal controller, it is necessary to obtain the corresponding discrete-time cost function. Begin by conceptually dividing the control interval  $t_0$  to  $t_{N+1}$  into (N+1) control intervals of duration equal to the intended controller sample period T. The cost can then be expressed as

$$J = \sum_{i=0}^N \left( \int_{t_i}^{t_i+T} \frac{1}{2} [\underline{x}^T(t) \underline{X}_C \underline{x}(t) + \underline{u}^T(t) \underline{U}_C \underline{u}(t) + 2 \underline{x}^T(t) \underline{Q}_C \underline{u}(t)] dt \right) \quad (\text{III-38})$$

where  $\underline{u}(t)$  is assumed constant over a sampling period of  $T$  seconds and  $\underline{x}(t)$  satisfies

$$\underline{x}(t) = \underline{\Phi}_f(t-t_i) \underline{x}(t_i) + \underline{B}_f(t-t_i) \underline{u}(t_i) \quad (\text{III-39})$$

where for any argument  $\tau$

$$\underline{\Phi}_f(\tau) = \begin{bmatrix} \underline{\Phi}(\tau) & \underline{0} \\ \underline{C} & \underline{I} \end{bmatrix} \quad (\text{III-40a})$$

with

$$\underline{\Phi}(\tau) = \exp\{\underline{A}\tau\} \quad (\text{III-40b})$$

where  $\underline{A}$  defines the homogeneous system dynamics in

$$\dot{\underline{x}} = \underline{A}\underline{x} + \underline{B}\underline{u} + \underline{G}\underline{w} \quad (\text{III-40c})$$

Also,

$$\underline{B}_f(\tau) = \begin{bmatrix} \underline{B}_d(\tau) \\ \underline{D}_y \end{bmatrix} \quad (\text{III-41a})$$

with

$$\underline{B}_d(\tau) = \int_0^{\tau} \underline{X}(\sigma) \underline{B} d\sigma \quad (\text{III-41b})$$

where  $\underline{B}$  is as given in Equation (III-40c). From Equation (III-12),  $\underline{X}_f = \underline{X}_f(t_{i+1}-t_i)$  and  $\underline{B}_f = \underline{B}_f(t_{i+1}-t_i)$  are given by

$$\underline{X}_f = \begin{bmatrix} \underline{X} & \underline{0} \\ \underline{C} & \underline{I} \end{bmatrix} \quad (\text{III-42a})$$

$$\underline{B}_f = \begin{bmatrix} \underline{B}_d \\ \underline{D}_y \end{bmatrix} \quad (\text{III-42b})$$

The discrete time cost function then becomes

$$J = \sum_{i=0}^N \frac{1}{2} [\underline{x}^T(t_i) \underline{X}_f \underline{x}(t_i) + \underline{u}^T(t_i) \underline{U}_f \underline{u}(t_i) + 2 \underline{x}^T(t_i) \underline{S}_f \underline{u}(t_i)] \quad (\text{III-43a})$$

where

$$\underline{X}_f = \int_{t_i}^{t_i+T} [\underline{X}_f^T(\tau) \underline{X}_c \underline{X}_f(\tau)] d\tau \quad (\text{III-43b})$$

$$\underline{U}_f = \int_{t_i}^{t_i+T} [\underline{B}_f^T(\tau) \underline{X}_c \underline{B}_f(\tau) + \underline{U}_c + \underline{B}_f^T(\tau) \underline{S}_c + \underline{S}_c^T \underline{B}_f(\tau)] d\tau \quad (\text{III-43c})$$

$$\underline{S}_f = \int_{t_i}^{t_i+T} [\underline{X}_f^T(\tau) \underline{X}_c \underline{B}_f(\tau) + \underline{X}_f^T(\tau) \underline{S}_c] d\tau \quad (\text{III-43d})$$

The integrals in Equations (III-43b,c,d) can be approximated in a two-step computation. First,  $\underline{X}_f$  and  $\underline{B}_f$  are treated as constants over the sample interval with value set to their respective averaged values at the beginning and end of the

interval:

$$\bar{\underline{x}}_f = [\underline{x}_f(0) + \underline{x}_f(t_{i+1}-t_i)] = \frac{1}{2}[\underline{I} + \underline{x}_f] \quad (\text{III-44a})$$

$$\bar{\underline{b}}_f = [\underline{b}_f(0) + \underline{b}_f(t_{i+1}-t_i)] = \frac{1}{2}[\underline{0} + \underline{b}_f] \quad (\text{III-44b})$$

(Where the overbar mean approximation). With these approximations, each of the integrands is constant over the integration time  $T$ , so the integrals can be obtained as

$$\bar{\underline{x}}_f = T[\bar{\underline{x}}_f^T \underline{x} \bar{\underline{x}}_f] \quad (\text{III-45a})$$

$$\bar{\underline{u}}_f = T[\bar{\underline{b}}_f^T \underline{x} \bar{\underline{b}}_f + \underline{u}_c + \bar{\underline{b}}_f^T \underline{s}_c + \underline{s}_c^T \bar{\underline{b}}_f] \quad (\text{III-45b})$$

$$\bar{\underline{s}}_f = T[\bar{\underline{x}}_f^T \underline{x} \bar{\underline{b}}_f + \bar{\underline{x}}_f^T \underline{s}_c] \quad (\text{III-45c})$$

where  $T = (t_{i+1}-t_i)$  is the sample period. This provides a better approximate evaluation than simple Euler integration provides. Now, expressing this last cost function in matrix format becomes

$$J = \sum_{i=0}^N \frac{1}{2} \begin{bmatrix} \underline{x}(t_i) \\ \underline{u}(t_i) \end{bmatrix}^T \begin{bmatrix} \bar{\underline{x}}_f & \bar{\underline{s}}_f \\ \bar{\underline{s}}_f^T & \bar{\underline{u}}_f \end{bmatrix} \begin{bmatrix} \underline{x}(t_i) \\ \underline{u}(t_i) \end{bmatrix} \quad (\text{III-46})$$

Note that the cross weighting matrix  $\bar{\underline{s}}_f$  has been introduced into the cost function by the discretization process and will generally be nonzero even if  $\underline{s}_c$  in Equation (III-33) were zero. This cost function is seen to be in the standard form used previously and all development can proceed as if the problem were a discrete problem and not a continuous one.

Now, in order to obtain an equivalent discrete-time cost function with no cross weighting (to allow use of standard Riccati equation solvers as in (Ref 12) that assume such a form), define a new system (Ref 15)

$$\underline{x}(t_{i+1}) = \underline{X}_f' \underline{x}(t_i) + \underline{B}_f \underline{u}'(t_i) \quad (\text{III-47a})$$

for which

$$\underline{X}_f' = \underline{X}_f - \underline{B}_f \underline{U}_f^{-1} \underline{S}_f^T \quad (\text{III-47b})$$

and

$$\underline{u}'(t_i) = \underline{u}(t_i) + \underline{U}_f^{-1} \underline{S}_f^T \underline{x}(t_i) \quad (\text{III-47c})$$

and for which the corresponding cost function to be minimized is

$$J' = \sum_{i=0}^N \frac{1}{2} [\underline{x}^T(t_i) \underline{X}_f' \underline{x}(t_i) + \underline{u}'^T(t_i) \underline{U}_f' \underline{u}'(t_i)] \quad (\text{III-48a})$$

with

$$\underline{X}_f' = \underline{X}_f - \underline{S}_f \underline{U}_f^{-1} \underline{S}_f^T \quad (\text{III-48b})$$

If the system of Equation (III-47a) is either controllable or stabilizable, letting  $N \rightarrow \infty$  leads to a steady state solution of the discrete Riccati equation represented as

(Ref 12)

$$\begin{aligned} \underline{K}_R' &= \underline{E}_f'^T \underline{K}_R' \underline{E}_f' + \underline{X}_f' \\ &\quad - \underline{E}_f' \underline{K}_R' \underline{E}_f'^T [\underline{U}_f + \underline{E}_f'^T \underline{K}_R' \underline{E}_f']^{-1} \underline{E}_f'^T \underline{K}_R' \underline{E}_f' \end{aligned} \quad (\text{III-49})$$

and the optimal feedback control is

$$\underline{u}^*(t_i) = -\underline{G}_C^* \underline{x}(t_i) \quad (\text{III-50})$$

where

$$\underline{G}_C^* = [\underline{U}_f + \underline{E}_f'^T \underline{K}_R' \underline{E}_f']^{-1} \underline{E}_f'^T \underline{K}_R' \underline{E}_f' \quad (\text{III-51})$$

The corresponding optimal feedback gain matrix for the original state system is

$$\underline{G}_C^* = \underline{G}_C^* + \underline{U}_f^{-1} \underline{E}_f'^T \quad (\text{III-52})$$

Remembering from Equation (III-19) that

$$\underline{G}_C^* = [\underline{G}_{C1}^* \quad \underline{G}_{C2}^*] \quad (\text{III-53})$$

the calculation beginning with a continuous-time cost description will produce the correct  $\underline{G}_C^*$ . The only question that might arise is whether the substitution of  $\underline{K}_R'$  for  $\underline{K}_C$  is a valid substitution. (See Appendix A for derivation showing that  $\underline{K}_R' = \underline{K}_C$ ). The  $\underline{G}_C^*$  thus determined determines the appropriate gains



to use in Equation (III-29) for the incremental PI control law.

### 3.3 CGT/PI Development

A natural extension of the controllers developed in the previous sections is provided by a Command Generator Tracker (CGT) in which we require a system to respond to command inputs, while rejecting disturbances, so that the states of the system maintain desired trajectories in real time. In an open loop conceptualization, the problem is to find the appropriate feedforward gains from the states of both the command generator and a disturbance linear model (and command generator inputs), to the system control inputs, that will yield command generator tracking. If the original system is unstable or just marginally stable, or if unmodeled disturbances and uncertainties affect the system, we are motivated to add the PI feedback as previously developed to the system.

The development presented in this section will start with the open loop format, developing the appropriate gains, and then closing the loop by adding the PI controller and utilizing the open loop gains to develop the complete CGT/PI controller. There are four formulations for this CGT/PI controller. Two are mathematically derived and two are ad-hoc. These four developments will be presented (all four CGT/PI controller formulations will be implemented in code (see Appendix C), and a comparison made between them (see Chapter V)).

### 3.3.1 Open Loop Command Generator Tracker

Consider a system described by the linear time invariant model

$$\underline{x}(t_{i+1}) = \underline{A}x(t_i) + \underline{B}_d u(t_i) + \underline{E}_x n_d(t_i) + \underline{w}_d(t_i) \quad (\text{III-54a})$$

$$y_c(t_i) = \underline{C}x(t_i) + \underline{D}_y u(t_i) + \underline{E}_y n_d(t_i) \quad (\text{III-54b})$$

In which  $n_d$  is a disturbance modeled by

$$n_d(t_{i+1}) = \underline{A}_n n_d(t_i) + \underline{G}_{dn} w_{dn}(t_i) \quad (\text{III-55})$$

and  $w_{dn}$  a zero-mean white Gaussian noise of covariance  $\underline{Q}_{dn}$  that is independent of  $w_d$ . The controlled system modeled by Equation (III-54) is to duplicate, as closely as possible, the output of a command generator model

$$\underline{x}_m(t_{i+1}) = \underline{A}_m \underline{x}_m(t_i) + \underline{B}_{dm} u_m \quad (\text{III-56a})$$

$$y_m(t_i) = \underline{C}_m \underline{x}_m(t_i) + \underline{D}_m u_m \quad (\text{III-56b})$$

Mathematically, the objective of the CGT is to force the error

$$\begin{aligned} \underline{e}(t_i) &= y_c(t_i) - y_m(t_i) \\ &= [\underline{C} \quad \underline{D}_y \quad \underline{E}_y] \begin{bmatrix} \underline{x}(t_i) \\ u(t_i) \\ n_d(t_i) \end{bmatrix} - [\underline{C}_m \quad \underline{D}_m] \begin{bmatrix} \underline{x}_m(t_i) \\ u_m \end{bmatrix} \end{aligned} \quad (\text{III-57})$$

to zero. When this command error is zero, the controlled system states and controls are tracking the ideal system trajectory (satisfying the original system dynamics less white noise, according to "Certainty Equivalence" ideas)

$$\underline{x}_I(t_{i+1}) = \underline{\Phi}\underline{x}_I(t_i) + \underline{B}_d\underline{u}_I(t_i) + \underline{E}_x\underline{n}_d(t_i) \quad (\text{III-58})$$

Another requirement is that the ideal system trajectory be a linear function of the model states, model controls, and disturbance states as shown by

$$\begin{bmatrix} \underline{x}_I(t_i) \\ \underline{u}_I(t_i) \end{bmatrix} = \begin{bmatrix} \underline{A}_{11} & \underline{A}_{12} & \underline{A}_{13} \\ \underline{A}_{21} & \underline{A}_{22} & \underline{A}_{23} \end{bmatrix} \begin{bmatrix} \underline{x}_m(t_i) \\ \underline{u}_m \\ \underline{n}_d(t_i) \end{bmatrix} \quad (\text{III-59})$$

where  $\underline{u}_m(t_i) = \underline{u}_m$  for all  $t_i$ .

The solution of the CGT problem entails setting up and solving the matrix equations that the constants  $\underline{A}_{11}$  through  $\underline{A}_{23}$  in Equation (III-59) must satisfy. Using Equations (III-54), (III-58), (II-18) and (III-59) it has been shown that (Ref 18:153-155)

$$\begin{bmatrix} \underline{A}_{11} & \underline{A}_{12} & \underline{A}_{13} \\ \underline{A}_{21} & \underline{A}_{22} & \underline{A}_{23} \end{bmatrix} = \begin{bmatrix} \underline{\Gamma}_{11} & \underline{\Gamma}_{12} \\ \underline{\Gamma}_{21} & \underline{\Gamma}_{22} \end{bmatrix} \begin{bmatrix} \{\underline{A}_{11}(\underline{\Phi}_m - \underline{I})\} & \{\underline{A}_{11}\underline{B}_{dm}\} & \{\underline{A}_{13}(\underline{\Phi}_n - \underline{I}) - \underline{E}_x\} \\ \underline{C}_m & \underline{D}_m & -\underline{E}_y \end{bmatrix} \quad (\text{III-60})$$

Thus, in partitioned form, the equations to solve are

$$\underline{A}_{11} = \underline{\pi}_{11}\underline{A}_{11}(\underline{E}_m - \underline{I}) + \underline{\pi}_{12}\underline{C}_m \quad (\text{III-61a})$$

$$\underline{A}_{12} = \underline{\pi}_{11}\underline{A}_{11}\underline{B}_{dm} + \underline{\pi}_{12}\underline{D}_m \quad (\text{III-61b})$$

$$\underline{A}_{13} = \underline{\pi}_{11}\underline{A}_{13}(\underline{E}_n - \underline{I}) - \underline{\pi}_{11}\underline{E}_x - \underline{\pi}_{12}\underline{E}_y \quad (\text{III-61c})$$

$$\underline{A}_{21} = \underline{\pi}_{21}\underline{A}_{11}(\underline{E}_m - \underline{I}) + \underline{\pi}_{22}\underline{C}_m \quad (\text{III-61d})$$

$$\underline{A}_{22} = \underline{\pi}_{21}\underline{A}_{11}\underline{B}_{dm} + \underline{\pi}_{22}\underline{D}_m \quad (\text{III-61e})$$

$$\underline{A}_{23} = \underline{\pi}_{21}\underline{A}_{13}(\underline{E}_n - \underline{I}) - \underline{\pi}_{21}\underline{E}_x - \underline{\pi}_{22}\underline{E}_y \quad (\text{III-61f})$$

If  $\underline{A}_{11}$  and  $\underline{A}_{13}$  can be determined from Equations (III-61a) and (III-61c), which are of the form

$$\underline{X} = \underline{A}\underline{X}\underline{B} + \underline{C} \quad (\text{III-62})$$

(for which an algorithm for solution is available in Ref (1)), then the other terms are readily solved from these. Once the values of the  $\underline{A}_{ij}$  are found, then the open loop command generator tracker control law is written from the lower partition of Equation (III-59) as

$$\underline{u}_I(t_i) = \underline{A}_{21}\underline{x}_m(t_i) + \underline{A}_{22}\underline{u}_m(t_i) + \underline{A}_{23}\underline{n}_d(t_i) \quad (\text{III-63})$$

$\underline{x}_I(t_i)$  can also be generated from Equation (III-59) as

$$\underline{x}_I(t_i) = \underline{A}_{11}\underline{x}_m(t_i) + \underline{A}_{12}\underline{u}_m(t_i) + \underline{A}_{13}\underline{n}_d(t_i) \quad (\text{III-64})$$

### 3.3.2 Closed Loop CGT/PI

It is useful to consider a PI closed loop law in conjunction with command generator tracking because (1) it forces the difference between actual system output and command generator model output to zero in steady state even in the face of some modeling errors, (2) it can accommodate unmodeled constant disturbances as well as reject the modeled ones, and (3) it will also turn out to include the model control's feedforward contribution to the actual system control signal. The four formulations for the closed-loop CGT/PI controller will now be presented. The first might be anticipated to be the most practical and give the best performance since it will assume the "pseudointegral" states are time varying, as they should be since the system states are time varying. The second assumes the "pseudointegral" states go from some initial equilibrium value to some new equilibrium value instantaneously with no time varying transient period. This would appear to give a faster transient response to the system. The third assumes that we have an open-loop CGT and a feedback PI controller and connect them in a feedback ad-hoc fashion. This method would seem to be logical but is not mathematically derivable (this method also adds a sixth gain to the system which will prevent it from being compatible with the program "PFEVAL" (Ref 21)). As a fourth formulation we can neglect this sixth gain, which is a direct feedthrough gain on the input  $y_m$ . This would

serve to slow down the response but would make the system compatible with the program "PFEVAL".

### 3.3.2.1 CGT/PI Formulation 1.

Assume that the open loop CGT law  $\underline{u}_I(t_i)$  and the associated ideal state trajectory  $\underline{x}_I(t_i)$  have been evaluated for all  $t_i$  as given by Equations (III-63) and (III-64). Now as done in Section 3.2.1, define perturbation variables as

$$\delta \underline{q}(t_i) = \underline{q}(t_i) - \underline{q}_I(t_i) \quad (\text{III-65a})$$

$$\delta \underline{x}(t_i) = \underline{x}(t_i) - \underline{x}_I(t_i) \quad (\text{III-65b})$$

$$\delta \underline{u}(t_i) = \underline{u}(t_i) - \underline{u}_I(t_i) \quad (\text{III-65c})$$

$$\delta \underline{y}_C(t_i) = \underline{y}_C(t_i) - \underline{y}_I(t_i) = \underline{y}_C(t_i) - \underline{y}_m(t_i) \quad (\text{III-65d})$$

and replacing  $\underline{y}_d$  with  $\underline{y}_m(t_i)$  in Equations (III-3), (III-4) and (III-5) we get

$$\begin{bmatrix} \delta \underline{x}(t_{i+1}) \\ \delta \underline{q}(t_{i+1}) \end{bmatrix} = \begin{bmatrix} \underline{A} & \underline{0} \\ \underline{C} & \underline{I} \end{bmatrix} \begin{bmatrix} \delta \underline{x}(t_i) \\ \delta \underline{q}(t_i) \end{bmatrix} + \begin{bmatrix} \underline{B}_d \\ \underline{D}_y \end{bmatrix} \delta \underline{u}(t_i) \quad (\text{III-66})$$

Now, using the cost function of Equation (III-13), the optimal control solution using perturbation equations is as in Equation (III-14) and, returning to the original coordinate system the optimal control becomes

$$\begin{aligned} \underline{u}^*(t_i) &= \underline{u}_I(t_i) + \underline{G}_{c1}^* \underline{x}_I(t_i) + \underline{G}_{c2}^* \underline{q}_I(t_i) \\ &\quad - \underline{G}_{c1}^* \underline{x}(t_i) - \underline{G}_{c2}^* \underline{q}(t_i) \end{aligned} \quad (\text{III-67})$$

As before, the issue is, what is the appropriate value of  $\underline{q}_I(t_i)$ . If we consider Equations (III-10a), (III-25) and (III-26a,b) we can let

$$\underline{q}_I(t_i) = -K_{c22}^{-1} K_{c12}^T \underline{x}_I(t_i) \quad (\text{III-68})$$

and, substituting this into Equation (III-67), we get the position form of the optimal controller

$$\begin{aligned} \underline{u}^*(t_i) = & \underline{u}_I(t_i) + [G_{c1}^* - G_{c2}^* K_{c22}^{-1} K_{c12}^T] \underline{x}_I(t_i) \\ & - G_{c1}^* \underline{x}(t_i) - G_{c2}^* \underline{q}(t_i) \end{aligned} \quad (\text{III-69})$$

with

$$\underline{q}(t_{i+1}) = \underline{q}(t_i) + [\underline{y}_c(t_i) - \underline{y}_m(t_i)] \quad (\text{III-70})$$

To get the preferred incremental form of the complete CGT/PI controller we need to write Equation (III-69) at time  $t_i$  and  $t_{i-1}$ , explicitly subtract the two, substitute for  $\underline{u}_I(t_i)$  and  $\underline{x}_I(t_i)$  Equations (III-63) and (III-64) respectively, rearrange terms and utilize Equation (III-70) to get

$$\begin{aligned} \underline{u}^*(t_i) = & \underline{u}^*(t_{i-1}) - G_{c1}^* [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\ & + G_{c2}^* [\underline{y}_m(t_{i-1}) - \underline{y}_c(t_{i-1})] \\ & + [A_{21} + LA_{11}] [\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\ & + [A_{22} + LA_{12}] [\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\ & + [A_{23} + LA_{13}] [\underline{n}_d(t_i) - \underline{n}_d(t_{i-1})] \end{aligned} \quad (\text{III-71})$$

where

$$\underline{L} = \underline{G}_{c1}^* - \underline{G}_{c2}^* \underline{K}_{c22}^{-1} \underline{K}_{c12}^T \quad (\text{III-72})$$

If we incorporate Equations (III-2) and (III-56b) into Equation (III-71) we get

$$\begin{aligned} \underline{u}^*(t_i) = & \underline{u}^*(t_{i-1}) - \underline{G}_{c1}^* [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\ & + \underline{G}_{c2}^* \left\{ [\underline{C}_m \ \underline{D}_m] \begin{bmatrix} \underline{x}_m(t_{i-1}) \\ \underline{u}_m(t_{i-1}) \end{bmatrix} - [\underline{C} \ \underline{D}_y] \begin{bmatrix} \underline{x}(t_{i-1}) \\ \underline{u}(t_{i-1}) \end{bmatrix} \right\} \\ & + [\underline{A}_{21} + \underline{L}\underline{A}_{11}] [\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\ & + [\underline{A}_{22} + \underline{L}\underline{A}_{12}] [\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\ & + [\underline{A}_{23} + \underline{L}\underline{A}_{13}] [\underline{n}_d(t_i) - \underline{n}_d(t_{i-1})] \quad (\text{III-73}) \end{aligned}$$

where  $\underline{L}$  is as in Equation (III-72).

We have always assumed that

$$\underline{u}_m(t_i) = \begin{cases} \underline{u}_m = \text{constant} & i = 0, 1, 2, \dots \\ \underline{u}_{m-} \neq \underline{u}_m & i = \dots, -2, -1 \end{cases}$$

i.e., that  $\underline{u}_m$  is constant from  $t_0$  forward. For practical implementation, any time that  $\underline{u}_m$  changes will cause  $i$  to be set to zero again. However, an inconsistency in the definition of the ideal trajectory, Equations (III-58) and (III-59), arises at the time of a step change in  $\underline{u}_m$ . It has been shown (Ref 18:161-162) that to avoid this inconsistency, whenever  $\underline{u}_m(t_i)$  changes, we go



back to time  $t_{i-1}$  and restart all variables under our control. This simply results in the command generator model, Equation (III-56a) becoming

$$\underline{x}_m(t_i) = \underline{\bar{x}}_m \underline{x}_m(t_{i-1}) + \underline{B}_{dm} \underline{u}_m(t_i) \quad (\text{III-74})$$

Incorporating this into Equation (III-73) will remove the inherent delay between system input and control output since the control is being applied one sample period earlier than before and yields the final CGT/PI control law as

$$\begin{aligned} \underline{u}^*(t_i) = & \underline{u}^*(t_{i-1}) - \underline{G}_{c1}^* [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\ & + \underline{G}_{c2}^* \left\{ \left[ \underline{C}_m \quad \underline{D}_m \right] \begin{bmatrix} \underline{x}_m(t_{i-1}) \\ \underline{u}_m(t_i) \end{bmatrix} - \left[ \underline{C} \quad \underline{D}_y \right] \begin{bmatrix} \underline{x}(t_{i-1}) \\ \underline{u}^*(t_{i-1}) \end{bmatrix} \right\} \\ & + [\underline{A}_{21} + \underline{L}\underline{A}_{11}] [\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\ & + [\underline{A}_{22} + \underline{L}\underline{A}_{12}] [\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\ & + [\underline{A}_{23} + \underline{L}\underline{A}_{13}] [\underline{D}_d(t_i) - \underline{D}_d(t_{i-1})] \quad (\text{III-75}) \end{aligned}$$

where  $\underline{L}$  is as given in Equation (III-72). (If we compare Equation (III-75) with Equation (II-18) we can see the similarities between the two CGT/PI control laws. These similarities are sufficient enough to allow the gains determined from this development of the CGT/PI control law based on the integral of the regulation error to fit directly into the CGT/PI/KF evaluation program "PFEVAL" without modifying "PFEVAL" in any way.)

### 3.3.2.2 CGT/PI Formulation 2.

Begin by considering the previous development up through Equation (III-67). As before, the issue is, what is the appropriate value of  $\underline{q}_I(t_i)$ . We could seek the best equilibrium  $\underline{q}_{I0}$  and if we combine Equations (III-56a) and (III-56b) for the equilibrium condition  $\underline{x}_m(t_{i+1}) = \underline{x}_m(t_i) = \underline{x}_{m0}$  we get

$$\underline{y}_{m0} = \{ \underline{C}_m (\underline{I} - \underline{z}_m)^{-1} \underline{B}_{dm} + \underline{D}_m \} \underline{u}_m \quad (\text{III-76})$$

If we assume this condition also applies for the transient period, we can combine Equation (III-68a) with Equation (III-26a), with  $\underline{y}_d = \underline{y}_{m0}$  to get

$$\underline{q}_{I0} = \underline{q}_I(t_i) = -\underline{K}_{c22}^{-1} \underline{K}_{c12}^T \underline{\pi}_{12} \{ \underline{C}_m (\underline{I} - \underline{z}_m)^{-1} \underline{B}_{dm} + \underline{D}_m \} \underline{u}_m \quad (\text{III-77})$$

Substituting this into Equation (III-67), we get the position form of the optimal controller as

$$\begin{aligned} \underline{u}^*(t_i) = & \underline{u}_I(t_i) + \underline{G}_{c1}^* \underline{x}_I(t_i) - \underline{G}_{c2}^* \underline{K}_{c22}^{-1} \underline{K}_{c12}^T \underline{\pi}_{12} \\ & \{ \underline{C}_m (\underline{I} - \underline{z}_m)^{-1} \underline{B}_{dm} + \underline{D}_m \} \underline{u}_m(t_i) - \underline{G}_{c1}^* \underline{x}(t_i) \\ & - \underline{G}_{c2}^* \underline{q}(t_i) \end{aligned} \quad (\text{III-78})$$

and Equation (III-70) still applies. To get the preferred incremental form of this CGT/PI controller we need to write Equation (III-78) at time  $t_i$  and  $t_{i-1}$ , explicitly subtract the two, substitute for  $\underline{u}_I(t_i)$  and

$\underline{x}_I(t_i)$  Equations (III-63) and (III-64), respectively, rearrange terms and utilize Equations (III-70) and (III-74) to get

$$\begin{aligned}
 \underline{u}^*(t_i) = & \underline{u}^*(t_{i-1}) - \underline{G}_{c1}^* [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\
 & + \underline{G}_{c2}^* \left\{ [\underline{C}_m \underline{D}_m] \begin{bmatrix} \underline{x}_m(t_{i-1}) \\ \underline{u}_m(t_i) \end{bmatrix} - [\underline{C} \underline{D}_y] \begin{bmatrix} \underline{x}(t_{i-1}) \\ \underline{u}^*(t_{i-1}) \end{bmatrix} \right\} \\
 & + [\underline{A}_{21} + \underline{G}_{c1}^* \underline{A}_{11}] [\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\
 & + [\underline{A}_{22} + \underline{G}_{c1}^* \underline{A}_{12} - \underline{N}] [\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\
 & + [\underline{A}_{23} + \underline{G}_{c1}^* \underline{A}_{13}] [\underline{n}_d(t_i) - \underline{n}_d(t_{i-1})]
 \end{aligned}
 \tag{III-79}$$

where

$$\underline{N} = \underline{G}_{c1}^* \underline{K}_{c22}^{-1} \underline{K}_{c12}^T \underline{\pi}_{12} \{ \underline{C}_m (\underline{I} - \underline{z}_m)^{-1} \underline{B}_{dm} + \underline{D}_m \} \tag{III-80}$$

### 3.3.2.3 CGT/PI Formulation 3.

Begin by assuming that we have the PI controller given by Equation (III-27) and the open-loop CGT given by Equation (III-63). If we put Equation (III-27) into terms of perturbation variables, replacing  $\underline{y}_d$  with  $\underline{y}_m$  we have

$$\underline{u}^*(t_i) = -\underline{G}_{c1}^* \int \underline{x}(t_i) - \underline{G}_{c2}^* \int \underline{q}(t_i) + \underline{E} \underline{y}_m(t_i) \tag{III-81}$$

and utilizing Equations (III-65a,b,c) we have

$$\begin{aligned}
\underline{u}^*(t_i) - \underline{u}_I(t_i) &= -\underline{G}_{c1}^* [\underline{x}(t_i) - \underline{x}_I(t_i)] \\
&\quad - \underline{G}_{c2}^* [\underline{q}(t_i) - \underline{q}_I(t_i)] \\
&\quad + \underline{E} \underline{y}_m(t_i)
\end{aligned} \tag{III-82}$$

Substituting in Equations (III-63) and (III-64), and rearranging terms we have the position form of this optimal controller as

$$\begin{aligned}
\underline{u}^*(t_i) &= [\underline{A}_{21} + \underline{G}_{c1}^* \underline{A}_{11}] \underline{x}_m(t_i) \\
&\quad + [\underline{A}_{22} + \underline{G}_{c1}^* \underline{A}_{12}] \underline{u}_m(t_i) \\
&\quad + [\underline{A}_{23} + \underline{G}_{c1}^* \underline{A}_{13}] \underline{n}_d(t_i) \\
&\quad - \underline{G}_{c1}^* \underline{x}(t_i) - \underline{G}_{c2}^* \underline{q}(t_i) + \underline{G}_{c2}^* \underline{q}_I(t_i) + \underline{E} \underline{y}_m(t_i)
\end{aligned} \tag{III-83}$$

To get the preferred incremental form of this CGT/PI controller we need to write Equation (III-83) at time  $t_i$  and  $t_{i-1}$ , explicitly subtract the two, utilize Equations (III-70) and (III-74), and let  $\int \underline{q}_I = 0$ , to get

$$\begin{aligned}
\underline{u}^*(t_i) &= \underline{u}^*(t_{i-1}) - \underline{G}_{c1}^* [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\
&\quad + \underline{G}_{c2}^* \left\{ [\underline{C}_m \ \underline{D}_m] \begin{bmatrix} \underline{x}_m(t_{i-1}) \\ \underline{u}_m(t_i) \end{bmatrix} - [\underline{C} \ \underline{D}_y] \begin{bmatrix} \underline{x}(t_{i-1}) \\ \underline{u}^*(t_{i-1}) \end{bmatrix} \right\} \\
&\quad + [\underline{A}_{21} + \underline{G}_{c1}^* \underline{A}_{11}] [\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\
&\quad + [\underline{A}_{22} + \underline{G}_{c1}^* \underline{A}_{12}] [\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\
&\quad + [\underline{A}_{23} + \underline{G}_{c1}^* \underline{A}_{13}] [\underline{n}_d(t_i) - \underline{n}_d(t_{i-1})] \\
&\quad + \underline{E} \left\{ [\underline{C}_m \ \underline{D}_m] \begin{bmatrix} \underline{x}_m(t_i) - \underline{x}_m(t_{i-1}) \\ \underline{u}_m(t_i) - \underline{u}_m(t_{i-1}) \end{bmatrix} \right\}
\end{aligned} \tag{III-84}$$

#### 3.3.2.4 CGT/PI Formulation 4.

Since the CGT/PI controller given by Equation (III-84) has six gains instead of the usual five of the other CGT/PI controllers, we could consider neglecting the sixth, that given by  $\underline{E}$ , which is a direct feedthrough speedup mechanism, and formulate a controller based on this simplification. (Note this has the same effect as neglecting the  $\underline{N}$  term in Equation (III-79)). (This formulation will allow this use of the program "PFEVAL" (Ref 21), which requires only five gains as inputs.) The resulting controller is given by

$$\begin{aligned}
 \underline{u}^*(t_i) = & \underline{u}^*(t_{i-1}) - \underline{G}_{c1}^* [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\
 & + \underline{G}_{c2}^* \left\{ [\underline{C}_m \ \underline{D}_m] \begin{bmatrix} \underline{x}_m(t_{i-1}) \\ \underline{u}_m(t_i) \end{bmatrix} - [\underline{C} \ \underline{D}_y] \begin{bmatrix} \underline{x}(t_{i-1}) \\ \underline{u}^*(t_{i-1}) \end{bmatrix} \right\} \\
 & + [\underline{A}_{21} + \underline{G}_{c1}^* \underline{A}_{11}] [\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\
 & + [\underline{A}_{22} + \underline{G}_{c1}^* \underline{A}_{12}] [\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\
 & + [\underline{A}_{23} + \underline{G}_{c1}^* \underline{A}_{13}] [\underline{n}_d(t_i) - \underline{n}_d(t_{i-1})]
 \end{aligned}
 \tag{III-85}$$

#### 3.4 Adding Implicit Model Following

In Chapter II, it was stated that implicit model following is achieved by including the model in a performance index that weights the error between system output derivatives and the desired model dynamics. A standard performance index is of the form of Equation (III-33)

$$J = \frac{1}{2} \int_{t_0}^{\infty} (\underline{x}^T \underline{X} \underline{x} + \underline{u}^T \underline{U} \underline{u}) dt \quad (\text{III-86})$$

(There may or may not be a cross weighting term  $\underline{S}$ )  
 where it is assumed that the system can be described as

$$\dot{\underline{x}} = \underline{A} \underline{x} + \underline{B} \underline{u} \quad (\text{III-87})$$

with output

$$\underline{y}_c = \underline{C} \underline{x} \quad (\text{III-88})$$

Now, instead of the index of Equation (III-86), define a performance index which weights the error between system output derivatives and the model dynamics, where the model is

$$\dot{\underline{x}}_m = \underline{A}_m \underline{x}_m \quad (\text{III-89})$$

and the corresponding performance index is

$$J_I = \frac{1}{2} \int_{t_0}^{\infty} [(\dot{\underline{y}}_c - \underline{A}_m \underline{y}_c)^T \underline{X}_I (\dot{\underline{y}}_c - \underline{A}_m \underline{y}_c) + \underline{u}^T \underline{U}_I \underline{u}] dt \quad (\text{III-90})$$

where the dimension of the output vector  $\underline{y}_c$  and the model state vector  $\underline{x}_m$  are equal. The weighting matrix  $\underline{X}_I$  weights errors between the output and model dynamics. Substituting Equations (III-87) and (III-88) into Equation (III-90) yields

$$J_I = \frac{1}{2} \int_{t_0}^{\infty} [(\underline{CA}\underline{x} + \underline{CB}\underline{u} - \underline{A}_m \underline{C}\underline{x})^T \underline{X}_I (\underline{CA}\underline{x} + \underline{CB}\underline{u} - \underline{A}_m \underline{C}\underline{x}) + \underline{u}^T \underline{U}_I \underline{u}] dt \quad (\text{III-91})$$

After collecting terms, Equation (III-91) leads to a performance index similar to Equation (III-86) but with a cross weighting term relating deviations in  $\underline{x}$  and  $\underline{u}$ :

$$J_I' = \frac{1}{2} \int_{t_0}^{\infty} [\underline{x}^T \hat{\underline{X}}_I \underline{x} + 2 \underline{x}^T \hat{\underline{S}}_I \underline{u} + \underline{u}^T \hat{\underline{U}}_I \underline{u}] dt \quad (\text{III-92})$$

where

$$\hat{\underline{X}}_I = (\underline{CA} - \underline{A}_m \underline{C})^T \underline{X}_I (\underline{CA} - \underline{A}_m \underline{C}) \quad (\text{III-93a})$$

$$\hat{\underline{S}}_I = (\underline{CA} - \underline{A}_m \underline{C})^T \underline{X}_I \underline{CB} \quad (\text{III-93b})$$

$$\hat{\underline{U}}_I = \underline{U}_I + \underline{B}^T \underline{C}^T \underline{X}_I \underline{CB} \quad (\text{III-93c})$$

and  $\underline{X}_I$  and  $\underline{U}_I$  are symmetric with

$$\underline{X}_I \approx \underline{Q} \quad (\text{III-94a})$$

$$\underline{U}_I > \underline{Q} \quad (\text{III-94b})$$

If we rewrite Equation (III-92) as

$$J_I' = \frac{1}{2} \int_{t_0}^{\infty} \begin{bmatrix} \underline{x} \\ \underline{u} \end{bmatrix}^T \begin{bmatrix} \hat{\underline{X}}_I & \hat{\underline{S}}_I \\ \hat{\underline{S}}_I^T & \hat{\underline{U}}_I \end{bmatrix} \begin{bmatrix} \underline{x} \\ \underline{u} \end{bmatrix} dt \quad (\text{III-95})$$

and comparing this with Equation (III-33), letting the combined implicit/explicit cost function be

$$J_{IE} = J_I' + J_E \quad (\text{III-96})$$

( $J_E$  = explicit cost function derived from the continuous cost function discussed previously), we have

$$J_{IE} = \frac{1}{2} \int_{t_0}^{t_{\text{final}}} \begin{bmatrix} \delta \underline{x} \\ \delta \underline{u} \end{bmatrix}^T \begin{bmatrix} \underline{x} + \hat{\underline{x}}_I & \underline{S} + \hat{\underline{S}}_I \\ (\underline{S} + \hat{\underline{S}}_I)^T & \underline{U} + \hat{\underline{U}}_I \end{bmatrix} \begin{bmatrix} \delta \underline{x} \\ \delta \underline{u} \end{bmatrix} dt \quad (\text{III-97})$$

Therefore, to add implicit model following, all we need do is add the appropriate implicit weights to the appropriate locations within the defining cost function. The overall cost weighting matrix thus becomes

$$J = \frac{1}{2} \int_{t_0}^{t_{\text{final}}} \begin{bmatrix} \delta \underline{x} \\ \delta \underline{q} \\ \delta \underline{u} \end{bmatrix}^T \begin{bmatrix} \underline{x} + \hat{\underline{x}}_I & \underline{Q} & \underline{S} + \hat{\underline{S}}_I \\ \underline{Q} & \underline{Uq} & \underline{Q} \\ (\underline{S} + \hat{\underline{S}}_I)^T & \underline{Q} & \underline{U} + \hat{\underline{U}}_I \end{bmatrix} \begin{bmatrix} \delta \underline{x} \\ \delta \underline{q} \\ \delta \underline{u} \end{bmatrix} dt \quad (\text{III-98})$$

### 3.5 Summary

Chapter III has presented a theoretical development of the PI and CGT/PI controller with the PI controller based on the integral of the regulation error. The equations presented in this chapter were implemented in code and evaluated. The following chapters and appendices will look at the programs developed from these equations and compare them.



## IV. CGT/PI/KF Design Computer Program

### 4.1 Introduction

The primary objective of this thesis effort is to create a computer program with which to design CGT/PI/KF controllers with the PI controller based on the integral of the regulation error. This chapter presents a general description of the program which has been developed --hereafter to be referred to as CGTPIQ--and incorporates a discussion of those portions of the program "CGTPIF" (Refs 9 and 21), upon which CGTPIQ is based, needed to add completeness of thought to the discussion. There were actually four programs developed to consider the four formulations of the CGT/PI presented in Chapter III. The discussion in this chapter pertains to the program developed which implements CGT/PI formulation 1 of Section 3.3.2.1. The other three programs are very similar as only a few lines of code needed to be changed to implement the other three CGT/PI formulations. (The required code changes are documented in Appendix C.)

While the specific test application for the program in the context of this thesis has been related to aircraft control design, CGTPIQ is written to be applicable to a wide variety of control design problems. It has the following attributes:

1. CGTPIQ executes interactively

2. The program utilizes efficient array allocation
  - a. Initial memory allocation easily set
  - b. Dynamic array allocation within total memory allocated
3. Various modes of entry are possible for the dynamics models
4. Design paths are automatically followed, with user prompts at necessary decision points
5. Requests for input include informative prompts
6. Copious program output is provided
  - a. Output most relevant to design decisions are provided directly to the terminal
  - b. Additional detailed output is provided to a separate output file
7. Information relevant to design iteration is preserved
8. Information needed for evaluation by computer program "PFEVAL" is preserved (Ref 21)
9. Error checking is performed, and messages given as appropriate

CGTPIQ employs computational routines available in a library of matrix computer routines described in Ref (13). Exclusive of the library routines, the program has a length of more than 2900 lines of source code. The programming language employed is ANSI Standard FORTRAN IV. Although the resulting source code is highly portable, local memory utilization limits for interactive execution may impose constraints. In use on a Control Data Corporation CYBER

machine, the necessary load size was achievable with no impact on the source code. Thus the existing source code is in a pure form for whatever system. However, the final program size is much greater than the normal 65000 octal word limitation of the CYBER interactive system. Thus, in order to achieve interactive operation and provide sufficient free memory for array allocation so that problems of large and variable dimensions can be treated, a CYBER Loader option referred to as "Segmentation" (Ref 7) must be used. The required segmentation code will be presented in Appendix B. (Even with segmentation, the interactive program uses nearly 67000 octal words.)

CGTPIQ was written specifically to run interactively. Requests for input, while intentionally brief, tell the user what is expected of him--what, how many, and in what units, as appropriate. Output of information, relevant to design decisions, to the terminal is compact and automatically provided. Also, the user can determine the amount and category of output to the terminal in some cases, and according to need.

An objective of this thesis effort was for CGTPIQ to be similar to the program "CGTPIF" by Floyd, as modified by Moseley, and every effort was made for this to be the case. For this reason the two program's are almost identical in operation. The differences are presented in the appendices. Appendix A will give a description of only those routines that had to be changed in going from "CGTPIF" to "CGTPIQ. Appendix B will give a complete User's Guide to enable the

user to use this program without having a copy of the thesis covering "CGTPIF".

#### 4.2 Program Operating Principles and Organization

CGTPIQ has three design paths: (1) design of a PI controller (using explicit and/or implicit quadratic weights); (2) design of either an open-loop CGT or closed-loop CGT/PI controller, and (3) design of a Kalman filter. Corresponding to the first two design options is a controller evaluation set of routines, and corresponding to the third design option is a set of routines for filter evaluation. The evaluation routines perform the computations discussed in Appendix D.

A general flowchart of CGTPIQ is given in Figure IV-1, showing the main execution paths and design entries. The controller sample period is entered, the design model is established, and then the desired design path can be followed. The elementary design path choice is between controller and filter designs. The CGT or CGT/PI, and the PI controller (for explicit and/or implicit quadratic weights) design paths are then options within the controller design. If the PI controller design is pursued prior to the CGT design path, the CGT design will automatically be of the CGT/PI controller. If the PI controller gains have not been determined during the current execution of the program, then the designer may elect to design either a CGT or a CGT/PI controller. However, the CGT controller design is not

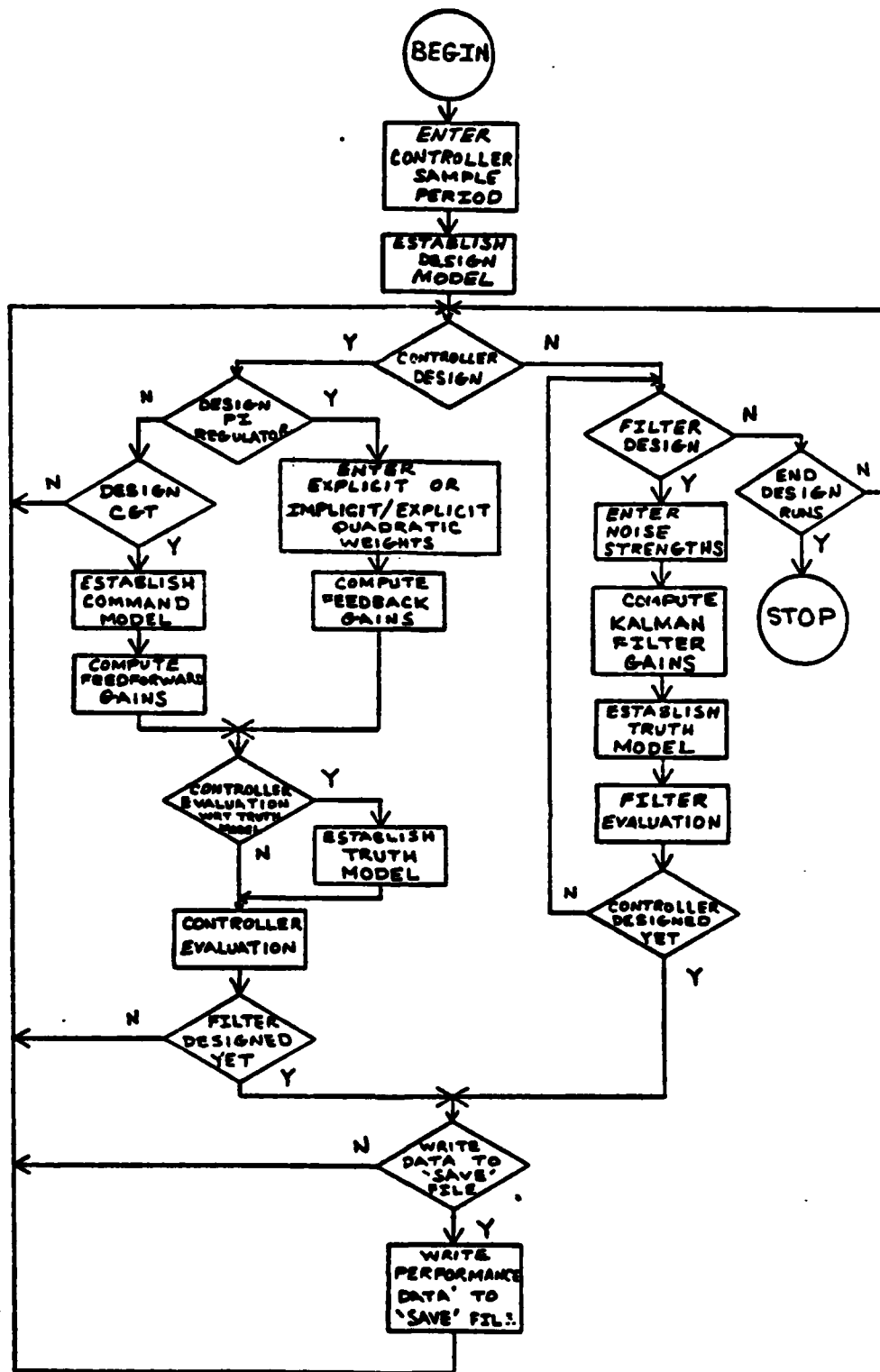


Fig. IV-1. CGTPIQ General Flowchart

pursued if the open-loop design model is unstable. The controller design path is followed automatically by the appropriate controller evaluation path. Similarly, the filter design path leads automatically to the filter evaluation. When the evaluation is complete the designer is given the opportunity to loop on the design path, choose a different design path, or terminate program execution.

#### 4.3 Dynamics Models

The system for which a CGT/PI/KF controller is to be developed is assumed to be well represented by a set of linear, time invariant, stochastic state differential equations with zero-mean white Gaussian noise driving the system and/or disturbance states, and corrupting the system measurements. Such equations generally are derived as linearized perturbation equations for a non-linear system about a nominal operating point.

Three system models are employed: a "truth model", a "design model", and a "command model". The truth model is a model of the system which is as complete and accurate as possible for the control task under consideration. The design model is generally a simpler model and is the basis for the controller and filter gains and provides the set of states to which these gains are applied. While the quality of the resulting design is often developed by initially evaluating their performance with respect to the design model, their fine tuning to "true" performance potential in the real world environment must ultimately be with respect

to the system truth model. The command model is a model representing the commands you wish the system to follow or the desirable characteristics you wish the system to emulate. Each of the three models is defined initially as a continuous-time system, then is discretized by the program for use within the program.

#### 4.3.1 Design Model

The design model is given by

$$\dot{\underline{x}}(t) = \underline{A}\underline{x}(t) + \underline{B}\underline{u}(t) + \underline{E}_x\underline{n}_d(t) + \underline{G}\underline{w}(t) \quad (\text{IV-1a})$$

$$\dot{\underline{n}}_d(t) = \underline{A}_n\underline{n}_d(t) + \underline{G}_n\underline{w}_d(t) \quad (\text{IV-1b})$$

$$\underline{y}_c(t) = \underline{C}\underline{x}(t) + \underline{D}_y\underline{u}(t) + \underline{E}_y\underline{n}_d(t) \quad (\text{IV-1c})$$

$$\underline{z}(t_i) = \underline{H}\underline{x}(t_i) + \underline{H}_n\underline{n}_d(t_i) + \underline{v}(t_i) \quad (\text{IV-1d})$$

and  $\underline{w}$ ,  $\underline{w}_d$ , and  $\underline{v}$  are independent zero-mean noises with statistics

$$E\{\underline{w}(t)\underline{w}^T(t+\tau)\} = \underline{Q}\delta(\tau) \quad (\text{IV-2a})$$

$$E\{\underline{w}_d(t)\underline{w}_d^T(t+\tau)\} = \underline{Q}_n\delta(\tau) \quad (\text{IV-2b})$$

$$E\{\underline{v}(t_i)\underline{v}^T(t_j)\} = \underline{R}\delta_{ij} \quad (\text{IV-2c})$$

In these equations,  $\underline{x}$ ,  $\underline{u}$ ,  $\underline{n}_d$ ,  $\underline{y}_c$ , and  $\underline{z}$  are the system state, input, disturbance state, output, and measurement vectors, respectively. The dimensions of the model are

$n$  = number of system states

$r$  = number of system inputs

$p$  = number of system outputs

$m$  = number of system measurements

$d$  = number of disturbance states

$w$  = number of independent system noises

$w_D$  = number of independent disturbance noises (IV-3)

and the dimensions of the matrices of the model are

$\underline{A}$  : n-by-n

$\underline{B}$  : n-by-r

$\underline{E}_x$  : n-by-d

$\underline{G}$  : n-by- $w$

$\underline{Q}$  :  $w$ -by- $w$

$\underline{C}$  : p-by-n

$\underline{D}_y$  : p-by-r

$\underline{E}_y$  : p-by-d

$\underline{H}$  : m-by-n

$\underline{H}_n$  : m-by-d

$\underline{R}$  : m-by-m

$\underline{A}_n$  : d-by-d

$\underline{G}_n$  : d-by- $w_D$

$\underline{Q}_n$  :  $w_D$ -by- $w_D$  (IV-4)

A constraint to be imposed is that the number of design system inputs and outputs be equal:  $r=p$ . Also, the number of system states may not be less than the number of disturbance states, due to the computational setup used for the CGT solution. The dimensions  $n$ ,  $r$ , and  $p$  must be non-zero; any of the other dimensions may be zero. If  $m$  is zero or if  $w$  and  $w_D$  are both zero, the Kalman filter design path cannot be pursued.

The design model is discretized at a specific fixed controller/filter sampling period  $T$  as follows. The disturbance state description is augmented to the system state model and discretized to form



$$\underline{x}_a(t_{i+1}) = \underline{\Phi}_a \underline{x}_a(t_i) + \underline{B}_{ad} \underline{u}(t_i) + \underline{w}_{ad}(t_i) \quad (\text{IV-5})$$

where "a" means augmented, and assuming the  $\underline{u}$  is constant over a sample period,

$$\underline{\Phi}_a = e^{\underline{A}_a T} \quad (\text{IV-6a})$$

$$\underline{B}_{ad} = \int_0^T \underline{\Phi}_a(\tau) \underline{B}_a d\tau \quad (\text{IV-6b})$$

where  $\underline{w}_{ad}$  is zero-mean white Gaussian discrete-time noise of discrete-time noise covariance

$$\underline{Q}_{ad} = \int_0^T \underline{\Phi}_a(\tau) \underline{G}_a \underline{Q}_a \underline{G}_a^T \underline{\Phi}_a^T(\tau) d\tau \quad (\text{IV-6c})$$

The matrices of Equations (IV-6a,b,c) may then be partitioned to the original component dimensions. Invoking the "Certainty Equivalence" property previously presented, the discrete-time models to be used for the deterministic controller design are the system state transition (propagation) equation, disturbance state equation, and output equation defined by

$$\underline{x}(t_{i+1}) = \underline{\Phi} \underline{x}(t_i) + \underline{B}_d \underline{u}(t_i) + \underline{E}_{xd} \underline{n}_d(t_i) \quad (\text{IV-7a})$$

$$\underline{n}_d(t_{i+1}) = \underline{\Phi}_n \underline{n}_d(t_i) \quad (\text{IV-7b})$$

$$\underline{y}_c(t_i) = \underline{C} \underline{x}(t_i) + \underline{D}_y \underline{u}(t_i) + \underline{E}_y \underline{n}_d(t_i) \quad (\text{IV-7c})$$

with  $\underline{C}$ ,  $\underline{D}_y$ , and  $\underline{E}_y$  as in Equation (IV-1c).

Henceforth, all equations relating to the controller design

are considered deterministic.

#### 4.3.2 Truth Model

The truth model is specified by

$$\dot{\underline{x}}_t(t) = \underline{A}_t \underline{x}_t(t) + \underline{B}_t \underline{u}_t(t) + \underline{G}_t \underline{w}_t(t) \quad (\text{IV-8a})$$

$$\underline{z}_t(t) = \underline{H}_t \underline{x}_t(t_i) + \underline{v}_t(t_i) \quad (\text{IV-8b})$$

$$\underline{x}'(t) = \underline{T}_{DT} \underline{x}_t(t) \quad (\text{IV-8c})$$

$$\underline{n}_d'(t) = \underline{T}_{NT} \underline{x}_t(t) \quad (\text{IV-8d})$$

and  $\underline{w}_t$  and  $\underline{v}_t$  are assumed to be independent zero-mean noises with

$$E\{\underline{w}_t(t) \underline{w}_t^T(t+\tau)\} = \underline{Q}_t \delta(\tau) \quad (\text{IV-9a})$$

$$E\{\underline{v}_t(t_i) \underline{v}_t^T(t_j)\} = \underline{R}_t \delta_{ij} \quad (\text{IV-9b})$$

where Equations (IV-8c) and (IV-8d) relate the system and disturbance states of the design model to the system states of the truth model. Note that  $\underline{Q}_t$  and  $\underline{R}_t$  are both assumed to be diagonal matrices. In these equations,  $\underline{x}_t$ ,  $\underline{u}_t$ , and  $\underline{z}_t$  are the truth model system state, input, and measurement vectors, respectively. The vectors  $\underline{x}'$  and  $\underline{n}_d'$  are as defined for the design model.

The dimensions of the truth model are

$$\begin{aligned} n_T &= \text{"number of system states"} \\ r_T &= \text{"number of system inputs"} \\ m_T &= \text{"number of system measurements"} \\ w_T &= \text{"number of independent noises driving system} \\ &\quad \text{dynamics"} \end{aligned} \quad (\text{IV-10})$$

and the dimensions of the matrices of the model are

$$\underline{A}_t: n_T \text{-by-} n_T$$

$$\underline{B}_t: n_T \text{-by-} r_T$$

$$\begin{aligned}
\mathbb{G}_t &: n_T\text{-by-}w_T \\
\mathbb{Q}_t &: w_T\text{-by-}w_T \\
\mathbb{H}_t &: m_T\text{-by-}n_T \\
\mathbb{R}_t &: m_T\text{-by-}m_T \\
\mathbb{T}_{DT} &: n\text{-by-}n_T \\
\mathbb{T}_{NT} &: d\text{-by-}n_T
\end{aligned}
\tag{IV-11}$$

Dimensional compatibility for computations requires that the numbers of inputs and of measurements for the truth and design model be the same:  $r_T=r$  and  $m_T=m$ . If the number of driving noises ( $w_T$ ) is zero, evaluation of a Kalman filter design is not pursued (since a covariance analysis with no truth model driving noise would not be very informative).

The truth model is discretized for a specific controller/filter sampling period  $T$ , yielding

$$\mathbb{x}_t(t_{i+1}) = \mathbb{\Phi}_t \mathbb{x}_t(t_i) + \mathbb{B}_{td} \mathbb{u}_t(t_i) + \mathbb{w}_{td}(t_i)
\tag{IV-12}$$

where, for  $\mathbb{u}$  constant over a sample period,

$$\mathbb{\Phi}_t = e^{\mathbb{A}_t T}
\tag{IV-13a}$$

$$\mathbb{B}_{td} = \int_0^T \mathbb{\Phi}_t(\tau) \mathbb{B}_t d\tau
\tag{IV-13b}$$

and  $\mathbb{w}_{td}$  is zero-mean white Gaussian discrete-time noise with covariance

$$\mathbb{Q}_{td} = \int_0^T \mathbb{\Phi}_t(\tau) \mathbb{G}_t \mathbb{Q}_t \mathbb{G}_t^T \mathbb{\Phi}_t^T(\tau) d\tau
\tag{IV-13c}$$

### 4.3.3 Command Model

The command model is given by

$$\dot{\underline{x}}_m(t) = \underline{A}_m \underline{x}_m(t) + \underline{B}_m \underline{u}_m(t) \quad (\text{IV-14a})$$

$$\underline{y}_m(t) = \underline{C}_m \underline{x}_m(t) + \underline{D}_m \underline{u}_m(t) \quad (\text{IV-14b})$$

In these equations,  $\underline{x}_m$ ,  $\underline{u}_m$ , and  $\underline{y}_m$  are the command model state, input, and output vectors, respectively.

The dimensions of the command model are

$n_M$  = "number of model states"

$r_M$  = "number of model inputs"

$p_M$  = "number of model outputs" (IV-15)

and the dimensions of the matrices are

$\underline{A}_m$ :  $n_M$ -by- $n_M$

$\underline{B}_m$ :  $n_M$ -by- $r_M$

$\underline{C}_m$ :  $p_M$ -by- $n_M$

$\underline{D}_m$ :  $p_M$ -by- $r_M$  (IV-16)

Since it is desired to cause the system outputs to follow those of the command model, it is necessary that the number of outputs of the command and design models be equal:  $p_M = p$ . Also, the number of system states of the command model ( $n_M$ ) cannot be greater than the number of system states of the design model ( $n$ ). This constraint is due to the setup for computation of the CGT solution.

The discretized command model becomes

$$\underline{x}_m(t_{i+1}) = \underline{A}_{md} \underline{x}_m(t_i) + \underline{B}_{md} \underline{u}_m(t_i) \quad (\text{IV-17})$$

$$\underline{y}_m(t_i) = \underline{C}_m \underline{x}_m(t_i) + \underline{D}_m \underline{u}_m(t_i) \quad (\text{IV-18})$$

where, for  $\underline{u}_m$  constant over a sample period

$$\underline{\underline{x}}_m = e^{\underline{A}_m T} \quad (\text{IV-19a})$$

$$\underline{B}_{md} = \int_0^T \underline{\underline{x}}_m(\tau) \underline{B}_m d\tau \quad (\text{IV-19b})$$

and  $\underline{C}_m$  and  $\underline{D}_m$  are as before in Equation (IV-14b).

(Note: the command model for explicit and implicit model following need not be the same, though they may be.)

#### 4.3.4 Overall Model Dimensions

Problems of the following dimension can be accommodated by CGTPIQ

$$n \leq 15$$

$$n+d \leq 15$$

$$r \leq 5$$

$$p \leq 5$$

$$m \leq 15$$

$$w \leq 15$$

$$w+w_D \leq 15$$

$$n_M \leq 10$$

$$r_M \leq 5$$

$$p_M \leq 5$$

$$n_t \leq 20$$

$$r_t \leq 5$$

$$m_t \leq 15$$

$$w_t \leq 20$$

(IV-20)

NOTE, other combinations of dimensions, some greater

than and some less than these specific dimensions, will also be accommodated due to the method by which arrays are allocated and stored. If the user has a problem that does not fit these size restraints, he should try the problem to see if it will work. Messages will be printed if he has exceeded total allocation, and in that case, the basic program code will have to be altered to proceed.

#### 4.4 Entry of Dynamics Models

Any of the three dynamics models described above may be established in any of three ways: (1) the dimensions and matrix elements may be entered directly from the terminal; (2) the dimensions and matrix elements may be entered from a "DATA" file; or (3) the dimensions and matrix elements may be established by user provided subroutines. When entered from the terminal directly or set by subroutines, only non-zero elements of the various matrices need be given. In many cases, this substantially simplifies establishing the matrices and reduces the probability of erroneous entries. Subsequent design runs for the same problem can then simply read the models from the "DATA" file previously created.

Before attempting to use the program the following should be noted:

1. The design model may be entered only once during a single program execution. Thus, in order to modify the design model, it is necessary to re-execute the program.
2. The truth and command models may be redefined as often as desired during a single program execution.

3. The SAVE and DATA files should be used to preserve the design, truth, and command models between distinct program executions. SAVE is a write only file and DATA is a read only file so information must be transferred from the SAVE to the DATA file between program executions (see Appendix B).

4. Models may be read from the DATA file repeatedly during program execution.

5. Changes in model dimensions require that all relevant defining matrices be reentered anew. Changes in dimension for a single model may require changes in dimensions for another due to the interrelationship of the different models. Also the matrices  $T_{DT}$  and  $T_{NT}$  may need to be changed.

#### 4.5 Using the CGTPIQ Design Program

A few simple considerations of the operation of the design program particularly impact its ease of application to specific design problems. These and other more specific considerations are discussed fully in the "User's Guide" of Appendix B, and the reader is encouraged to refer to this manual before attempting to use the program. The following should be noted in addition to that discussed in Section 4.4 above:

1. Open-loop CGT designs can only be pursued in a given execution of the program if a PI controller design has not previously been accomplished and PI gains have not been read from the DATA file.

2. Any of the three design paths (PI controller, CGT controller, or Kalman filter) may be executed in any order and as often as desired during a single program execution. Results from each design path are preserved independently throughout execution.

3. In addition to the output available at the user's terminal, the same and much additional information is output to the file named 'LIST'. Following execution, this LIST file may be routed to a line printer for listing.

4. Plots of system time-response at the user terminal provide a very useful evaluation tool.

5. Regardless of the plot duration specified, the plot will include 50 time samples. These samples are uniformly distributed in time over the entire duration specified or automatically adjusted by the program.

6. In order to bypass the time-response evaluation (no plots to the terminal or to the LIST file) one need only specify that no plots are wished. For the CGT evaluation, specifying a zero index for the command input also bypasses the time-response evaluation.

7. The user must have a basic idea of how to design CGT/PI/KF controllers using this program before beginning execution so that questions asked of the user by the program can be answered correctly. This knowledge can be gained by reading the "User's Guide" of Appendix B.



#### 4.6 Interpreting Plots to the Terminal

The plots of system response produced by CGTPIQ are of the "line printer" type. As printed at the terminal, the time axis runs vertically down the page with the initial time at the top-left margin and time points printed for each sample down the left margin. The dependent variables are plotted in the horizontal sense from left to right for increasing magnitude. Each variable plotted is marked by a distinct number (1 to 5) at each sample time. In the event that two variables occupy the same location in the plot field at the sample time, only the plot symbol of largest value will be marked at the point in question. Such coincidences of position can be inferred from the behavior of the variable with missing symbol at proximate time samples. Note that a special case of this is when two or more variables to be plotted actually represent the same variable.

The horizontal width of the plot field is 50 print positions. The scale of each plot is printed along the bottom margin and includes the values of the grid at each multiple of 10 print positions. In the usual case, each variable is plotted on its own unique scale and thus a scale range for each is given corresponding to the plot symbol used, but in some cases only a single scale is used for all variables plotted (i.e., anytime that the model output is requested to be plotted). Each plot will include an identifying title given it by the user.

#### 4.7 Summary

This chapter has discussed the CGT/PI/KF design computer program by giving the models and some of the characteristics of the program. Chapter V will now demonstrate the use of the program to design CGT/PI/KF controllers. A complete sample run for a simple design problem is presented in the User's Guide, Appendix B. The main context of Chapter V will be a comparison of the four programs developed using the four formulations of the CGT/PI control law.

## V. Analysis and Comparison of Design Results

### 5.1 Introduction

This chapter presents the results of the design and comparison efforts of this study. The design model upon which the analysis and comparisons were made is presented first. A baseline is then established by using the design model with the program "CGTPIF" (Refs 9 and 21), which designs a CGT/PI controller with the PI controller based on augmenting the original state equations with difference equations for control variables, treating control rates as driving functions, instead of augmenting the original state equations with the integrals of regulation error as done in "CGTPIQ". Only explicit model following is pursued in detail in this study since another thesis effort using "CGTPIF" with implicit model following is currently underway (Ref 20) and the results of that study are not available yet for comparison; however, it is anticipated that the formulation in this thesis may be very useful in conjunction with implicit model following, particularly since the proportional channel,  $K_p$ , and the integral channel,  $K_i$ , of the PI controller are not forced to be equal. The same design model is used in all of these thesis efforts to provide continuity and comparison. (Note: it is recommended that this thesis, (Ref 20), should be required reading before using any of these software packages. There

were software errors in the original "CGTPIF" program (Refs 9 and 21) that were not discovered until "CGTPIQ" was programmed. These errors have now been corrected in the original "CGTPIF". Ref (20) documents these errors and gives a good insight into the effects of these errors on program execution. Also, the results of using implicit model following is thoroughly discussed in Ref (20)). This design model is then applied to the four programs developed in this study to determine the characteristics of each. A comparison is made between the results obtained from each of the four programs and a comparison with the baseline analysis. (The four programs are the programs which implement the four formulations for the closed-loop CGT/PI discussed in Chapter III, Section 3.3.2. All four of these programs employ the same PI controller.) The "best" of the four programs is then applied to a simple design problem in which constant disturbances, an alternate truth model which represents degraded performance due to misrepresentation of system dynamics in the design model, and initial conditions are applied to determine if this "best" design program can handle these situations. All designs are full-state feedback designs (no Kalman filter in the loop). The tables and time-response plots referred to in this chapter have been placed together at the end of the chapter to make the text easier to read.

## 5.2 Models

### A CGT/PI controller for the Advanced Fighter

Technology Integration (AFTI) F-16 was chosen as the example controller to be designed using each of the programs. The AFTI F-16 is an aircraft which has been modified for advanced flight control research. Through the use of two independently controlled longitudinal flight control surfaces (a horizontal tail and a trailing edge wing flap), it is possible to achieve direct control of the aircraft's pitch attitude without changing its flight path angle and, hence, its flight trajectory. This capability is expected to be very useful in situations such as air-to-air gunnery, in which the attacker must match the target's trajectory while simultaneously achieving the required gun lead angle in the pitch plane. Such a design was of interest for this study, since it inherently requires the use of multiple-input multiple-output (MIMO) design methodology to achieve decoupled control of the two outputs and maintain closed-loop stability with a plant (the F-16 aircraft) which is unstable.

The efforts of this study and comparison used a five-state design model for the AFTI F-16 (Refs 8 and 9). The model represents the linearized flight characteristics of the aircraft operating at 0.8 mach at 10,000 feet. This particular flight condition is representative of an operating point within the usual air-to-air combat flight regime. Since the AFTI F-16 is unstable in pitch in this regime, open-loop CGT designs are infeasible. Therefore, only CGT/PI designs were pursued. The design model is a time-invariant, five state model of the form

$$\dot{\underline{x}}(t) = \underline{A}\underline{x}(t) + \underline{B}u(t) \quad (V-1)$$

where the state vector  $\underline{x}$  consists of

$x(1)$  = pitch angle (degrees)

$x(2)$  = angle of attack (degrees)

$x(3)$  = pitch rate (degrees per second)

$x(4)$  = horizontal tail deflection (degrees)

$x(5)$  = trailing edge flap deflection (degrees)

$x(1) - x(2)$  = flight path angle (degrees) (V-2)

and

$$\underline{A} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ -1.08E-3 & -1.7 & 0.994 & -0.179 & -0.295 \\ 0 & 5.93 & -0.668 & -25.3 & -5.88 \\ 0 & 0 & 0 & -20.0 & 0 \\ 0 & 0 & 0 & 0 & -20.0 \end{bmatrix} \quad (V-3)$$

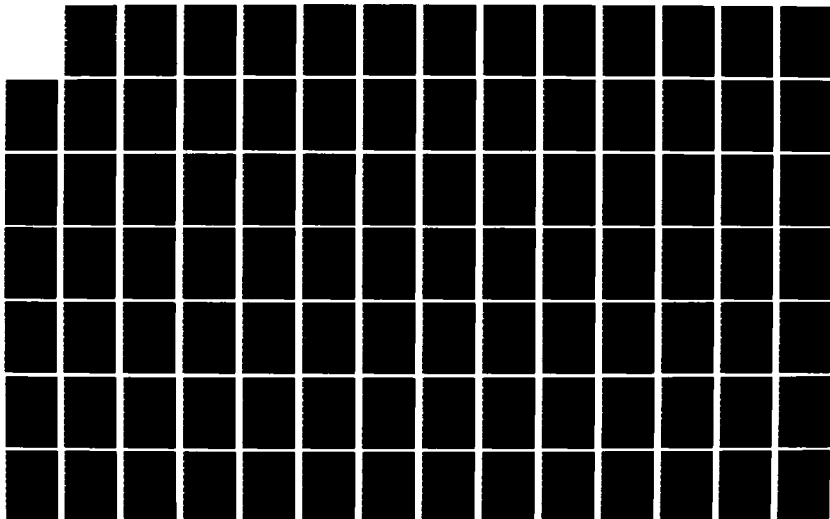
$$\underline{B} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 20.0 & 0 \\ 0 & 20.0 \end{bmatrix} \quad (V-4)$$

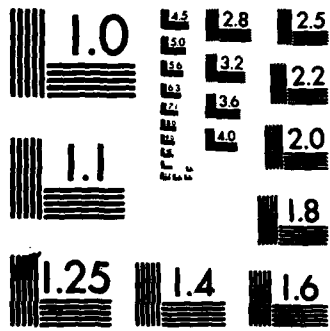
(Note: In this design model, actuators are represented as having characteristics of a first-order lag response to commands.) The outputs are expressed as

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COMMAND GENERATOR TRACKER SYNTHESIS METHODS USING AN 2/4  
LQG (LINEAR SYSTEM M. (U) AIR FORCE INST OF TECH  
WRIGHT-PATTERSON AFB OH SCHOOL OF ENGI. J P MCMILLIAN  
DEC 83 AFIT/GE/EE/83D-46 F/G 9/2 NL

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MICROCOPY RESOLUTION TEST CHART  
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$$\underline{y}_c(t) = \underline{C}\underline{x}(t) \quad (V-5)$$

where

$$\underline{C} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 \end{bmatrix} \quad (V-6)$$

indicating that the outputs of interest are the pitch angle ( $y_1=x_1$ ) and the flight path angle ( $y_2=x_1-x_2$ ). The limits to be considered in the design included a maximum deflection of 25 degrees in either direction at a maximum rate of 60 degrees per second for the horizontal tail, and +20 degrees to -23 degrees at a maximum rate of 52 degrees per second for the flap (Ref 9).

A two state command model was used in the design with

$$\underline{A}_m = \begin{bmatrix} -5 & 0 \\ 0 & -5 \end{bmatrix} \quad (V-7)$$

$$\underline{B}_m = \begin{bmatrix} 5 & 0 \\ 0 & 5 \end{bmatrix} \quad (V-8)$$

$$\underline{C}_m = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (V-9)$$

and  $\underline{D}_m = \underline{0}$ . The command model was chosen to represent the ideal output characteristics of decoupled first-order responses for the pitch and flight path angles.

## 5.3 Design Analysis

### 5.3.1 Introduction

The design analysis consists of sets of time response plots, tables of PI and CGT/PI gains, and PI pole locations for several different sets of quadratic weights applied to each of the five programs (CGTPIF and the four versions of CGTPIQ).

For CGTPIF, initial quadratic weights of one each were entered for output deviations (Y), control magnitude (UM), control rates (UR), and the (3,3) element of the resultant state weighting  $\underline{X}$  matrix (to limit the pitch rate magnitude). Each of these was increased one at a time to ten and another set of time response plots made. By noting the effects of changing the weightings, one at a time, the designer will get a feel for what weights to apply to get the effects he desires. A final run is made with CGTPIF using a "best" selected set of weights. Each of these runs is discussed in the following subsections. (A set of time response plots using CGTPIF consists of first the PI time response and second the corresponding CGT/PI time response using the just-determined PI gains.)

For CGTPIQ, initial quadratic weights of one were entered for output deviations (Y), integral of the regulation error (UQ), control magnitudes (UM), and the (3,3) element of the resultant state weighting  $\underline{X}$  matrix. (Note: the selection of one for each weight has no correlation with the designs using CGTPIF other than to give

a starting point for the discussion.) Each of these was increased one at a time to ten and another set of time response plots made. Again, by noting the effects of changing the weightings, one at a time, the designer will get a feel for what weights to apply to get the effects he desires. Three additional runs were made using CGTPIQ. The first was obtained by using the same set of weights as the "best" run made using CGTPIF with the weights for UR in CGTPIF applied to UQ in CGTPIQ, all other weights remaining the same. This was done to see if in fact there was any direct correlation between the two designs. The second was achieved by applying weights to every diagonal element in the  $\underline{X}$  matrix (i.e., adding quadratic cost associated with the two actuator states. A weight of one was arbitrarily selected for each of these.) and the third by applying explicit and implicit weights just to see the effect. (A set of time responses using CGTPIQ consists first of the PI time response followed by four CGT/PI time responses using each of the four formulations presented in Chapter III, each based on the same set of PI gains just determined.)

All PI time response plots represent the same four variables. Symbol '1' represents the pitch angle, symbol '2' the flight path angle, '3' is the position of the horizontal tail and '4' is the position of the trailing edge flaps. Each PI time response represents the response to an initial condition of one degree in the pitch angle state.

All CGT/PI time response plots represent the same three variables. Symbol '1' represents the pitch angle,

symbol '2' is the model output that the pitch angle is to follow, and '3' is the flight path angle which is desired to stay at zero. Each CGT/PI time response represents the response to a step input of magnitude one for the model. All state initial conditions are zero for the CGT/PI.

### 5.3.2 CGTPIF Baseline Design

The baseline design using CGTPIF is shown in Figures V-1 through V-12 and in Table V-1. Figure V-1 represents the PI controller for quadratic weight set (abbreviated QWS in all of the figures) number one of Table V-1. Figure V-2 is the corresponding CGT/PI for the same quadratic weight set. Figures V-3 and V-4 are the PI and CGT/PI, respectively, corresponding to quadratic weight set number two of Table V-1. This two plot set for one quadratic weight set correspondence continues up to Figures V-11 and V-12 corresponding to quadratic weight set six of Table V-1.

Observation of the CGT/PI performance for all six sets of quadratic weights indicates a good model following of the pitch angle (there are slight differences in the transient performance of each) with very little deviation in the flight path angle. Therefore, the only observations that will be discussed in detail is how the quadratic weights affected the motion of the horizontal tail and trailing edge flap to achieve this good model following of the CGT/PI. To determine this we need to look at the PI time response for each set of quadratic weights. Figure V-1 will be used as a base to judge the effects of increasing

each quadratic weight.

Increasing the weight on the output deviation (Y) had very slight effect on the performance, as shown in Figure V-3, but did show a slight decrease in rise time with a corresponding larger overshoot as would be expected.

(Note: due to the effects of scaling of each variable on a time response plot, the designer will need to be careful, in that, what looks to be a "better" or "worse" response may just be due to a different scale for that variable from one run to the next. This is not that critical for this first comparison but is critical on some of the other CGT/PI time response plots.)

Increasing the weight on the (3,3) element of the  $X$  weighting matrix (i.e., on pitch rate) again had very little effect, as shown in Figure V-5, but did decrease the rise time and settling time, as expected, with a corresponding greater overshoot.

Increasing the weight on the control magnitude (UM) had the effect of slowing down the horizontal tail motion but greatly increasing the speed and deflection of the trailing edge flap as shown in Figure V-7. This difference in effect on the two control surfaces was not expected since weighting the control for each should have allowed each to move faster and further initially.

Increasing the weight on the control rate (UR) had the effect of slowing down both the tail and flap motion as expected, producing very little overshoot with trailing edge flap motion almost within tolerance limits as shown in

Figure V-9.

As a last set of quadratic weights to be used which were considered the "best" for this application, the weights (Y) and X(3,3) were increased to decrease the rise time, thereby speeding up the motion of the flaps and tail, but at the same time the weight (UR) was increased to limit the deflection and overshoot of each. This combination produced flap and tail motion that stayed in limits and gave good model following characteristics to the CGT/PI while maintaining the flight path angle near zero, as shown in Figures V-11 and V-12.

The corresponding PI pole motion for each of the sets of quadratic weights is shown in Table V-1 along with the corresponding PI and CGT/PI gains needed to produce the responses noted. The PI pole motion may give insight into design characteristics but this is not discussed here. The pole locations are included in the table since some readers/designers may wish to know this information.

### 5.3.3 CGTPIQ Design Analysis

The design and comparisons using the four versions of CGTPIQ are presented in Figures V-13 through V-52 and Table V-2. There are eight sets of five time response plots. The first plot of each set is the PI time response for the set of quadratic weights shown in Table V-2. Plot two of each set is the CGT/PI time response produced using CGT/PI formulation 1. Similarly, the third, fourth and fifth plots of each set are the CGT/PI time responses

produced using CGT/PI formulations 2, 3, and 4, respectively. Each CGT/PI is based on the same PI gains previously determined for that set.

The determination of a "best" CGT/PI out of the four possible will be the one that most closely approaches the performance noted by using CGTPIF. This was very easy to determine, for, if we notice, every CGT/PI based on formulations 1 and 2, no matter what the quadratic weights were that were applied to the PI, showed an inherent lag between model output and system output. This lag was greater for the CGT/PI based on formulation 2. (If we recall from Chapter III, this was not supposed to be the case when comparing these two. The cause of this characteristic is not yet resolved.) The CGT/PI based on CGT/PI formulation 3 showed an inherent overshoot due to faster transient performance for all quadratic weight sets. This was to be expected, as noted in Chapter III, due to the extra gain,  $E$ , providing a direct feedthrough of the input. Only the ad-hoc formulation 4 (based on neglecting the terms,  $E_s y_m$ , from formulation 3 which produced a fast transient and also the term,  $N$ , from formulation 2, which turns out to be the term which slows down the transient response) yields a CGT/PI controller that appears to give satisfactory performance (satisfactory in the sense that it most closely approaches the performance noted using CGTPIF) for a given PI set of quadratic weights. What we need to look at now is what effect the different sets of quadratic weights, as presented in Table V-2, have on the PI

performance.

We will use Figure V-13, which is the PI time response based on quadratic weight set 1 of Table V-2, as the base from which to determine the effects of increasing each quadratic weight. The first thing that is noted in looking at Figure V-13 is the much slower response of this PI controller compared to the one used in CGTPIF. This slowness shows in every PI time response for every set of quadratic weights. (This may or may not be a good trait depending on the desires of the designer.) But, at the same time, it is noted that the motion of the flaps and tail are not nearly as harsh as in the PI controller produced by CGTPIF. This would be important for saturation concerns and for robustness (these issues are among those being investigated by Capt Miller, Ref (20), using the program "CGTPIF").

Increasing the weight on the output deviation (Y) had very little effect on the system as shown in Figure V-18. This same response was noted using CGTPIF as mentioned in the previous section.

Increasing the weight on the (3,3) element of the  $X$  matrix had a very definite slowing effect on the system and the corresponding reduction in overshoot as shown in Figure V-23. This was as expected due to the increased weight on the pitch rate. Also, the motion of the horizontal tail is not nearly as smooth.

Increasing the weight on the integral of the regulation error (UQ) had the effect of speeding up the



system with the corresponding overshoot produced, as shown in Figure V-28. (All things considered, this is not a bad PI design in itself and it produces acceptable CGT/PI performance as shown in Figure V-32.)

Increasing the weight on the control magnitude (UM) had the effect of greatly slowing down the system, as expected, with the motion of the flap and tail greatly reduced, as shown in Figure V-33.

Figure V-38 shows the PI time response for the same set of quadratic weights as the "best" design using CGTPIF. In this case this is not a bad design either as response time is reasonable and flap and tail motion are maintained within the required limits. The CGT/PI also shows satisfactory results with good model following and flight path angle deviations very slight, as shown in Figure V-42. The purpose of this test was to determine if there was a weight that could be applied to UQ, all other weights remaining the same as in CGTPIF, that would produce a response exactly like that obtained using CGTPIF. Although the response was similar, we were not able to find a weight for UQ that would produce the exact results.

The last two sets of quadratic weights were used to determine if perhaps additional weights could be added, either manually in the  $\underline{X}$  matrix or by using implicit weights, which also fills in the  $\underline{X}$  matrix with off-diagonal elements, to improve the performance of the PI controller (making it more closely approximate the good performance as seen using CGTPIF). Nothing spectacular was noted in these

two as shown in Figures V-43 and V-48 but it was noted that adding small implicit weights did give performance similar to that obtained by manually adding additional weights in the  $X$  matrix, thereby relieving the designer of the burden of guessing weights to add. This is an expected characteristic of using implicit model following.

The corresponding PI pole motion for each of the sets of quadratic weights is shown in Table V-2 along with the corresponding PI and CGT/PI gains needed to produce the responses noted. The PI proportional gains,  $K_p$ , and integral gains,  $K_i$ , are also listed. As expected, they are different, and therefore are a potentially very useful tool in design work. By being able to adjust the proportional and integral gains, the designer would be able to compensate for a bad trait of PI controllers known as wind-up. This was not investigated in this study and is left for follow-on work.

#### 5.4 Simple Design Problem Using CGT/PI Formulation 4

Since CGT/PI formulation 4 was shown to be a candidate for a good CGT/PI controller, it was decided to test this controller's performance against adverse conditions. A simple design problem was selected that contained disturbance states, an alternate truth model used to evaluate the degradation in performance due to misrepresented system dynamics in the design model, and initial conditions. This is the same simple design model as presented in Floyd's thesis (Ref 9), and is presented here

as

Design Model

$$\dot{\underline{x}}(t) = \begin{bmatrix} -2 & 5 \\ -5 & -2 \end{bmatrix} \underline{x}(t) + \begin{bmatrix} 3 & -1 \\ 1 & 5 \end{bmatrix} \underline{n}_d(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \underline{u}(t) \quad (V-10)$$

$$\dot{\underline{n}}_d(t) = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \underline{n}_d(t) \quad (V-11)$$

$$\underline{y}_c(t) = [1 \ 0] \underline{x}(t) \quad (V-12)$$

$$\underline{n}_d(0) = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} -1 \\ 2 \end{bmatrix} \quad (V-13)$$

Truth Model

$$\dot{\underline{x}}_t(t) = \begin{bmatrix} -2 & 5 & 3 & -1 \\ -5 & -2 & 1 & 5 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \underline{x}_t(t) + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \underline{u}_t(t) \quad (V-14)$$

Alternate Truth Model

$$\dot{\underline{x}}'_t(t) = \begin{bmatrix} -1 & 5 & 3 & -1 \\ -5 & -1 & 1 & 5 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \underline{x}'_t(t) + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \underline{u}_t(t) \quad (V-15)$$

Command Models

First order command model (CM01):

$$\dot{\underline{x}}_m(t) = -5 \underline{x}_m(t) + \underline{u}_m(t) \quad (V-16)$$

$$\underline{y}_m(t) = 5 \underline{x}_m(t) \quad (V-17)$$

Second order command model (CM02):

$$\dot{\underline{x}}_m(t) = \begin{bmatrix} -5 & 5 \\ -5 & -5 \end{bmatrix} \underline{x}_m(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \underline{u}_m(t) \quad (V-18)$$

$$\underline{y}_m(t) = [10 \ 0] \underline{x}_m(t) \quad (V-19)$$

Figure V-53 shows an open-loop CGT design (1 is the

system output and 2 is the command model output) to demonstrate the effects of adding the PI feedback controller design of Figure V-54 (1 is state  $x_2$ , 2 is the system output, and 3 is the applied control). Figure V-55 shows the improved performance of the closed-loop CGT/PI over the open-loop CGT. This figure is based on the first order command model (CM01). When the same PI controller is applied, and the second order command model (CM02) selected, the performance is drastically improved as shown in Figure V-56. (There is no difference between model and system outputs.) These last four time response plots are based on the nominal truth model. Figure V-57 shows the effect on the CGT/PI of adding a constant disturbance and Figure V-58 shows the effect of not only having disturbances but also the alternate truth model. The performance of these two CGT/PI controllers compares favorable with that obtained by Floyd when using the program "CGTPIF" (Ref 9). As a final test, Figure V-59 adds initial conditions to the design with disturbance and alternate truth model. Note the CGT/PI controller takes a little time to recover from all the discrepancies, but it does recover and gives good performance as steady-state conditions are approached.

## 5.5 Summary

Chapter V has presented and compared each of the PI and CGT/PI controllers discussed in this thesis through use of the programs which were developed to implement them. A comparison was also made with the original program "CGTPIF".

Initial indications are that the program "CGTPIF" has certain advantages over "CGTPIQ" in that it offers greater control over the PI controller, but this does not necessarily mean better performance in the CGT/PI controller when we note the performance due to CGT/PI formulation 4. This particular CGT/PI controller was shown to be able to generate designs with desirable closed-loop characteristics and to handle adverse conditions just as well as the CGT/PI controller implemented in the program "CGTPIF".

Table V-1: CGTPIF Gains and Pole Positions for Various PI Quadratic Weights

Wts Y;X33;UM;UR	KX		KZ		PI Poles		KXM		KXU			
1,1;1;1,1;1,1 1	-62.21	30.86	-3.13	2.19	0.12	0.39	1.17	-1.51+j0.45	-14.13	-24.43	-12.22	-11.43
	124.5	-134.1	0.57	0.12	1.69	-4.7	4.64	-18.1+j13.6	-27.20	103.4	-0.71	48.96
10,10;1;1,1;1,1 2	-70.33	32.42	-3.34	2.25	0.13	-0.9	-1.6	-18+j13.62	-19.62	-25.94	-13.24	-11.52
	124.8	-135.1	0.55	0.13	1.70	-4.9	4.93	-2.76+j0.79	-27.82	104.4	-0.80	49.02
1,1;10;1,1;1,1 3	-104.2	30.55	-4.77	2.66	0.23	0.47	-1.1	-24.8+j28.9	-48.48	-24.24	-20.04	-11.41
	114.8	-134.2	0.19	0.23	1.72	-4.7	4.66	-0.45,-1.74,-62,-55	-35.17	103.5	-2.53	48.96
1,1;1;10,10;1,1 4	-79.24	56.58	-3.85	3.21	0.04	1.54	-2.0	-1.44+j46.1	-0.45	-46.22	-14.73	-17.83
	236.4	-246.2	1.48	0.03	3.07	-8.6	8.48	-74.5+j157	-40.5	197.6	2.78	76.5
1,1;1;1,1;10,10 5	-26.24	12.52	-1.65	1.29	0.14	0.15	-0.5	-12.7+j12.7	-4.74	-8.82	-5.76	-6.91
	50.87	-54.99	0.15	0.14	0.72	-1.9	1.90	-1.5+j45.2	-13.56	37.0	-2.11	29.54
5,5;2;1,1;10,10 6	-32.34	12.92	-1.96	1.44	0.17	-0.15	-0.6	-13.56+j15.5	-8.93	-9.23	-7.21	-6.97
	50.08	-55.29	0.09	0.17	0.72	-1.99	2.0	-1.87+j0.7	-14.4	37.3	-2.39	29.57

SCALE 4	SCALE 3	SCALE 2	SCALE 1
0.00	0.02	0.04	0.06
0.02	0.04	0.06	0.08
0.04	0.06	0.08	0.10
0.06	0.08	0.10	0.12
0.08	0.10	0.12	0.14
0.10	0.12	0.14	0.16
0.12	0.14	0.16	0.18
0.14	0.16	0.18	0.20
0.16	0.18	0.20	0.22
0.18	0.20	0.22	0.24
0.20	0.22	0.24	0.26
0.22	0.24	0.26	0.28
0.24	0.26	0.28	0.30
0.26	0.28	0.30	0.32
0.28	0.30	0.32	0.34
0.30	0.32	0.34	0.36
0.32	0.34	0.36	0.38
0.34	0.36	0.38	0.40
0.36	0.38	0.40	0.42
0.38	0.40	0.42	0.44
0.40	0.42	0.44	0.46
0.42	0.44	0.46	0.48
0.44	0.46	0.48	0.50
0.46	0.48	0.50	0.52
0.48	0.50	0.52	0.54
0.50	0.52	0.54	0.56
0.52	0.54	0.56	0.58
0.54	0.56	0.58	0.60
0.56	0.58	0.60	0.62
0.58	0.60	0.62	0.64
0.60	0.62	0.64	0.66
0.62	0.64	0.66	0.68
0.64	0.66	0.68	0.70
0.66	0.68	0.70	0.72
0.68	0.70	0.72	0.74
0.70	0.72	0.74	0.76
0.72	0.74	0.76	0.78
0.74	0.76	0.78	0.80
0.76	0.78	0.80	0.82
0.78	0.80	0.82	0.84
0.80	0.82	0.84	0.86
0.82	0.84	0.86	0.88
0.84	0.86	0.88	0.90
0.86	0.88	0.90	0.92
0.88	0.90	0.92	0.94
0.90	0.92	0.94	0.96
0.92	0.94	0.96	0.98
0.94	0.96	0.98	1.00
0.96	0.98	1.00	1.02
0.98	1.00	1.02	1.04
1.00	1.02	1.04	1.06
1.02	1.04	1.06	1.08
1.04	1.06	1.08	1.10
1.06	1.08	1.10	1.12
1.08	1.10	1.12	1.14
1.10	1.12	1.14	1.16
1.12	1.14	1.16	1.18
1.14	1.16	1.18	1.20
1.16	1.18	1.20	1.22
1.18	1.20	1.22	1.24
1.20	1.22	1.24	1.26
1.22	1.24	1.26	1.28
1.24	1.26	1.28	1.30
1.26	1.28	1.30	1.32
1.28	1.30	1.32	1.34
1.30	1.32	1.34	1.36
1.32	1.34	1.36	1.38
1.34	1.36	1.38	1.40
1.36	1.38	1.40	1.42
1.38	1.40	1.42	1.44
1.40	1.42	1.44	1.46
1.42	1.44	1.46	1.48
1.44	1.46	1.48	1.50
1.46	1.48	1.50	1.52
1.48	1.50	1.52	1.54
1.50	1.52	1.54	1.56
1.52	1.54	1.56	1.58
1.54	1.56	1.58	1.60
1.56	1.58	1.60	1.62
1.58	1.60	1.62	1.64
1.60	1.62	1.64	1.66
1.62	1.64	1.66	1.68
1.64	1.66	1.68	1.70
1.66	1.68	1.70	1.72
1.68	1.70	1.72	1.74
1.70	1.72	1.74	1.76
1.72	1.74	1.76	1.78
1.74	1.76	1.78	1.80
1.76	1.78	1.80	1.82
1.78	1.80	1.82	1.84
1.80	1.82	1.84	1.86
1.82	1.84	1.86	1.88
1.84	1.86	1.88	1.90
1.86	1.88	1.90	1.92
1.88	1.90	1.92	1.94
1.90	1.92	1.94	1.96
1.92	1.94	1.96	1.98
1.94	1.96	1.98	2.00
1.96	1.98	2.00	2.02
1.98	2.00	2.02	2.04
2.00	2.02	2.04	2.06
2.02	2.04	2.06	2.08
2.04	2.06	2.08	2.10
2.06	2.08	2.10	2.12
2.08	2.10	2.12	2.14
2.10	2.12	2.14	2.16
2.12	2.14	2.16	2.18
2.14	2.16	2.18	2.20
2.16	2.18	2.20	2.22
2.18	2.20	2.22	2.24
2.20	2.22	2.24	2.26
2.22	2.24	2.26	2.28
2.24	2.26	2.28	2.30
2.26	2.28	2.30	2.32
2.28	2.30	2.32	2.34
2.30	2.32	2.34	2.36
2.32	2.34	2.36	2.38
2.34	2.36	2.38	2.40
2.36	2.38	2.40	2.42
2.38	2.40	2.42	2.44
2.40	2.42	2.44	2.46
2.42	2.44	2.46	2.48
2.44	2.46	2.48	2.50
2.46	2.48	2.50	2.52
2.48	2.50	2.52	2.54
2.50	2.52	2.54	2.56
2.52	2.54	2.56	2.58
2.54	2.56	2.58	2.60
2.56	2.58	2.60	2.62
2.58	2.60	2.62	2.64
2.60	2.62	2.64	2.66
2.62	2.64	2.66	2.68
2.64	2.66	2.68	2.70
2.66	2.68	2.70	2.72
2.68	2.70	2.72	2.74
2.70	2.72	2.74	2.76
2.72	2.74	2.76	2.78
2.74	2.76	2.78	2.80
2.76	2.78	2.80	2.82
2.78	2.80	2.82	2.84
2.80	2.82	2.84	2.86
2.82	2.84	2.86	2.88
2.84	2.86	2.88	2.90
2.86	2.88	2.90	2.92
2.88	2.90	2.92	2.94
2.90	2.92	2.94	2.96
2.92	2.94	2.96	2.98
2.94	2.96	2.98	3.00
2.96	2.98	3.00	3.02
2.98	3.00	3.02	3.04
3.00	3.02	3.04	3.06
3.02	3.04	3.06	3.08
3.04	3.06	3.08	3.10
3.06	3.08	3.10	3.12
3.08	3.10	3.12	3.14
3.10	3.12	3.14	3.16
3.12	3.14	3.16	3.18
3.14	3.16	3.18	3.20
3.16	3.18	3.20	3.22
3.18	3.20	3.22	3.24
3.20	3.22	3.24	3.26
3.22	3.24	3.26	3.28
3.24	3.26	3.28	3.30
3.26	3.28	3.30	3.32
3.28	3.30	3.32	3.34
3.30	3.32	3.34	3.36
3.32	3.34	3.36	3.38
3.34	3.36	3.38	3.40
3.36	3.38	3.40	3.42
3.38	3.40	3.42	3.44
3.40	3.42	3.44	3.46
3.42	3.44	3.46	3.48
3.44	3.46	3.48	3.50
3.46	3.48	3.50	3.52
3.48	3.50	3.52	3.54
3.50	3.52	3.54	3.56
3.52	3.54	3.56	3.58
3.54	3.56	3.58	3.60
3.56	3.58	3.60	3.62
3.58	3.60	3.62	3.64
3.60	3.62	3.64	3.66
3.62	3.64	3.66	3.68
3.64	3.66	3.68	3.70
3.66	3.68	3.70	3.72
3.68	3.70	3.72	3.74
3.70	3.72	3.74	3.76
3.72	3.74	3.76	3.78
3.74	3.76	3.78	3.80
3.76	3.78	3.80	3.82
3.78	3.80	3.82	3.84
3.80	3.82	3.84	3.86
3.82	3.84	3.86	3.88
3.84	3.86	3.88	3.90
3.86	3.88	3.90	3.92
3.88	3.90	3.92	3.94
3.90	3.92	3.94	3.96
3.92	3.94	3.96	3.98
3.94	3.96	3.98	4.00

Figure V-1. PI for QWS-1 (CGTPIF)





SCALE 4	SCALE 3	SCALE 2	SCALE 1
0.00	0.02	0.04	0.06
0.08	0.10	0.12	0.14
0.16	0.18	0.20	0.22
0.24	0.26	0.28	0.30
0.32	0.34	0.36	0.38
0.40	0.42	0.44	0.46
0.48	0.50	0.52	0.54
0.56	0.58	0.60	0.62
0.64	0.66	0.68	0.70
0.72	0.74	0.76	0.78
0.80	0.82	0.84	0.86
0.88	0.90	0.92	0.94
0.96	0.98		
-0.00	-0.02	-0.04	-0.06
-0.08	-0.10	-0.12	-0.14
-0.16	-0.18	-0.20	-0.22
-0.24	-0.26	-0.28	-0.30
-0.32	-0.34	-0.36	-0.38
-0.40	-0.42	-0.44	-0.46
-0.48	-0.50	-0.52	-0.54
-0.56	-0.58	-0.60	-0.62
-0.64	-0.66	-0.68	-0.70
-0.72	-0.74	-0.76	-0.78
-0.80	-0.82	-0.84	-0.86
-0.88	-0.90	-0.92	-0.94
-0.96	-0.98		
-1.00	-1.0000	-1.0000	-1.0000
-2.00	-2.0000	-2.0000	-2.0000
-3.00	-3.0000	-3.0000	-3.0000
-4.00	-4.0000	-4.0000	-4.0000

Figure V-3. PI for QWS-2 (CGTPIF)

SCALE	0000	2000	5000	8000	10000	14000
1.00	3	+	+	+	+	+
.98	3	+	+	+	+	+
.96	3	+	+	+	+	+
.94	3	+	+	+	+	+
.92	3	+	+	+	+	+
.90	3	+	+	+	+	+
.88	3	+	+	+	+	+
.86	3	+	+	+	+	+
.84	3	+	+	+	+	+
.82	3	+	+	+	+	+
.80	3	+	+	+	+	+
.78	3	+	+	21	+	+
.76	3	+	+	21	+	+
.74	3	+	+	21	+	+
.72	3	+	+	2	+	+
.70	3	+	+	2	+	+
.68	3	+	+	2	+	+
.66	3	+	+	2	+	+
.64	3	+	+	2	+	+
.62	3	+	+	2	+	+
.60	3	+	+	2	+	+
.58	3	+	+	21	+	+
.56	3	+	+	21	+	+
.54	3	+	+	2	+	+
.52	3	+	+	2	+	+
.50	3	+	+	21	+	+
.48	3	+	+	21	+	+
.46	3	+	+	2	+	+
.44	3	+	+	21	+	+
.42	3	+	+	21	+	+
.40	3	+	+	2	+	+
.38	3	+	+	21	+	+
.36	3	+	+	2	+	+
.34	3	+	+	21	+	+
.32	3	+	+	21	+	+
.30	3	+	+	21	+	+
.28	3	+	+	21	+	+
.26	3	+	+	21	+	+
.24	3	+	+	21	+	+
.22	3	+	+	21	+	+
.20	3	+	+	21	+	+
.18	3	+	2	+	+	+
.16	3	+	2	+	+	+
.14	3	+	12	+	+	+
.12	3	+	12	+	+	+
.10	3	+	2	+	+	+
.08	3	+	1	+	+	+
.06	3	+	2	+	+	+
.04	3	+	2	+	+	+
.02	3	+	2	+	+	+
0.00	3	+	+	+	+	+

Figure V-4. CGT/PI for QWS-2 (CGTPIF)

SCALE 4	SCALE 3	SCALE 2	SCALE 1
0.00	0.02	0.04	0.06
0.08	0.10	0.12	0.14
0.16	0.18	0.20	0.22
0.24	0.26	0.28	0.30
0.32	0.34	0.36	0.38
0.40	0.42	0.44	0.46
0.48	0.50	0.52	0.54
0.56	0.58	0.60	0.62
0.64	0.66	0.68	0.70
0.72	0.74	0.76	0.78
0.80	0.82	0.84	0.86
0.88	0.90	0.92	0.94
0.96	0.98		
-1.0000	-1.0000	-1.0000	-1.0000
-2.0000	-2.0000	-2.0000	-2.0000
-3.0000	-3.0000	-3.0000	-3.0000
-4.0000	-4.0000	-4.0000	-4.0000
-5.0000	-5.0000	-5.0000	-5.0000
-6.0000	-6.0000	-6.0000	-6.0000
-7.0000	-7.0000	-7.0000	-7.0000
-8.0000	-8.0000	-8.0000	-8.0000
-9.0000	-9.0000	-9.0000	-9.0000
-10.0000	-10.0000	-10.0000	-10.0000
-11.0000	-11.0000	-11.0000	-11.0000
-12.0000	-12.0000	-12.0000	-12.0000
-13.0000	-13.0000	-13.0000	-13.0000
-14.0000	-14.0000	-14.0000	-14.0000
-15.0000	-15.0000	-15.0000	-15.0000
-16.0000	-16.0000	-16.0000	-16.0000
-17.0000	-17.0000	-17.0000	-17.0000
-18.0000	-18.0000	-18.0000	-18.0000
-19.0000	-19.0000	-19.0000	-19.0000
-20.0000	-20.0000	-20.0000	-20.0000
-21.0000	-21.0000	-21.0000	-21.0000
-22.0000	-22.0000	-22.0000	-22.0000
-23.0000	-23.0000	-23.0000	-23.0000
-24.0000	-24.0000	-24.0000	-24.0000
-25.0000	-25.0000	-25.0000	-25.0000
-26.0000	-26.0000	-26.0000	-26.0000
-27.0000	-27.0000	-27.0000	-27.0000
-28.0000	-28.0000	-28.0000	-28.0000
-29.0000	-29.0000	-29.0000	-29.0000
-30.0000	-30.0000	-30.0000	-30.0000
-31.0000	-31.0000	-31.0000	-31.0000
-32.0000	-32.0000	-32.0000	-32.0000
-33.0000	-33.0000	-33.0000	-33.0000
-34.0000	-34.0000	-34.0000	-34.0000
-35.0000	-35.0000	-35.0000	-35.0000
-36.0000	-36.0000	-36.0000	-36.0000
-37.0000	-37.0000	-37.0000	-37.0000
-38.0000	-38.0000	-38.0000	-38.0000
-39.0000	-39.0000	-39.0000	-39.0000
-40.0000	-40.0000	-40.0000	-40.0000
-41.0000	-41.0000	-41.0000	-41.0000
-42.0000	-42.0000	-42.0000	-42.0000
-43.0000	-43.0000	-43.0000	-43.0000
-44.0000	-44.0000	-44.0000	-44.0000
-45.0000	-45.0000	-45.0000	-45.0000
-46.0000	-46.0000	-46.0000	-46.0000
-47.0000	-47.0000	-47.0000	-47.0000
-48.0000	-48.0000	-48.0000	-48.0000
-49.0000	-49.0000	-49.0000	-49.0000
-50.0000	-50.0000	-50.0000	-50.0000

Figure V-5. PI for QWS-3 (CGTPIF)



SCALE 4	SCALE 3	SCALE 2	SCALE 1
0.00	+3	1.000	1.000
0.02	4	1.000	1.000
0.04	+	1.000	1.000
0.06	+	1.000	1.000
0.08	+	1.000	1.000
0.10	+	1.000	1.000
0.12	+	1.000	1.000
0.14	+	1.000	1.000
0.16	+	1.000	1.000
0.18	+	1.000	1.000
0.20	+	1.000	1.000
0.22	+	1.000	1.000
0.24	+	1.000	1.000
0.26	+	1.000	1.000
0.28	+	1.000	1.000
0.30	+	1.000	1.000
0.32	+	1.000	1.000
0.34	+	1.000	1.000
0.36	+	1.000	1.000
0.38	+	1.000	1.000
0.40	+	1.000	1.000
0.42	+	1.000	1.000
0.44	+	1.000	1.000
0.46	+	1.000	1.000
0.48	+	1.000	1.000
0.50	+	1.000	1.000
0.52	+	1.000	1.000
0.54	+	1.000	1.000
0.56	+	1.000	1.000
0.58	+	1.000	1.000
0.60	+	1.000	1.000
0.62	+	1.000	1.000
0.64	+	1.000	1.000
0.66	+	1.000	1.000
0.68	+	1.000	1.000
0.70	+	1.000	1.000
0.72	+	1.000	1.000
0.74	+	1.000	1.000
0.76	+	1.000	1.000
0.78	+	1.000	1.000
0.80	+	1.000	1.000
0.82	+	1.000	1.000
0.84	+	1.000	1.000
0.86	+	1.000	1.000
0.88	+	1.000	1.000
0.90	+	1.000	1.000
0.92	+	1.000	1.000
0.94	+	1.000	1.000
0.96	+	1.000	1.000
0.98	+	1.000	1.000
1.00	+	1.000	1.000
1.02	+	1.000	1.000
1.04	+	1.000	1.000
1.06	+	1.000	1.000
1.08	+	1.000	1.000
1.10	+	1.000	1.000
1.12	+	1.000	1.000
1.14	+	1.000	1.000
1.16	+	1.000	1.000
1.18	+	1.000	1.000
1.20	+	1.000	1.000
1.22	+	1.000	1.000
1.24	+	1.000	1.000
1.26	+	1.000	1.000
1.28	+	1.000	1.000
1.30	+	1.000	1.000
1.32	+	1.000	1.000
1.34	+	1.000	1.000
1.36	+	1.000	1.000
1.38	+	1.000	1.000
1.40	+	1.000	1.000
1.42	+	1.000	1.000
1.44	+	1.000	1.000
1.46	+	1.000	1.000
1.48	+	1.000	1.000
1.50	+	1.000	1.000
1.52	+	1.000	1.000
1.54	+	1.000	1.000
1.56	+	1.000	1.000
1.58	+	1.000	1.000
1.60	+	1.000	1.000
1.62	+	1.000	1.000
1.64	+	1.000	1.000
1.66	+	1.000	1.000
1.68	+	1.000	1.000
1.70	+	1.000	1.000
1.72	+	1.000	1.000
1.74	+	1.000	1.000
1.76	+	1.000	1.000
1.78	+	1.000	1.000
1.80	+	1.000	1.000
1.82	+	1.000	1.000
1.84	+	1.000	1.000
1.86	+	1.000	1.000
1.88	+	1.000	1.000
1.90	+	1.000	1.000
1.92	+	1.000	1.000
1.94	+	1.000	1.000
1.96	+	1.000	1.000
1.98	+	1.000	1.000
2.00	+	1.000	1.000

Figure V-7. PI for QWS-4 (CGTPIF)



SCALE 4	SCALE 3	SCALE 2	SCALE 1
0.00	0.02	0.04	0.06
0.08	0.10	0.12	0.14
0.16	0.18	0.20	0.22
0.24	0.26	0.28	0.30
0.32	0.34	0.36	0.38
0.40	0.42	0.44	0.46
0.48	0.50	0.52	0.54
0.56	0.58	0.60	0.62
0.64	0.66	0.68	0.70
0.72	0.74	0.76	0.78
0.80	0.82	0.84	0.86
0.88	0.90	0.92	0.94
0.96	0.98		
-1.0000	-1.0000	-1.0000	-2.0000
-20.0000	2.0000	.2000	.1000
-14.0000	5.0000	.5000	.4000
-8.0000	8.0000	.8000	.7000
-2.0000	11.0000	1.1000	1.0000
4.0000	14.0000	1.4000	1.3000

Figure V-9. PI for QWS-5 (CGTPIF)





SCALE 4	SCALE 3	SCALE 2	SCALE 1
4.0000	1.2000	1.3000	1.2000
4.0000	1.3000	1.4000	1.3000
4.0000	1.4000	1.5000	1.4000
4.0000	1.5000	1.6000	1.5000
4.0000	1.6000	1.7000	1.6000
4.0000	1.7000	1.8000	1.7000
4.0000	1.8000	1.9000	1.8000
4.0000	1.9000	2.0000	1.9000
4.0000	2.0000	2.1000	2.0000
4.0000	2.1000	2.2000	2.1000
4.0000	2.2000	2.3000	2.2000
4.0000	2.3000	2.4000	2.3000
4.0000	2.4000	2.5000	2.4000
4.0000	2.5000	2.6000	2.5000
4.0000	2.6000	2.7000	2.6000
4.0000	2.7000	2.8000	2.7000
4.0000	2.8000	2.9000	2.8000
4.0000	2.9000	3.0000	2.9000
4.0000	3.0000	3.1000	3.0000
4.0000	3.1000	3.2000	3.1000
4.0000	3.2000	3.3000	3.2000
4.0000	3.3000	3.4000	3.3000
4.0000	3.4000	3.5000	3.4000
4.0000	3.5000	3.6000	3.5000
4.0000	3.6000	3.7000	3.6000
4.0000	3.7000	3.8000	3.7000
4.0000	3.8000	3.9000	3.8000
4.0000	3.9000	4.0000	3.9000
4.0000	4.0000	4.1000	4.0000
4.0000	4.1000	4.2000	4.1000
4.0000	4.2000	4.3000	4.2000
4.0000	4.3000	4.4000	4.3000
4.0000	4.4000	4.5000	4.4000
4.0000	4.5000	4.6000	4.5000
4.0000	4.6000	4.7000	4.6000
4.0000	4.7000	4.8000	4.7000
4.0000	4.8000	4.9000	4.8000
4.0000	4.9000	5.0000	4.9000
4.0000	5.0000	5.1000	5.0000
4.0000	5.1000	5.2000	5.1000
4.0000	5.2000	5.3000	5.2000
4.0000	5.3000	5.4000	5.3000
4.0000	5.4000	5.5000	5.4000
4.0000	5.5000	5.6000	5.5000
4.0000	5.6000	5.7000	5.6000
4.0000	5.7000	5.8000	5.7000
4.0000	5.8000	5.9000	5.8000
4.0000	5.9000	6.0000	5.9000
4.0000	6.0000	6.1000	6.0000
4.0000	6.1000	6.2000	6.1000
4.0000	6.2000	6.3000	6.2000
4.0000	6.3000	6.4000	6.3000
4.0000	6.4000	6.5000	6.4000
4.0000	6.5000	6.6000	6.5000
4.0000	6.6000	6.7000	6.6000
4.0000	6.7000	6.8000	6.7000
4.0000	6.8000	6.9000	6.8000
4.0000	6.9000	7.0000	6.9000
4.0000	7.0000	7.1000	7.0000
4.0000	7.1000	7.2000	7.1000
4.0000	7.2000	7.3000	7.2000
4.0000	7.3000	7.4000	7.3000
4.0000	7.4000	7.5000	7.4000
4.0000	7.5000	7.6000	7.5000
4.0000	7.6000	7.7000	7.6000
4.0000	7.7000	7.8000	7.7000
4.0000	7.8000	7.9000	7.8000
4.0000	7.9000	8.0000	7.9000
4.0000	8.0000	8.1000	8.0000
4.0000	8.1000	8.2000	8.1000
4.0000	8.2000	8.3000	8.2000
4.0000	8.3000	8.4000	8.3000
4.0000	8.4000	8.5000	8.4000
4.0000	8.5000	8.6000	8.5000
4.0000	8.6000	8.7000	8.6000
4.0000	8.7000	8.8000	8.7000
4.0000	8.8000	8.9000	8.8000
4.0000	8.9000	9.0000	8.9000
4.0000	9.0000	9.1000	9.0000
4.0000	9.1000	9.2000	9.1000
4.0000	9.2000	9.3000	9.2000
4.0000	9.3000	9.4000	9.3000
4.0000	9.4000	9.5000	9.4000
4.0000	9.5000	9.6000	9.5000
4.0000	9.6000	9.7000	9.6000
4.0000	9.7000	9.8000	9.7000
4.0000	9.8000	9.9000	9.8000
4.0000	9.9000	10.0000	9.9000

Figure V-11. PI for QWS-6 (CGTPIF)

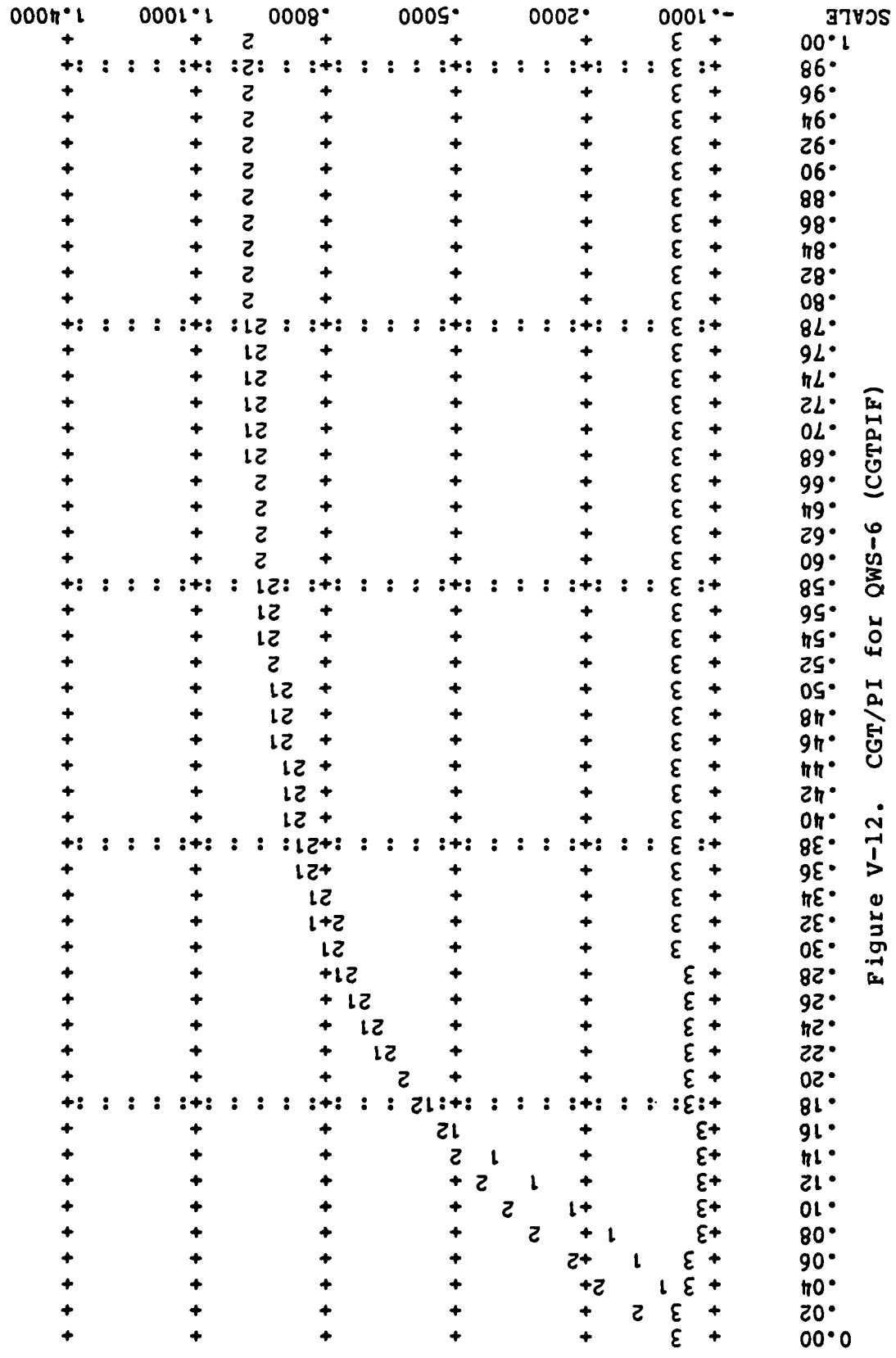


Figure V-12. CGT/PI for QWS-6 (CGTPIF)

Table V-2: CGTPIQ Gains and Pole Positions for Various PI Quadratic Weights

Wts Y;X33;UM;UR	GC1		GC2=KI		PI Poles		KP			
1 1,1;1,1;1,1	-17.83 12.75	5.71 -13.9	-1.51 0.15	1.17 0.20	0.21 0.20	-0.65 -0.43	-0.41 0.86	-19.2+j12.4 -4.88+j5.18 -2.73+j2.2, -20	-4.66 -7.45	-5.46 11.67
2 10,10;1,1;1,1	-18.16 12.93	5.75 -14.1	-1.53 -0.15	1.18 -0.2	0.21 0.20	-0.65 -0.43	-0.40 0.86	-19.1+j12.5 -5.14+j4.97 -2.76+j2.1, -20	-5.03 -7.51	-5.51 11.95
3 1,1;10;1,1;1,1	-18.84 13.75	4.63 -14.5	-2.49 -0.44	1.75 0.35	0.35 0.24	-0.55 -0.33	-0.33 0.89	-30.6+j26.2 -2.8+j3.1 -2.66+j2.0, -19.9	-5.68 -6.96	-4.39 12.19
4 1,1;1;10,10;1,1	-34.28 29.88	10.64 -31.88	-2.06 -0.07	1.44 0.21	0.22 0.38	-2.04 -0.97	-0.97 2.76	-19.4+j11.9 -4.4+j4.3 -8.3+j9.6, -20.1	-10.5 -8.28	-8.62 21.05
5 1,1;1;1,1;10,10	-8.54 4.46	2.98 -5.28	-0.83 -0.10	0.74 0.13	0.14 0.09	-0.20 -0.19	-0.2 0.24	-4.0+j5.2 -1.2+j65.9 -11,-17.5, -20	-1.29 -7.3	-3.69 7.84
6 5,5;2;1,1;10,10	-34.59 30.12	10.36 -32.04	-2.22 -0.11	1.53 0.23	0.25 0.38	-1.98 -0.93	-0.9 2.77	-21.8+j16.0 -7.37+j7.8 -4.4+j4.3, -20.1	-10.87 -8.18	-8.32 21.25
7 5,5;20;5,5;1,1 X44=1, X55=1	-29.43 24.63	7.77 -26.0	-3.13 -0.53	2.07 0.36	0.35 0.61	-1.08 -0.60	-0.6 1.88	-36.5+j30 -3.5+j3.8 -3.3+j2.7, -28.3	-9.13 -9.26	-6.62 19.41
8 Ex:5,5;5,5;1,1 Im:2,2;2,2	-20.97 16.12	6.63 -17.2	-1.57 -0.10	1.20 0.19	0.20 0.25	-0.85 -0.51	-0.5 1.12	-17.8+j10.4 -6.6+j6.1 -3.04+j2.5, -20.4	-6.19 -7.58	-6.15 13.64

Table V-2 continued: CGTPIQ Gains and Pole Positions For Various Quadratic Weights

KXM-1	KXU-1	KXM-2	KXU-2	KXM-3,4	KXU-3,4
1 -0.54 -0.81 -4.19 -5.51	-4.12 -4.65 -3.26 17.18	-4.31 -3.18 -5.92 2.69	-0.36 -2.28 -1.52 8.98	-4.31 -3.18 -5.92 2.69	-5.25 -5.09 -3.16 19.14
2 -0.80 -0.85 -4.24 -5.29	-4.23 -4.66 -3.27 17.24	-4.51 -3.21 -5.95 2.86	-0.51 -2.31 -1.56 9.09	-4.51 -3.21 -5.95 2.86	-5.33 -5.10 -3.17 19.18
3 2.96 -0.04 -2.25 -5.05	-8.64 -4.34 -4.71 17.24	-1.95 -2.39 -4.09 3.17	-3.73 -2.00 -2.87 9.02	-1.95 -2.39 -4.09 3.17	-9.66 -4.84 -4.53 19.19
4 -4.67 -3.27 -5.18 1.77	-5.86 -5.35 -3.10 19.28	-13.0 -7.58 -8.21 18.43	2.44 -1.04 -0.07 2.62	-13.0 -7.58 -8.21 18.43	-7.73 -5.99 -2.88 22.53
5 0.25 0.55 -4.35 -8.44	-1.55 -4.25 -2.95 16.28	-1.06 -0.72 -5.16 -4.73	-0.2 -2.97 -2.14 12.6	-1.06 -0.72 -5.16 -4.73	-2.24 -4.51 -2.93 17.28
6 -4.24 -3.04 -4.87 1.93	-6.63 -5.27 -3.32 19.32	-12.8 -7.35 -7.94 18.57	1.96 -0.96 -0.2 2.68	-12.8 -7.35 -7.94 18.57	-8.47 -5.94 -3.07 22.55
7 2.02 -0.77 -3.70 -4.61	-11.2 -5.85 -5.57 24.02	-5.88 -4.58 -6.56 10.05	-3.2 -2.04 -2.71 9.36	-5.88 -4.58 -6.56 10.05	-12.5 -6.42 -5.20 26.34
8 -19.0 -1.33 -4.50 -4.28	-4.29 -4.82 -3.08 17.91	-6.19 -3.97 -6.37 5.35	0.01 -2.17 -1.2 8.29	-6.19 -3.97 -6.37 5.35	-5.52 -5.29 -2.95 20.08

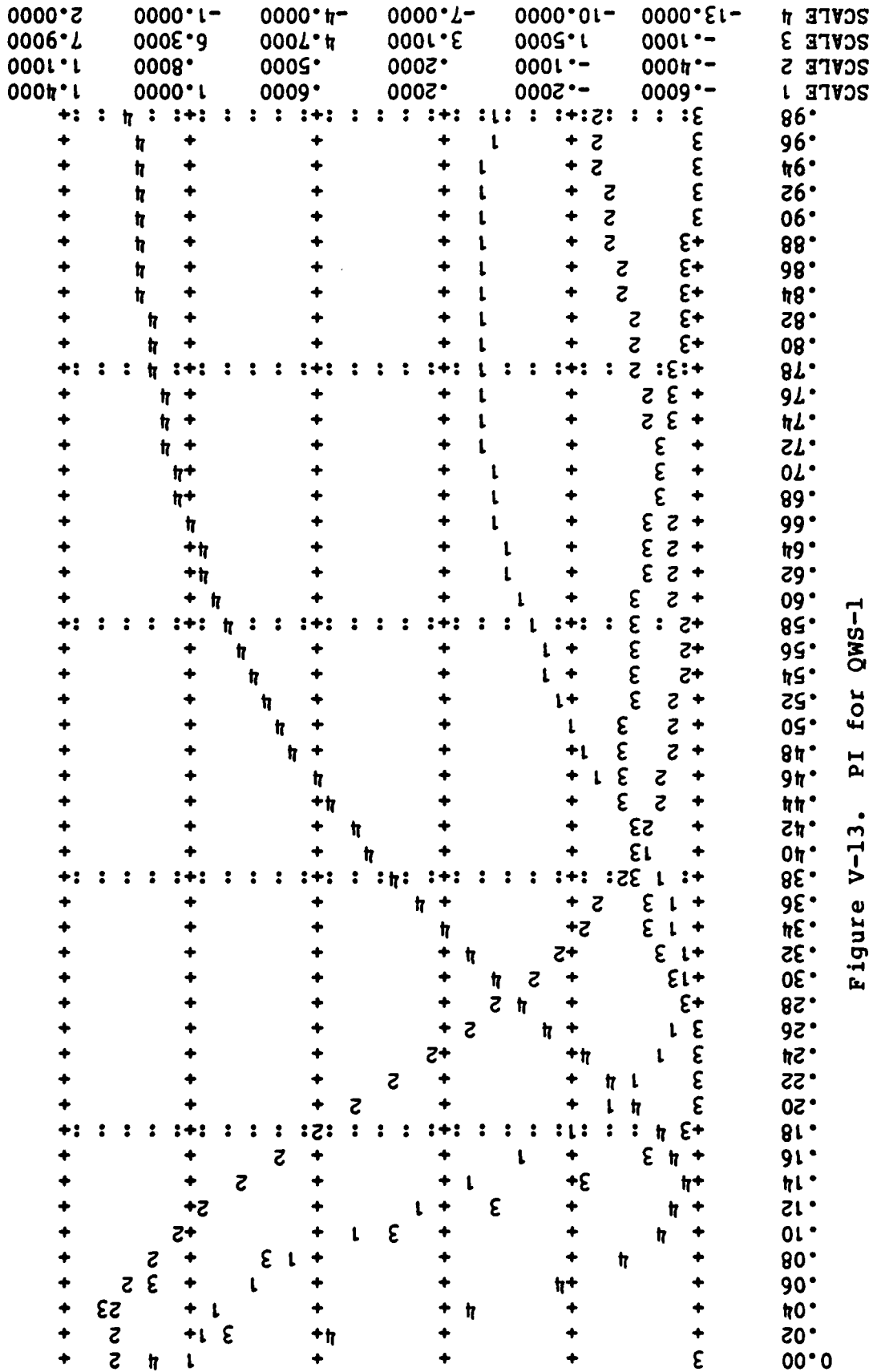
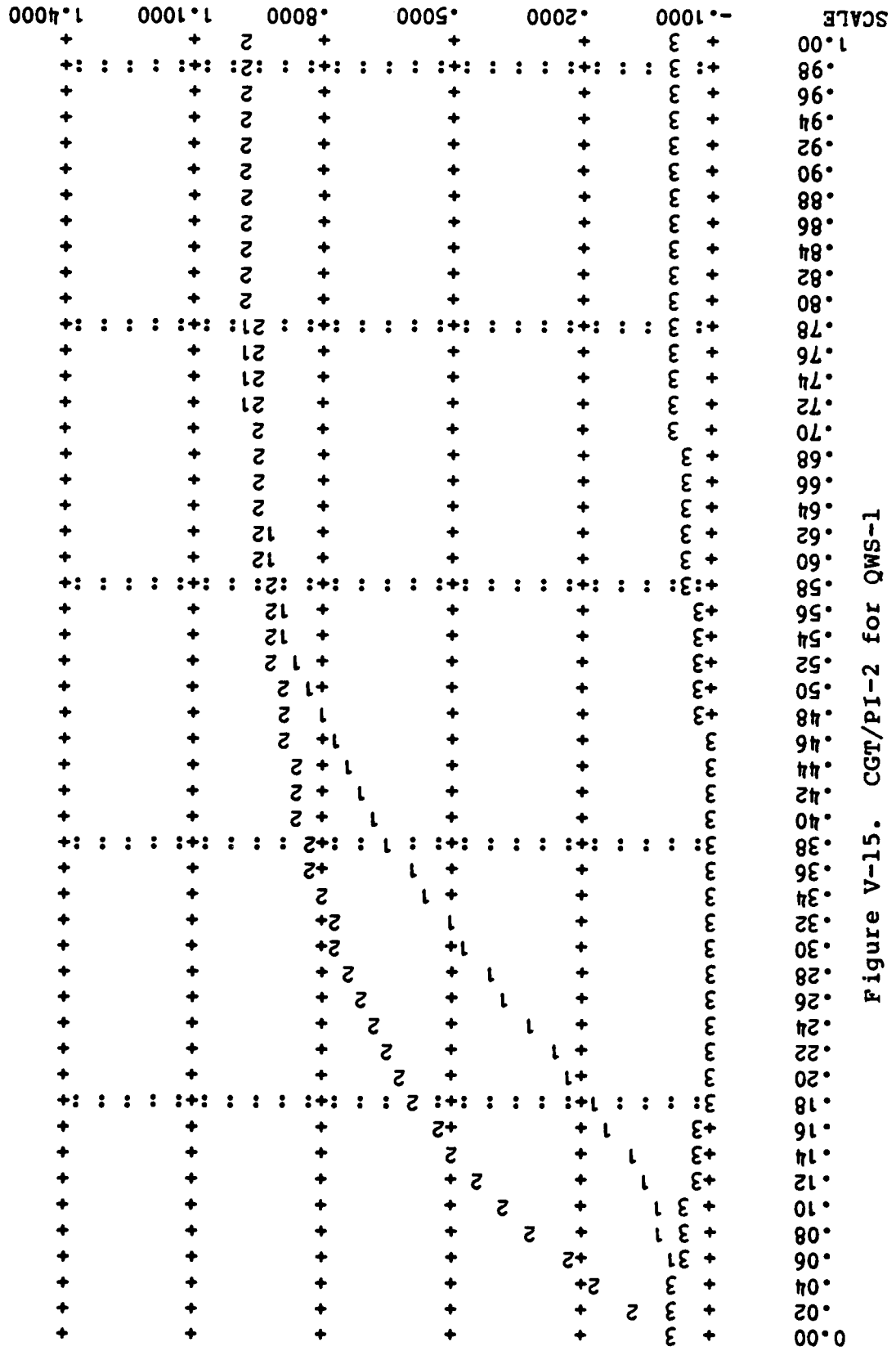


Figure V-13. PI for QWS-1





SCALE	1.000	2000	5000	8000	1.1000	1.4000
1.00	+	+	+	+	+	+
.98	+	+	+	+	+	+
.96	+	+	+	+	+	+
.94	+	+	+	+	+	+
.92	+	+	+	+	+	+
.90	+	+	+	+	+	+
.88	+	+	+	+	+	+
.86	+	+	+	+	+	+
.84	+	+	+	+	+	+
.82	+	+	+	+	+	+
.80	+	+	+	+	+	+
.78	+	+	+	+	+	+
.76	+	+	+	+	+	+
.74	+	+	+	+	+	+
.72	+	+	+	+	+	+
.70	+	+	+	+	+	+
.68	+	+	+	+	+	+
.66	+	+	+	+	+	+
.64	+	+	+	+	+	+
.62	+	+	+	+	+	+
.60	+	+	+	+	+	+
.58	+	+	+	+	+	+
.56	+	+	+	+	+	+
.54	+	+	+	+	+	+
.52	+	+	+	+	+	+
.50	+	+	+	+	+	+
.48	+	+	+	+	+	+
.46	+	+	+	+	+	+
.44	+	+	+	+	+	+
.42	+	+	+	+	+	+
.40	+	+	+	+	+	+
.38	+	+	+	+	+	+
.36	+	+	+	+	+	+
.34	+	+	+	+	+	+
.32	+	+	+	+	+	+
.30	+	+	+	+	+	+
.28	+	+	+	+	+	+
.26	+	+	+	+	+	+
.24	+	+	+	+	+	+
.22	+	+	+	+	+	+
.20	+	+	+	+	+	+
.18	+	+	+	+	+	+
.16	+	+	+	+	+	+
.14	+	+	+	+	+	+
.12	+	+	+	+	+	+
.10	+	+	+	+	+	+
.08	+	+	+	+	+	+
.06	+	+	+	+	+	+
.04	+	+	+	+	+	+
.02	+	+	+	+	+	+
0.00	+	+	+	+	+	+

Figure V-16. CGT/PI-3 for QWS-1



SCALE	.1000	.2000	.5000	.8000	1.1000	1.4000
1.00	+	+	+	+	+	+
.98	+	+	+	+	+	+
.96	+	+	+	+	+	+
.94	+	+	+	+	+	+
.92	+	+	+	+	+	+
.90	+	+	+	+	+	+
.88	+	+	+	+	+	+
.86	+	+	+	+	+	+
.84	+	+	+	+	+	+
.82	+	+	+	+	+	+
.80	+	+	+	+	+	+
.78	+	+	+	+	+	+
.76	+	+	+	+	+	+
.74	+	+	+	+	+	+
.72	+	+	+	+	+	+
.70	+	+	+	+	+	+
.68	+	+	+	+	+	+
.66	+	+	+	+	+	+
.64	+	+	+	+	+	+
.62	+	+	+	+	+	+
.60	+	+	+	+	+	+
.58	+	+	+	+	+	+
.56	+	+	+	+	+	+
.54	+	+	+	+	+	+
.52	+	+	+	+	+	+
.50	+	+	+	+	+	+
.48	+	+	+	+	+	+
.46	+	+	+	+	+	+
.44	+	+	+	+	+	+
.42	+	+	+	+	+	+
.40	+	+	+	+	+	+
.38	+	+	+	+	+	+
.36	+	+	+	+	+	+
.34	+	+	+	+	+	+
.32	+	+	+	+	+	+
.30	+	+	+	+	+	+
.28	+	+	+	+	+	+
.26	+	+	+	+	+	+
.24	+	+	+	+	+	+
.22	+	+	+	+	+	+
.20	+	+	+	+	+	+
.18	+	+	+	+	+	+
.16	+	+	+	+	+	+
.14	+	+	+	+	+	+
.12	+	+	+	+	+	+
.10	+	+	+	+	+	+
.08	+	+	+	+	+	+
.06	+	+	+	+	+	+
.04	+	+	+	+	+	+
.02	+	+	+	+	+	+
0.00	+	+	+	+	+	+

Figure V-17. CGT/PI-4 for QWS-1

SCALE 4	SCALE 3	SCALE 2	SCALE 1
2.0000	1.4000	-6000	-2000
7.9000	1.0000	-4000	-1000
1.0000	.8000	-1000	.2000
6.3000	1.0000	3.1000	3.1000
1.0000	.6000	4.7000	4.7000
2.0000	1.0000	7.0000	7.0000
		10.0000	10.0000
		13.0000	13.0000
		16.0000	16.0000
		19.0000	19.0000
		22.0000	22.0000
		25.0000	25.0000
		28.0000	28.0000
		31.0000	31.0000
		34.0000	34.0000
		37.0000	37.0000
		40.0000	40.0000
		43.0000	43.0000
		46.0000	46.0000
		49.0000	49.0000
		52.0000	52.0000
		55.0000	55.0000
		58.0000	58.0000
		61.0000	61.0000
		64.0000	64.0000
		67.0000	67.0000
		70.0000	70.0000
		73.0000	73.0000
		76.0000	76.0000
		79.0000	79.0000
		82.0000	82.0000
		85.0000	85.0000
		88.0000	88.0000
		91.0000	91.0000
		94.0000	94.0000
		97.0000	97.0000
		100.0000	100.0000

Figure V-18. PI for QWS-2

SCALE	1.4000	1.1000	.8000	.5000	.2000	-.1000	0.00
1.00	+	+	+	+	+	+	+
.98	+	+	+	+	+	+	+
.96	+	+	+	+	+	+	+
.94	+	+	+	+	+	+	+
.92	+	+	+	+	+	+	+
.90	+	+	+	+	+	+	+
.88	+	+	+	+	+	+	+
.86	+	+	+	+	+	+	+
.84	+	+	+	+	+	+	+
.82	+	+	+	+	+	+	+
.80	+	+	+	+	+	+	+
.78	+	+	+	+	+	+	+
.76	+	+	+	+	+	+	+
.74	+	+	+	+	+	+	+
.72	+	+	+	+	+	+	+
.70	+	+	+	+	+	+	+
.68	+	+	+	+	+	+	+
.66	+	+	+	+	+	+	+
.64	+	+	+	+	+	+	+
.62	+	+	+	+	+	+	+
.60	+	+	+	+	+	+	+
.58	+	+	+	+	+	+	+
.56	+	+	+	+	+	+	+
.54	+	+	+	+	+	+	+
.52	+	+	+	+	+	+	+
.50	+	+	+	+	+	+	+
.48	+	+	+	+	+	+	+
.46	+	+	+	+	+	+	+
.44	+	+	+	+	+	+	+
.42	+	+	+	+	+	+	+
.40	+	+	+	+	+	+	+
.38	+	+	+	+	+	+	+
.36	+	+	+	+	+	+	+
.34	+	+	+	+	+	+	+
.32	+	+	+	+	+	+	+
.30	+	+	+	+	+	+	+
.28	+	+	+	+	+	+	+
.26	+	+	+	+	+	+	+
.24	+	+	+	+	+	+	+
.22	+	+	+	+	+	+	+
.20	+	+	+	+	+	+	+
.18	+	+	+	+	+	+	+
.16	+	+	+	+	+	+	+
.14	+	+	+	+	+	+	+
.12	+	+	+	+	+	+	+
.10	+	+	+	+	+	+	+
.08	+	+	+	+	+	+	+
.06	+	+	+	+	+	+	+
.04	+	+	+	+	+	+	+
.02	+	+	+	+	+	+	+
0.00	+	+	+	+	+	+	+

Figure V-19. CGT/PI-1 for QWS-2

SCALE	1.000	2000	5000	8000	1.1000	1.4000
1.00	+	+	+	+	+	+
.98	+	+	+	+	+	+
.96	+	+	+	+	+	+
.94	+	+	+	+	+	+
.92	+	+	+	+	+	+
.90	+	+	+	+	+	+
.88	+	+	+	+	+	+
.86	+	+	+	+	+	+
.84	+	+	+	+	+	+
.82	+	+	+	+	+	+
.80	+	+	+	+	+	+
.78	+	+	+	+	+	+
.76	+	+	+	+	+	+
.74	+	+	+	+	+	+
.72	+	+	+	+	+	+
.70	+	+	+	+	+	+
.68	+	+	+	+	+	+
.66	+	+	+	+	+	+
.64	+	+	+	+	+	+
.62	+	+	+	+	+	+
.60	+	+	+	+	+	+
.58	+	+	+	+	+	+
.56	+	+	+	+	+	+
.54	+	+	+	+	+	+
.52	+	+	+	+	+	+
.50	+	+	+	+	+	+
.48	+	+	+	+	+	+
.46	+	+	+	+	+	+
.44	+	+	+	+	+	+
.42	+	+	+	+	+	+
.40	+	+	+	+	+	+
.38	+	+	+	+	+	+
.36	+	+	+	+	+	+
.34	+	+	+	+	+	+
.32	+	+	+	+	+	+
.30	+	+	+	+	+	+
.28	+	+	+	+	+	+
.26	+	+	+	+	+	+
.24	+	+	+	+	+	+
.22	+	+	+	+	+	+
.20	+	+	+	+	+	+
.18	+	+	+	+	+	+
.16	+	+	+	+	+	+
.14	+	+	+	+	+	+
.12	+	+	+	+	+	+
.10	+	+	+	+	+	+
.08	+	+	+	+	+	+
.06	+	+	+	+	+	+
.04	+	+	+	+	+	+
.02	+	+	+	+	+	+
0.00	+	+	+	+	+	+

Figure V-20. CGT/PI-2 for QWS-2

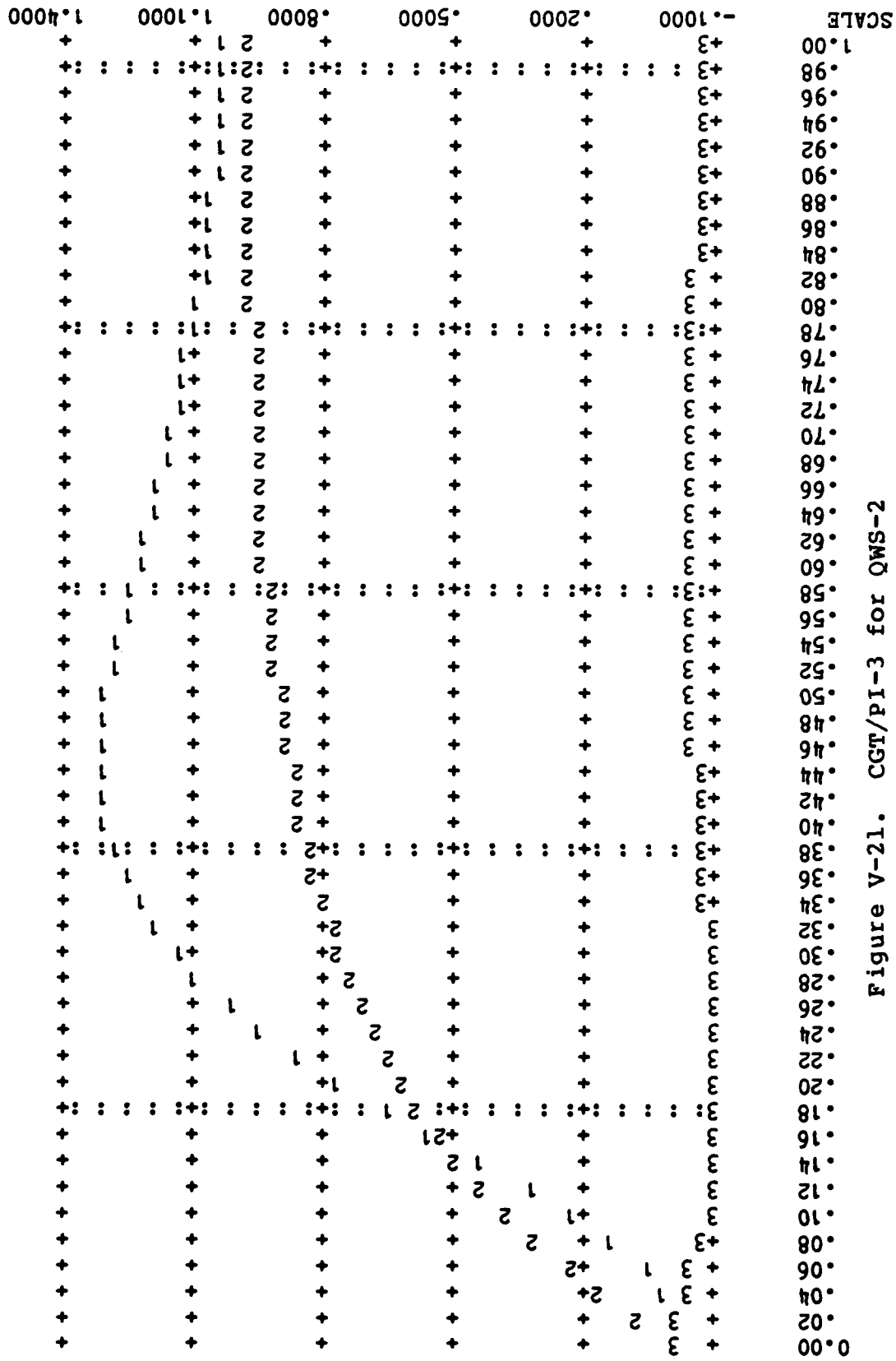


Figure V-21. CGT/PI-3 for QWS-2



SCALE 1	SCALE 2	SCALE 3	SCALE 4
0.00	+	+	+
.02	+	+	+
.04	+	+	+
.06	+	+	+
.08	+	+	+
.10	+	+	+
.12	+	+	+
.14	+	+	+
.16	+	+	+
.18	+	+	+
.20	+	+	+
.22	+	+	+
.24	+	+	+
.26	+	+	+
.28	+	+	+
.30	+	+	+
.32	+	+	+
.34	+	+	+
.36	+	+	+
.38	+	+	+
.40	+	+	+
.42	+	+	+
.44	+	+	+
.46	+	+	+
.48	+	+	+
.50	+	+	+
.52	+	+	+
.54	+	+	+
.56	+	+	+
.58	+	+	+
.60	+	+	+
.62	+	+	+
.64	+	+	+
.66	+	+	+
.68	+	+	+
.70	+	+	+
.72	+	+	+
.74	+	+	+
.76	+	+	+
.78	+	+	+
.80	+	+	+
.82	+	+	+
.84	+	+	+
.86	+	+	+
.88	+	+	+
.90	+	+	+
.92	+	+	+
.94	+	+	+
.96	+	+	+
.98	+	+	+

Figure V-23. PI for QWS-3

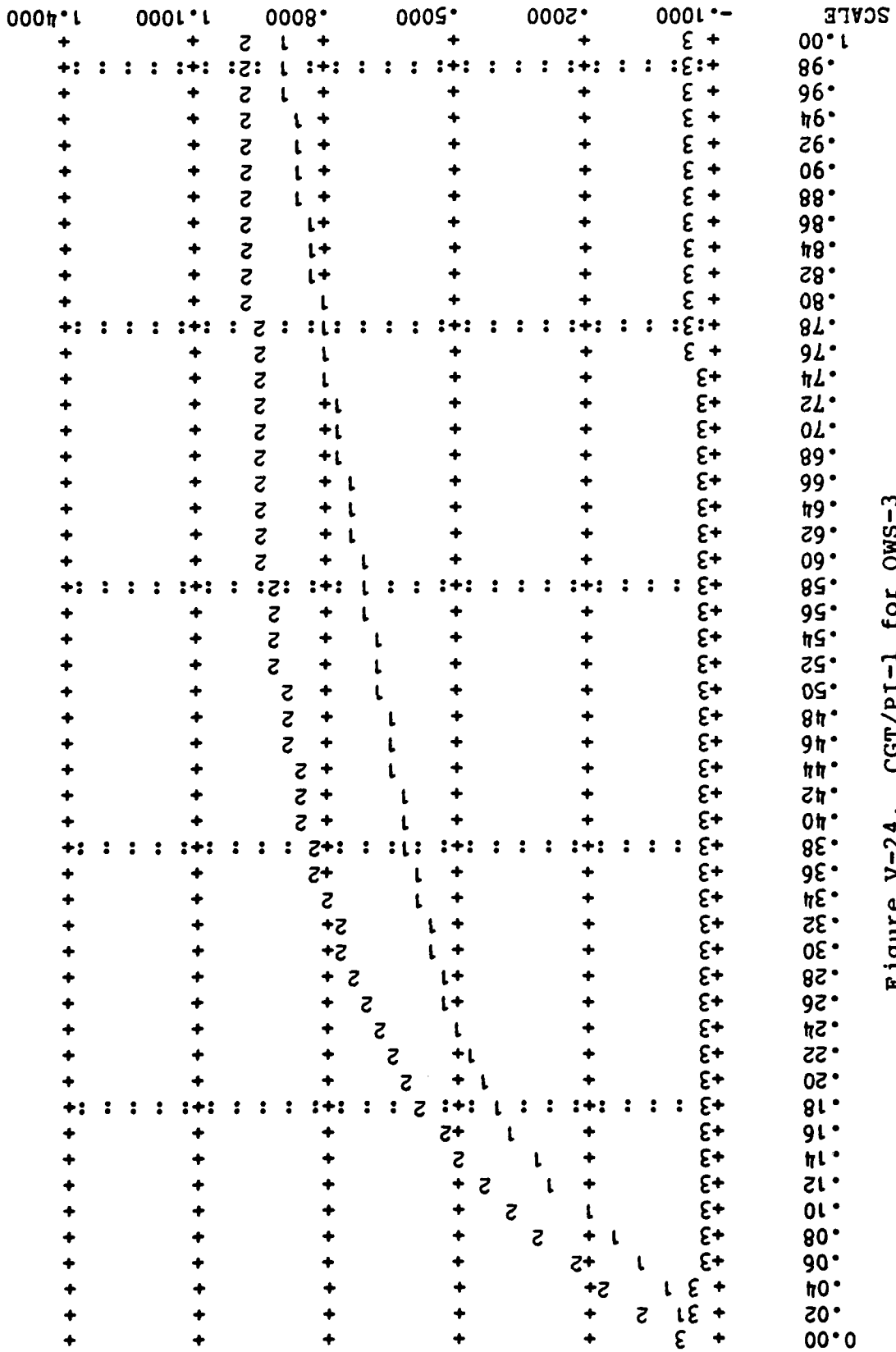


Figure V-24. CGT/PI-1 for QWS-3





SCALE	0000	2000	5000	8000	10000	14000
1.00	3					
.98	3					
.96	3					
.94	3					
.92	3					
.90	3					
.88	3					
.86	3					
.84	3					
.82	3					
.80	3					
.78	3					
.76	3					
.74	3					
.72	3					
.70	3					
.68	3					
.66	3					
.64	3					
.62	3					
.60	3					
.58	3					
.56	3					
.54	3					
.52	3					
.50	3					
.48	3					
.46	3					
.44	3					
.42	3					
.40	3					
.38	3					
.36	3					
.34	3					
.32	3					
.30	3					
.28	3					
.26	3					
.24	3					
.22	3					
.20	3					
.18	3					
.16	3					
.14	3					
.12	3					
.10	3					
.08	3					
.06	3					
.04	3					
.02	3					
0.00	3					

Figure V-26. CGT/PI-3 for QWS-3

SCALE	0000	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
1.00	+	+	+	+	+	+	+	+	+	+	+
.98	3	3	3	3	3	3	3	3	3	3	3
.96	+	+	+	+	+	+	+	+	+	+	+
.94	+	+	+	+	+	+	+	+	+	+	+
.92	+	+	+	+	+	+	+	+	+	+	+
.90	+	+	+	+	+	+	+	+	+	+	+
.88	+	+	+	+	+	+	+	+	+	+	+
.86	+	+	+	+	+	+	+	+	+	+	+
.84	+	+	+	+	+	+	+	+	+	+	+
.82	+	+	+	+	+	+	+	+	+	+	+
.80	+	+	+	+	+	+	+	+	+	+	+
.78	3	3	3	3	3	3	3	3	3	3	3
.76	+	+	+	+	+	+	+	+	+	+	+
.74	3	3	3	3	3	3	3	3	3	3	3
.72	+	+	+	+	+	+	+	+	+	+	+
.70	3	3	3	3	3	3	3	3	3	3	3
.68	+	+	+	+	+	+	+	+	+	+	+
.66	3	3	3	3	3	3	3	3	3	3	3
.64	+	+	+	+	+	+	+	+	+	+	+
.62	3	3	3	3	3	3	3	3	3	3	3
.60	+	+	+	+	+	+	+	+	+	+	+
.58	3	3	3	3	3	3	3	3	3	3	3
.56	+	+	+	+	+	+	+	+	+	+	+
.54	3	3	3	3	3	3	3	3	3	3	3
.52	+	+	+	+	+	+	+	+	+	+	+
.50	3	3	3	3	3	3	3	3	3	3	3
.48	+	+	+	+	+	+	+	+	+	+	+
.46	3	3	3	3	3	3	3	3	3	3	3
.44	+	+	+	+	+	+	+	+	+	+	+
.42	3	3	3	3	3	3	3	3	3	3	3
.40	+	+	+	+	+	+	+	+	+	+	+
.38	3	3	3	3	3	3	3	3	3	3	3
.36	+	+	+	+	+	+	+	+	+	+	+
.34	3	3	3	3	3	3	3	3	3	3	3
.32	+	+	+	+	+	+	+	+	+	+	+
.30	3	3	3	3	3	3	3	3	3	3	3
.28	+	+	+	+	+	+	+	+	+	+	+
.26	3	3	3	3	3	3	3	3	3	3	3
.24	+	+	+	+	+	+	+	+	+	+	+
.22	3	3	3	3	3	3	3	3	3	3	3
.20	+	+	+	+	+	+	+	+	+	+	+
.18	3	3	3	3	3	3	3	3	3	3	3
.16	+	+	+	+	+	+	+	+	+	+	+
.14	3	3	3	3	3	3	3	3	3	3	3
.12	+	+	+	+	+	+	+	+	+	+	+
.10	3	3	3	3	3	3	3	3	3	3	3
.08	+	+	+	+	+	+	+	+	+	+	+
.06	3	3	3	3	3	3	3	3	3	3	3
.04	+	+	+	+	+	+	+	+	+	+	+
.02	3	3	3	3	3	3	3	3	3	3	3
0.00	+	+	+	+	+	+	+	+	+	+	+

Figure V-27. CGT/PI-4 for QWS-3

SCALE 4	SCALE 3	SCALE 2	SCALE 1
0.00	+	3	+
0.02	+	+	+
0.04	+	4	+
0.06	+	4	+
0.08	+	4	+
0.10	+	4	+
0.12	+	4	+
0.14	+	4	+
0.16	+	4	+
0.18	+	4	+
0.20	+	4	+
0.22	+	4	+
0.24	+	4	+
0.26	+	4	+
0.28	+	4	+
0.30	+	4	+
0.32	+	4	+
0.34	+	4	+
0.36	+	4	+
0.38	+	4	+
0.40	+	4	+
0.42	+	4	+
0.44	+	4	+
0.46	+	4	+
0.48	+	4	+
0.50	+	4	+
0.52	+	4	+
0.54	+	4	+
0.56	+	4	+
0.58	+	4	+
0.60	+	4	+
0.62	+	4	+
0.64	+	4	+
0.66	+	4	+
0.68	+	4	+
0.70	+	4	+
0.72	+	4	+
0.74	+	4	+
0.76	+	4	+
0.78	+	4	+
0.80	+	4	+
0.82	+	4	+
0.84	+	4	+
0.86	+	4	+
0.88	+	4	+
0.90	+	4	+
0.92	+	4	+
0.94	+	4	+
0.96	+	4	+
0.98	+	4	+

Figure V-28. PI for QWS-4

SCALE	- .1000	.2000	.5000	.8000	1.1000	1.4000
0.00	3					
.02	3					
.04	3	2				
.06	3	1				
.08	3	2				
.10	3	1				
.12	3	2				
.14	3	1				
.16	3	2	1			
.18	3	1	2			
.20	3	1	2			
.22	3	1	2			
.24	3	1	2			
.26	3	1	2			
.28	3	1	2			
.30	3	1	2			
.32	3	1	2			
.34	3	1	2			
.36	3	1	2			
.38	3	1	2			
.40	3	1	2			
.42	3	1	2			
.44	3	1	2			
.46	3	1	2			
.48	3	1	2			
.50	3	1	2			
.52	3	1	2			
.54	3	1	2			
.56	3	1	2			
.58	3	1	2			
.60	3	1	2			
.62	3	1	2			
.64	3	1	2			
.66	3	1	2			
.68	3	1	2			
.70	3	1	2			
.72	3	1	2			
.74	3	1	2			
.76	3	1	2			
.78	3	1	2			
.80	3	1	2			
.82	3	1	2			
.84	3	1	2			
.86	3	1	2			
.88	3	1	2			
.90	3	1	2			
.92	3	1	2			
.94	3	1	2			
.96	3	1	2			
.98	3	1	2			
1.00	3	1	2			

Figure V-29. CGT/PI-1 for QWS-4

SCALE

SCALE	0.00	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.70	0.72	0.74	0.76	0.78	0.80	0.82	0.84	0.86	0.88	0.90	0.92	0.94	0.96	0.98	1.00								
+ .1000	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3								
+ .2000		2																																																									
+ .5000			2							2																																																	
+ .8000						2							2					1																																									
+ 1.0000																																																											
+ 1.4000																																																											

Figure V-30. CGT/PI-2 for QWS-4

SCALE	1.000	2000	5000	8000	1.1000	1.4000
1.00	3	+	+	+	+	+
.98	3	+	+	+	+	+
.96	3	+	+	+	+	+
.94	3	+	+	+	+	+
.92	3	+	+	+	+	+
.90	3	+	+	+	+	+
.88	3	+	+	+	+	+
.86	3	+	+	+	+	+
.84	3	+	+	+	+	+
.82	3	+	+	+	+	+
.80	3	+	+	+	+	+
.78	3	+	+	+	+	+
.76	3	+	+	+	+	+
.74	3	+	+	+	+	+
.72	3	+	+	+	+	+
.70	3	+	+	+	+	+
.68	3	+	+	+	+	+
.66	3	+	+	+	+	+
.64	3	+	+	+	+	+
.62	3	+	+	+	+	+
.60	3	+	+	+	+	+
.58	3	+	+	+	+	+
.56	3	+	+	+	+	+
.54	3	+	+	+	+	+
.52	3	+	+	+	+	+
.50	3	+	+	+	+	+
.48	3	+	+	+	+	+
.46	3	+	+	+	+	+
.44	3	+	+	+	+	+
.42	3	+	+	+	+	+
.40	3	+	+	+	+	+
.38	3	+	+	+	+	+
.36	3	+	+	+	+	+
.34	3	+	+	+	+	+
.32	3	+	+	+	+	+
.30	3	+	+	+	+	+
.28	3	+	+	+	+	+
.26	3	+	+	+	+	+
.24	3	+	+	+	+	+
.22	3	+	+	+	+	+
.20	3	+	+	+	+	+
.18	3	+	+	+	+	+
.16	3	+	+	+	+	+
.14	3	+	+	+	+	+
.12	3	+	+	+	+	+
.10	3	+	+	+	+	+
.08	3	+	+	+	+	+
.06	3	+	+	+	+	+
.04	3	+	+	+	+	+
.02	3	+	+	+	+	+
0.00	3	+	+	+	+	+

Figure V-31. CGT/PI-3 for QWS-4

SCALE	0000	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
1.00	3	3	3	3	3	3	3	3	3	3	3
.98	3	3	3	3	3	3	3	3	3	3	3
.96	3	3	3	3	3	3	3	3	3	3	3
.94	3	3	3	3	3	3	3	3	3	3	3
.92	3	3	3	3	3	3	3	3	3	3	3
.90	3	3	3	3	3	3	3	3	3	3	3
.88	3	3	3	3	3	3	3	3	3	3	3
.86	3	3	3	3	3	3	3	3	3	3	3
.84	3	3	3	3	3	3	3	3	3	3	3
.82	3	3	3	3	3	3	3	3	3	3	3
.80	3	3	3	3	3	3	3	3	3	3	3
.78	3	3	3	3	3	3	3	3	3	3	3
.76	3	3	3	3	3	3	3	3	3	3	3
.74	3	3	3	3	3	3	3	3	3	3	3
.72	3	3	3	3	3	3	3	3	3	3	3
.70	3	3	3	3	3	3	3	3	3	3	3
.68	3	3	3	3	3	3	3	3	3	3	3
.66	3	3	3	3	3	3	3	3	3	3	3
.64	3	3	3	3	3	3	3	3	3	3	3
.62	3	3	3	3	3	3	3	3	3	3	3
.60	3	3	3	3	3	3	3	3	3	3	3
.58	3	3	3	3	3	3	3	3	3	3	3
.56	3	3	3	3	3	3	3	3	3	3	3
.54	3	3	3	3	3	3	3	3	3	3	3
.52	3	3	3	3	3	3	3	3	3	3	3
.50	3	3	3	3	3	3	3	3	3	3	3
.48	3	3	3	3	3	3	3	3	3	3	3
.46	3	3	3	3	3	3	3	3	3	3	3
.44	3	3	3	3	3	3	3	3	3	3	3
.42	3	3	3	3	3	3	3	3	3	3	3
.40	3	3	3	3	3	3	3	3	3	3	3
.38	3	3	3	3	3	3	3	3	3	3	3
.36	3	3	3	3	3	3	3	3	3	3	3
.34	3	3	3	3	3	3	3	3	3	3	3
.32	3	3	3	3	3	3	3	3	3	3	3
.30	3	3	3	3	3	3	3	3	3	3	3
.28	3	3	3	3	3	3	3	3	3	3	3
.26	3	3	3	3	3	3	3	3	3	3	3
.24	3	3	3	3	3	3	3	3	3	3	3
.22	3	3	3	3	3	3	3	3	3	3	3
.20	3	3	3	3	3	3	3	3	3	3	3
.18	3	3	3	3	3	3	3	3	3	3	3
.16	3	3	3	3	3	3	3	3	3	3	3
.14	3	3	3	3	3	3	3	3	3	3	3
.12	3	3	3	3	3	3	3	3	3	3	3
.10	3	3	3	3	3	3	3	3	3	3	3
.08	3	3	3	3	3	3	3	3	3	3	3
.06	3	3	3	3	3	3	3	3	3	3	3
.04	3	3	3	3	3	3	3	3	3	3	3
.02	3	3	3	3	3	3	3	3	3	3	3
0.00	3	3	3	3	3	3	3	3	3	3	3

Figure V-32. CGT/PI-4 for QWS-4



SCALE 4	SCALE 3	SCALE 2	SCALE 1
.98	+	+	+
.96	+	+	+
.94	+	+	+
.92	+	+	+
.90	+	+	+
.88	+	+	+
.86	+	+	+
.84	+	+	+
.82	+	+	+
.80	+	+	+
.78	+	+	+
.76	+	+	+
.74	+	+	+
.72	+	+	+
.70	+	+	+
.68	+	+	+
.66	+	+	+
.64	+	+	+
.62	+	+	+
.60	+	+	+
.58	+	+	+
.56	+	+	+
.54	+	+	+
.52	+	+	+
.50	+	+	+
.48	+	+	+
.46	+	+	+
.44	+	+	+
.42	+	+	+
.40	+	+	+
.38	+	+	+
.36	+	+	+
.34	+	+	+
.32	+	+	+
.30	+	+	+
.28	+	+	+
.26	+	+	+
.24	+	+	+
.22	+	+	+
.20	+	+	+
.18	+	+	+
.16	+	+	+
.14	+	+	+
.12	+	+	+
.10	+	+	+
.08	+	+	+
.06	+	+	+
.04	+	+	+
.02	+	+	+
.00	+	+	+

Figure V-33. PI for QWS-5

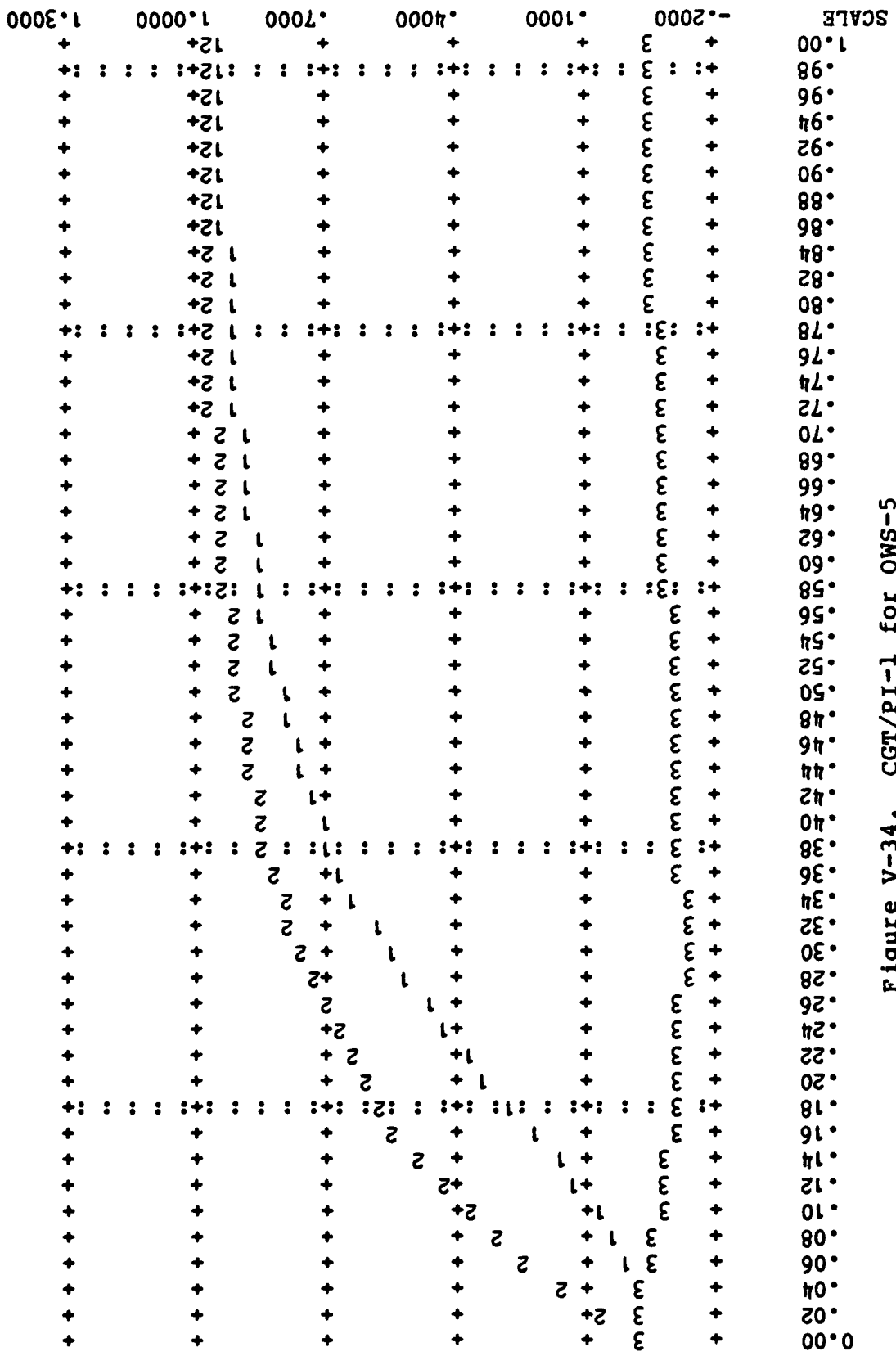


Figure V-34. CGT/PI-1 for QWS-5

SCALE	-.2000	.1000	.4000	.7000	1.0000	1.3000
1.00	+	+	+	+	+	+
.98	+	+	+	+	+	+
.96	+	+	+	+	+	+
.94	+	+	+	+	+	+
.92	+	+	+	+	+	+
.90	+	+	+	+	+	+
.88	+	+	+	+	+	+
.86	+	+	+	+	+	+
.84	+	+	+	+	+	+
.82	+	+	+	+	+	+
.80	+	+	+	+	+	+
.78	+	+	+	+	+	+
.76	+	+	+	+	+	+
.74	+	+	+	+	+	+
.72	+	+	+	+	+	+
.70	+	+	+	+	+	+
.68	+	+	+	+	+	+
.66	+	+	+	+	+	+
.64	+	+	+	+	+	+
.62	+	+	+	+	+	+
.60	+	+	+	+	+	+
.58	+	+	+	+	+	+
.56	+	+	+	+	+	+
.54	+	+	+	+	+	+
.52	+	+	+	+	+	+
.50	+	+	+	+	+	+
.48	+	+	+	+	+	+
.46	+	+	+	+	+	+
.44	+	+	+	+	+	+
.42	+	+	+	+	+	+
.40	+	+	+	+	+	+
.38	+	+	+	+	+	+
.36	+	+	+	+	+	+
.34	+	+	+	+	+	+
.32	+	+	+	+	+	+
.30	+	+	+	+	+	+
.28	+	+	+	+	+	+
.26	+	+	+	+	+	+
.24	+	+	+	+	+	+
.22	+	+	+	+	+	+
.20	+	+	+	+	+	+
.18	+	+	+	+	+	+
.16	+	+	+	+	+	+
.14	+	+	+	+	+	+
.12	+	+	+	+	+	+
.10	+	+	+	+	+	+
.08	+	+	+	+	+	+
.06	+	+	+	+	+	+
.04	+	+	+	+	+	+
.02	+	+	+	+	+	+
0.00	+	+	+	+	+	+

Figure V-35. CGT/PI-2 for QWS-5

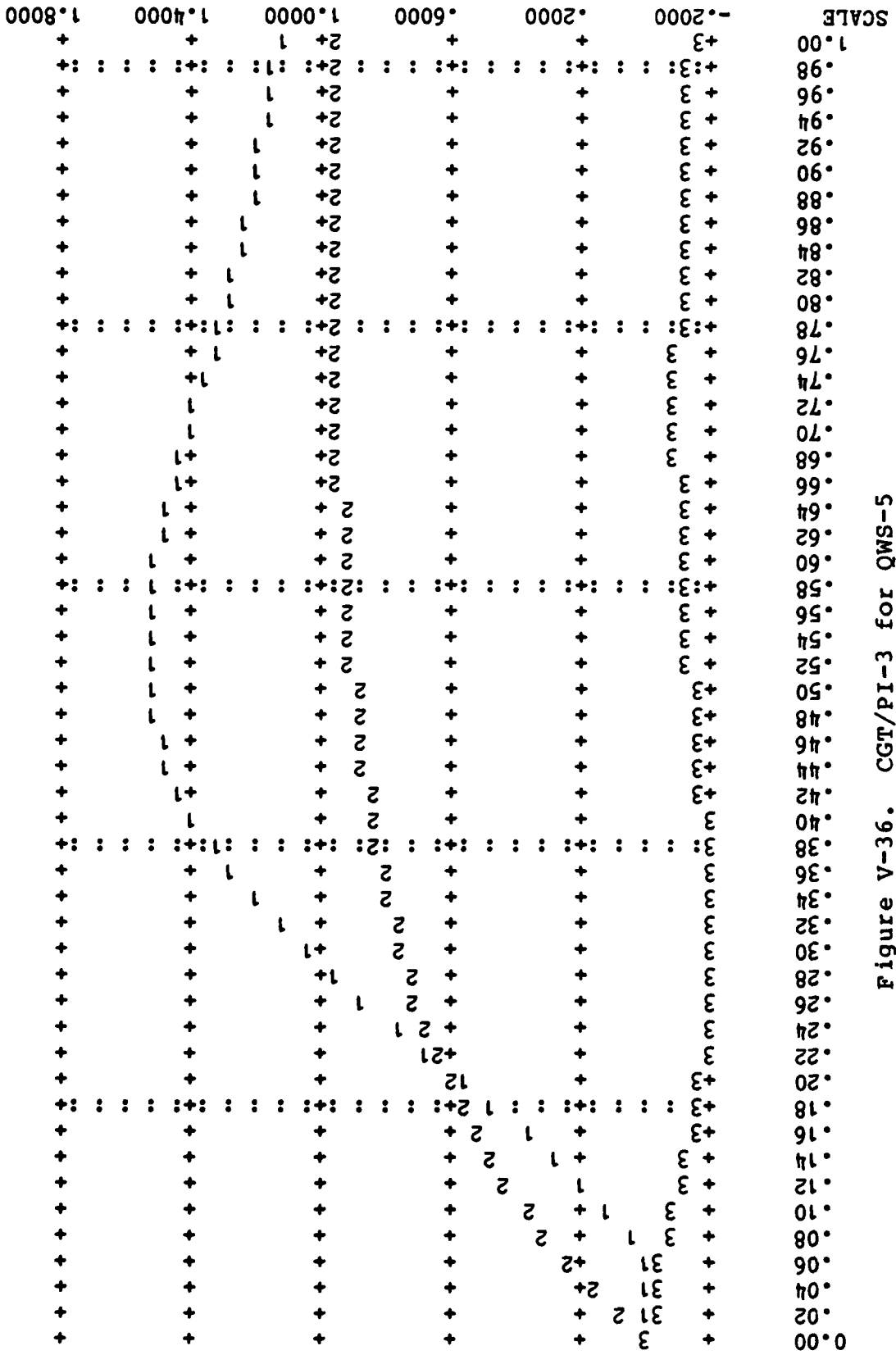
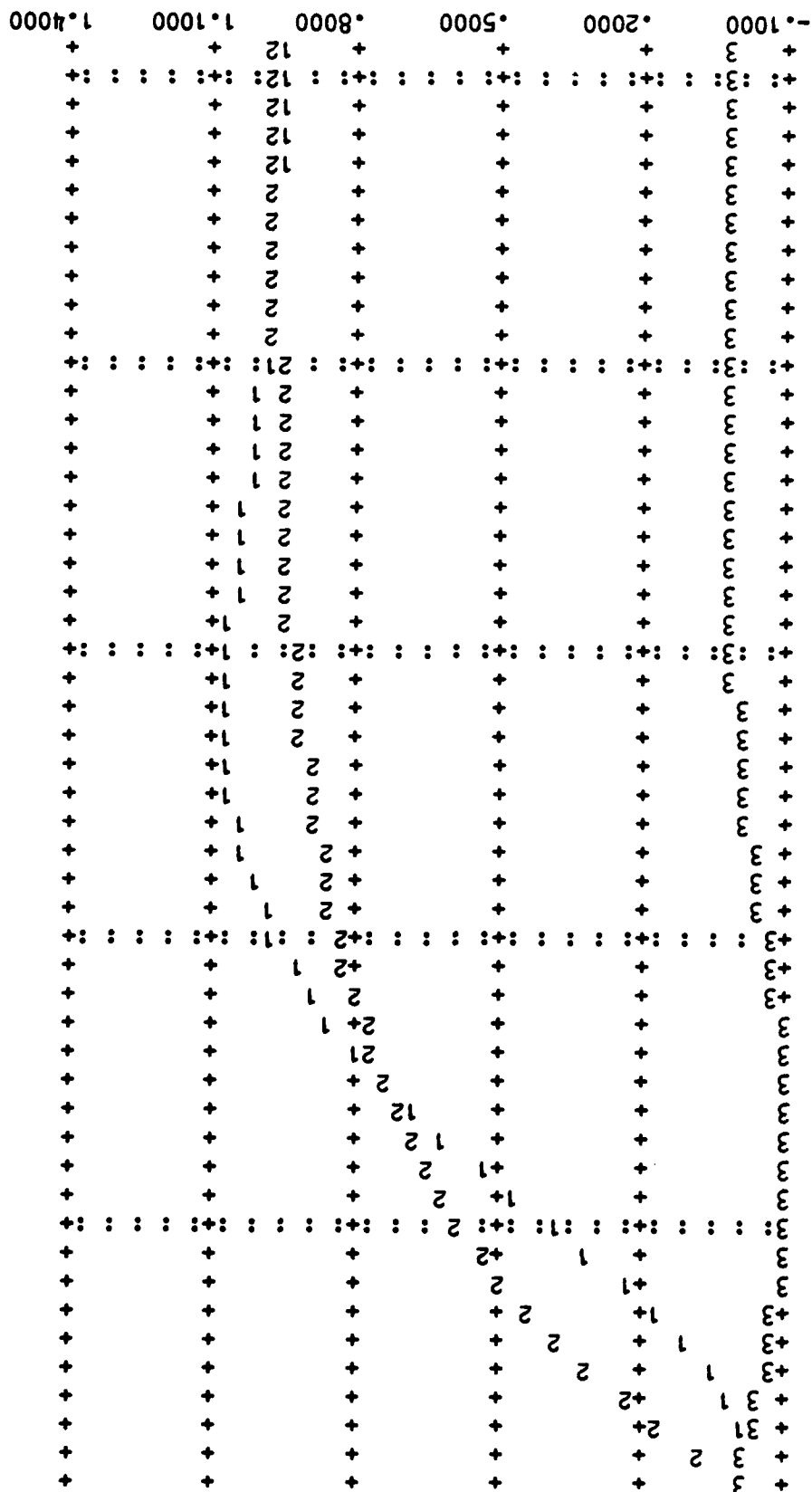


Figure V-36. CGT/PI-3 for QWS-5

SCALE  
 1.00  
 .98  
 .96  
 .94  
 .92  
 .90  
 .88  
 .86  
 .84  
 .82  
 .80  
 .78  
 .76  
 .74  
 .72  
 .70  
 .68  
 .66  
 .64  
 .62  
 .60  
 .58  
 .56  
 .54  
 .52  
 .50  
 .48  
 .46  
 .44  
 .42  
 .40  
 .38  
 .36  
 .34  
 .32  
 .30  
 .28  
 .26  
 .24  
 .22  
 .20  
 .18  
 .16  
 .14  
 .12  
 .10  
 .08  
 .06  
 .04  
 .02  
 0.00

Figure V-37. CGT/PI-4 for QWS-5



SCALE 4	SCALE 3	SCALE 2	SCALE 1
0.00	3	+	+
0.02	+	+	+
0.04	+	+	+
0.06	+	+	+
0.08	+	+	+
0.10	+	+	+
0.12	+	+	+
0.14	+	+	+
0.16	+	+	+
0.18	+	+	+
0.20	+	+	+
0.22	+	+	+
0.24	+	+	+
0.26	+	+	+
0.28	+	+	+
0.30	+	+	+
0.32	+	+	+
0.34	+	+	+
0.36	+	+	+
0.38	+	+	+
0.40	+	+	+
0.42	+	+	+
0.44	+	+	+
0.46	+	+	+
0.48	+	+	+
0.50	+	+	+
0.52	+	+	+
0.54	+	+	+
0.56	+	+	+
0.58	+	+	+
0.60	+	+	+
0.62	+	+	+
0.64	+	+	+
0.66	+	+	+
0.68	+	+	+
0.70	+	+	+
0.72	+	+	+
0.74	+	+	+
0.76	+	+	+
0.78	+	+	+
0.80	+	+	+
0.82	+	+	+
0.84	+	+	+
0.86	+	+	+
0.88	+	+	+
0.90	+	+	+
0.92	+	+	+
0.94	+	+	+
0.96	+	+	+
0.98	+	+	+

Figure V-38. PI for QWS-6

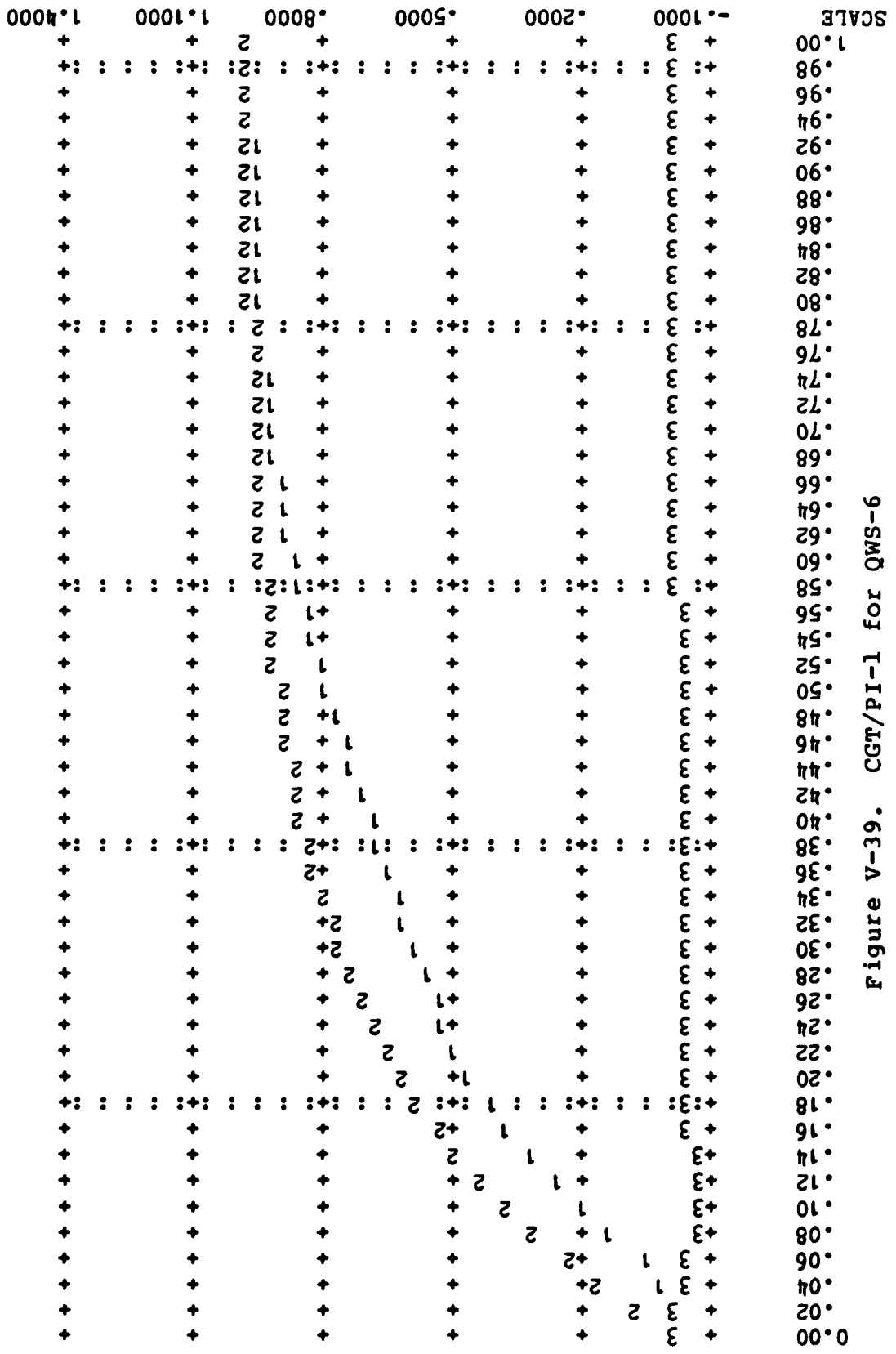


Figure V-39. CGT/PI-1 for QWS-6

SCALE	1.00	0.98	0.96	0.94	0.92	0.90	0.88	0.86	0.84	0.82	0.80	0.78	0.76	0.74	0.72	0.70	0.68	0.66	0.64	0.62	0.60	0.58	0.56	0.54	0.52	0.50	0.48	0.46	0.44	0.42	0.40	0.38	0.36	0.34	0.32	0.30	0.28	0.26	0.24	0.22	0.20	0.18	0.16	0.14	0.12	0.10	0.08	0.06	0.04	0.02	0.00				
1.4000	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		
1.1000	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
.8000	+	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	21	21	21	21	21	21	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
.5000	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
.2000	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
-.1000	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	

Figure V-40. CGT/PI-2 for QWS-6



SCALE	.0000	.0002	.0005	.0008	.0010	.0014
1.00	3	3	3	3	3	3
.98	3	3	3	3	3	3
.96	3	3	3	3	3	3
.94	3	3	3	3	3	3
.92	3	3	3	3	3	3
.90	3	3	3	3	3	3
.88	3	3	3	3	3	3
.86	3	3	3	3	3	3
.84	3	3	3	3	3	3
.82	3	3	3	3	3	3
.80	3	3	3	3	3	3
.78	3	3	3	3	3	3
.76	3	3	3	3	3	3
.74	3	3	3	3	3	3
.72	3	3	3	3	3	3
.70	3	3	3	3	3	3
.68	3	3	3	3	3	3
.66	3	3	3	3	3	3
.64	3	3	3	3	3	3
.62	3	3	3	3	3	3
.60	3	3	3	3	3	3
.58	3	3	3	3	3	3
.56	3	3	3	3	3	3
.54	3	3	3	3	3	3
.52	3	3	3	3	3	3
.50	3	3	3	3	3	3
.48	3	3	3	3	3	3
.46	3	3	3	3	3	3
.44	3	3	3	3	3	3
.42	3	3	3	3	3	3
.40	3	3	3	3	3	3
.38	3	3	3	3	3	3
.36	3	3	3	3	3	3
.34	3	3	3	3	3	3
.32	3	3	3	3	3	3
.30	3	3	3	3	3	3
.28	3	3	3	3	3	3
.26	3	3	3	3	3	3
.24	3	3	3	3	3	3
.22	3	3	3	3	3	3
.20	3	3	3	3	3	3
.18	3	3	3	3	3	3
.16	3	3	3	3	3	3
.14	3	3	3	3	3	3
.12	3	3	3	3	3	3
.10	3	3	3	3	3	3
.08	3	3	3	3	3	3
.06	3	3	3	3	3	3
.04	3	3	3	3	3	3
.02	3	3	3	3	3	3
0.00	3	3	3	3	3	3

Figure V-41. CGT/PI-3 for QWS-6

SCALE	1.0000	2000	5000	8000	1.1000	1.4000
1.00	3	+	+	+	+	+
.98	3	+	+	+	+	+
.96	3	+	+	+	+	+
.94	3	+	+	+	+	+
.92	3	+	+	+	+	+
.90	3	+	+	+	+	+
.88	3	+	+	+	+	+
.86	3	+	+	+	+	+
.84	3	+	+	+	+	+
.82	3	+	+	+	+	+
.80	3	+	+	+	+	+
.78	3	+	+	+	+	+
.76	3	+	+	+	+	+
.74	3	+	+	+	+	+
.72	3	+	+	+	+	+
.70	3	+	+	+	+	+
.68	3	+	+	+	+	+
.66	3	+	+	+	+	+
.64	3	+	+	+	+	+
.62	3	+	+	+	+	+
.60	3	+	+	+	+	+
.58	3	+	+	+	+	+
.56	3	+	+	+	+	+
.54	3	+	+	+	+	+
.52	3	+	+	+	+	+
.50	3	+	+	+	+	+
.48	3	+	+	+	+	+
.46	3	+	+	+	+	+
.44	3	+	+	+	+	+
.42	3	+	+	+	+	+
.40	3	+	+	+	+	+
.38	3	+	+	+	+	+
.36	3	+	+	+	+	+
.34	3	+	+	+	+	+
.32	3	+	+	+	+	+
.30	3	+	+	+	+	+
.28	3	+	+	+	+	+
.26	3	+	+	+	+	+
.24	3	+	+	+	+	+
.22	3	+	+	+	+	+
.20	3	+	+	+	+	+
.18	3	+	+	+	+	+
.16	3	+	+	+	+	+
.14	3	+	+	+	+	+
.12	3	+	+	+	+	+
.10	3	+	+	+	+	+
.08	3	+	+	+	+	+
.06	3	+	+	+	+	+
.04	3	+	+	+	+	+
.02	3	+	+	+	+	+
0.00	3	+	+	+	+	+

Figure V-42. CGT/PI-4 for QWS-6

SCALE 4	SCALE 3	SCALE 2	SCALE 1
0.00	3	+	+
.02	+	+	+
.04	+	+	+
.06	+	+	+
.08	+	+	+
.10	+	+	+
.12	+	+	+
.14	+	+	+
.16	+	+	+
.18	+	+	+
.20	+	+	+
.22	+	+	+
.24	+	+	+
.26	+	+	+
.28	+	+	+
.30	+	+	+
.32	+	+	+
.34	+	+	+
.36	+	+	+
.38	+	+	+
.40	+	+	+
.42	+	+	+
.44	+	+	+
.46	+	+	+
.48	+	+	+
.50	+	+	+
.52	+	+	+
.54	+	+	+
.56	+	+	+
.58	+	+	+
.60	+	+	+
.62	+	+	+
.64	+	+	+
.66	+	+	+
.68	+	+	+
.70	+	+	+
.72	+	+	+
.74	+	+	+
.76	+	+	+
.78	+	+	+
.80	+	+	+
.82	+	+	+
.84	+	+	+
.86	+	+	+
.88	+	+	+
.90	+	+	+
.92	+	+	+
.94	+	+	+
.96	+	+	+
.98	+	+	+

Figure V-43. PI for QWS-7

SCALE	-0.1000	.2000	.5000	.8000	1.1000	1.4000
1.00	+	+	+	+	+	+
.98	3	3	3	3	3	3
.96	3	3	3	3	3	3
.94	3	3	3	3	3	3
.92	3	3	3	3	3	3
.90	3	3	3	3	3	3
.88	3	3	3	3	3	3
.86	3	3	3	3	3	3
.84	3	3	3	3	3	3
.82	3	3	3	3	3	3
.80	3	3	3	3	3	3
.78	3	3	3	3	3	3
.76	3	3	3	3	3	3
.74	3	3	3	3	3	3
.72	3	3	3	3	3	3
.70	3	3	3	3	3	3
.68	3	3	3	3	3	3
.66	3	3	3	3	3	3
.64	3	3	3	3	3	3
.62	3	3	3	3	3	3
.60	3	3	3	3	3	3
.58	3	3	3	3	3	3
.56	3	3	3	3	3	3
.54	3	3	3	3	3	3
.52	3	3	3	3	3	3
.50	3	3	3	3	3	3
.48	3	3	3	3	3	3
.46	3	3	3	3	3	3
.44	3	3	3	3	3	3
.42	3	3	3	3	3	3
.40	3	3	3	3	3	3
.38	3	3	3	3	3	3
.36	3	3	3	3	3	3
.34	3	3	3	3	3	3
.32	3	3	3	3	3	3
.30	3	3	3	3	3	3
.28	3	3	3	3	3	3
.26	3	3	3	3	3	3
.24	3	3	3	3	3	3
.22	3	3	3	3	3	3
.20	3	3	3	3	3	3
.18	3	3	3	3	3	3
.16	3	3	3	3	3	3
.14	3	3	3	3	3	3
.12	3	3	3	3	3	3
.10	3	3	3	3	3	3
.08	3	3	3	3	3	3
.06	3	3	3	3	3	3
.04	3	3	3	3	3	3
.02	3	3	3	3	3	3
0.00	3	3	3	3	3	3

Figure V-44. CGT/PI-1 for QWS-7

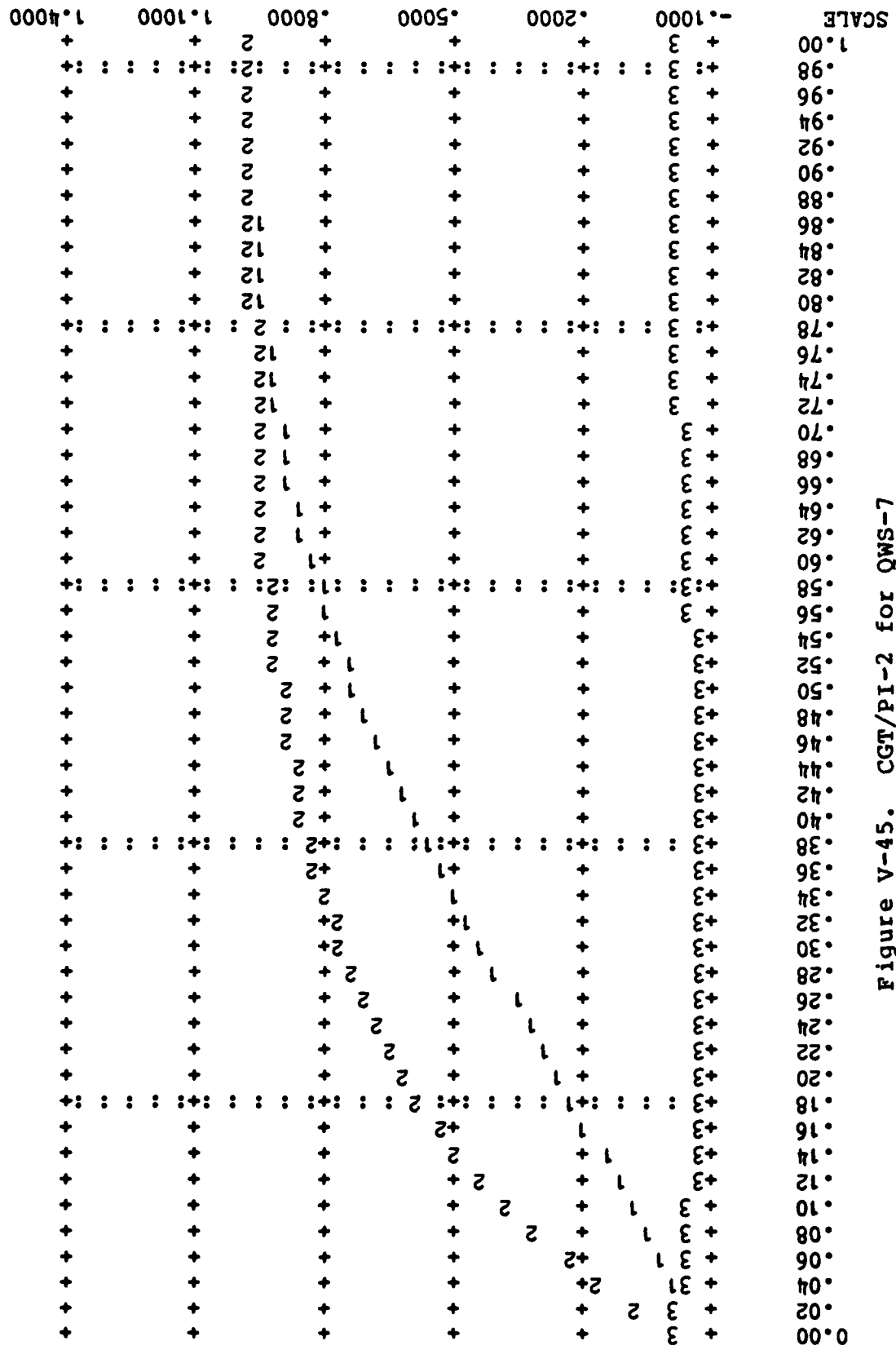


Figure V-45. CGT/PI-2 for QWS-7

SCALE	1.000	2000	5000	8000	10000	14000
1.00	+	+	+	+	+	+
.98	+	+	+	+	+	+
.96	+	+	+	+	+	+
.94	+	+	+	+	+	+
.92	+	+	+	+	+	+
.90	+	+	+	+	+	+
.88	+	+	+	+	+	+
.86	+	+	+	+	+	+
.84	+	+	+	+	+	+
.82	+	+	+	+	+	+
.80	+	+	+	+	+	+
.78	+	+	+	+	+	+
.76	+	+	+	+	+	+
.74	+	+	+	+	+	+
.72	+	+	+	+	+	+
.70	+	+	+	+	+	+
.68	+	+	+	+	+	+
.66	+	+	+	+	+	+
.64	+	+	+	+	+	+
.62	+	+	+	+	+	+
.60	+	+	+	+	+	+
.58	+	+	+	+	+	+
.56	+	+	+	+	+	+
.54	+	+	+	+	+	+
.52	+	+	+	+	+	+
.50	+	+	+	+	+	+
.48	+	+	+	+	+	+
.46	+	+	+	+	+	+
.44	+	+	+	+	+	+
.42	+	+	+	+	+	+
.40	+	+	+	+	+	+
.38	+	+	+	+	+	+
.36	+	+	+	+	+	+
.34	+	+	+	+	+	+
.32	+	+	+	+	+	+
.30	+	+	+	+	+	+
.28	+	+	+	+	+	+
.26	+	+	+	+	+	+
.24	+	+	+	+	+	+
.22	+	+	+	+	+	+
.20	+	+	+	+	+	+
.18	+	+	+	+	+	+
.16	+	+	+	+	+	+
.14	+	+	+	+	+	+
.12	+	+	+	+	+	+
.10	+	+	+	+	+	+
.08	+	+	+	+	+	+
.06	+	+	+	+	+	+
.04	+	+	+	+	+	+
.02	+	+	+	+	+	+
0.00	+	+	+	+	+	+

Figure V-46. CGT/PI-3 for QWS-7

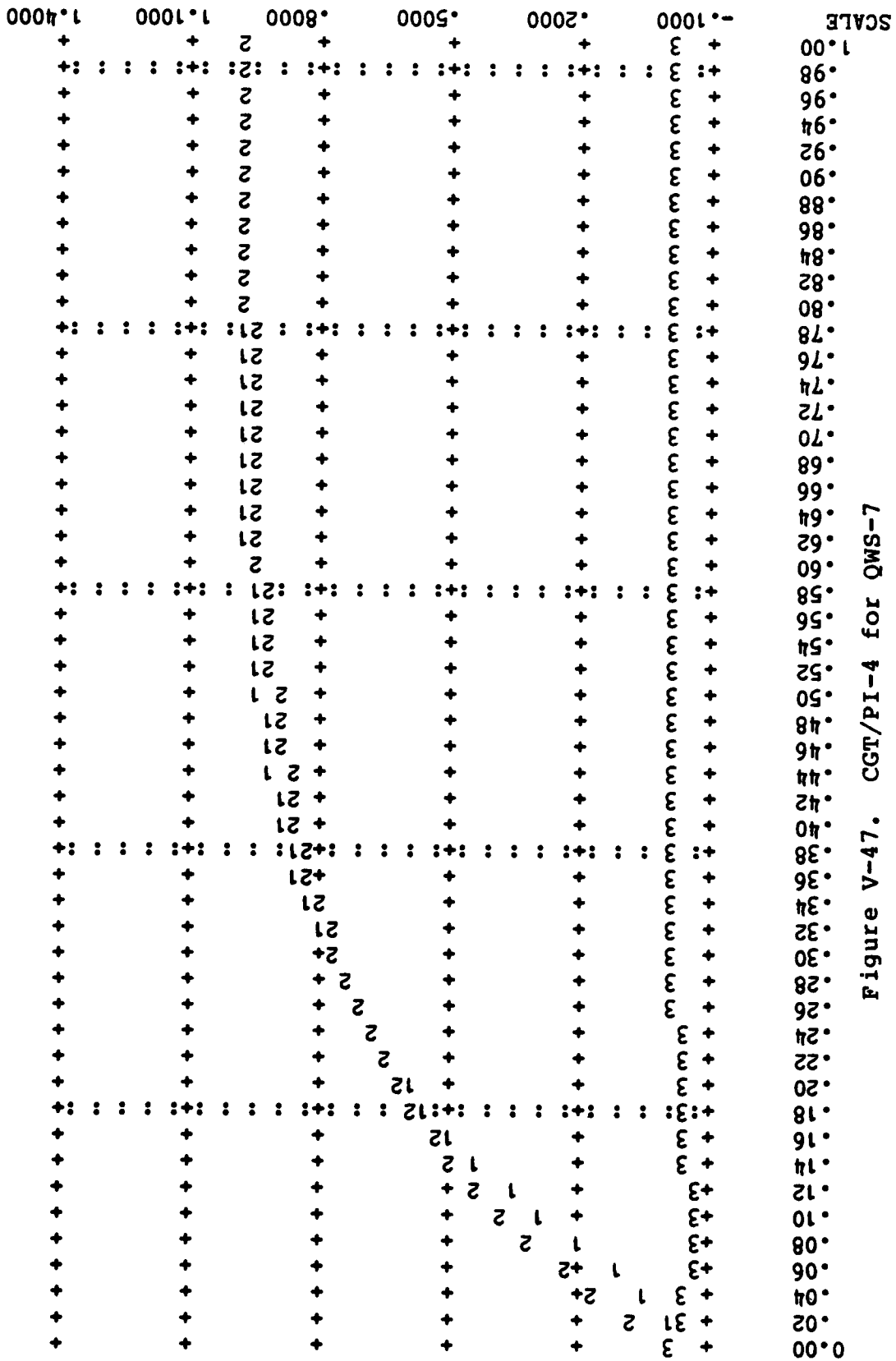


Figure V-47. CGT/PI-4 for QWS-7

SCALE 4 15.0000	SCALE 3 6.0000	SCALE 2 4.0000	SCALE 1 2.0000	SCALE 4 5.0000	SCALE 3 7.0000	SCALE 2 8.0000	SCALE 1 1.4000
0.00	3						
.02							
.04							
.06							
.08							
.10							
.12							
.14							
.16							
.18							
.20							
.22							
.24							
.26							
.28							
.30							
.32							
.34							
.36							
.38							
.40							
.42							
.44							
.46							
.48							
.50							
.52							
.54							
.56							
.58							
.60							
.62							
.64							
.66							
.68							
.70							
.72							
.74							
.76							
.78							
.80							
.82							
.84							
.86							
.88							
.90							
.92							
.94							
.96							
.98							

Figure V-48. PI for QWS-8



SCALE	0000	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
1.00	+	+	+	+	+	+	+	+	+	+	+
.98	+	+	+	+	+	+	+	+	+	+	+
.96	+	+	+	+	+	+	+	+	+	+	+
.94	+	+	+	+	+	+	+	+	+	+	+
.92	+	+	+	+	+	+	+	+	+	+	+
.90	+	+	+	+	+	+	+	+	+	+	+
.88	+	+	+	+	+	+	+	+	+	+	+
.86	+	+	+	+	+	+	+	+	+	+	+
.84	+	+	+	+	+	+	+	+	+	+	+
.82	+	+	+	+	+	+	+	+	+	+	+
.80	+	+	+	+	+	+	+	+	+	+	+
.78	+	+	+	+	+	+	+	+	+	+	+
.76	+	+	+	+	+	+	+	+	+	+	+
.74	+	+	+	+	+	+	+	+	+	+	+
.72	+	+	+	+	+	+	+	+	+	+	+
.70	+	+	+	+	+	+	+	+	+	+	+
.68	+	+	+	+	+	+	+	+	+	+	+
.66	+	+	+	+	+	+	+	+	+	+	+
.64	+	+	+	+	+	+	+	+	+	+	+
.62	+	+	+	+	+	+	+	+	+	+	+
.60	+	+	+	+	+	+	+	+	+	+	+
.58	+	+	+	+	+	+	+	+	+	+	+
.56	+	+	+	+	+	+	+	+	+	+	+
.54	+	+	+	+	+	+	+	+	+	+	+
.52	+	+	+	+	+	+	+	+	+	+	+
.50	+	+	+	+	+	+	+	+	+	+	+
.48	+	+	+	+	+	+	+	+	+	+	+
.46	+	+	+	+	+	+	+	+	+	+	+
.44	+	+	+	+	+	+	+	+	+	+	+
.42	+	+	+	+	+	+	+	+	+	+	+
.40	+	+	+	+	+	+	+	+	+	+	+
.38	+	+	+	+	+	+	+	+	+	+	+
.36	+	+	+	+	+	+	+	+	+	+	+
.34	+	+	+	+	+	+	+	+	+	+	+
.32	+	+	+	+	+	+	+	+	+	+	+
.30	+	+	+	+	+	+	+	+	+	+	+
.28	+	+	+	+	+	+	+	+	+	+	+
.26	+	+	+	+	+	+	+	+	+	+	+
.24	+	+	+	+	+	+	+	+	+	+	+
.22	+	+	+	+	+	+	+	+	+	+	+
.20	+	+	+	+	+	+	+	+	+	+	+
.18	+	+	+	+	+	+	+	+	+	+	+
.16	+	+	+	+	+	+	+	+	+	+	+
.14	+	+	+	+	+	+	+	+	+	+	+
.12	+	+	+	+	+	+	+	+	+	+	+
.10	+	+	+	+	+	+	+	+	+	+	+
.08	+	+	+	+	+	+	+	+	+	+	+
.06	+	+	+	+	+	+	+	+	+	+	+
.04	+	+	+	+	+	+	+	+	+	+	+
.02	+	+	+	+	+	+	+	+	+	+	+
0.00	+	+	+	+	+	+	+	+	+	+	+

Figure V-49. CGT/PI-1 for QWS-8

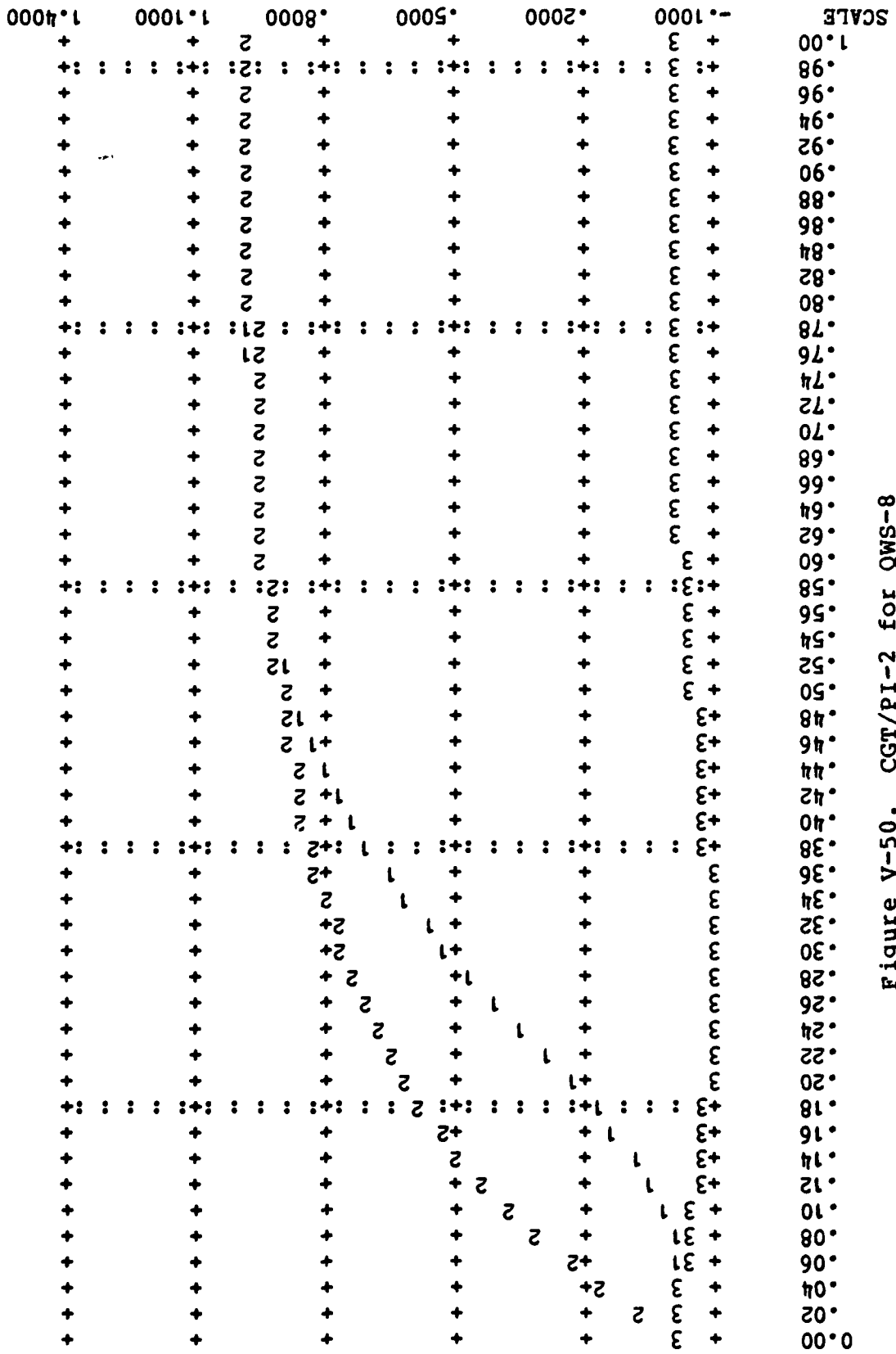
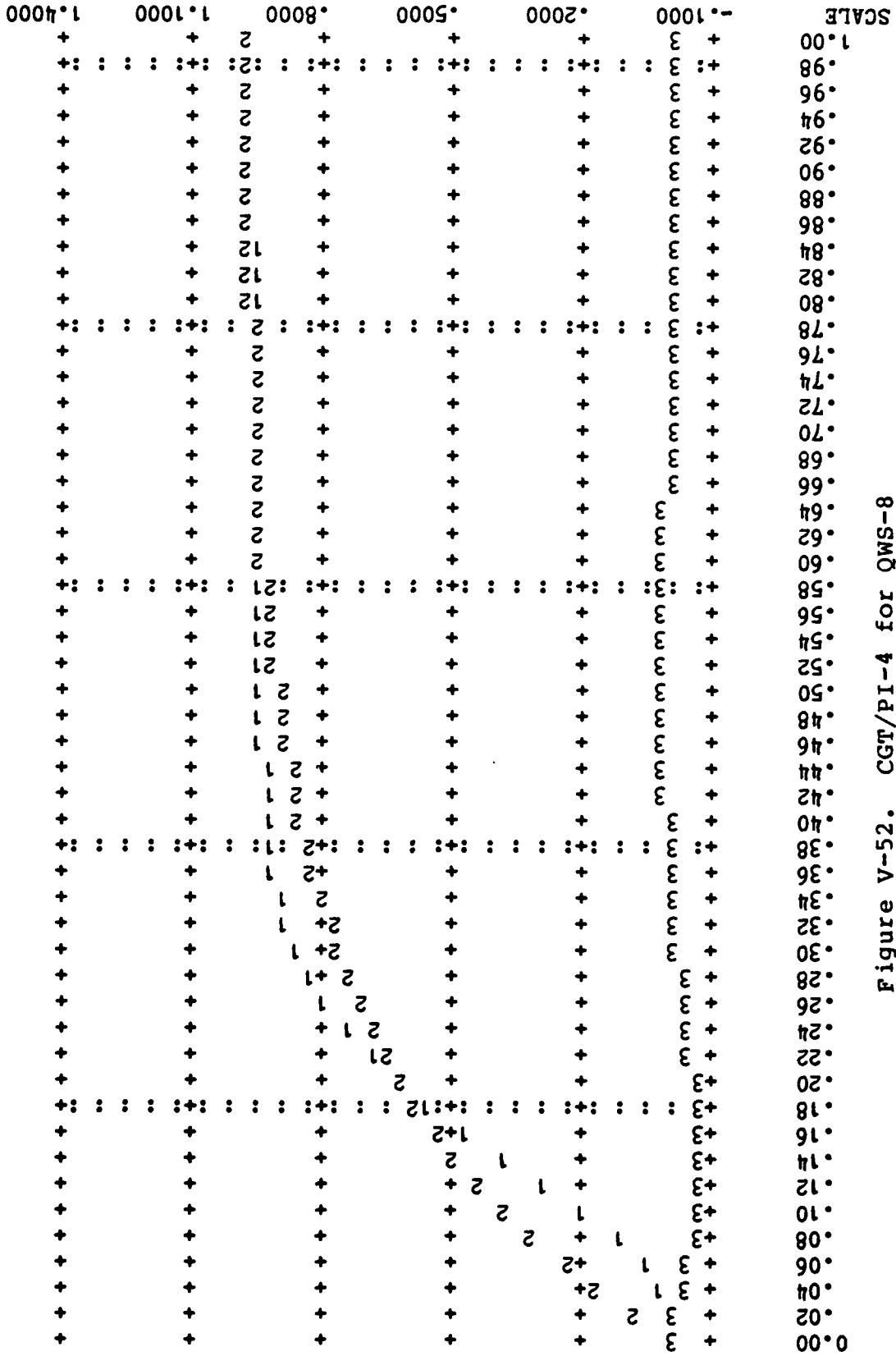


Figure V-50. CGT/PI-2 for QWS-8

SCALE	1.0000	2000	5000	8000	1.1000	1.4000
1.00	3	+	+	+	+	+
.98	3	+	+	+	+	+
.96	3	+	+	+	+	+
.94	3	+	+	+	+	+
.92	3	+	+	+	+	+
.90	3	+	+	+	+	+
.88	3	+	+	+	+	+
.86	3	+	+	+	+	+
.84	3	+	+	+	+	+
.82	3	+	+	+	+	+
.80	3	+	+	+	+	+
.78	3	+	+	+	+	+
.76	3	+	+	+	+	+
.74	3	+	+	+	+	+
.72	3	+	+	+	+	+
.70	3	+	+	+	+	+
.68	3	+	+	+	+	+
.66	3	+	+	+	+	+
.64	3	+	+	+	+	+
.62	3	+	+	+	+	+
.60	3	+	+	+	+	+
.58	3	+	+	+	+	+
.56	3	+	+	+	+	+
.54	3	+	+	+	+	+
.52	3	+	+	+	+	+
.50	3	+	+	+	+	+
.48	3	+	+	+	+	+
.46	3	+	+	+	+	+
.44	3	+	+	+	+	+
.42	3	+	+	+	+	+
.40	3	+	+	+	+	+
.38	3	+	+	+	+	+
.36	3	+	+	+	+	+
.34	3	+	+	+	+	+
.32	3	+	+	+	+	+
.30	3	+	+	+	+	+
.28	3	+	+	+	+	+
.26	3	+	+	+	+	+
.24	3	+	+	+	+	+
.22	3	+	+	+	+	+
.20	3	+	+	+	+	+
.18	3	+	+	+	+	+
.16	3	+	+	+	+	+
.14	3	+	+	+	+	+
.12	3	+	+	+	+	+
.10	3	+	+	+	+	+
.08	3	+	+	+	+	+
.06	3	+	+	+	+	+
.04	3	+	+	+	+	+
.02	3	+	+	+	+	+
0.00	3	+	+	+	+	+

Figure V-51. CGT/PI-3 for QWS-8

Figure V-52. CGT/PI-4 for QWS-8



SCALE	0.0000	.3000	.6000	.9000	1.2000	1.5000
1.00	+	+	+	+	+	+
.98	+	+	+	+	+	+
.96	+	+	+	+	+	+
.94	+	+	+	+	+	+
.92	+	+	+	+	+	+
.90	+	+	+	+	+	+
.88	+	+	+	+	+	+
.86	+	+	+	+	+	+
.84	+	+	+	+	+	+
.82	+	+	+	+	+	+
.80	+	+	+	+	+	+
.78	+	+	+	+	+	+
.76	+	+	+	+	+	+
.74	+	+	+	+	+	+
.72	+	+	+	+	+	+
.70	+	+	+	+	+	+
.68	+	+	+	+	+	+
.66	+	+	+	+	+	+
.64	+	+	+	+	+	+
.62	+	+	+	+	+	+
.60	+	+	+	+	+	+
.58	+	+	+	+	+	+
.56	+	+	+	+	+	+
.54	+	+	+	+	+	+
.52	+	+	+	+	+	+
.50	+	+	+	+	+	+
.48	+	+	+	+	+	+
.46	+	+	+	+	+	+
.44	+	+	+	+	+	+
.42	+	+	+	+	+	+
.40	+	+	+	+	+	+
.38	+	+	+	+	+	+
.36	+	+	+	+	+	+
.34	+	+	+	+	+	+
.32	+	+	+	+	+	+
.30	+	+	+	+	+	+
.28	+	+	+	+	+	+
.26	+	+	+	+	+	+
.24	+	+	+	+	+	+
.22	+	+	+	+	+	+
.20	+	+	+	+	+	+
.18	+	+	+	+	+	+
.16	+	+	+	+	+	+
.14	+	+	+	+	+	+
.12	+	+	+	+	+	+
.10	+	+	+	+	+	+
.08	+	+	+	+	+	+
.06	+	+	+	+	+	+
.04	+	+	+	+	+	+
.02	+	+	+	+	+	+
0.00	+	+	+	+	+	+

Figure V-53. Simple Design CGT (no disturbances, nominal truth model, command model 1)

SCALE 1	SCALE 2	SCALE 3
1.00	1.00	1.00
.98	.98	.98
.96	.96	.96
.94	.94	.94
.92	.92	.92
.90	.90	.90
.88	.88	.88
.86	.86	.86
.84	.84	.84
.82	.82	.82
.80	.80	.80
.78	.78	.78
.76	.76	.76
.74	.74	.74
.72	.72	.72
.70	.70	.70
.68	.68	.68
.66	.66	.66
.64	.64	.64
.62	.62	.62
.60	.60	.60
.58	.58	.58
.56	.56	.56
.54	.54	.54
.52	.52	.52
.50	.50	.50
.48	.48	.48
.46	.46	.46
.44	.44	.44
.42	.42	.42
.40	.40	.40
.38	.38	.38
.36	.36	.36
.34	.34	.34
.32	.32	.32
.30	.30	.30
.28	.28	.28
.26	.26	.26
.24	.24	.24
.22	.22	.22
.20	.20	.20
.18	.18	.18
.16	.16	.16
.14	.14	.14
.12	.12	.12
.10	.10	.10
.08	.08	.08
.06	.06	.06
.04	.04	.04
.02	.02	.02
0.00	0.00	0.00

Figure V-54. Simple Design PI

SCALE	0.0000	0.0002	0.0004	0.0006	0.0008	0.0010
1.00	+	+	+	+	+	+
.98	+	+	+	+	+	+
.96	+	+	+	+	+	+
.94	+	+	+	+	+	+
.92	+	+	+	+	+	+
.90	+	+	+	+	+	+
.88	+	+	+	+	+	+
.86	+	+	+	+	+	+
.84	+	+	+	+	+	+
.82	+	+	+	+	+	+
.80	+	+	+	+	+	+
.78	+	+	+	+	+	+
.76	+	+	+	+	+	+
.74	+	+	+	+	+	+
.72	+	+	+	+	+	+
.70	+	+	+	+	+	+
.68	+	+	+	+	+	+
.66	+	+	+	+	+	+
.64	+	+	+	+	+	+
.62	+	+	+	+	+	+
.60	+	+	+	+	+	+
.58	+	+	+	+	+	+
.56	+	+	+	+	+	+
.54	+	+	+	+	+	+
.52	+	+	+	+	+	+
.50	+	+	+	+	+	+
.48	+	+	+	+	+	+
.46	+	+	+	+	+	+
.44	+	+	+	+	+	+
.42	+	+	+	+	+	+
.40	+	+	+	+	+	+
.38	+	+	+	+	+	+
.36	+	+	+	+	+	+
.34	+	+	+	+	+	+
.32	+	+	+	+	+	+
.30	+	+	+	+	+	+
.28	+	+	+	+	+	+
.26	+	+	+	+	+	+
.24	+	+	+	+	+	+
.22	+	+	+	+	+	+
.20	+	+	+	+	+	+
.18	+	+	+	+	+	+
.16	+	+	+	+	+	+
.14	+	+	+	+	+	+
.12	+	+	+	+	+	+
.10	+	+	+	+	+	+
.08	+	+	+	+	+	+
.06	+	+	+	+	+	+
.04	+	+	+	+	+	+
.02	+	+	+	+	+	+
0.00	+	+	+	+	+	+

Figure V-55. Simple Design CGT/PI (no disturbances, nominal truth model, command model 1)

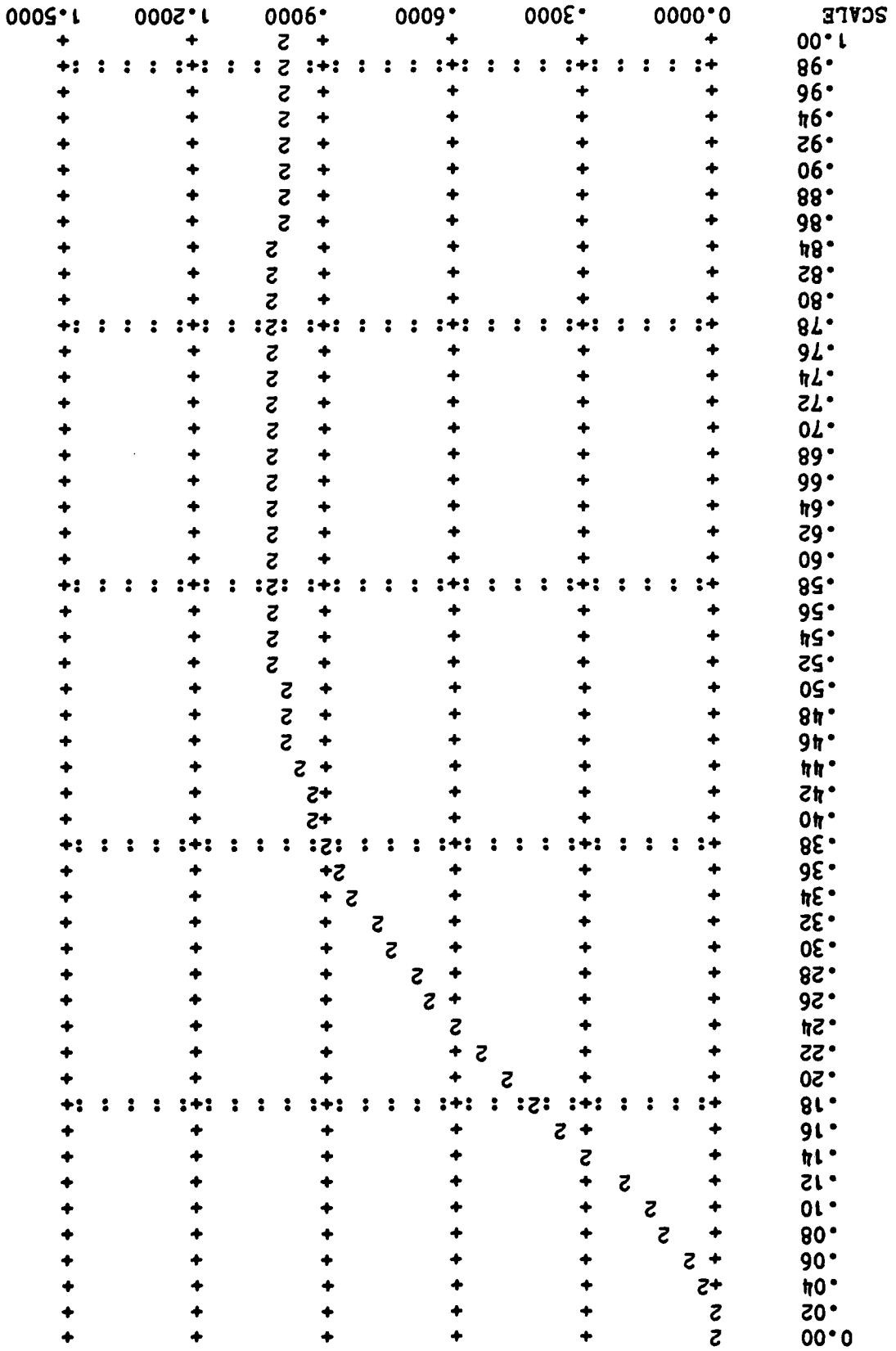


Figure V-56. Simple Design CGT/PI (no disturbances, nominal truth model, command model 2)





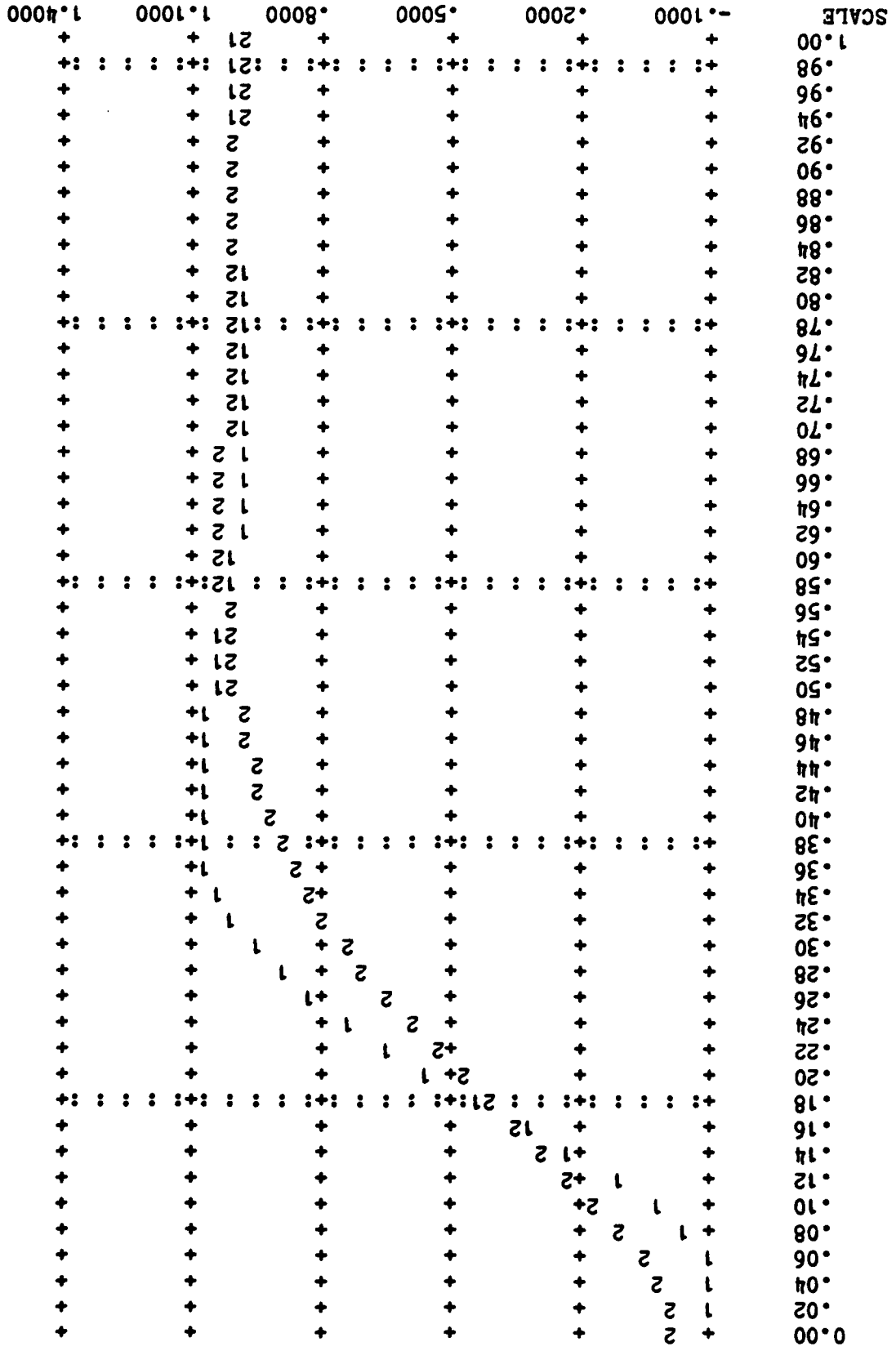


Figure V-58. Simple Design CGT/PI (constant disturbances, alternate truth model, command model 2)



## VI. Summary and Recommendations

### 6.1 Summary

The first primary objective of this thesis has been to develop an interactive, user-oriented computer program similar to "CGTPIF" (Refs 9 and 21), which will also interface with "PFEVAL" (Ref 21), to aid in the design of CGT/PI/KF controllers, basing the design of the PI controller on the integral of the regulation error. Secondly, the design program was to be applied to an aircraft flight control problem to evaluate characteristics of this PI controller design, to compare the different CGT/PI designs within CGTPIQ, and to compare CGTPIQ with CGTPIF.

Chapter II introduced the CGT/PI/KF controller concept by briefly summarizing what is currently implemented in the interactive computer programs "CGTPIF" and "PFEVAL". The basic structure of the controller and the development of the necessary equations were presented.

Chapter III presented the theoretical development of the alternate PI and CGT/PI controller based on the integral of the regulation error. Four different formulations were presented and discussed for this CGT/PI controller. Each of these CGT/PI controllers were eventually implemented in code and compared.

Chapter IV discussed the CGT/PI/KF design computer

program that was developed and gave the models that were employed in the design.

Chapter V presented and compared each of the PI and CGT/PI controllers discussed in Chapters II and III through use of the programs which were developed to implement them. General comments were made as to the usefulness of each program.

Appendix A is the CGTPIQ programmer's guide and contains a discussion of only those subroutines that were changed in "CGTPIF" to produce "CGTPIQ".

Appendix B is a complete, stand-alone, user's guide that contains all the information needed by the user of "CGTPIQ" to run the program successfully.

Appendix C is a complete listing of the program "CGTPIQ" as well as a listing of the subroutines that were changed for each of the CGT/PI formulations presented in Chapter III.

Appendix D contains a discussion of the CGT/PI/KF design evaluation equations that are used in "CGTPIQ".

## 6.2 Recommendations

During the development of the alternate PI controller equations, concepts such as better anti-windup capabilities due to separate proportional and integral gain channels and implicit model following were presented. As a follow-on study, these concepts could be thoroughly investigated using the program "CGTPIQ". Also, synthesis and analysis of complete CGT/PI/KF controllers (i.e. with

Kalman filters in the loop rather than assuming full state feedback) using the programs "CGTPIQ" and "PFEVAL" could be performed, to include: robustness characteristics, actuator saturation and associated windup phenomenon with a PI controller, reduced order design models (particularly actuator models and neglected bending/aeroelastic effects), and different equilibrium points for expansion of the linearized models. A similar study by Lt. Jean Howey using the programs "CGTPIF" and "PFEVAL" is currently underway ("Robust Flight Controllers". MS Thesis. Air Force Institute of Technology, Wright-Patterson AFB, Ohio, December, 1983). It would also be useful to explore more fully the relative benefits of the two different types of PI designs embodied in "CGTPIQ" vs "CGTPIF", considering ease of achieving useful designs, capabilities to enhance robustness of the full-state feedback controller as well as CGT/PI/KF controllers, and other pertinent issues. As an additional area of endeavor, the two programs, "CGTPIF" and "CGTPIQ", could be combined into one program using the concepts presented in Ref (18) for a PIF controller. It would also be worthwhile for the entire man-machine interface (i.e., put the pilot in the loop with the CGT/PI/KF controller) to be implemented in a computer program to understand the inter-relationships of the overall system.

## Bibliography

1. Barraud, A. Y. "A Numerical Algorithm to Solve  $A^T XA - A = Q$ ," IEEE Trans. Automatic Control, AC-22 : 883-885, Oct 1977.
2. Broussard, J. R. "Command Generator Tracking," TASC TIM-612-3, The Analytic Sciences Corp., Reading, Massachusetts, March 1978.
3. Broussard, J. R. "Command Generator Tracking - The Discrete Time Case," TASC TIM-612-2, The Analytic Sciences Corp., Reading Massachusetts, March 1978.
4. Broussard, J.R., D.R. Downing and W.H. Bryant. "Design and Flight Testing of a Digital Optimal Control General Aviation Autopilot." 13th Congress of the International Council of the Aeronautical Sciences/AIAA Aircraft Systems and Technology Conference, Seattle, Washington, August, 1982.
5. Broussard, J. R., and M. G. Safanov. "Design of Generalized Discrete Proportional - Integral Controllers by Linear-Optimal Control Theory," TASC TIM-804-1, The Analytic Sciences Corp., Reading, Massachusetts, October, 1976.
6. Broussard, J. R., P. W. Berry, and R. F. Stengel. "Modern Digital Flight Control System Design For VTOL Aircraft," NASA CR-1159019. National Aeronautics and Space Administration, Hampton, Virginia, March 1979.
7. CYBER Loader Version 1 Reference Manual. Publication number 60429800. Control Data Corporation, Sunnyvale, California, 1979.
8. Floyd, R. M. Aircraft Control Engineer. Unpublished AFTI/F-16 Aerodynamic Stability Derivative Data. Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, June 1980.
9. Floyd, Richard M. "Design of Advanced Digital Flight Control Systems Via Command Generator Tracker (CGT) Synthesis Methods." Volumes 1 and 2. MS Thesis. Air Force Institute of Technology, Wright-Patterson AFB, Ohio, December, 1981.
10. Govindaraj, K.S. and E.G. Rynaski. "Design Criteria for Optimal Flight Control Systems," AIAA Journal of Guidance and Control, Vol 3, No 4: 376-378, 1980.
11. Kalman, R. E., T. S. Englar, and R. S. Bucy. Fundamental Study of Adaptive Control Systems, ASD-TR-61-77, Wright-Patterson AFB, Ohio, 1961.

12. Kleinman, D. L., "A Description of Computer Programs Useful in Linear Systems Studies," Tec. Rep. TR-75-4. University of Connecticut, Storrs, Connecticut, October, 1975.
13. Kreindler, E., and D. Rothschild. "Model-Following in Linear-Quadratic Optimization," AIAA Journal, 14: 835-842, 1976.
14. Kuo, B. C. Digital Control Systems. Champaign, Illinois: SRL Publishing Company, 1979.
15. Kwakernaak, H., and R. Sivan. Linear Optimal Control Systems. New York: Wiley, 1972.
16. McRuer, D., I. Ashkenas, and D. Graham. Aircraft Dynamics and Automatic Control. Princeton, New Jersey: Princeton University Press, 1973.
17. Maybeck, Peter S., Stochastic Models, Estimation and Control, Vol 1. New York: Academic Press, 1979.
18. Maybeck, Peter S., Stochastic Models, Estimation and Control, Vol 3. New York: Academic Press, 1982.
19. Maybeck, Peter S., Richard M. Floyd and Alphonzo Moseley. "Synthesis and Performance Evaluation Tools for CGT/PI Advanced Digital Flight Control Systems." IEEE NAECON, May, 1983.
20. Miller, William G. "Robust Multivariable Controller Design Via Implicit Model Following Methods". MS Thesis. Air Force Institute of Technology, Wright-Patterson AFB, Ohio, December, 1983.
21. Moseley, Alphonzo. "Design of Advanced Digital Flight Control Systems Via Command Generator Tracker (CGT) Synthesis Methods." Volumes 1 and 2. MS Thesis. Air Force Institute of Technology, Wright-Patterson AFB, Ohio, December, 1982.



## Appendix A

### CGTPIQ Programmer's Guide

#### A.1 Introduction

CGTPIQ is a controller design program in which the PI controller is based on the integral of the regulation error. The program is designed to execute interactively. Three design paths are offered: (1) design of a Proportional-plus-Integral (PI) controller via linear-quadratic (LQ) methodology using implicit and/or explicit quadratic weights; (2) design of a Command Generator Tracker, either open-loop (CGT) or closed-loop (CGT/PI); and (3) design of a Kalman filter (KF). These three designs are components of a final controller implemented as a Command Generator Tracker, with an inner-loop proportional-plus-integral controller, and a Kalman filter for state estimation (CGT/PI/KF). For each design path there is a corresponding set of routines to evaluate the quality of the design achieved (see Appendix D).

The program is written in FORTRAN IV and consists of more than 2900 lines of source code. In addition, numerous routines are employed from a library of matrix routines described in Ref (12). Since the resulting program is large both in code and in memory utilization for array storage, direct and complete loading of the program exceeds memory limits for interactive execution on the ASD CYBER computer

system. A technique referred to as "segmentation" is employed to provide selective loading of routines during execution so that memory usage remains within the limits for interactive execution.

This guide is a brief discussion of the subroutines that were changed in converting the program written by Floyd (Ref 9), as modified by Moseley (Ref 21), called "CGTPIF" to the program called "CGTPIQ" which bases the PI controller on the integral of the regulation error instead of the control difference or "pseudorate" as done in "CGTPIF". The equations presented in this guide reflect the development presented in Chapter III (only CGT/PI formulation 1, Section 3.3.2.1 is presented in detail). Since the two programs are exactly alike except for a few subroutines, it is felt that repeating the entire development presented in Floyd's and Moseley's theses would not be required by most users. If the user wishes to understand the entire program development he should obtain copies of Floyd's and Moseley's theses (Refs 9 and 21), and taking their development along with the changes presented in this guide, a complete description of the program will be available.

In converting CGTPIF to CGTPIQ major changes were made to subroutines CDIF, SREGPI, WXUS, FORMX (name also changed to FORMXU), CGTKX, and MODIFX (name also changed to MODXU) with minor changes made to MAIN, CGTXQ, UCGT, and SCMD. There were also numerous cosmetic changes made so that the program elements sounded like what they were actually representing. All of these changes will be

presented in the following sections.

## A.2 Program Changes

### A.2.1 CDIF

'CDIF' is called by the subroutine 'PIMTX'. 'CDIF' sets up two augmented matrices for the integral of the regulation error PI controller. These matrices are:

$$\underline{E}_f = \begin{bmatrix} \underline{E} & \underline{0} \\ \underline{C} & \underline{I} \end{bmatrix} \quad (\text{A-1a})$$

$$\underline{B}_f = \begin{bmatrix} \underline{B}_d \\ \underline{D}_y \end{bmatrix} \quad (\text{A-1b})$$

$\underline{E}_f$  and  $\underline{B}_f$  are stored in vector CTL of /CONTROL/.

### A.2.2 SREGPI, WXUS, and FORMXU

Computations involved in the design of the PI controller are directed by routine SREGPI. Routine 'WXUS' is called first to determine the quadratic weighting matrices of the discrete-time optimal cost function from the continuous-time input quadratic weights. Quadratic weighting matrices (assumed diagonal) are entered directly by the user from the terminal for costs assigned to output, integral of the regulation error, and control magnitudes-- $\underline{U}_q$ ,  $\underline{U}_y$  respectively. These matrices are stored in vector "RPI" of /CREGPI/. An augmented perturbation state vector is defined to be

$$\underline{x} = \begin{bmatrix} \int \underline{x} \\ \int \underline{q} \end{bmatrix} \quad (\text{A-2})$$

A weighting matrix on the state vector  $\underline{x}$  is formed as

$$\underline{X}_{c11} = \underline{C}^T \underline{Y} \underline{C} \quad (\text{A-3a})$$

$$\underline{X}_{c22} = \underline{U}_q \quad (\text{A-3b})$$

$$\underline{X}_{c12} = \underline{0} \quad (\text{A-3c})$$

Routine 'FORMXU' performs these computations and forms

$$\underline{XU} = \begin{bmatrix} \underline{X} & \underline{S}_c \\ \underline{S}_c^T & \underline{U}_c \end{bmatrix} \quad (\text{A-4})$$

where

$$\underline{X} = \begin{bmatrix} \underline{X}_{c11} & \underline{X}_{c12} \\ \underline{X}_{c12}^T & \underline{X}_{c22} \end{bmatrix} \quad (\text{A-5a})$$

$$\underline{U}_c = \underline{U}_y + \underline{D}_y^T \underline{Y} \underline{D}_y \quad (\text{A-5b})$$

$$\underline{S}_c = \begin{bmatrix} \underline{C}^T \underline{Y} \underline{D}_y \\ \underline{0} \end{bmatrix} \quad (\text{A-5c})$$

The user is then given the opportunity to modify individual elements of  $\underline{X}$  (symmetry is preserved automatically by WXUS), as for instance, to alter individual diagonal elements of

$\underline{X}_{c11}$ . The associated continuous-time cost function is,

$$J_C = \frac{1}{2} \int_{t_0}^{t_{N+1}} \begin{bmatrix} \underline{x}(t) \\ \underline{u}(t) \end{bmatrix}^T \begin{bmatrix} \underline{X}_C & \underline{S}_C \\ \underline{S}_C^T & \underline{U}_C \end{bmatrix} \begin{bmatrix} \underline{x}(t) \\ \underline{u}(t) \end{bmatrix} dt \quad (A-6)$$

where

$$\underline{x} = \begin{bmatrix} \int \underline{x} \\ \int \underline{q} \end{bmatrix} \quad (A-6a)$$

$$\underline{u} = \int \underline{u} \quad (A-6b)$$

$$\underline{X}_C = \begin{bmatrix} \underline{X}_{c11} & \underline{X}_{c12} \\ \underline{X}_{c12}^T & \underline{X}_{c22} \end{bmatrix} \quad (A-6c)$$

where  $\underline{q}$  is the integral of the regulation error. The corresponding discrete-time cost function is defined by:

$$J = \sum_{i=0}^N \frac{1}{2} [\underline{x}^T(t_i) \underline{X}_f \underline{x}(t_i) + \underline{u}^T(t_i) \underline{U}_f \underline{u}(t_i) + 2 \underline{x}^T(t_i) \underline{S}_f \underline{u}(t_i)] \quad (A-7)$$

and the discrete costs are,

$$\underline{X}_f = \int_{t_i}^{t_i+T} [\underline{x}_f^T(\tau) \underline{X}_C \underline{x}_f(\tau)] d\tau \quad (A-8a)$$

$$\underline{U}_f = \int_{t_i}^{t_i+T} [\underline{u}_f^T(\tau) \underline{X}_C \underline{u}_f(\tau) + \underline{U}_C + \underline{u}_f^T(\tau) \underline{S}_C + \underline{S}_C^T \underline{u}_f(\tau)] d\tau \quad (A-8b)$$

$$\underline{S}_f = \int_{t_i}^{t_i+T} [\underline{x}_f^T(\tau) \underline{X}_C \underline{u}_f(\tau) + \underline{x}_f^T(\tau) \underline{S}_C] d\tau \quad (A-8c)$$

in which

$$\underline{\bar{x}}_f(\tau) = \begin{bmatrix} \underline{x}(\tau) & \underline{0} \\ \underline{c} & \underline{I} \end{bmatrix} \quad (\text{A-9a})$$

$$\underline{\bar{B}}_f(\tau) = \begin{bmatrix} \underline{B}_d(\tau) \\ \underline{D}_y \end{bmatrix} \quad (\text{A-9b})$$

$$\underline{B}_d(\tau) = \int_0^T \underline{x}(\sigma) \underline{B} d\sigma \quad (\text{A-9c})$$

The integrals in Equations (A-8a,b,c) are approximated in a two-step computation. First,  $\underline{\bar{x}}_f$  and  $\underline{\bar{B}}_f$  are treated as constants over the sample interval with value set to their respective averaged values at the beginning and end of the interval:

$$\underline{\bar{x}}_f = \frac{1}{2} [\underline{I} + \underline{x}_f] \quad (\text{A-10a})$$

$$\underline{\bar{B}}_f = \frac{1}{2} [\underline{0} + \underline{B}_f] \quad (\text{A-10b})$$

(where the overbar means approximation) in which  $\underline{\bar{x}}_f$  and  $\underline{\bar{B}}_f$  are as defined in Equations (A-1a,b). With these approximations, each of the integrands is constant over the integration time T, so the integrals are obtained as

$$\underline{\bar{X}}_f = T [\underline{\bar{x}}_f^T \underline{X} \underline{\bar{x}}_f] \quad (\text{A-11a})$$

$$\underline{\bar{U}}_f = T [\underline{\bar{B}}_f^T \underline{X} \underline{\bar{B}}_f + \underline{U}_c + \underline{\bar{B}}_f^T \underline{S}_c + \underline{S}_c^T \underline{\bar{B}}_f] \quad (\text{A-11b})$$

$$\underline{\bar{S}}_f = T [\underline{\bar{x}}_f^T \underline{X} \underline{\bar{B}}_f + \underline{\bar{x}}_f^T \underline{S}_c] \quad (\text{A-11c})$$

This provides a better approximate evaluation than simple Euler integration provides. These three discrete-time costs are returned by 'WXUS' as arguments "X", "U", and "S", respectively.

Note that the cross weighting matrix  $\bar{\underline{S}}_f$  has been introduced into the cost function by the discretization process and will generally be nonzero even if  $\underline{S}_c$  in Equation (A-6) were zero. This cost function is seen to be in the standard form used previously and all development can proceed as if the problem were a discrete problem and not a continuous one.

Now, in order to obtain an equivalent discrete-time cost function with no cross weighting (to allow use of standard Riccati equation solvers as in Ref (12) that assume such a form), routine 'PXUP' is called to compute a modified system and weighting matrices. Define a new system (Ref 14)

$$\underline{x}(t_{i+1}) = \bar{\underline{X}}_f' \underline{x}(t_i) + \bar{\underline{B}}_f \underline{u}'(t_i) \quad (\text{A-12})$$

for which

$$\bar{\underline{X}}_f' = \underline{X}_f - \bar{\underline{B}}_f \bar{\underline{U}}_f^{-1} \bar{\underline{S}}_f^T \quad (\text{A-13a})$$

and

$$\underline{u}'(t_i) = \underline{u}(t_i) + \bar{\underline{U}}_f^{-1} \bar{\underline{S}}_f^T \underline{x}(t_i) \quad (\text{A-13b})$$

for which the corresponding cost function becomes

$$J' = \sum_{i=0}^N \frac{1}{2} [\underline{x}^T(t_i) \bar{\underline{X}}_f' \underline{x}(t_i) + \underline{u}'^T(t_i) \bar{\underline{U}}_f' \underline{u}'(t_i)] \quad (\text{A-14})$$

with

$$\bar{\mathbf{X}}_s' = \bar{\mathbf{X}}_s - \bar{\mathbf{S}}_s \bar{\mathbf{U}}_s^{-1} \bar{\mathbf{S}}_s^T \quad (\text{A-15})$$

The cost function of Equation (A-14) is now in standard form for solution of the steady-state Riccati equation. PXUP returns matrices  $\bar{\mathbf{X}}_s'$ ,  $\bar{\mathbf{X}}_s'$ , and  $\bar{\mathbf{U}}_s^{-1} \bar{\mathbf{S}}_s^T$  of Equations (A-13a), (A-15), and (A-13b), respectively. An additional matrix needed for the routine which computes the solution to the Riccati equation is also computed by PXUP:

$$\bar{\mathbf{U}}_s' = \bar{\mathbf{B}}_s \bar{\mathbf{U}}_s^{-1} \bar{\mathbf{B}}_s^T \quad (\text{A-16})$$

SREGPI next computes the steady-state solution to the discrete-time Riccati equation using routine 'DRIC' of LIBRARY. DRIC solves for  $\mathbf{K}_R$  in

$$\mathbf{K}_R = \bar{\mathbf{X}}_s'^T \mathbf{K}_R (\mathbf{I} + \bar{\mathbf{U}}_s' \mathbf{K}_R)^{-1} \bar{\mathbf{X}}_s' + \bar{\mathbf{X}}_s' \quad (\text{A-17})$$

using an iterative procedure discussed in Ref (12). In addition to  $\mathbf{K}_R$ , DRIC returns the closed-loop system matrix

$$\bar{\mathbf{X}}_{s\text{CL}} = (\mathbf{I} + \bar{\mathbf{U}}_s' \mathbf{K}_R)^{-1} \bar{\mathbf{X}}_s' \quad (\text{A-18})$$

which is stored in vector RPI.

Routine 'GCSTAR' then is called to compute the optimal feedback gain matrix for the original system. The optimal feedback gains for the modified system of Equation



(A-12) are,

$$\underline{G}_C^* = [\underline{U}_s + \underline{E}_s^T \underline{K}_R \underline{E}_s]^{-1} \underline{E}_s^T \underline{K}_R \underline{E}_s' \quad (\text{A-19})$$

and from these the optimal feedback gains for the original system are

$$\underline{G}_C^* = \underline{G}_C^* + \underline{U}_s^{-1} \underline{E}_s^T \quad (\text{A-20})$$

Remembering from Equation (III-25) that

$$\underline{G}_C^* = [\underline{G}_{C1}^* \quad \underline{G}_{C2}^*] \quad (\text{A-21})$$

the calculation beginning with a continuous-time cost description will produce the correct  $\underline{G}_C^*$ . The only question that might arise is whether the substitution of  $\underline{K}_R'$  for  $\underline{K}_C$  is a valid substitution. This will be shown in the last section of this guide. The PI controller in incremental form utilizing these gains is implemented as

$$\begin{aligned} \underline{u}^*(t_i) = & \underline{u}^*(t_{i-1}) - \underline{G}_{C1}^* [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\ & - \underline{G}_{C2}^* [\underline{C} \quad \underline{D}_y] \begin{bmatrix} \underline{x}(t_{i-1}) \\ \underline{u}(t_{i-1}) \end{bmatrix} \end{aligned} \quad (\text{A-22})$$

The controller evaluation routines which propagate the response of the PI controlled system to non-zero initial conditions use Equation (A-22) to compute the control input. Note that this assumes that the outputs are to be driven to

zero by the PI controller. No provision is made for evaluation of the PI controller in response to control inputs, therefore,  $\underline{y}_d$  will be zero for all time. Thus the matrix  $\underline{E}$  is not required in the computation, but is computed and saved in vector LEE of /LREGPI/ so that a comparison can be made between the proportional and integral channels of the PI controller according to

$$\underline{K}_p = [\underline{I} - \underline{E}\underline{D}_y]^{-1} \underline{E} \quad (\text{A-23a})$$

$$\underline{K}_i = [\underline{I} - \underline{E}\underline{D}_y]^{-1} \underline{G}_{c2}^* \quad (\text{A-23b})$$

(These are computed at the end of SREGPI.) and since a major portion of  $\underline{E}$  known as the  $\underline{L}$  matrix where

$$\underline{L} = \underline{G}_{c1}^* - \underline{G}_{c2}^* \underline{K}_{c22}^{-1} \underline{K}_{c12}^T \quad (\text{A-23c})$$

is needed in the closed-loop CGT/PI controller development. The  $\underline{L}$  matrix is saved in vector LEL of /LREGPI/. (See Section 3.3.2 for changes for CGT/PI formulations 2,3,4.)

### A.2.3 CGTKX and SCMD

SCGT directs the computations involved in design of an open-loop CGT or closed-loop CGT/PI controller. SCGT calls routine CGTKX to compute the gains employed by the CGT and CGT/PI controllers. For the open-loop CGT controller routine SCMD sets matrices  $\underline{G}_{c1}^*$  and  $\underline{G}_{c2}^*$  to zero. CGTKX computes gains on command model states and inputs and disturbance states, respectively, as

$$\underline{K}_{xm} = \underline{L}\underline{A}_{11} + \underline{A}_{21} \quad (\text{A-24a})$$

$$\underline{K}_{xu} = \underline{L}\underline{A}_{12} + \underline{A}_{22} \quad (\text{A-24b})$$

$$\underline{K}_{xn} = \underline{L}\underline{A}_{13} + \underline{A}_{23} \quad (\text{A-24c})$$

These three gains are stored in vector CGT. (See Section 3.3.2 for changes for CGT/PI formulations 2,3,4.)

The closed-loop CGT/PI control law is implemented in incremental form as

$$\begin{aligned} \underline{u}^*(t_i) = & \underline{u}^*(t_{i-1}) - \underline{G}_{c1}^* [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\ & + \underline{K}_{xm} [\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\ & + \underline{K}_{xu} [\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\ & + \underline{K}_{xn} [\underline{n}_d(t_i) - \underline{n}_d(t_{i-1})] \\ & + \underline{G}_{c2}^* \left\{ \begin{bmatrix} \underline{C}_m & \underline{D}_m \end{bmatrix} \begin{bmatrix} \underline{x}_m(t_{i-1}) \\ \underline{u}_m(t_i) \end{bmatrix} - \begin{bmatrix} \underline{C} & \underline{D}_y \end{bmatrix} \begin{bmatrix} \underline{x}(t_{i-1}) \\ \underline{u}(t_{i-1}) \end{bmatrix} \right\} \end{aligned} \quad (\text{A-25})$$

(See Section 3.3.2 for changes for CGT/PI formulations 2,3,4.) The open-loop CGT is obtained by employing Equation (A-25) with PI gains  $\underline{G}_{c1}^*$  and  $\underline{G}_{c2}^*$  both zero matrices, giving the effective result for the open-loop CGT control law as

$$\begin{aligned} \underline{u}^*(t_i) = & \underline{u}^*(t_{i-1}) + \underline{A}_{21} [\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\ & + \underline{A}_{22} [\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\ & + \underline{A}_{23} [\underline{n}_d(t_i) - \underline{n}_d(t_{i-1})] \end{aligned} \quad (\text{A-26})$$

Equation (A-25) is used by the controller evaluation routines to compute control inputs for either CGT controller.

#### A.2.4 UCGT

UCGT computes the control input due to the CGT controller alone and adds it to the control given by the PI controller from URPI. The increment due to the CGT or CGT/PI alone is added as

$$\begin{aligned}
 \underline{u}^*(t_i) \leftarrow & \underline{u}^*(t_i) + \underline{K}_{xm} [\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\
 & + \underline{K}_{xu} [\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\
 & + \underline{K}_{xn} [\underline{n}_d(t_i) - \underline{n}_d(t_{i-1})] \\
 & + \underline{G}_{c2}^* [\underline{C}_m \quad \underline{D}_m] \begin{bmatrix} \underline{x}_m(t_{i-1}) \\ \underline{u}_m(t_i) \end{bmatrix}
 \end{aligned} \tag{A-27}$$

(See Section 3.3.2 for changes for CGT/PI formulations 2,3,4.)

#### A.2.5 MODXU

MODXU computes the combined implicit/explicit quadratic weights according to

$$\underline{XU} = \begin{bmatrix} \underline{X}_c + \hat{\underline{X}}_I & \underline{0} & \underline{S}_c + \hat{\underline{S}}_I \\ \underline{0} & \underline{U}_q & \underline{0} \\ (\underline{S}_c + \hat{\underline{S}}_I)^T & \underline{0} & \underline{U}_c + \hat{\underline{U}}_I \end{bmatrix} \tag{A-28}$$

### A.2.6 MAIN and CGTXQ

MAIN is changed by increasing the storage space allotted to common /CREGPI/ and vector NVRPI to 675 to take care of the two added matrices L and E.

CGTXQ is changed by adding vector space for matrices L and E in Common /LREGPI/. These are called LEL and LEE, respectively.

### A.2.7 Cosmetic Changes

All reference to the vector notation on the left has been changed to the notation on the right

KX - GC1  
KZ - GC2  
LKX - LGC1  
LKZ - LGC2  
LKXAx - LELAx  
RKX - RGC1 (in subroutine URPI)  
RKZ - RGC2 (in subroutine URPI)  
RXX - REL (in subroutine CGTKX)

(See Appendix C for changes for CGT/PI formulations 2,3,4.)

### A.3 Derivation Showing that $K_R' = K_C$

In the simple proof we know that the cost to be minimized in the case of both K's is given by (Ref 15)

$$\underline{x}^T \underline{K}_C \underline{x} = J_{\min} = J_{\min}' = \underline{x}^T \underline{K}_R' \underline{x} \quad (A-29)$$

and since the states, the x's, are the same on both sides of

Equation (A-29), it follows directly that

$$\underline{K}_C = \underline{K}_R' \quad (A-30)$$

It can also be shown rigorously that

$$\underline{K}_R' = \underline{K}_C = \underline{X} + \underline{\delta}^T \underline{K}_C \underline{\delta} - [\underline{B}_d^T \underline{K}_C \underline{\delta} + \underline{S}^T] \underline{T} \underline{G}_C^* \quad (A-31)$$

Given Equation (III-18a) which is the  $\underline{K}_C$  portion of Equation (A-31), let's show that  $\underline{K}_R'$  is equal to the same relationship. Starting with our equation in question, Equation (III-49), utilize Equation (III-51) to get (dropping the delta subscripts)

$$\underline{K}_R' = \underline{X}' + \underline{\delta}'^T \underline{K}_R' \underline{\delta}' - \underline{\delta}'^T \underline{K}_R' \underline{B} \underline{G}_C^* \quad (A-32)$$

Substituting Equation (III-48b) for  $\underline{X}'$ , Equation (III-47b) for  $\underline{\delta}'$ , Equation (III-52) for  $\underline{G}_C^*$ , multiplying out the resultant equation and canceling like terms, we have

$$\underline{K}_R' = [\underline{X} + \underline{\delta}^T \underline{K}_R' \underline{\delta} - \underline{\delta}^T \underline{K}_R' \underline{B} \underline{G}_C^*] - [\underline{S} \underline{U}^{-1} \{ \underline{B}^T \underline{K}_R' \underline{\delta} + \underline{S}^T \} - \underline{S} \underline{U}^{-1} \underline{B}^T \underline{K}_R' \underline{B} \underline{G}_C^*] \quad (A-33)$$

Noting that the portion of Equation (A-33) in braces {} is equal to

$$\{ \} = [\underline{U} + \underline{B}^T \underline{K}_R' \underline{B}] \underline{G}_C^* = \underline{U} \underline{G}_C^* + \underline{B}^T \underline{K}_R' \underline{B} \underline{G}_C^* \quad (A-34)$$

and making this substitution, canceling the resultant like terms, we have

$$\underline{K}_R' = \underline{X} + \underline{S}^T \underline{K}_R' \underline{S} - \underline{S}^T \underline{K}_R' \underline{B} \underline{G}_C^* - \underline{S} \underline{G}_C^* \quad (\text{A-35a})$$

$$= \underline{X} + \underline{S}^T \underline{K}_R' \underline{S} - [\underline{B}^T \underline{K}_R' \underline{S} - \underline{S}^T] \underline{G}_C^* \quad (\text{A-35b})$$

which is the result we were seeking. So  $\underline{K}_C$  and  $\underline{K}_R'$  satisfy the same terminal condition and the same difference equation, so they are equal for all time.

## Appendix B

### CGTPIQ User's Guide

#### B.1 Introduction

The primary objective of this thesis effort is to create a computer program with which to design CGT/PI/KF controllers with the PI controller based on the integral of the regulation error. This user's guide discusses the program which has been developed--hereafter to be referred to as CGTPIQ--as an existing program (as it executes under CYBER INTERCOM) and with the intention of providing information appropriate to successful execution when applied to the user's design problem. It discusses program operation from the input/output perspective: the specific input and output of each design/evaluation path and the terminology employed in each input/output item. It also discusses what the user must do both before and immediately following program execution. The discussion presented in this guide is based on the program developed using CGT/PI formulation 1 (see Section 3.3.2). Appendix C gives the required code changes for the other formulations, but they are not discussed here. The changes to program execution by each CGT/PI formulation is either very minor or non-existent. (Note: the reader will see duplicated material from other chapters. This is done so that this User's Guide will be complete by itself.)

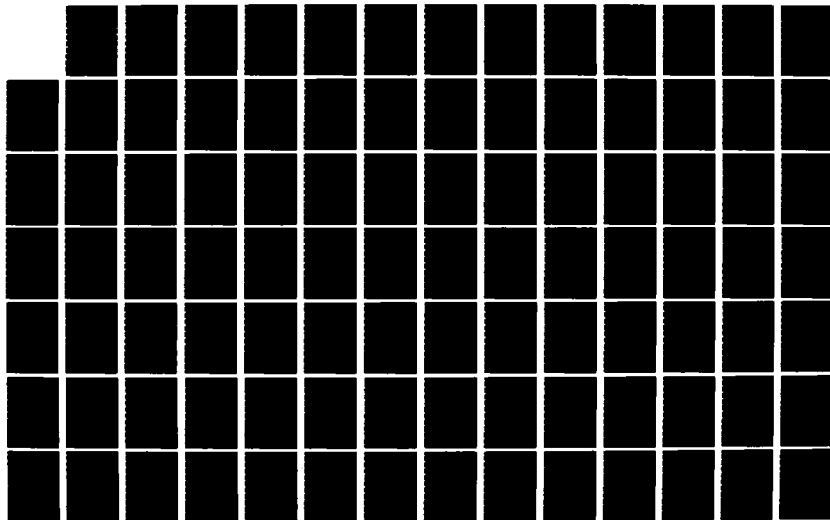
While the specific test application for the program

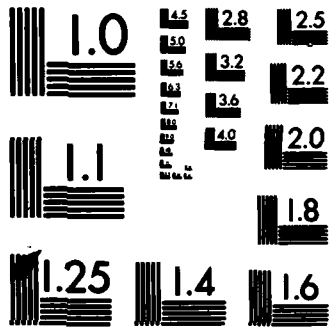


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COMMAND GENERATOR TRACKER SYNTHESIS METHODS USING AN 3/4  
LQG (LINEAR SYSTEM M. (U) AIR FORCE INST OF TECH  
WRIGHT-PATTERSON AFB OH SCHOOL OF ENGI. J P MCMILLIAN  
DEC 83 AFIT/GE/EE/83D-46 F/G 9/2 NL

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MICROCOPY RESOLUTION TEST CHART  
 NATIONAL BUREAU OF STANDARDS-1963-A

## Appendix B

### CGTPIQ User's Guide

#### B.1 Introduction

The primary objective of this thesis effort is to create a computer program with which to design CGT/PI/KF controllers with the PI controller based on the integral of the regulation error. This user's guide discusses the program which has been developed--hereafter to be referred to as CGTPIQ--as an existing program (as it executes under CYBER INTERCOM) and with the intention of providing information appropriate to successful execution when applied to the user's design problem. It discusses program operation from the input/output perspective: the specific input and output of each design/evaluation path and the terminology employed in each input/output item. It also discusses what the user must do both before and immediately following program execution. The discussion presented in this guide is based on the program developed using CGT/PI formulation 1 (see Section 3.3.2). Appendix C gives the required code changes for the other formulations, but they are not discussed here. The changes to program execution by each CGT/PI formulation is either very minor or non-existent. (Note: the reader will see duplicated material from other chapters. This is done so that this User's Guide will be complete by itself.)

While the specific test application for the program

in the context of this thesis has been related to aircraft control design, CGTPIQ is written to be applicable to a wide variety of control design problems. It has the following attributes:

1. CGTPIQ executes interactively
2. The program utilizes efficient array allocation
  - a. Initial memory allocation easily set
  - b. Dynamic array allocation within total memory allocated
3. Various modes of entry are possible for the dynamics models
4. Design paths are automatically followed, with user prompts at necessary decision points
5. Requests for input include informative prompts
6. Copious program output is provided
  - a. Output most relevant to design decisions are provided directly to the terminal
  - b. Additional detailed output is provided to a separate output file
7. Information relevant to design iteration is preserved
8. Information needed for evaluation by computer program "PFEVAL" is preserved (Ref 21)
9. Error checking is performed, and messages given as appropriate

CGTPIQ employs computational routines available in a library of matrix computer routines described in Ref (12). Exclusive of the library routines, the program has a length

of more than 2900 lines of source code. The programming language employed is ANSI Standard FORTRAN IV. Although the resulting source code is highly portable, local memory utilization limits for interactive execution may impose constraints. In use on a Control Data Corporation CYBER machine, the necessary load size was achievable with no impact on the source code. Thus the existing source code is in a pure form for whatever system. The final program size is much greater than the normal 65000 octal word limitation of the CYBER interactive system. Thus, in order to achieve interactive operation and provide sufficient free memory for array allocation so that problems of large and variable dimensions can be treated, a CYBER Loader option referred to as "Segmentation" (Ref 7) must be used. (Note: even with segmentation the program requires nearly 67000 octal words.) The required segmentation code will be presented later in this guide.

CGTPIQ was written specifically to run interactively. Requests for input, while intentionally brief, tell the user what is expected of him--what, how many, and in what units, as appropriate. Output of information, relevant to design decisions, to the terminal is compact and automatically provided. Also, the user can determine the amount and category of output to the terminal in some cases, and according to need.

An objective of this thesis effort was for CGTPIQ to be similar to the program CGTPIF by Floyd (Ref 9), as modified by Moseley (Ref 21), and every effort was made for

this to be the case. For this reason the two program's are almost identical in operation. Appendix A, which discussed the actual programming text changes, assumed that the user must have copies of Floyd's and Moseley's Theses to effect any change to the program. Appendix A was not discussed in detail since most users will not need to change the program. On the other hand, a complete user's guide is necessary for the user to be able to use the program; therefore, this user's guide is taken entirely from the theses by Floyd and Moseley (Refs 9 and 21), with necessary changes to reflect the changes made in the program, so that the user will not need copies of the other two theses to use this program.

## B.2 Program Operating Principles and Organization

CGTPIQ has three design paths: (1) design of a PI controller (using explicit and/or implicit quadratic weights); (2) design of either an open-loop CGT or closed-loop CGT/PI controller, and (3) design of a Kalman filter. Corresponding to the first two design options is a controller evaluation set of routines, and corresponding to the third design option is a set of routines for filter evaluation. The evaluation routines perform the computations discussed in Appendix D.

A general flowchart of CGTPIQ is given in Figure B-1, showing the main execution paths and design entries. The controller sample period is entered, the design model is established, and then the desired design path can be

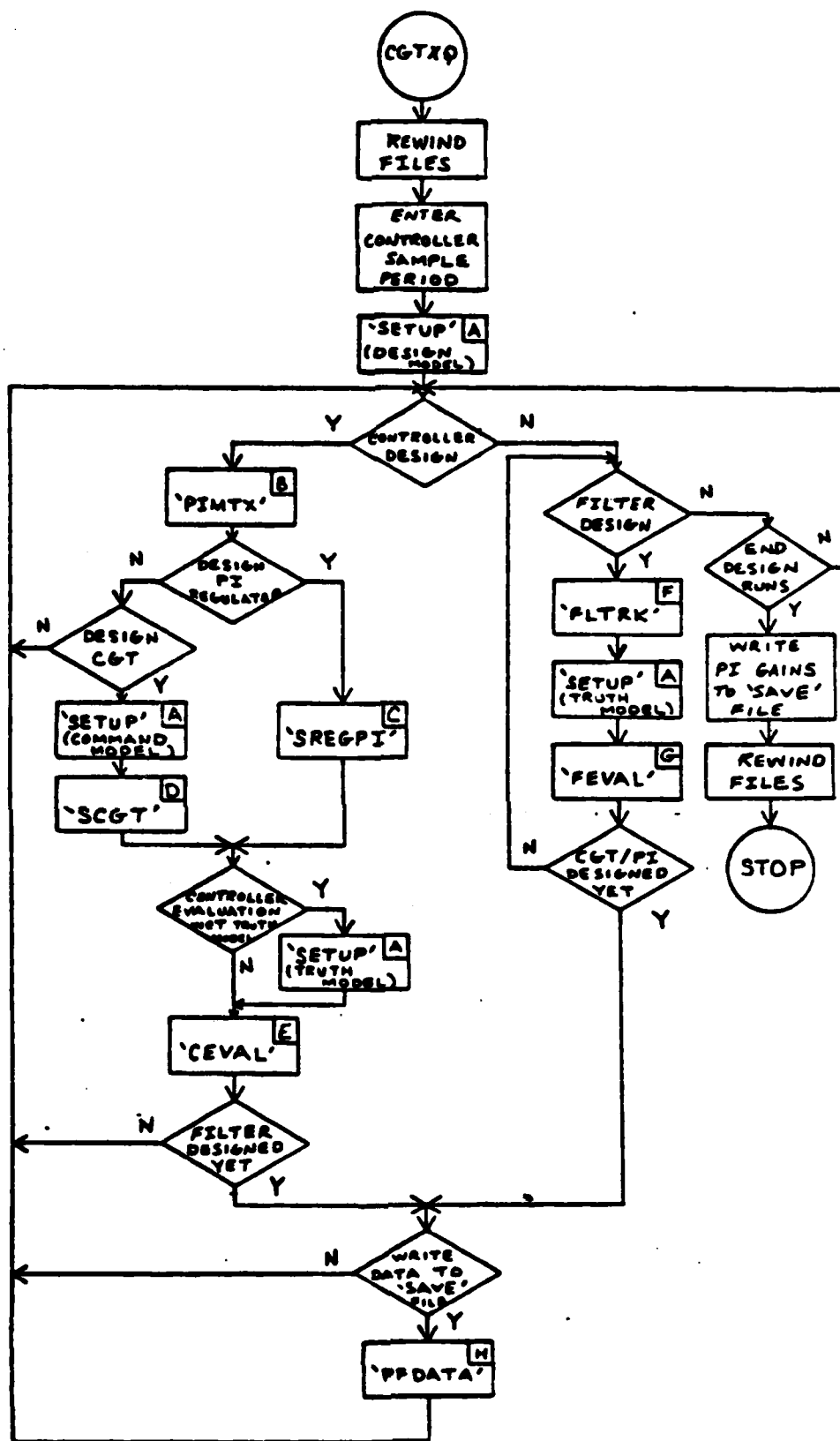


Fig. B-1. CGTPIQ General Flowchart

followed. The elementary design path choice is between controller and filter designs. The CGT or CGT/PI, and the PI controller (for explicit and/or implicit quadratic weights) design paths are then options within the controller design. If the PI controller design is pursued prior to the CGT design path, the CGT design will automatically be of the CGT/PI controller. If the PI is not already determined during the current execution of the program, then the designer may elect to design either a CGT or a CGT/PI controller. However, the CGT controller design is not pursued if the open-loop design model is unstable. The controller design path is followed automatically by the appropriate controller evaluation path. Similarly, the filter design path leads automatically to the filter evaluation. When the evaluation is complete the designer is given the opportunity to loop on the design path, choose a different design path, or terminate program execution. More detailed flowcharts and functional diagrams are given later.

### B.3 Dynamics Models

Each of the dynamics models entered into CGTPIQ is represented by a set of continuous-time state differential equations. The names used in the equations to follow are exactly those used by CGTPIQ in reference to these same dimensions and arrays in its Input/Output (I/O). Note that here each name is a single character, possibly subscripted, while in its I/O, CGTPIQ incorporates subscripts into the name (e.g.,  $A_t$  becomes "AT"). Constraints on the models



that are presented below are tested by CGTPIQ and, if not satisfied, a message is written to the user terminal and execution is aborted. These will be discussed later.

### B.3.1 Design Model

The design model is given by

$$\dot{\underline{x}}(t) = \underline{A}\underline{x}(t) + \underline{B}\underline{u}(t) + \underline{E}_x \underline{n}_d(t) + \underline{G}\underline{w}(t) \quad (\text{B-1a})$$

$$\dot{\underline{n}}_d(t) = \underline{A}_n \underline{n}_d(t) + \underline{G}_n \underline{w}_d(t) \quad (\text{B-1b})$$

$$\underline{y}(t) = \underline{C}\underline{x}(t) + \underline{D}_y \underline{u}(t) + \underline{E}_y \underline{n}_d(t) \quad (\text{B-1c})$$

$$\underline{z}(t_i) = \underline{H}\underline{x}(t_i) + \underline{H}_n \underline{n}_d(t_i) + \underline{v}(t_i) \quad (\text{B-1d})$$

and  $\underline{w}$ ,  $\underline{w}_d$  and  $\underline{v}$  are independent zero-mean noises with statistics

$$E\{\underline{w}(t)\underline{w}^T(t+\tau)\} = \underline{Q}\delta(\tau) \quad (\text{B-2a})$$

$$E\{\underline{w}_d(t)\underline{w}_d^T(t+\tau)\} = \underline{Q}_n\delta(\tau) \quad (\text{B-2b})$$

$$E\{\underline{v}(t_i)\underline{v}^T(t_j)\} = \underline{R}\delta_{ij} \quad (\text{B-2c})$$

In these equations,  $\underline{x}$ ,  $\underline{u}$ ,  $\underline{n}_d$ ,  $\underline{y}$ , and  $\underline{z}$  are the system state, input, disturbance state, output, and measurement vectors, respectively. In input prompts, CGTPIQ refers to the diagonal elements of the noise covariance matrices as

$$\underline{Q}: \text{"state noise strengths"} \quad (\text{B-3a})$$

$$\underline{Q}_n: \text{"disturbance noise strengths"} \quad (\text{B-3b})$$

$$\underline{R}: \text{"measurement noise strengths"} \quad (\text{B-3c})$$

Note the  $\underline{Q}$ ,  $\underline{Q}_n$ , and  $\underline{R}$  are all assumed to be diagonal matrices. The dimensions of the model are

$n$  = number of system states

$r$  = number of system inputs

$p$  = number of system outputs

$m$  = number of system measurements

$d$  = number of disturbance states  
 $w$  = number of independent system noises  
 $w_D$  = number of independent disturbance noises (B-4)

and the dimensions of the matrices of the model are

$\underline{A}$  : n-by-n  
 $\underline{B}$  : n-by-r  
 $\underline{E}_x$  : n-by-d  
 $\underline{G}$  : n-by-w  
 $\underline{Q}$  : w-by-w  
 $\underline{C}$  : p-by-n  
 $\underline{D}_y$  : p-by-r  
 $\underline{E}_y$  : p-by-d  
 $\underline{H}$  : m-by-n  
 $\underline{H}_n$  : m-by-d  
 $\underline{R}$  : m-by-m  
 $\underline{A}_n$  : d-by-d  
 $\underline{G}_n$  : d-by- $w_D$   
 $\underline{Q}_n$  :  $w_D$ -by- $w_D$  (B-5)

CGTPIQ requires that the numbers of design systems inputs and outputs be equal:  $r=p$ . Also, the number of system states may not be less than the number of disturbance states, due to the computational setup used for the CGT solution. The dimensions  $n$ ,  $r$ , and  $p$  must be non-zero; any of the other dimensions may be zero. If  $m$  is zero or if  $w$  and  $w_D$  are both zero, the Kalman filter design path cannot be pursued. Matrices having either dimension zero, do not exist and are not entered.

### B.3.2 Truth Model

The truth model is specified by

$$\dot{\underline{x}}_t(t) = \underline{A}_t \underline{x}_t(t) + \underline{B}_t \underline{u}_t(t) + \underline{G}_t \underline{w}_t(t) \quad (\text{B-6a})$$

$$\underline{z}_t(t) = \underline{H}_t \underline{x}_t(t_i) + \underline{v}_t(t_i) \quad (\text{B-6b})$$

$$\underline{x}'(t) = \underline{T}_{DT} \underline{x}_t(t) \quad (\text{B-6c})$$

$$\underline{n}_d'(t) = \underline{T}_{NT} \underline{x}_t(t) \quad (\text{B-6d})$$

and  $\underline{w}_t$  and  $\underline{v}_t$  are assumed to be independent zero mean noises with

$$E\{\underline{w}_t(t) \underline{w}_t^T(t+\tau)\} = \underline{Q}_t \delta(\tau) \quad (\text{B-7a})$$

$$E\{\underline{v}_t(t_i) \underline{v}_t^T(t_j)\} = \underline{R}_t \delta_{ij} \quad (\text{B-7b})$$

where Equations (B-6c) and (B-6d) relate the system and disturbance states of the design model to the system states of the truth model. Note that  $\underline{Q}_t$  and  $\underline{R}_t$  are both assumed to be diagonal matrices. In these equations,  $\underline{x}_t$ ,  $\underline{u}_t$ , and  $\underline{z}_t$  are the truth model system state, input, and measurement vectors, respectively. The vectors  $\underline{x}'$  and  $\underline{n}_d'$  are as defined for the design model.

The dimensions of the truth model are

$$\begin{aligned} n_T &= \text{"number of system states"} \\ r_T &= \text{"number of system inputs"} \\ m_T &= \text{"number of system measurements"} \\ w_T &= \text{"number of independent noises driving system} \\ &\quad \text{dynamics"} \end{aligned} \quad (\text{B-8})$$

and the dimensions of the matrices of the model are

$$\begin{aligned} \underline{A}_t &: n_T \text{-by-} n_T \\ \underline{B}_t &: n_T \text{-by-} r_T \\ \underline{G}_t &: n_T \text{-by-} w_T \\ \underline{Q}_t &: w_T \text{-by-} w_T \end{aligned}$$

$$\underline{H}_t: m_T\text{-by-}n_T$$

$$\underline{R}_t: m_T\text{-by-}m_T$$

$$\underline{I}_{DT}: n\text{-by-}n_T$$

$$\underline{I}_{NT}: d\text{-by-}n_T$$

(B-9)

CGTPIQ requires that the numbers of inputs and of measurements for the truth and design model be the same:  $r_T=r$  and  $m_T=m$ . If the number of driving noises ( $w_T$ ) is zero, evaluation of a Kalman filter design is not pursued (since a covariance analysis with no truth model driving noise would not be very informative). Matrices having either dimension zero, do not exist and are not entered.

### B.3.3 Command Model

The command model is given by

$$\dot{\underline{x}}_m(t) = \underline{A}_m \underline{x}_m(t) + \underline{B}_m \underline{u}_m(t) \quad (\text{B-10a})$$

$$\underline{y}_m(t) = \underline{C}_m \underline{x}_m(t) + \underline{D}_m \underline{u}_m(t) \quad (\text{B-10b})$$

In these equations,  $\underline{x}_m$ ,  $\underline{u}_m$ , and  $\underline{y}_m$  are the command model state, input, and output vectors, respectively.

The dimensions of the command model are

$n_M$  = "number of model states"

$r_M$  = "number of model inputs"

$p_M$  = "number of model outputs"

(B-11)

and the dimensions of the matrices are

$$\underline{A}_m: n_M\text{-by-}n_M$$

$$\underline{B}_m: n_M\text{-by-}r_M$$

$$\underline{C}_m: p_M\text{-by-}n_M$$

$$D_m: p_M\text{-by-}r_M \quad (B-12)$$

CGTPIQ requires that the number of outputs of the command and design models are equal:  $p_M=p$ . Also, the number of system states of the command model ( $n_M$ ) cannot be greater than the number of system states of the design model ( $n$ ). This constraint is due to the setup for computation of the CGT solution. (Note: the command model for explicit and implicit model following need not be the same, though they may be.)

#### B.3.4 Overall Model Dimensions

Problems of the following dimension can be accommodated by CGTPIQ

$$n \leq 15$$

$$n+d \leq 15$$

$$r \leq 5$$

$$p \leq 5$$

$$m \leq 15$$

$$w \leq 15$$

$$w+w_D \leq 15$$

$$n_M \leq 10$$

$$r_M \leq 5$$

$$p_M \leq 5$$

$$n_t \leq 20$$

$$r_t \leq 5$$

$$m_t \leq 15$$

$$w_t \leq 20$$

(B-13)

NOTE, other combinations of dimensions, some greater

than and some less than these specific dimensions, will also be accommodated due to the method by which arrays are allocated and stored. If the user has a problem that does not fit these size restraints he should try the problem to see if it will work. Messages will be printed if he has exceeded total allocation, and in that case, the basic program code will have to be altered to proceed.

#### B.4 Entry of Dynamics Models

Any of the three dynamics models described above may be established in any of three ways: (1) the dimensions and matrix elements may be entered directly from the terminal with input prompting from CGTPIQ; (2) the dimensions and matrix elements may be entered from a "DATA" file on which the dynamics model from a previous run of the program was written (the writing of such a file entry for each model is a program option); or (3) the dimensions and matrix elements may be established by user provided subroutines as was done for some of the airplane models used and discussed in Floyd's thesis (Ref 9). These models are also in CGTPIQ.

When entered from the terminal directly or set by subroutines, only non-zero elements of the various matrices need be given. In many cases, this substantially simplifies establishing the matrices and reduces the probability of erroneous entries. Subsequent design runs for the same problem can then simply read the models from the "DATA" file previously created.

Each request for input from the user includes a

prompt by CGTPIQ of information defining the input desired, whether this input is the dynamics models or any other required input. When an option is offered, the prompt succinctly describes the option and specifies the appropriate form of response (e.g., "Y or N", signifying and yes or no response.) When a dimension is to be entered, the dimension is identified. When a matrix is to be entered, the matrix is identified, as is its dimension, and the appropriate form of input. Similarly, all other requests for input identify the input expected and the form the entry is to take. The messages to the user are brief and require that the user have some understanding of what is involved in achieving each of the designs. The prompts are intended to assist users familiar with the elements of the PI, CGT, CGT/PI, and KF design methods and with the terminology used in this thesis to enter the necessary information for such designs into the program.

#### B.5 Program Output

In the computations involved in the various design paths, a great deal of information is generated. While all the information generated may be relevant to the design, in the usual case only a small fraction of the information is needed to pursue iteration of the design paths. Information most relevant to achieving the various designs is output to the terminal either automatically or at the user's option. The same information, along with all other potentially useful information generated by the program, is also output

to a "LIST" file. After program execution is complete, the user may then look through this file at the terminal or may "ROUTE" it to a line printer for a complete listing. All output is given an identifying name or description which is consistent with the terminology of this thesis.

Plots are available as options of the design evaluation routines. The plots produced are of the "line printer" type. For the controller, plots of selected variables may be output to the terminal, in addition to the full set of plots output to the "LIST" file.

During program execution, user entries in the design iteration are preserved. Thus, for each iteration only those entries to be changed need be given as input, making design iteration both fast and easy in terms of the simple mechanics of the process. Also, computations which are not modified by design iteration are performed only once and the results are preserved for reuse within the current run, as needed.

#### B.5.1 File Usage: PLOT, SAVE, DATA, LIST

In addition to the I/O communication directly with the user terminal, CGTPIQ employs four disk files for I/O purposes. One of these ('PLOT') is for temporary use by CGTPIQ only. The other three files ('SAVE', 'DATA', and 'LIST') benefit the user by providing continuity between distinct executions of the program (SAVE, DATA) or providing supplementary design output data (LIST).

CGTPIQ preserves information for use in distinct



execution of the program through use of the SAVE and DATA files. During program execution, the dynamics models as well as the PI controller gains (if available) may be written to the SAVE file. Following execution, the user may wish to catalog SAVE as a permanent file. In subsequent executions, CGTPIQ may (at the user's option) read any of the dynamics models or PI gains from the file named DATA. (Also the gains to be used by the program "PFEVAL" are also written to the SAVE file). Both files are rewound prior to and following program execution. Letting the abbreviations "BE" and "AE" mean before and after execution, respectively, typical operations on these files include:

1. Catalog SAVE file:

a. BE:REQUEST,SAVE,\*PF

AE:CATALOG,SAVE,pfn

b. AE:REQUEST,DUM,\*PF

AE:COPYBF,SAVE,DUM

AE:CATALOG,DUM,pfn

2. Attach DATA file:

BE:ATTACH,DATA,pfn

3. Reuse SAVE file as new DATA file

AE:RETURN,DATA

BE:COPYBF,SAVE,DATA

None of these operations are required; they are simply useful operations in the event the user chooses to employ the files to streamline repeated executions of a given design problem. Note that SAVE and DATA are local file names and that the permanent file names are represented here

by the abbreviations "pfn". Other operations (e.g., PURGE) and other combinations of operations are possible as for any files, and the usual rules for these operations apply here as well. The essential points to understand are that the SAVE file is created by CGTPIQ and is an output file only, and that DATA is a previously SAVE'd file under a new local file name and is an input file only. During a single program execution the two files are distinct and these roles cannot be changed.

During program execution, extensive design information is output to the LIST file. After execution is complete, the user may wish to route LIST to a line printer for listing (or it may be "PAGED" at the user terminal). The file is rewound before and after execution. To send LIST to a line printer, the following command is used after execution:

```
ROUTE,LIST,DC=PR,TID=nn,ST=CSB,FID=abc
```

in which "nn" is the identification number of the terminal to which the file is to be sent (for AFIT ,nn=AF), and "abc" is any three character output banner for the listing.

The PLOT file is used internally by CGTPIQ for temporary storage of the variables generated by time response evaluations of the controller or filter. If desired, it may be eliminated following execution using the command:

```
RETURN,PLOT
```

## B.6 Error Checking

A common problem encountered in executing computer programs with variable dimension array storage is the unintentional (and often unknown) over-running of the allocated storage area. When this happens, the program may fail (due to the over-writing of program code, for example) or, even worse, the program may appear to run properly but provide erroneous results. To avoid these difficulties, before using each of the Common arrays, CGTPIQ computes the allocation needed for the arrays it will generate and compares it with the number of words of memory actually allocated. If more memory is needed than has been provided, a message is written indicating the problem, the Common in question, and the minimum allocation needed. Execution is then aborted.

Error checks for array entry from the terminal are also performed. Not only are the array dimensions identified in prompts requesting entry of arrays, but each entry is checked to verify that it is within the row, column bounds for the array. If not within bounds, the entry is not accepted and a message identifying the problem is given. Also, for matrices requiring special properties (e.g., positive semi-definiteness), entries which clearly violate these requirements (e.g., negative diagonal elements) are not accepted and a message is written to the terminal.

Various other error checks are performed for each input entered from the terminal. These checks ensure that no obviously invalid entries are accepted (e.g.,

non-positive controller sample time), and no storage out of array bounds occurs. Obviously, it is not possible to guard against valid yet erroneous entries, but in most cases the program provides opportunities to correct mistaken entries made and discovered by the user. Additional tests are performed to ensure dimensional consistency of the dynamic models. These dimensions were discussed previously. For example, CGTPIQ checks that the numbers of inputs and outputs defined for the design model are equal, as well as checking each of the other dimensional conditions as each model is established. If the condition is not met, a message identifying the problem is written and the program execution is aborted.

#### B.7 Preparation Prior to Program Execution

Preparation for use of the program consists primarily in determining the dimensions of the models to be employed and the specific coefficients of the matrices comprising those models. It is appropriate for the PI design that an initial set of quadratic weights be established also, in order to begin the design iteration process.

Assuming that the user understands the nature and requirements of the various design elements, and is familiar with terminology related to such designs, the actual execution of the program involves straightforward response to input prompts. The specific meaning of all program prompts employed will be discussed later. Information most

useful to the design iterations is available directly as output to the terminal, while additional information is provided in the separate output 'LIST' file. The terminology employed in the output is defined later.

#### B.7.1 Determine Dynamics Models

CGTPIQ employs three dynamics models as discussed previously. It is necessary that the user determine the dimensions and parameters of these models prior to execution of the program. The specific models needed to execute the design paths of interest need be known. At a minimum, the design model must be known in order to execute any of the designs. The truth model is required for evaluation of the Kalman filter (to perform a covariance analysis) and is optional for evaluation of the PI controller or CGT and CGT/PI controllers. The command model must be known in order to effect either CGT or CGT/PI designs. The dynamics models are entered into the program during execution as needed and under input prompting provided by CGTPIQ.

#### B.7.2 Define Objectives and Specifications

Before embarking upon design of the controller, the designer should define: (1) the objectives which are to be sought, and (2) appropriate specifications and constraints to apply to the controller. These may be rather loosely defined initially, then become more specific and firm as the design progresses. Objectives will vary with the problem under consideration, but might be exemplified by formulation

of a desired controlled output response behavior.

Specifications and constraints derive from the problem application and from the objectives for the design. Typical considerations include time-delay, overshoot, and settling time of the response, and input magnitudes and rate limits.

### B.7.3 Determine Appropriate Initial Quadratic Weights

Execution of the PI controller design entails entry of quadratic weights for the optimal cost function. Such weighting matrices are required for the outputs, the input magnitudes, and the integral of the regulation error (also implicit weights to be discussed later). For these, only diagonal elements are required as input, since CGTPIQ assumes them to be diagonal matrices. However, after CGTPIQ computes the resulting augmented state and integral of the regulation error weighting matrix (Equation (III-36c)), the user may modify any element of it to achieve design goals.

Although final selection of appropriate quadratic weighting values to achieve design requirements is achieved in an iterative (trial-and-error, hopefully with insight) fashion, it is possible to make initial choices which are plausible. A common method for determining initial quadratic weights involves inverse square weighting of maximum deviations of outputs and inputs to achieve regulation for an assumed perturbation of the system (Refs 15 and 18:10-11). For example, the diagonal output weighting matrix element  $\underline{y}_{ii}$  would be

$$\underline{y}_{ii} = 1./(\text{maximum allowable } y_i)^2.$$

Beginning with the initial set of quadratic weights, the PI design path is executed repeatedly with changes in the choice of weighting elements until the design is satisfactory. CGTPIQ provides information during execution which allows the design to be evaluated and iteration of the design to be pursued effectively.

For open-loop CGT designs and Kalman filter designs, preparation consists of defining the various dynamics models. The open-loop CGT design depends only on the design and command models. The initial execution of the Kalman filter path depends only on the design model (and truth model for evaluation). Further refinements to either design are achieved through modifications of the appropriate dynamics model (command or design).

## B.8 CGTPIQ Execution

### B.8.1 Introduction

An important feature of CGTPIQ is that it follows appropriate paths through execution automatically, prompting the user for input as necessary. The basic design paths are selected by the user under prompting, but within a given path, only information needed to execute the specific design and evaluation is requested by the program. The user thus does not need any predetermined sequence of command entries to the program, nor are the commands coded in any way.

Figure B-1 gave a general flowchart of CGTPIQ. Each of the decision blocks (diamond shaped) represent a prompted request for input to choose the design to be pursued. Each

rectangular block with an alphabetic character ("A" through "H") in the lower right corner represents a computational element of CGTPIQ and is discussed individually in the following subsections. The subsections which follow discuss the I/O of each computational element. In identifying items of I/O, reference will sometimes be made to array names and equations which are specified elsewhere in this thesis (equation references will be in parentheses following the array name). All prompts for input define the input that is being requested and the manner in which the entry should be given. Since the actual prompts are themselves understandable, they will not be quoted here. Instead, flowcharts will be used to show where prompts occur and how execution depends on user entries. Blocks involving I/O will be identified by function: an "I" block will signify prompted input from the terminal; an "OT" or "OL" block will signify output to the user terminal or LIST file, respectively. All output to LIST is separated and identified according to the computational element which generated it.

#### B.8.2 Types of Entries

Required inputs may entail entry of a decision logic value, a single numerical or character value, or multiple numerical values for arrays or vectors. In all cases, CGTPIQ prompts the user with messages identifying the nature of the input requested and each prompt ends with the character ">".



All requests for decisions affecting execution are framed as questions requiring a YES ("Y") or NO ("N") response. The user entry is read as character input. Execution proceeds according to a default "YES" assumption: all decision tests assume that if the answer is not "NO", then it is "YES".

Requests requiring single entry responses always specify the variable requested. If there are constraints on acceptable input they are indicated in the prompt and adherence is tested in the program after entry. If the entry is not "valid", a message is written to the terminal and the prompt is repeated.

All requests for entry of vector or array elements specify the name of the array in question and its actual dimensions. Entries for vector elements include an integer specifying the index of the element, and a real specifying its value. For most arrays, all elements may be given values, while for some square matrices, only diagonal elements may be set (the prompt format will distinguish between the two). In the usual case, elements are entered into arrays by specifying two integers for the [row,column] address and a real for the value of that element. In cases in which only diagonal elements can be specified, entry is the same as for vectors, with the matrix diagonal considered a vector. As many entries as desired may be made and any entry can be repeated (e.g., to correct previous erroneous entries). Entry is terminated by specifying a row index of zero. Each entry is tested to verify that it lies within

the [row,column] bounds of the array (vector). If an index is not "valid", a message is written to the terminal indicating the error and the initial prompt with the array dimensions is given again (previous valid entries are not affected, only the specific invalid entry is rejected). If an entry is valid, the element value is set and the next entry is awaited without additional prompting. For example, if it is desired to set a square matrix of dimension three to an identity matrix, then according to whether the specific matrix is to be entered in [row,column] or diagonal form, entries would be as follows:

1. For [row,column] entry format

1 1 1. (enter)

2 2 1. (enter)

3 3 1. (enter)

0/

2. For diagonal element entry format

1 1. (enter)

2 1. (enter)

3 1. (enter)

0/

Items of information may be separated by one or more blanks or by a comma. These entries set specific elements of the matrix to non-zero values (the matrix was initialized automatically with all elements zeroed). The following sections will now discuss the individual boxes denoted with a letter in Figure B-1.

### B.8.3 Establishing Dynamics Models ("A")

All three dynamics models (design, truth, and command) are entered under the control of a single set of routines. The options for entry and the type of I/O involved for each is of identical format, but prompts and output employ terminology specific to each model to identify items of I/O.

Figures B-2a,b,c give flowcharts of the I/O involved in entry of the models. Note that any of the dynamics models may be entered in any of the following ways:

1. The dimensions and array elements may be read from the DATA file.
2. The dimensions and array elements may be entered from the user terminal as prompted by CGTPIQ.
3. The dimensions and array elements may be determined by user-provided subroutines.

These modes of entry are offered by CGTPIQ in the order above, with option 3 assumed selected if options 1 and 2 are declined. If option 1 is selected, the reading of the model is automatically performed. If the model is found not to exist in the DATA file, the other options are offered. For option 3, if the subroutines needed to define the model are not loaded, option 1 and 2 are offered again. This logic is illustrated in Figure B-2a.

Prior to entry of the model matrices, all matrix elements are initialized to zero. Using option 1, all array elements are then read automatically from the DATA file. For options 2 and 3 only the non-zero array elements must be

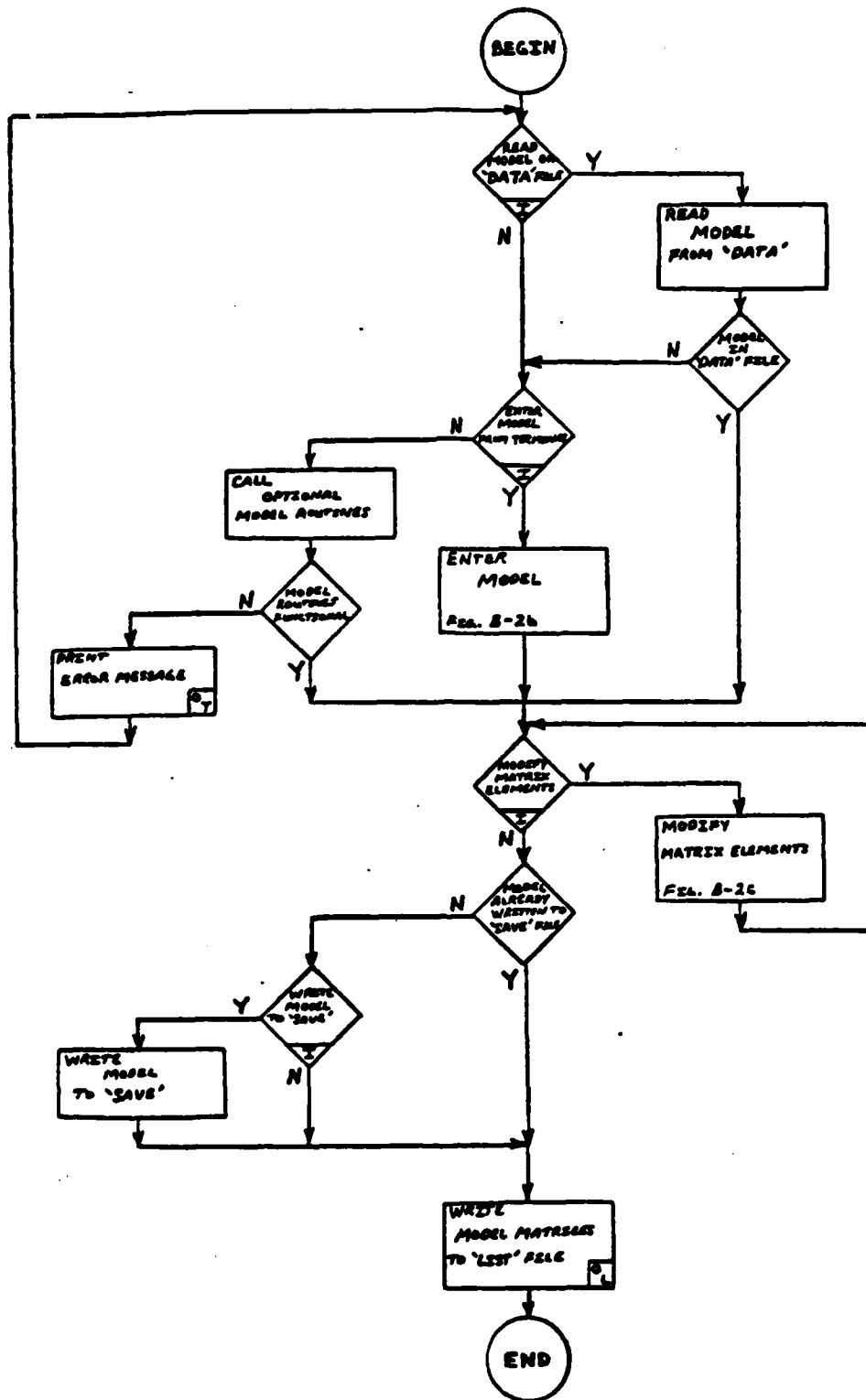


Fig. B-2a. Dynamics Model Entry (Executive)

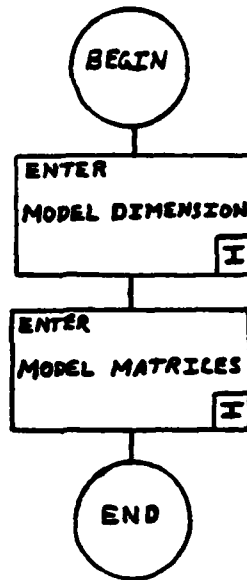


Fig. B-2b. Enter Dynamics Model from Terminal

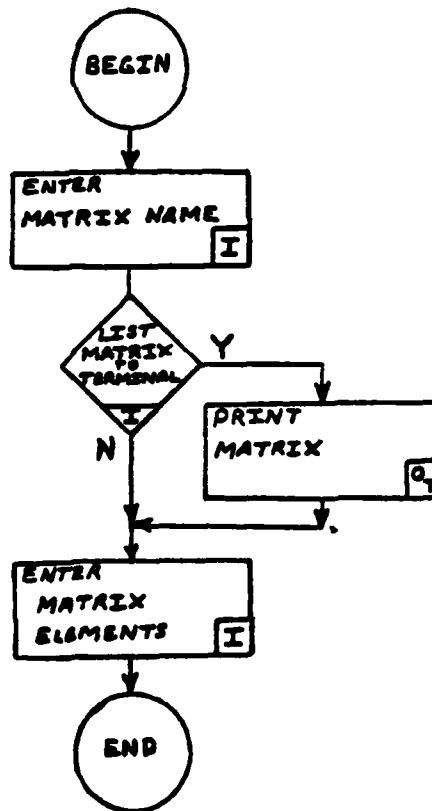


Fig. B-2c. Modify/List Model Arrays

established.

Figure B-2b illustrates model definition under option 2. Entry of the dimensions and arrays is according to prompts by CGTPIQ. The dimensions are requested first by the names and in the order of Equation (B-4), (B-8), or (B-11), as appropriate. The arrays are then requested, also by name and in the order of Equation (B-5), (B-9), or (B-12), as appropriate. An array is not requested if its dimension is zero. Each prompt includes the actual dimensions of the array according to the model dimensions previously entered. Elements of arrays are entered by address, and value by giving the [row,column] address and element value as a three item input. Entry of a zero row address terminates entry of the array.

For option 3, each model requires two user-provided routines of prescribed names, argument lists, and characteristics. These must be compiled with the main routine of CGTPIQ and a segmented executable object file created. For each model defined by subroutines, one subroutine must establish the dimensions of the model, and another must set the values for all matrices of that model. Each routine must have the appropriate name and argument list. All model arrays appearing in the argument lists must be allocated in full manner: the array dimensions specified by "Dimension" statements within the routines must be exactly those implied by the routine specifying model dimensionalities and the array sizing given by Equations (B-5), (B-9), and (B-12). For example, if the number of

design model states (n) is established as 10, then according to Equation (B-5) the system matrix must be explicitly dimensioned A(10,10) in the subroutine which sets array values for the design model. All of these arrays are initialized to zero before the array setting routines are called, so it is necessary only to set non-zero array elements within the subroutines. Any arrays of dimension one in both row and column are actually scalars and need not be included in a Dimension statement. Any arrays with row or column dimension of zero are in fact nonexistent arrays and must not be included in Dimension statements, although they still must be included in the subroutine's argument list (since calls to these routines from within CGTPIQ assume full argument lists).

After a model is defined using any of the three entry options, the user may list any matrix and modify any array elements, again under prompting by CGTPIQ. If a modification/list is desired, the names of the model's matrices are listed at the terminal and the user specifies the array of interest by name. Elements are entered by address and value as described previously. Figure B-2c illustrates the I/O involved in modifying/listing model arrays.

When the model has been defined to the user's satisfaction, it may be written to the SAVE file by CGTPIQ if the user chooses. In the course of design iteration, the truth and command models may be redefined if desired, but only a single copy of any model may be written to the SAVE

file during a given execution of the program (CGTPIQ will not offer additional opportunities after a given model has been SAVE'd).

For each model, the discrete-time representation is computed for the controller sample period specified. Later computations do not depend on the continuous-time dynamics models, so the arrays defining them are not retained.

(Note: To consider effects of different sample periods, the program will require re-execution with re-entry of the models.)

Arrays defining both the continuous-time and discrete-time models are given in output to the LIST file. The specific output items, their names, and the reference equations are listed below for each model

#### Design Model

Continuous-time model matrices as listed in Equation (B-5), plus discretized model matrices as:

PHI:	$\underline{\Phi}$	(IV-5)
BD:	$\underline{B}_d$	(IV-5)
QD:	$\underline{Q}_{ad}$	(IV-6c)
HA:	$\underline{H}_a$	(IV-1d)
EXD:	$\underline{E}_{xd}$	(IV-7a)
PHN:	$\underline{\Phi}_n$	(IV-7b)

#### Command Model

Continuous-time model matrices as listed in Equation (B-12), plus discretized model matrices as:



PHM:  $\underline{A}_m$  (IV-17)  
 BDM:  $\underline{B}_{md}$  (IV-17)  
 CM:  $\underline{C}_m$  (IV-18)  
 DM:  $\underline{D}_m$  (IV-18)

### Truth Model

Continuous-time model matrices as listed in Equation (B-9), plus discretized model matrices as:

PHT:  $\underline{A}_t$  (IV-12)  
 BDT:  $\underline{B}_{td}$  (IV-12)  
 QDT:  $\underline{Q}_{td}$  (IV-13c))

In addition, the eigenvalues of the system matrices of each model ( $\underline{A}$ ,  $\underline{A}_m$ ,  $\underline{A}_t$ ) are computed and output both to the user terminal and the LIST file. The system model is identified by type (design, command, truth). Eigenvalues of the corresponding discretized system matrices are not computed.

#### B.8.4 Controller Setup ("B")

The "controller setup" routines perform computations needed for the controller designs. No input is required of the user and the output is to the LIST file only. The output is the matrix  $\underline{\pi}$ :

PI:  $\underline{\pi}$  (II-18)

#### B.8.5 PI Design ("C")

The PI design has as a first question to the user

whether he wishes to use and/or combine implicit/explicit model following by incorporating implicit weights. If the user responds with no ("N") then execution of the PI design path entails user entry of only explicit quadratic weighting matrices defining the costs associated with output deviation, control magnitudes, and integrals of the regulation error (see Figure B-3) (the results of a yes answer to this question will be discussed later in this subsection):

OUTPUT DEVIATION:  $\underline{Y}$  (A-3a)

CONTROL MAGNITUDES:  $\underline{U}_y$  (A-5b)

INTEGRAL OF THE

REGULATION ERROR:  $\underline{U}_q$  (A-3b)

For each of these matrices, only the diagonal elements are entered. On the first execution of the PI design, all weighting matrices are initialized to zero. Subsequent iterations preserve the elements of these matrices so only desired changes in specific weighting elements need be entered. Weights on output deviations should be non-negative, while weights on control magnitudes and integrals of the regulation error should be positive. Entries are tested for positive or non-negative values as appropriate. If an entry is not valid, a message is written to the user terminal and that entry is not accepted.

Matrices  $\underline{Y}$  and  $\underline{U}_q$  are used to compute a quadratic weighting matrix on the state deviations (using an augmented state vector composed of system state and integral of the regulation error perturbations from nominal). This

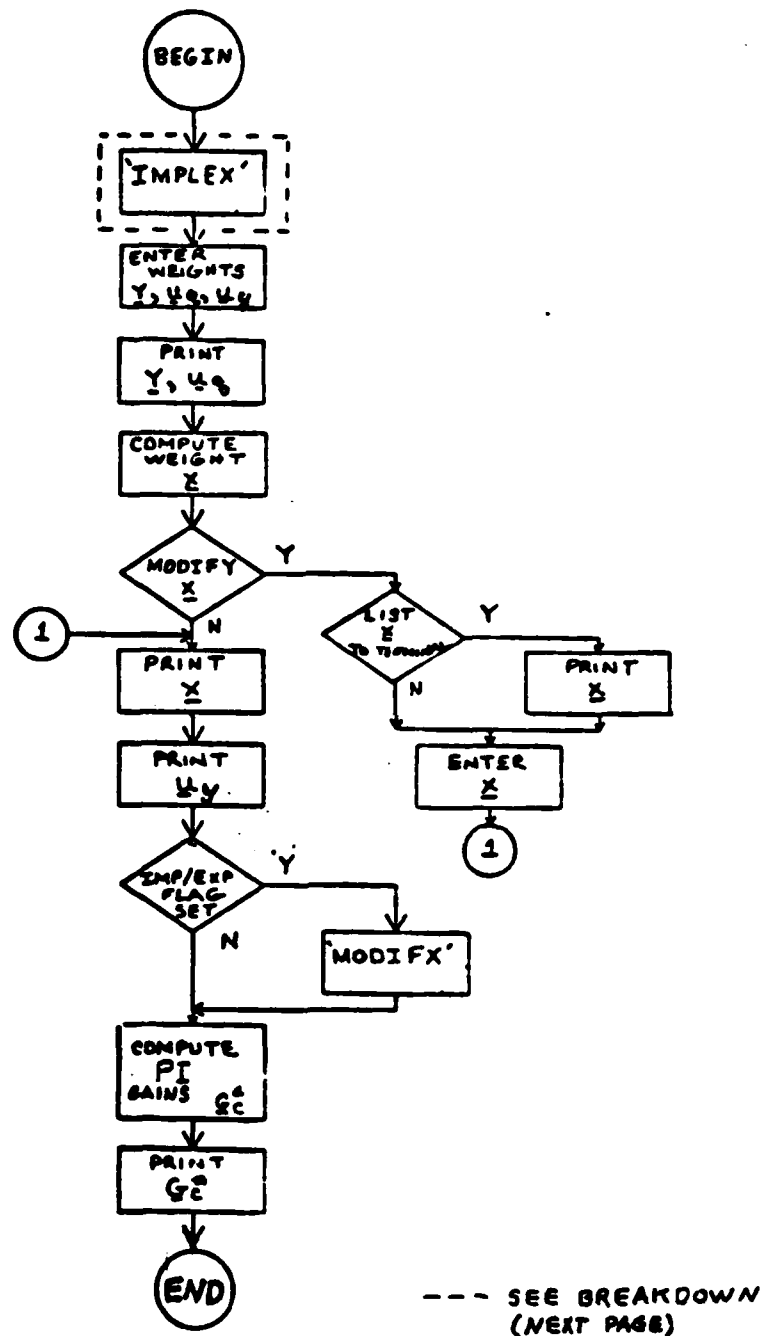


Fig. B-3. PI Controller Design

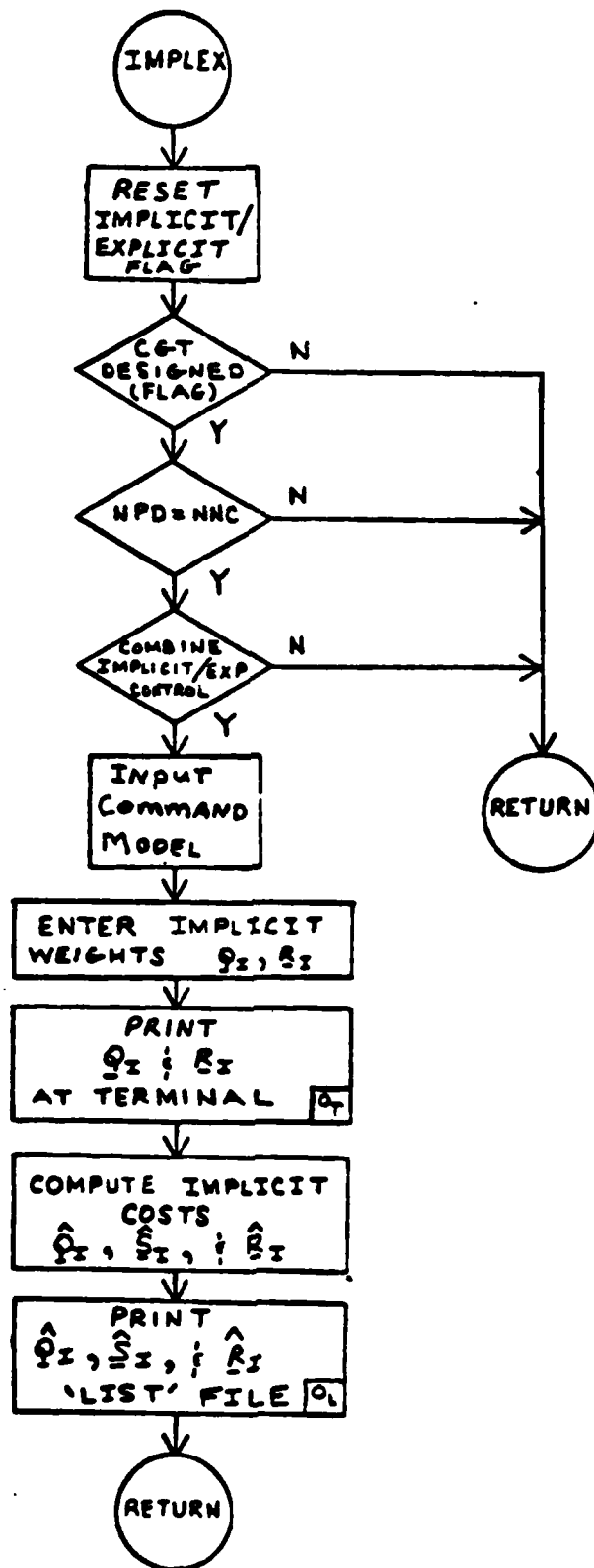


Fig. B-3-- Continued

new matrix is referred to as "X" (Equations (III-34c) and (III-35a,b,c)). The user may then modify any element of X and/or list it at the terminal. Elements entered into X are automatically set symmetrically by CGTPIQ, but the sign of diagonal elements entered is not tested. X is not preserved between PI design iterations, so any desired changes in elements with respect to their values as determined from Y and U<sub>q</sub> must be re-entered each design pass.

The diagonal elements of Y, U<sub>q</sub>, and U<sub>y</sub> are printed at the user terminal and the entire Y, U<sub>q</sub>, U<sub>y</sub>, and X matrices are output to the LIST files. Next, the controller gains and PI gains are computed. The PI gains are printed at the terminal ("GC1" and "GC2") and all gains are output to the LIST file. The intermediate product "E" is also output to the LIST file. The proportional "KP" and integral "KI" gains of the PI controller are also output to the LIST file.

The outputs to the LIST file are:

Y:	<u>Y</u>	(A-3a)
UQ:	<u>U<sub>q</sub></u>	(A-3b)
UM:	<u>U<sub>y</sub></u>	(A-5b)
E:	<u>E</u>	(III-28a)
GC1:	<u>G<sub>c1</sub></u> *	(III-20)
GC2:	<u>G<sub>c2</sub></u> *	(III-20)
KI:	<u>K<sub>i</sub></u>	(III-31c)
KP:	<u>K<sub>p</sub></u>	(III-31b)

Note that the mnemonics "UQ" and "UM" refer to integral of the regulation error and input magnitude weighting matrices,

respectively.

If the user responded with a yes to the first question of combining implicit/explicit control, the program prompts the user with messages identifying the required implicit model-following related inputs. Entries are requested for the command model first (this need not be the same command model as in explicit design but the number of model states must equal the number of system outputs,  $nM=p$ ), and then for the quadratic weighting on the implicit output derivatives and then the implicit control magnitudes. Note that only diagonal elements can be specified using the format discussed previously. After entry of the implicit quadratic weights, the user is permitted to see the "XIE" matrix (the upper left partition of Equation (III-98)) that is generated and he is asked if new implicit weights are required to be entered. If yes, the program re-initializes the implicit matrices and asks for the implicit weights again. If no, the implicit weighting matrices  $\underline{Q}_I$  and  $\underline{R}_I$  are then printed at the terminal. Matrix  $\underline{Q}_I$  is the implicit output derivatives matrix; matrix  $\underline{R}_I$  is the implicit control magnitude matrix.  $\underline{Q}_I$  and  $\underline{R}_I$  are equivalent to  $\underline{X}_I$  and  $\underline{U}_I$  of Equation (III-93), respectively. Following this, the program returns back for the normal explicit weights to be input as discussed previously. The user may design an implicit only (with limitations), explicit only, or a combined implicit/explicit controller via his selection of quadratic weights. An implicit model-following controller is pursued if the

explicit quadratic weights are all chosen as zero (limitation: experience has shown that UQ should not be zero or the Riccati equation solver typically will not converge to a solution in the maximum permitted iterations). On the other hand, an explicit model-following controller is pursued if the implicit quadratic weights are chosen as zero; or if the user responds with no ("N") to the first question. If the implicit or combined implicit/explicit model-following is chosen the program utilizes the appropriate combined quadratic weights according to Equation (III-98). This also results in additional outputs to the LIST file

QI:  $\underline{X}_I$  (III-91)  
 RI:  $\underline{U}_I$  (III-91)  
 QIH:  $\hat{\underline{X}}_I$  (III-93a)  
 SIH:  $\hat{\underline{S}}_I$  (III-93b)  
 RIH:  $\hat{\underline{U}}_I$  (III-93c)  
 XIE:  $\underline{X}$ (modified) (III-98)

When execution of the PI design computations is complete, the "controller evaluation" set of routines is automatically executed. These are discussed in a later subsection as a separate computational element.

#### B.8.6 CGT Design ("D")

Execution of the "CGT design" path requires that a command model be established. If desired, a new command model can be established during any iteration of the design. The model is actually entered using the routines described

in Section B.8.3 above ("Establishing Dynamics Models").

If PI gains already exist in the program storage, then a closed-loop CGT/PI design is effected automatically. If not, the user may elect to have the program read the PI gains from the DATA file and design a closed-loop CGT/PI controller. However, if the user chooses not to have the gains read from DATA or if the gains are found not to exist on the DATA file, an open-loop CGT design is effected automatically (by setting PI gains to zero), but only if the open-loop system is stable. For either open-or closed-loop CGT design, the matrices  $\underline{A}_{ij}$  (Equation (III-61)) are automatically output to the LIST file.

Figure B-4 illustrates the I/O, logic, and computations of the CGT design path. Details involved in entering the command model are given in Section B.8.3 and are indicated in this figure by a block titled "Establish Command Model". Note that since the continuous-time representation of the command model is not preserved, "modification" of the command model actually entails complete redefinition of it. In case the command model exists on the DATA file and only specific elements are to be changed, this can be accomplished readily by reading the model from DATA and then modifying individual arrays (as shown in Figure B-2c).

In establishing the command model, I/O is as described in Section B.8.3. Additional output to the LIST file is

$$\text{All: } \underline{A}_{11} \quad (\text{III-61a})$$



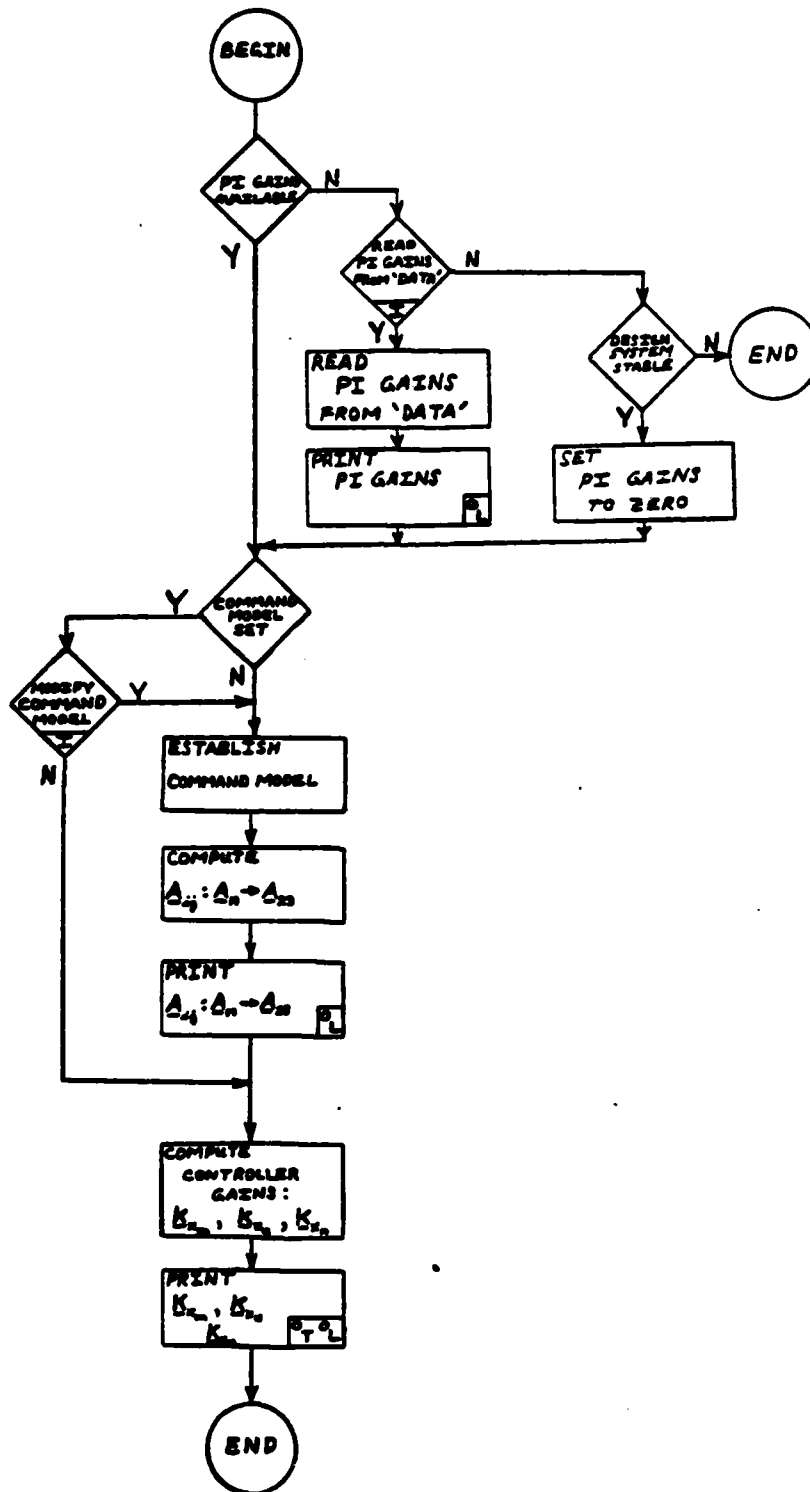


Fig. B-4. CGT Controller Design

A21:	$\underline{A}_{21}$	(III-61d)
A12:	$\underline{A}_{12}$	(III-61b)
A22:	$\underline{A}_{22}$	(III-61e)
A13:	$\underline{A}_{13}$	(III-61c)
A23:	$\underline{A}_{23}$	(III-61f)
KXM:	$\underline{K}_{xm}$	(A-24a)
KXU:	$\underline{K}_{xu}$	(A-24b)
KXN:	$\underline{K}_{xn}$	(A-24c)

The controller gains ("KXM", "KXU", and "KXN") are also printed directly at the user terminal. Note that arrays  $\underline{A}_{13}$ ,  $\underline{A}_{23}$ , and  $\underline{K}_{xn}$  exist only if disturbance states are specifically modeled in the design model ( $n_d$  of Equations (B-1a,b)).

When execution of the CGT design computations is complete, the "controller evaluation" set of routines is automatically executed. These are discussed in the next subsection.

#### B.8.7 Controller Evaluation ("E")

A single set of routines performs the controller evaluation for both the PI and CGT designs. For the PI controller, the poles of the closed-loop discrete-time system matrix  $\underline{z}_{CL}$  (Equation (A-18)) are computed and mapped into the primary strip in the continuous-time domain (the z-plane poles are not listed in output). These mapped closed-loop poles are printed to both the user terminal and the LIST file. The primary evaluation tool for both controllers is a time-response simulation. For the PI

controller, the response is taken for non-zero initial conditions (IC's) on the states; for the CGT controller the response is given for a step input on any of the command model's inputs. In either case, the system dynamics can be propagated using the design model or truth model state transition equations. Time response runs may be run repeatedly for a specific controller design.

The I/O, logic, and computations involved in the controller evaluation are shown in Figure B-5. Decision blocks labeled "CGT" test for the type of controller being evaluated (CGT or PI). Decision blocks labeled "LTEVAL" test if the truth model is being used to propagate system dynamics (if not, the design model is being used).

The first prompt of the controller evaluation computational element asks if the evaluation is to be conducted with respect to truth model dynamics. If yes, the truth model may be established or modified (if previously established) in the manner described in Section B.8.3 above. Note that, since the continuous-time representation of the truth model is not preserved within CGTPIQ, "modifications" actually entails complete redefinition of the model. In the case that the truth model exists on the DATA file and only specific array elements are to be modified, it is convenient simply to read the truth model from the DATA file and modify matrix elements as shown in Figure B-2c. If the truth model had been established previously and no modification to it is desired, the existing discrete-time representation of the truth model is used. The design model is used to propagate

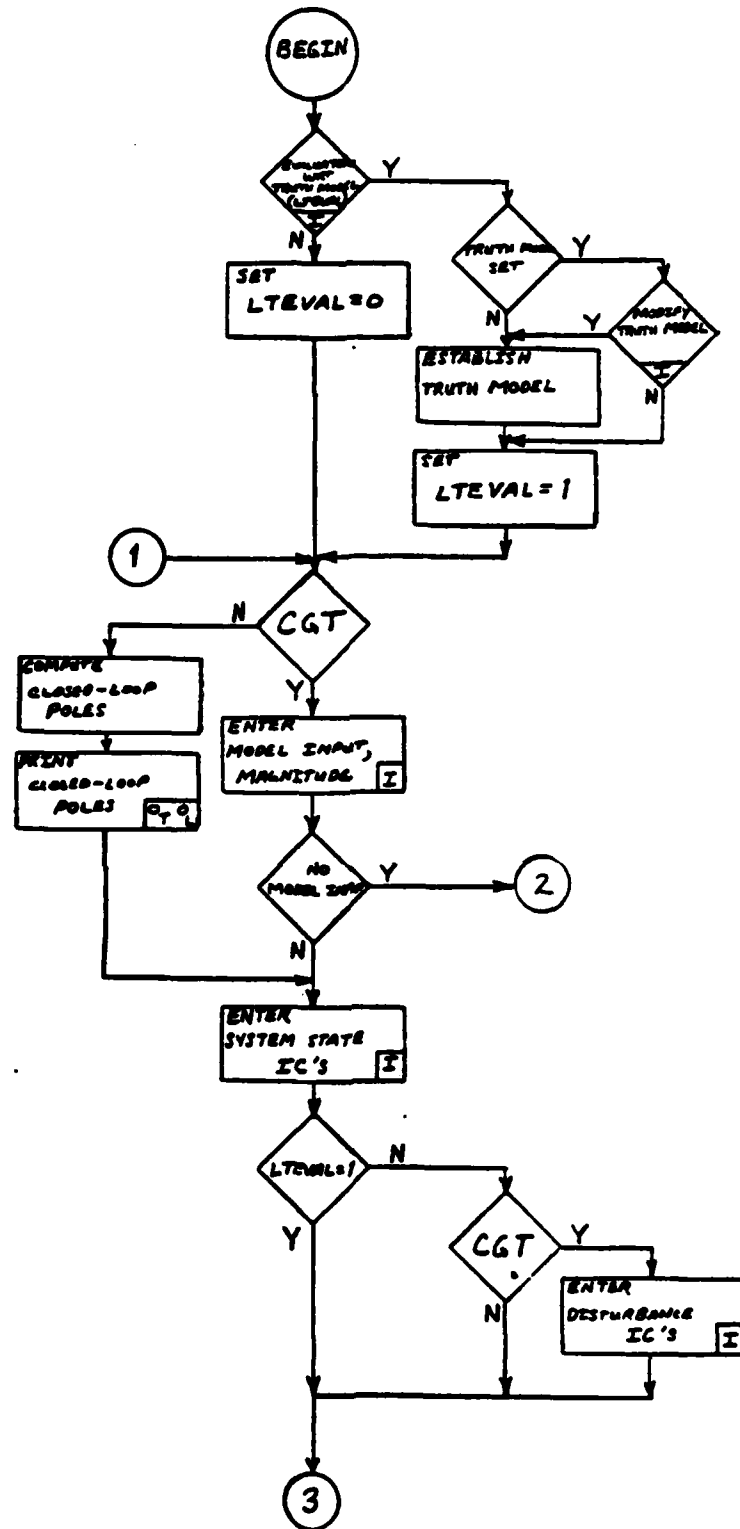


Fig. B-5. Controller Evaluation

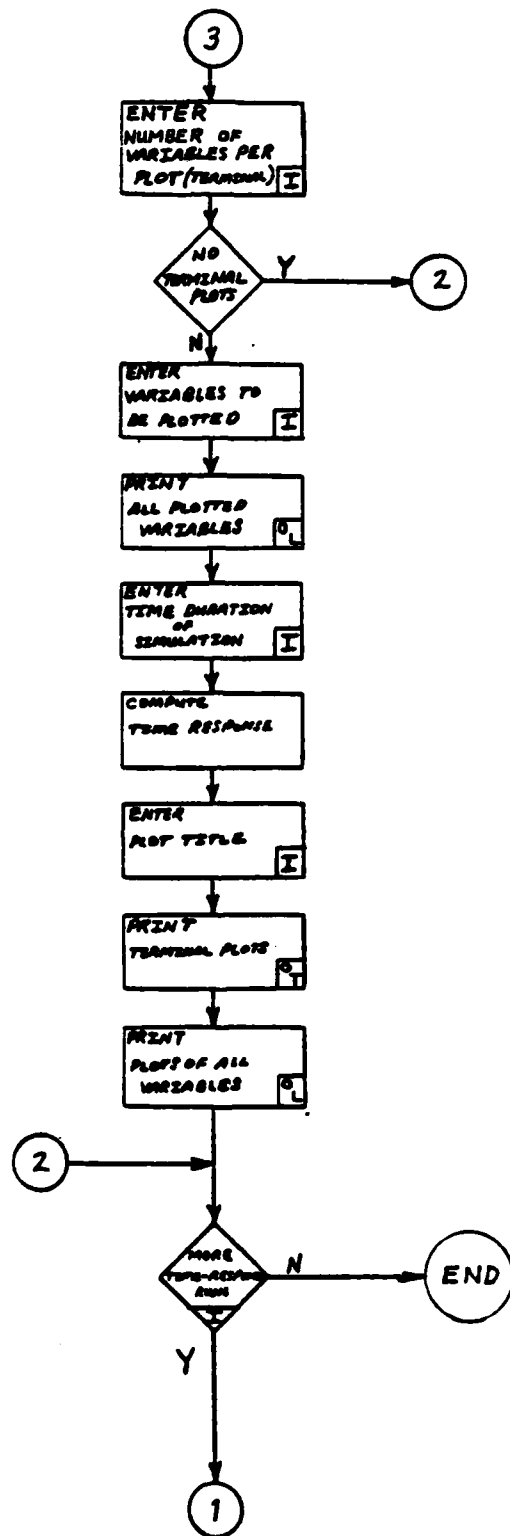


Fig. B-5--Continued

system dynamics if the truth model evaluation is not selected.

For the CGT evaluation, the first input prompt is for the index of the command input vector to which a step input is to be applied, and the magnitude of that step (only one command input is allowed at a time). CGTPIQ tests the input index for validity (within vector length bounds); if it is invalid the prompt is repeated. If the index is zero (or negative) the input is not accepted and the user is queried as to whether time-response runs are desired. If no time-responses are to be run, the controller evaluation routines are exited; otherwise, the prompt requesting command model input specification is repeated. If the CGT controller response is to be run, initial conditions on the system states may be entered. If the design model is used for evaluation and disturbance states exist in the model, they may be given initial conditions also.

For the PI evaluation the first input prompt is for initial conditions for the system states. The states that are actually given initial values are those of the design or truth model, according to the model used for propagation of dynamics. Initial conditions are entered for either controller in the same manner. Entry is of the index of the state within its appropriate state vector (design or truth model, or disturbance state vectors) and its initial value. Tests and termination of entry are as described in Section B.8.2 for multiple entries.

### B.8.7.1 Time Response Plots

Time-response plots are of the "line printer" type and are output both to the terminal and to the LIST file. As many as two plots, each with as many as five dependent variables, may be printed at the user terminal. CGTPIQ prompts the user to specify the number of variables for each of the two plots (the user is to enter two integers). If the user enters non-positive integers for both plots, then a prompt queries the user as to whether time-response runs are desired. If no time-responses are to be run, the routines are exited. Note that when no plots are selected for terminal printing, none are output to LIST either and no time-responses are simulated.

In the case that plots are to be printed at the terminal, a series of prompts allow the user to specify exactly which variables shall be included. Variables are selected by specifying a name of the vector type for that variable and its index in two entries for each variable. The names of the vectors are:

- X: system state vector
- Y: system output vector
- U: system input vector
- D: disturbance state vector
- M: command model output vector

The system state vector is that of the design or truth models, according to the model used for propagation of dynamics. For example, the pair of entries "U" and "1" specifies that element 1 of the input vector U is to be

plotted (note that "entry" includes a carriage return). The input prompt includes these definitions and includes only those variables relevant to the controller being evaluated. The model output and disturbance state vectors are only offered for CGT evaluations, and for the latter also only if the disturbance states are explicitly modeled and the design model propagates dynamics of the time-response (since for the truth model the system state vector includes all disturbance states which are considered to act on the system). Each user entry is tested for valid (and relevant) name and for valid index. Prompts specify the plot number and output number for each requested entry.

The user next is prompted to enter the time duration for the simulation. However, the duration actually simulated may be adjusted by the program: a time span that is the nearest integer multiple of 100 times the controller sample period is selected. Plots to the LIST file include the entire time span and use 100 equal time interval samples. Plots to the terminal include 50 time samples selected as follows: if the time duration specified by the user is less than 50 times the controller sample period, the samples plotted are the first 50 time samples from the simulation; otherwise, the entire time span is included in 50 equal-interval samples. Thus, for example, with a controller sample period of .02 seconds, a user-specified time duration of less than 1. second would yield plots to the terminal running from time=0. to time=1. and with .02 seconds between each sample; plots to the line printer from



LIST would include samples at the same interval but extending to time=2.

After completing the time-response simulation, a prompt requests a title for the plot and prescribes the field width available for the entry (50 characters). The title is applied to all plots generated from the single simulation.

Plots are printed with the independent (time) axis running vertically along the length of the output page with the origin at the top. Each sample time is identified along the left margin of the plot. The dependent axis is horizontal. Each variable is marked with an integer from 1 to 5 at each sample time. Note that since only one character can be printed in each location of the plot field, when two or more variables would occupy a single print position at a sample time, only the symbol of largest value (1 to 5) is printed. For plots to the terminal, if a model output is among the variables of a plot, then all variables in the plot are plotted over a single scale range to facilitate comparison of actual and desired output responses. In all other cases every variable plotted is scaled over its own range independently in order to achieve greater resolution for each in the plot field. The scale(s) are listed along the bottom of the plot. Rotation of the output page through 90 degrees in a counter-clockwise sense gives the usual abscissa-ordinate orientation. Terminal plots are 50 print positions wide; plots to LIST are 100 print positions wide.

Plots of all relevant variables in a time-response simulation (all states, inputs, and so on) are automatically output to the LIST file if terminal plots are requested. Five variables are included in each plot. A list identifying all the variables by type and index for each plot number and plot symbol is written to LIST prior to the plots.

When all plots have been printed, a prompt queries the user as to whether additional time-response runs are desired. If more are wished, the entire set of plotting options is repeated and the same controller may be evaluated under different conditions and/or different variables may be plotted. If no additional simulations are wished, the controller evaluation routines are exited.

#### B.8.8 Kalman Filter Design ("F")

The Kalman filter design routines compute the steady-state Kalman filter gains for the design model. Figure B-6 shows the I/O, logic, and computations involved. Note that the first execution of the filter design path bases its filter computations on the noise strengths specified upon initial entry of the design model. In subsequent executions, any of the noise strengths may be modified. The noise strengths are entered as vectors of the matrix diagonals (only diagonal elements may be modified). The matrices are

"STATE NOISE STRENGTHS":  $\underline{Q}$  (B-2a)

"DISTURBANCE NOISE STRENGTHS":  $\underline{Q}_n$  (B-2b)

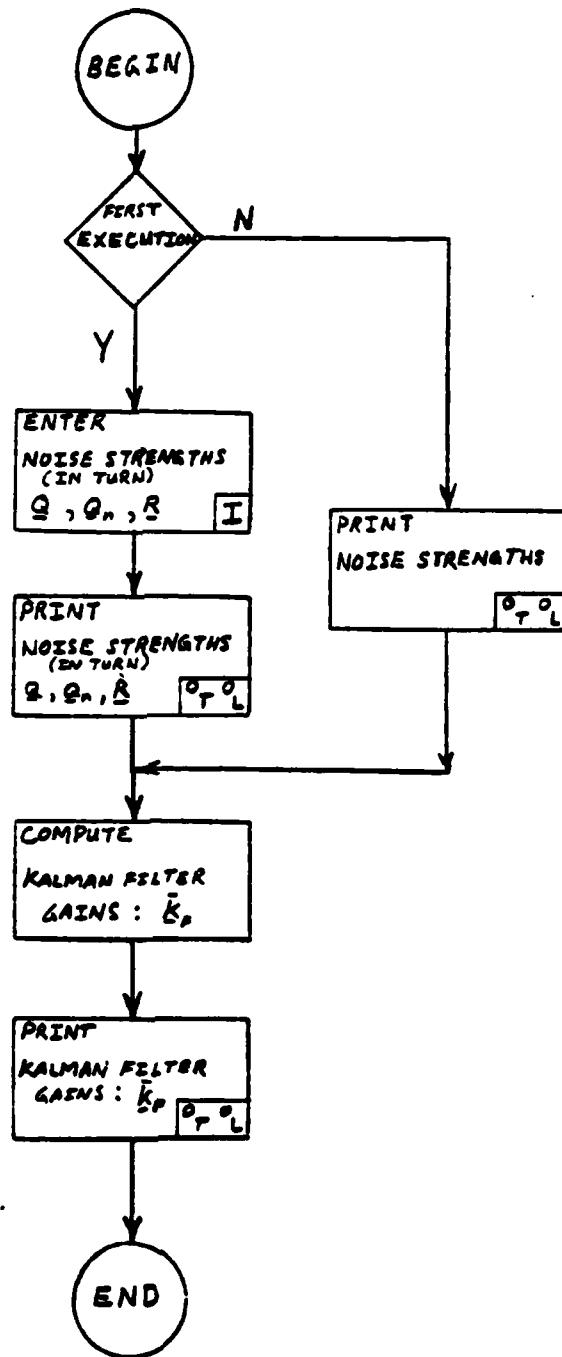


Fig. B-6. Kalman Filter Design

"MEASUREMENT NOISE STRENGTHS":R (B-2c)

Prompts for state or disturbance noise strengths are given only if the design model specifies driving noises for the respective process dynamics. Negative noise strengths are not accepted.

In each execution of the filter design path the entire noise strength matrices and Kalman filter gain matrix are output to the terminal and LIST file. However, only the diagonal elements of the noise strength matrices are printed at the terminal.

Following computation of the filter gains, the Kalman filter design routines are exited. Execution proceeds automatically to the filter evaluation computational element described in the next subsection.

B.8.9 Filter Evaluation ("G")

Figure B-7 shows the I/O, logic, and computations of the filter evaluation routines. Execution of the filter evaluation requires that the system truth model be established, since the covariance analysis is performed with respect to the truth model. Comments in Section B.8.7 dealing with establishing the truth model apply equally in this set of routines, except that here use of the truth model is not optional.

Evaluation begins with computation of the eigenvalues of the system-filter matrix  $\mathbf{I}_{KF}$  (Equation (D-6)). As for the closed-loop PI regulated system, the discrete-time eigenvalues are mapped to the primary strip in

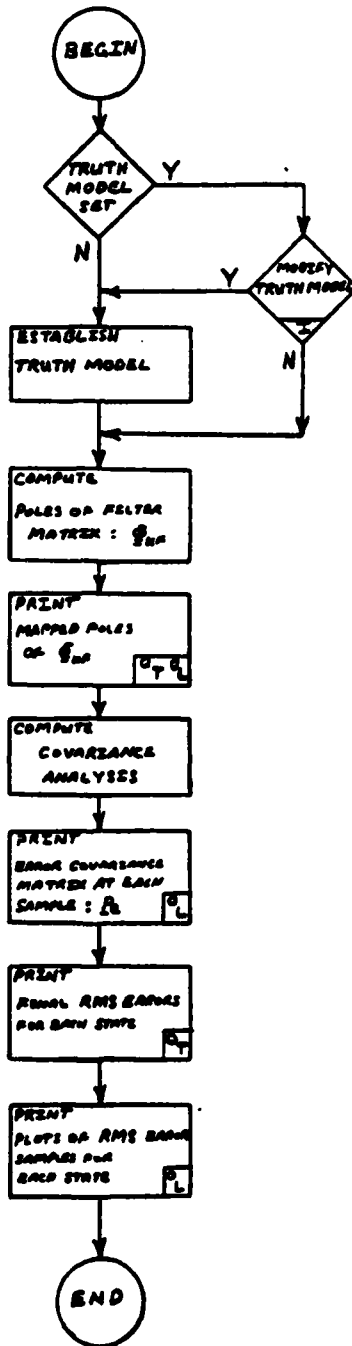


Fig. B-7. Filter Evaluation

the continuous-time domain. These mapped poles are printed at the user terminal and output to the LIST file (the z-plane eigenvalues are not printed).

The primary evaluation tool applied to the filter design is a steady-state covariance analysis. The covariance matrix of the estimation errors of the filter using measurements of the truth model dynamics is propagated for 50 filter (controller) sample periods. Samples are coincident with the filter's sample times and the total number is fixed at 50. At each time sample the standard deviations of these "true" errors are computed as the square-roots of the diagonal elements of the error covariance matrix. The filter's own computed error covariance matrix, because of the steady-state assumption, is constant for all time samples. Taking the square-roots of the diagonal elements then gives the filter's estimate of the standard deviations of its errors in state estimation. Plots for each state are output to the LIST file showing the "true" and "computed" RMS errors for the 50 time samples. A title may be entered to be applied to all plots from the covariance analysis. In addition, the "true" and "computed" RMS errors at the final time sample are printed at the terminal.

This completes the filter evaluation. A new filter design may then be pursued, or any other design option may be selected.

#### B.8.10 Performance Evaluation Data ("H")

In performance evaluation data, the performance data determined throughout the program is written to the SAVE file (via the user's response to input prompts) for use in the performance evaluation accomplished via the program "PFEVAL" (Ref 21). (As a special note, if this data is to be used in the program "PFEVAL", the SAVE file must be transferred to a DATA file as discussed previously). Decision blocks "filter designed yet" and "CGT/PI designed yet" correspond to program decision "flags". Note that performance data may be written to the SAVE file from either the controller or the filter design path.

#### B.9 Program Messages

A variety of messages may be printed at the terminal and/or output to the LIST file during program execution. Some are purely informational, are clear in their meaning, and provide no essential insight into progress of the design or possible difficulties in program execution. Such messages are not discussed here. The remaining messages relate to errors or potential design difficulties and are considered in categories of memory allocation, dimensional errors, or computational problems.

##### B.9.1 Memory Allocation

CGTPIQ uses vectors in named Commons for array storage. These vectors are dimensioned in the main routine and a variable in the Common is set to the value allocated.

These vectors are then partitioned within CGTPIQ to store individual arrays. Before storing arrays into each vector in Common, the storage needed is computed. In the case of temporary storage vectors, at each point in execution at which a new allocation is needed, the required storage is recomputed. If more memory will be needed in a vector than has been allocated, a message is written specifying the name of the Common and the necessary minimum allocation. A typical message of this type is

"INSUFFICIENT MEMORY /SYSMTX/, NEED: nnnn"

in which the common /SYSMTX/ has too little storage for the problem and 'nnnn' is the dimension required for the vector in that common. For the vectors containing the dynamics models, the model with insufficient memory is identified by name. The Commons for the design, truth, and command models are /DSNMTX/, /TRUMTX/, and /CMDMTX/, respectively. After printing such a message to the user terminal, execution is aborted.

In its existing form, CGTPIQ will have sufficient vector allocations to deal successfully with problems of many different combinations of dimensions and with system matrices in the range of 10 to 20 states. Since the program will not allow allocated memory to be exceeded, it is reasonable to attempt any given problem and let the program either deal with it successfully, or let it write the appropriate memory message if the problem cannot be accommodated. (Section A.9 of the programmer's manual of the thesis by Floyd (Ref 9) discusses the steps necessary to



obtain a new CGTPIQ with different memory allocations)

### B.9.2 Dimensional Errors

As each of the dynamics models is established, or just prior to computations which assume relations among the design and command system and disturbance state dimensions (CGT computations), the dimensional constraints mentioned previously are tested. In terms of the dimension notation of Equations (B-4), (B-8), and (B-11) the constraints are

Design model:  $p=r$  and  $n \geq d$

Truth model:  $r_T=r$  and  $m_T=m$

Command model:  $p_M=p$  and  $n \geq n_M$

$p=n_M$  (for implicit design only)

If such a constraint is not satisfied, a message is written to the user terminal identifying the problem and execution is aborted. When the constraint affects only a specific section of code, or if redefinition of the model (command or truth) can resolve the error, then only the affected execution path is aborted. In other cases, execution is aborted completely.

Other dimensional tests are made in the Kalman filter design and evaluation computational elements. For filter design, it is necessary that the system state and disturbance state driving noise dimensions not both be equal to zero, and that the number of measurements be non-zero. These are constraints on the design model:

$$\begin{bmatrix} w > 0 \\ \text{or} \\ w_D > 0 \end{bmatrix}$$

and

$m > 0$

For filter evaluation, the number of driving noises for the truth model must be non-zero:

$$w_T > 0$$

since in the case of  $w_T = 0$ , the system is deterministic and the covariance analysis would not provide much useful information for evaluation of the filter's performance. If any of these constraints are not satisfied, a message is written to the user terminal identifying the problem and execution of the filter design-evaluation computational elements is aborted.

### B.9.3 Computational Problems

In certain of the computations, characteristics of the particular design problem may be identified as having potential impact on the attainment of design objectives. Messages identifying these characteristics may be considered informational. Other messages describe computational problems that are immediately fatal.

In computing the Pi matrix of Equation (II-18), a pair of messages may be generated to the LIST file:

"PI MATRIX IS RANK DEFECTIVE"

and

"nr X nc MT RANK mr"

in which "nr" and "nc" are the row and column dimensions of the Pi matrix and "mr" is its rank. The first message is also printed at the user terminal. The equations employing Pi assume it to be an ordinary matrix inverse. If it is rank defective, the matrix pseudo-inverse is computed instead. Execution of the program continues since useful results may still be obtained through use of the pseudo-inverse (Ref 18:124).

Solution of the Riccati equations for the PI controller and the Kalman filter is achieved using an iterative algorithm (Ref 12) which may generate messages of information or fatal error. The information message for the PI is,

"RICCATI SOLN IS PSD--RANK mr"

in which "PSD" means positive semi-definite. For the Kalman filter the corresponding message is,

"OBSERVABILITY MATRIX IS nr X nc OF RANK mr"

in which "nr", "nc", and "mr" are the row, column dimensions and the rank, respectively. These messages convey the same information concerning system observability. The message is written in the case of the PI Riccati equation only if the solution is positive semi-definite (rank defective). Both messages are output to the LIST file only.

For both the PI and filter Riccati equations fatal error messages are identical:

"RICCATI NON-CONVERGENT IN nn ITERATIONS"

or

"RICCATI BLOW UP AT ITERATION nn INITIAL N = mm"

in which "nn" is the iteration counter at the occurrence of the error and "mm" is the value of a variable set internally and used in achieving initialization of the iterative sequence (the internal variable is not available for modification by the user). The first message indicates that the sequence of iterates did not converge. The second message may indicate numerical difficulties or uncontrollability (unobservability) of the system of the PI (filter) equations. Both messages are output to the LIST file only; a system error exit routine is then called which writes "EXIT" to the user terminal and aborts program execution. Note that in the event of such an abort, the local files SAVE, DATA, and LIST are not rewound automatically.

In computing the CGT controller gains an error may occur in solving for the matrix partitions  $A_{11}$  or  $A_{13}$  (Equation (III-61)). If the iterative refinements to these solutions do not converge to within the established tolerance (1.E-6), then the following message is written both to the terminal and the LIST file:

"SOLUTION ERROR FOR 'A' (CGT) AFTER 3 ITERATIONS =  
nnn"

in which "nnn" is the Euclidean norm of the refining matrix solution (residual) at the last iteration. The message is considered to be informational, and execution proceeds normally. However, in case the value of the residual norm is large compared to the convergence tolerance, the CGT design solution can be expected to be invalid.

## B.10 CGTPIQ Segmentation Job Control

The following listing shows the job control commands and segmentation directives used in obtaining a segmented object file suitable for interactive execution on the CDC CYBER computer system. The job employs three object files: "L", "S", and "A". The routines on each of these files are (see the program listing)

"L": 'MAIN' and all optional routines('MAIN' through 'TBLUP1')

"S": 'CGTPIQ SUBS' ('CGTXQ' through 'VARSCl')

"A": 'LIBRARY'

Object files L and S are loaded into memory in the order of MAIN, then CGTPIQ SUBS. The "NOGO" command then completes the load from LIBRARY and system routines in order, but does not initiate execution. Next, the segmentation directives are executed (segmentation directives appear between the pair of "\*EOR" lines). When segmentation is complete, the resulting object file is cataloged.

In this listing, the names given the various object files ("L", "S", "A") are arbitrary, and the "ATTACH" commands may occur in any order. The file name ("lfn") given in the "LIBRARY,lfn" command must correspond to the name used in attaching the object file of 'LIBRARY' routines. The name given to the segmented object file is arbitrary but must be consistent in the "REQUEST", "SEGLOAD", and "CATALOG" commands. The segmentation directives should not be modified in any way.

100=JPM. T830287,MCMILLIAN  
 110=MAP,FULL.  
 120=ATTACH,CGTX.  
 130=ATTACH,DLKLIB,ID=T820303.  
 140=LIBRARY,DLKLIB.  
 150=REQUEST,CGTPIQ,\*PF.  
 160=SEGLOAD(B=CGTPIQ)  
 170=LOAD(CGTX)  
 180=NOGO.  
 190=REWIND,CGTPIQ.  
 200=CATALOG,CGTPIQ,CGTPIQ.  
 210=\*EOR  
 220=SETUP           INCLUDE DSCRT  
 230=SREGPI         INCLUDE RQWGTS,MLINEQ,SYMFCT  
 240=FLTRK          INCLUDE RQWGTS,KFLTR,MLINEQ,SYMFCT,INTEG  
 250=STRTH          INCLUDE DSCRTT,INTEG  
 260=SDSN           INCLUDE QDSCRT  
 270=CEVAL          INCLUDE PLOTLP,VARSC,RPLOTF,WPLOTF,STRPLT  
 280=FEVAL          INCLUDE PLOTLP,VARSC,RPLOTF,WPLOTF,STRPLT,DACOV  
 290=B1             TREE SETUP-(SDSN,SCMD,STRTH)  
 300=B2             TREE PIMTX  
 310=B3             TREE SREGPI  
 320=B4             TREE SCGT  
 330=B5             TREE CEVAL  
 340=B6             TREE FLTRK  
 350=B7             TREE FEVAL  
 360=B8             TREE PFDATA  
 370=A              TREE CGTXQ-(B1,B2,B3,B4,B5,B6,B7,B8)  
 380=ROOT           TREE MAIN-A  
 390=                GLOBAL MAIN1,MAIN2,INO,DESIGN,FILES,SYSMTX,ZMTX1,ZMTX2,  
 400=,NDIMD,LOCD,DSNMTX,NDIMC,LOCC,CMDMTX,NDIMT,LOCT,TRUMTX,LCNTRL,CONTROL,  
 410=,LREGPI,CREGPI,LCGT,CCGT,LKF,CKF,AMC,BDG  
 420=                END  
 430=\*EOR  
 440=\*EOF

### B.11 Running CGTPIQ

This "User's Guide" assumes that a segmented executable object file of CGTPIQ exists according to the previous section. For an existing CGTPIQ object file in the permanent file system, the following commands must be entered in INTERCOM to run the program:

```
CONNECT,INPUT,OUTPUT
```

```
ATTACH,CGTPIQ,pfn
```

```
CGTPIQ
```

in which 'pfn' is the permanent file on which the object file is cataloged. CGTPIQ will then execute as described in Section B.8. Additional commands before and after execution may be appropriate according to one's intended use of the various local files which CGTPIQ employs during execution (like attaching a DATA file).

### B.12 CGTPIQ Input/Output Listing

The input/output (I/O) listing given at the end of this section is from a single execution of CGTPIQ. It shows a CGT design, a PI controller design, a CGT/PI controller design, and a Kalman filter design for a simple design model. Details concerning the design, truth, and command models employed are presented in Section B.12.2. The models were selected to test the program thoroughly and give the user a good feel for program execution. The models are otherwise meaningless in the real world context. The I/O shown is that obtained directly at the user terminal during execution. The listing is complete and in order. The

additional information written to the LIST file is not presented here but the last section of this guide gives a brief description of the output appearing on a LIST file.

Prior to and following program execution, INTERCOM prompts for input are given by "COMMAND-". Within program execution entries occur in two ways: (1) when the entry is on the same line as an input prompt, the entry is bounded on the left by the symbol ">"; (2) in case of multiple entries for a single prompt, the second and subsequent entries are not prompted but are entered on the next lines, one entry per line.

Portions of I/O are discussed within individual numbered paragraphs. Each portion of listing is identified by a number in parentheses at the top center of the page where it begins, and these numbers correspond to the paragraph numbers below.

#### B.12.1 Summary of Input/Output

(1) Following "LOGIN", the executable object file 'CGTPIQ' is attached. Next, permanent file space is requested for the local file name 'SAVE'; the SAVE file will be generated during subsequent execution of the program. The "CONNECT" command defines the user terminal as the device that communicates through the FORTRAN standard 'INPUT' and 'OUTPUT' files. Program execution is initiated with the simple command "CGTPIQ", which loads the local file CGTPIQ and begins execution at its starting address.

(2) Program execution begins with output of an



identifying header which includes the current date and time (obtained from a call to system real-time clock routines). The first user entry is the sample period of the controller. Next, the design model is established under prompt from the terminal. The design model is then written to the SAVE file. The poles (eigenvalues) of the design model ( $\underline{A}$  matrix) are automatically computed and printed.

(3) The controller design path is then pursued with selection of an open-loop CGT design requested (since there are no PI gains yet). The command model is then input, written to the SAVE file, and the poles of the command matrix ( $\underline{A}_m$ ) automatically output. An informational error message is then printed. This does not affect operation but the validity of the solution is in question (see Section B.9).

(4) The open-loop CGT gains (KXM, KXU and KXN) are then computed and printed. The evaluation is chosen with respect to the truth model, so the truth model is input next and written to the SAVE file. The poles of the truth matrix ( $\underline{A}_t$ ) are automatically computed and printed.

(5) A step of magnitude one is input on model input one. There are no initial conditions (IC) placed on the states. One plot of two variables is selected with Y1 and M1 being the variables to be plotted. A plot duration of one second is chosen and a title given to the plot. The open-loop CGT time response is then plotted at the terminal.

(6) A PI design is chosen next and implicit model following requested, but, since the command model state

dimension did not equal the design model output dimension, this request was aborted (another command model would need to be input to use the implicit path). The explicit weights were then input and displayed with the (2,2) element of the  $\underline{X}$  matrix being modified. (Note that the  $\underline{X}$  matrix is computed anew each iteration from the weighting matrices on the outputs and on the integral of the regulation error. Thus, modifications made explicitly to  $\underline{X}$  are not preserved between design iterations.)

(7) The PI gains GC1 and GC2 are computed and displayed followed by the printout of the continuous-time mapped poles of the closed loop system matrix (note the lack of one complex complementary pole of the closed-loop system matrix: when this happens it usually indicates a poor choice of quadratic weights, sampling time, etc., and a potentially useless design, and is caused by a pole in the right-half z-plane not being able to be mapped to the s-plane). Initial conditions of one are placed on states one and two, and one plot of three variables is requested with X2, Y1 and U1 being the variables to be plotted. A plot duration of one second is requested and a title given to the plot. The time response plot of the PI controller is then presented.

(8) A closed-loop CGT/PI is then selected since the PI gains have been computed. The CGT/PI gains (KXM, KXU and KXN) are computed and printed. Controller evaluation with respect to the truth model is selected, a step input of magnitude one placed on model input one, and zero initial

conditions placed on the states. One plot of two variables is requested with Y1 and M1 chosen as the variables. A duration of one second is chosen and a plot title is given. The closed-loop CGT/PI time response is then plotted at the terminal. Note the difference in performance between the open-loop CGT and the closed-loop CGT/PI controllers.

(9) No additional time-responses of the CGT/PI controller are requested. The Kalman filter path is then selected. Since this is the first execution of the Kalman filter design, the noise strength matrices (Q and R) specified in the existing definition of the design model are used to compute the Kalman filter gain matrix (note that in subsequent iterations of the Kalman filter design path, the user may modify the diagonal elements (only) of the noise strength matrices). The diagonal elements of the noise strength matrices and the entire filter gain matrix are printed. Next, a title is entered to apply to the plots of state estimation error standard deviations (output to LIST file only). The final values of true and filter computed RMS errors for the design model state estimates are printed. The performance evaluation data is then written to the SAVE file. (This is the information needed by the program "PFEVAL".)

(10) The filter design is not repeated, nor are any of the other designs. Upon terminating execution, the PI gains determined previously are written to the SAVE file. The command "FILES" gives a listing of existing files. Note that files SAVE, LIST and PLOT have been generated

automatically during program execution. The SAVE file (containing the design, truth, and command model data as well as the PI gains GC1 and GC2, and the Kalman filter performance data) is then cataloged for future use (as a DATA file). The just-created SAVE file is then copied to the local file named DATA. Next, the LIST file is sent to a line printer for listing. Finally, the SAVE file is returned, making re-execution of the program feasible (since SAVE had been made a permanent file, it could not be written to in subsequent executions). In a subsequent execution, the various dynamics models and the PI gains would be available from the new DATA file and a new SAVE file would be created (if desired). (Note: The required parameters to run the evaluation program "PFEVAL" are also written to the SAVE file.) However, in this case there is no repeated execution of the program, and the user enters a "LOGOUT" from the system.

### B.12.2 Simple Design Problem

#### Design Model

$$\dot{\underline{x}}(t) = \begin{bmatrix} -2 & 5 \\ -5 & 2 \end{bmatrix} \underline{x}(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \underline{u}(t) + \begin{bmatrix} 3 & -1 \\ 1 & 5 \end{bmatrix} \underline{n}_d(t) + \begin{bmatrix} .1 \\ .1 \end{bmatrix} \underline{w}(t)$$

$$\underline{Q} = 1$$

$$\dot{\underline{n}}_d(t) = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \underline{n}_d(t) + \begin{bmatrix} .1 \\ .1 \end{bmatrix} \underline{w}_d(t)$$

$$\underline{Q}_n = 1$$

$$\underline{y}(t) = [1 \ 0] \underline{x}(t) + [1] \underline{u}(t) + [1 \ 1] \underline{n}_d(t)$$

$$\underline{z}(t_i) = [1 \ 0] \underline{x}(t_i) + [0 \ 1] \underline{n}_d(t_i) + \underline{v}(t_i)$$

$$\underline{R} = .1$$

### Truth Model

$$\dot{\underline{x}}_t(t) = \begin{bmatrix} -2 & 5 & 3 & 1 \\ -5 & -2 & 1 & 5 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \underline{x}_t(t) + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} u_t(t) + \begin{bmatrix} .1 \\ .1 \\ 0 \\ 0 \end{bmatrix} \underline{w}_t(t)$$

$$\underline{Q}_t = 1$$

$$\underline{z}_t(t_i) = [1 \ 0 \ 0 \ 1] \underline{x}_t(t_i) + \underline{v}_t(t_i)$$

$$\underline{R}_t = .1$$

$$\underline{x}'(t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \underline{x}_t(t)$$

$$\underline{n}_d'(t) = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \underline{x}_t(t)$$

### Command Model

$$\dot{\underline{x}}_m(t) = \begin{bmatrix} -5 & 5 \\ -5 & -5 \end{bmatrix} \underline{x}_m(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_m(t)$$

$$\underline{y}_m(t) = [10 \ 0] \underline{x}_m(t) + [1] u_m(t)$$

(1)

DATE 11/09/83  
TIME 21.25.21.

PLEASE LOGIN  
LOGIN,T830287

XXXXXXXXXX ENTER PASSWORD-

11/09/83 LOGGED IN AT 21.26.08.  
WITH USER-ID X3  
EQUIP/PORT 14/021  
LOGIN CREATED 11/09/83 TODAY IS 11/09/83

COMMAND- BEGIN,CLASS,,MACM,JPM

COMMAND- CONNECT,INPUT,OUTPUT

COMMAND- GET,CGTPIQ,ID=MACM

FILE NAME CGTPIQ HAS BEEN RETRIEVED  
COMMAND- REQUEST,SAVE,\*PF

COMMAND- CGTPIQ

(2)

\*\*\* CGTPIQ \*\*\*  
PROGRAM TO DESIGN A COMMAND GENERATOR TRACKER  
USING A REGULATOR WITH PROPORTIONAL PLUS INTEGRAL CONTROL  
BASED ON THE INTEGRAL OF THE REGULATION ERROR,  
AND A KALMAN FILTER FOR STATE ESTIMATION.  
\*\*\* CGTPIQ \*\*\*

DATE : 11/09/83

TIME : 21.28.36.

ENTER SAMPLE PERIOD FOR DIGITAL CONTROLLER >.02

READ DESIGN MODEL FROM 'DATA' FILE (Y OR N) >N

ENTER DESIGN MODEL FROM TERMINAL (Y OR N) >Y

ENTER N >2

ENTER R >1

ENTER P >1

ENTER M >1

ENTER D >2

ENTER W >1

ENTER WD >1

ENTER A  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 2 BY 2 >1 1 -2  
1 2 5  
2 1 -5  
2 2 -2  
0/

ENTER B  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 2 BY 1 >2 1 1  
0/

ENTER EX  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 2 BY 2 >1 1 3  
1 2 -1  
2 1 1  
2 2 5  
0/

ENTER G  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 2 BY 1 >1 1 .1  
2 1 .1  
0/

ENTER Q  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 1 >1 1 1  
0/

ENTER C  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 2 >1 1 1  
0/

ENTER DY  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 1 >1 1 1  
0/

ENTER EY  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 2 >1 1 1  
1 2 1  
0/

ENTER H  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 2 >1 1 1  
0/



ENTER HN  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 2 >1 2 1  
0/

ENTER R  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 1 >1 1 .1  
0/

ENTER AN  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 2 BY 2 >1 1 1  
1 2 1  
2 1 1  
2 2 1  
0/

ENTER GN  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 2 BY 1 >1 1 .1  
2 1 .1  
0/

ENTER QN  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 1 >1 1 1  
0/

MODIFY MATRIX ELEMENTS (Y OR N) >N

WRITE DESIGN MODEL TO 'SAVE' FILE (Y OR N) >Y

DESIGN MODEL WRITTEN TO 'SAVE' FILE

POLES OF DESIGN MATRIX

-2.0000000E+00 +J( 5.0000000E+00)  
-2.0000000E+00 +J( -5.0000000E+00)

(3)  
CONTROLLER DESIGN (Y OR N) >Y  
DESIGN REG/PI (Y OR N) >N  
DESIGN CGT (Y OR N) >Y  
READ REG/PI GAINS FROM 'DATA' FILE (Y OR N) >N  
READ COMMAND MODEL FROM 'DATA' FILE (Y OR N) >N  
ENTER COMMAND MODEL FROM TERMINAL (Y OR N) >Y  
ENTER NM >2  
ENTER RM >1  
ENTER PM >1  
  
ENTER AM  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 2 BY 2 >1 1 -5  
1 2 5  
2 1 -5  
2 2 -5  
0/  
  
ENTER BM  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 2 BY 1 >2 1 1  
0/  
  
ENTER CM  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 2 >1 1 10  
0/  
  
ENTER DM  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 1 >1 1 1  
0/  
  
MODIFY MATRIX ELEMENTS (Y OR N) >N  
WRITE COMMAND MODEL TO 'SAVE' FILE (Y OR N) >Y  
COMMAND MODEL WRITTEN TO 'SAVE' FILE  
POLES OF COMMAND MATRIX  
-5.0000000E+00 +J( 5.0000000E+00)  
-5.0000000E+00 +J( -5.0000000E+00)  
  
SOLUTION ERROR FOR 'A' (CGT) AFTER 3 ITERATIONS = 2.1370445E+01

(4)

KXM MATRIX

33.44 -13.57

KXU MATRIX

-.2812

KXN MATRIX

-1.131 -1.484

CONTROLLER EVALUATION WRT TRUTH MODEL (Y OR N) >Y

READ TRUTH MODEL FROM 'DATA' FILE (Y OR N) >N

ENTER TRUTH MODEL FROM TERMINAL (Y OR N) >Y

ENTER NT >4

ENTER RT >1

ENTER MT >1

ENTER WT >1

ENTER AT

ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 4 BY 4 >1 1 -2

1 2 5

1 3 3

1 4 -1

2 1 -5

2 2 -2

2 3 1

2 4 5

0/

ENTER BT

ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 4 BY 1 >2 1 1

0/

ENTER GT

ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 4 BY 1 >1 1 .1

2 1 .1

0/

ENTER QT

ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 1 >1 1 1

0/

ENTER HT  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 4 >1 1 1  
1 4 1  
0/

ENTER RT  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 1 BY 1 >1 1 .1  
0/

ENTER TDT  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 2 BY 4 >1 1 1  
2 2 1  
0/

ENTER TNT  
ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 2 BY 4 >1 3 1  
2 4 1  
0/

MODIFY MATRIX ELEMENTS (Y OR N) >N

WRITE TRUTH MODEL TO 'SAVE' FILE (Y OR N) >Y

TRUTH MODEL WRITTEN TO 'SAVE' FILE

POLES OF TRUTH MATRIX

-2.0000000E+00	+J( 5.0000000E+00)
-2.0000000E+00	+J( -5.0000000E+00)
0.	+J( 0. )
0.	+J( 0. )

(5)

ENTER MODEL INPUT AND STEP VALUE : 1 >1 1

ENTER STATE AND IC VALUE (0/ TERMINATES): 4 >0/

2 PLOTS OF 5 VARIABLES MAY BE PRINTED AT THE TERMINAL -- SPECIFY NUMBER  
FOR EACH (N1,N2) >2 0

ENTER OUTPUTS BY TYPE AND INDEX IN 2 ENTRIES--TYPES ARE

STATE : 'X'

OUTPUT : 'Y'

INPUT : 'U'

MODEL : 'M'

PLOT 1

OUTPUT 1 >Y

>1

OUTPUT 2 >M

>1

ENTER TIME DURATION FOR RESPONSE, IN SECONDS >1

+----- ENTER TITLE IN GIVEN FIELD -----+  
SIMPLE DESIGN TEST OF CGT

SIMPLE DESIGN TEST OF CGT

0.00	+		+ 1	+		2	+		+			
.02	+		1 +	+		2	+		+			
.04	+	1	+	+		2	+		+			
.06	+	1	+	+		+2	+		+			
.08	+1		+	+		+ 2	+		+			
.10	1		+	+		+ 2	+		+			
.12	+1		+	+		+ 2	+		+			
.14	+ 1		+	+		+ 2	+		+			
.16	+ 1		+	+		+ 2	+		+			
.18	+: : 1 :	+: :	+: :	+: :	+: :	+: :	+: 2	+: :	+: :			
.20	+		1 +	+		+		2 +	+			
.22	+		1	+		+		2+	+			
.24	+		+ 1	+		+		2	+			
.26	+		+	1	+	+		+2	+			
.28	+		+	1	+	+		+2	+			
.30	+		+	1	+	+		+ 2	+			
.32	+		+	+ 1	+	+		+ 2	+			
.34	+		+	+	1	+		+ 2	+			
.36	+		+	+	1	+		+ 2	+			
.38	+: : : :	+: :	+: :	+: :	+: :	1+: :	+: :	+: 2 :	+: :			
.40	+		+	+		+1	+		2 +			
.42	+		+	+		+ 1	+		2 +			
.44	+		+	+		+ 1	+		2 +			
.46	+		+	+		+ 1	+		2 +			
.48	+		+	+		+ 1	+		2 +			
.50	+		+	+		+ 1	+		2 +			
.52	+		+	+		+	+1		2 +			
.54	+		+	+		+	+ 1		2 +			
.56	+		+	+		+	+ 1		2 +			
.58	+: : : :	+: :	+: :	+: :	+: :	+: :	+: :	+: 1: 2 :	+: :			
.60	+		+	+		+		1	2 +			
.62	+		+	+		+		1	2 +			
.64	+		+	+		+			12 +			
.66	+		+	+		+			12 +			
.68	+		+	+		+			2 +			
.70	+		+	+		+			2 +			
.72	+		+	+		+			2 +			
.74	+		+	+		+			21 +			
.76	+		+	+		+			21 +			
.78	+: : : :	+: :	+: :	+: :	+: :	+: :	+: :	+: :	21: +			
.80	+		+	+		+			21 +			
.82	+		+	+		+			2 1+			
.84	+		+	+		+			2 1+			
.86	+		+	+		+			2 1+			
.88	+		+	+		+			2 1+			
.90	+		+	+		+			2 1+			
.92	+		+	+		+			2 1+			
.94	+		+	+		+			2 1+			
.96	+		+	+		+			2 1+			
.98	+: : : :	+: :	+: :	+: :	+: :	+: :	+: :	+: :	2: 1+			
1.00	+		+	+		+			2 1 +			
SCALE		-.8000		-.2000		.4000		1.0000		1.6000		2.2000

(6)  
 MORE TIME RESPONSE RUNS (Y OR N) >N  
 CONTROLLER DESIGN (Y OR N) >Y  
 DESIGN REG/PI (Y OR N) >Y  
 INCORPORATE IMPLICIT MODEL (Y OR N) >Y  
 MODIFY COMMAND MODEL (Y OR N) >N  
 COMMAND MODEL STATE DIM MUST EQUAL SYSTEM OUTPUT DIM  
 CONTROLLER DESIGN (Y OR N) >Y  
 DESIGN REG/PI (Y OR N) >Y  
 INCORPORATE IMPLICIT MODEL (Y OR N) >N  
 ENTER WEIGHTS ON OUTPUT DEVIATIONS: 1  
 ENTER I AND QW(I,I)--(0/ WHEN COMPLETE) >1 5  
 0/  
 ENTER WEIGHTS ON INTEGRAL OF REGULATION ERROR: 1  
 ENTER I AND QW(I,I)--(0/ WHEN COMPLETE) >1 20  
 0/  
 ENTER WEIGHTS ON CONTROL MAGNITUDES: 1  
 ENTER I AND QW(I,I)--(0/ WHEN COMPLETE) >1 1  
 0/  
 Y MATRIX  
 5.000  
 UQ MATRIX  
 20.00  
 MODIFY ELEMENTS OF 'X' MATRIX (Y OR N) >Y  
 LIST 'X' MATRIX TO TERMINAL (Y OR N) >Y  
 X MATRIX  
 5.000 0. 0.  
 0. 0. 0.  
 0. 0. 20.00  
 ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : 3 BY 3 >2 2 10  
 0/

(7)

UM MATRIX

1.000

GC1 MATRIX

1.006 4.9054E-02

GC2 MATRIX

1.381

CONTROLLER EVALUATION WRT TRUTH MODEL (Y OR N) >Y

MODIFY TRUTH MODEL (Y OR N) >N

POLES OF REGPI MATRIX

-1.9740188E+00 +J( 5.4833537E+00)  
-1.9740188E+00 +J( -5.4833537E+00)  
-4.8082993E+01 +J( 1.5707963E+02)

ENTER STATE AND IC VALUE (0/ TERMINATES): 4 >1 1  
2 1  
0/

2 PLOTS OF 5 VARIABLES MAY BE PRINTED AT THE TERMINAL -- SPECIFY NUMBER  
FOR EACH (N1,N2) >3 0

ENTER OUTPUTS BY TYPE AND INDEX IN 2 ENTRIES--TYPES ARE  
STATE : 'X'  
OUTPUT : 'Y'  
INPUT : 'U'

PLOT 1  
OUTPUT 1 >X

>2

OUTPUT 2 >Y

>1

OUTPUT 3 >U

>1

ENTER TIME DURATION FOR RESPONSE, IN SECONDS >1

+----- ENTER TITLE IN GIVEN FIELD -----+  
SIMPLE DESIGN TEST, PI



SIMPLE DESIGN TEST, PI

0.00	+	+	+	+	3	+ 1	+
.02	+3	2	+	+	+	1	+
.04	+ 3	2	+	+	1	+	+
.06	3	2	+	+	1	+	+
.08	3	2	+	+	1	+	+
.10	3	2	+	+	1	+	+
.12	3	2	+	1+	+	+	+
.14	+32	+	1	+	+	+	+
.16	+23	+	1	+	+	+	+
.18	+2	:3:	: :	:+1	: :	: :	:+:
.20	+2	3	1	+	+	+	+
.22	+2	1	3	+	+	+	+
.24	2	1	3	+	+	+	+
.26	2	1	+	3	+	+	+
.28	2	1	+	3	+	+	+
.30	21	+	3	+	+	+	+
.32	2	+	+	+3	+	+	+
.34	2	+	+	3	+	+	+
.36	2	+	+	3	+	+	+
.38	2:	: :	: :	:+:	: :	:3:	: :
.40	2	+	+	+	+3	+	+
.42	+2	+	+	+	3	+	+
.44	+21	+	+	+	3	+	+
.46	+21	+	+	+	3	+	+
.48	+2	1	+	+	+	3	+
.50	+2	1	+	+	+	3	+
.52	+ 2	1	+	+	+	3	+
.54	+ 2	1	+	+	+	3	+
.56	+ 2	1	+	+	+	3	+
.58	+ :2:	: :	:+1	: :	: :	:+:	: :3:
.60	+ 2	+	+1	+	+	+	3
.62	+ 2	+	1	+	+	+	3
.64	+ 2	+	1	+	+	+	3
.66	+ 2	+	1	+	+	+	3
.68	+ 2	+	1	+	+	+	3
.70	+ 2	+	1	+	+	+	3
.72	+ 2	+	1	+	+	+	3
.74	+ 2	+	1	+	+	+	3
.76	+ 2	+	1+	+	+	+	3
.78	+ :2:	: :	:+:	: :	: :	:+:	: :3:
.80	+ 2	+	+	+1	+	+	3
.82	+ 2	+	+	+1	+	+	3
.84	+ 2	+	+	+ 1	+	+	3
.86	+ 2	+	+	+ 1	+	+	3
.88	+ 2	+	+	+ 1	+	+	3
.90	+ 2	+	+	+ 1	+	+3	+
.92	+ 2	+	+	+ 1	+	3	+
.94	+ 2	+	+	+ 1	+	3+	+
.96	+ 2	+	+	+ 1	+	3	+
.98	+ :2:	: :	:+:	: :	: :	:3:	: :
SCALE 1	-.7000	-.3000	.1000	.5000	.9000	1.3000	
SCALE 2	-.1000	.2000	.5000	.8000	1.1000	1.4000	
SCALE 3	-1.1000	-.8000	-.5000	-.2000	.1000	.4000	

(8)  
MORE TIME RESPONSE RUNS (Y OR N) >N

CONTROLLER DESIGN (Y OR N) >Y

DESIGN REG/PI (Y OR N) >N

DESIGN CGT (Y OR N) >Y

MODIFY COMMAND MODEL (Y OR N) >N

KXM MATRIX

11.61 3.312

KXU MATRIX

-4.361

KXN MATRIX

-1.653 -1.380

CONTROLLER EVALUATION WRT TRUTH MODEL (Y OR N) >Y

MODIFY TRUTH MODEL (Y OR N) >N

ENTER MODEL INPUT AND STEP VALUE : 1 >1 1

ENTER STATE AND IC VALUE (0/ TERMINATES): 4 >0/

2 PLOTS OF 5 VARIABLES MAY BE PRINTED AT THE TERMINAL -- SPECIFY NUMBER  
FOR EACH (N1,N2) >2 0

ENTER OUTPUTS BY TYPE AND INDEX IN 2 ENTRIES--TYPES ARE

STATE : 'X'

OUTPUT : 'Y'

INPUT : 'U'

MODEL : 'M'

PLOT 1

OUTPUT 1 >Y

>1

OUTPUT 2 >M

>1

ENTER TIME DURATION FOR RESPONSE, IN SECONDS >1

----- ENTER TITLE IN GIVEN FIELD -----  
SIMPLE DESIGN TEST, CGT/PI

SIMPLE DESIGN TEST, CGT/PI

0.00	+	+	+	1	+	2	+	+
.02	1	+	+		+	2	+	+
.04	+	+	+		+	2	+	1
.06	+	+	+		1+	2	+	+
.08	+	+	+		+	2 1	+	+
.10	+	+	+		+	12	+	+
.12	+	+	+		+	2	+	+
.14	+	+	+		+	2	+	+
.16	+	+	+		+	2	+	+
.18	+:	: : : :	+:	: : : :	+:	: : : :	: 2:	+: : : : :+
.20	+	+	+		+	2	+	+
.22	+	+	+		+	2	+	+
.24	+	+	+		+	2	+	+
.26	+	+	+		+	2	+	+
.28	+	+	+		+	2+	+	+
.30	+	+	+		+	2+	+	+
.32	+	+	+		+	12	+	+
.34	+	+	+		+	2	+	+
.36	+	+	+		+	2	+	+
.38	+:	: : : :	+:	: : : :	+:	: : : :	: 2:	: : : : :+
.40	+	+	+		+		+2	+
.42	+	+	+		+		+2	+
.44	+	+	+		+		+2	+
.46	+	+	+		+		+2	+
.48	+	+	+		+		+2	+
.50	+	+	+		+		+2	+
.52	+	+	+		+		+2	+
.54	+	+	+		+		+2	+
.56	+	+	+		+		+21	+
.58	+:	: : : :	+:	: : : :	+:	: : : :	: 2:	: : : : :+
.60	+	+	+		+		+ 2	+
.62	+	+	+		+		+ 2	+
.64	+	+	+		+		+ 2	+
.66	+	+	+		+		+ 2	+
.68	+	+	+		+		+ 2	+
.70	+	+	+		+		+21	+
.72	+	+	+		+		+2	+
.74	+	+	+		+		+2	+
.76	+	+	+		+		+2	+
.78	+:	: : : :	+:	: : : :	+:	: : : :	: 2:	: : : : :+
.80	+	+	+		+		+2	+
.82	+	+	+		+		+2	+
.84	+	+	+		+		+2	+
.86	+	+	+		+		+2	+
.88	+	+	+		+		+2	+
.90	+	+	+		+		+2	+
.92	+	+	+		+		+2	+
.94	+	+	+		+		+2	+
.96	+	+	+		+		+2	+
.98	+:	: : : :	+:	: : : :	+:	: : : :	: 2:	: : : : :+
1.00	+	+	+		+		+2	+
SCALE		-3.0000	-1.8000	-.6000	.6000	1.8000	3.0000	

(9)  
MORE TIME RESPONSE RUNS (Y OR N) >N

CONTROLLER DESIGN (Y OR N) >N

FILTER DESIGN (Y OR N) >Y

Q MATRIX

1.000

QN MATRIX

1.000

R MATRIX

.1000

KF MATRIX

6.3304E-02

4.9510E-02

7.4844E-02

7.4844E-02

MODIFY TRUTH MODEL (Y OR N) >N

POLES OF FILTER MATRIX

-2.5838398E+00 +J( 5.4568219E+00)

-2.5838398E+00 +J( -5.4568219E+00)

-4.2659165E+00 +J( 0. )

-4.2632564E-12 +J( 0. )

+----- ENTER TITLE IN GIVEN FIELD -----+

SIMPLE DESIGN TEST, KALMAN FILTER

FINAL RMS ERRORS : TRUE = 6.3143454E-02

(STATE 1) COMPUTED = 6.7931977E-02

FINAL RMS ERRORS : TRUE = 5.0726138E-02

(STATE 2) COMPUTED = 5.9937274E-02

FINAL RMS ERRORS : TRUE = 5.8594898E-02

(STATE 3) COMPUTED = 7.7160159E-02

FINAL RMS ERRORS : TRUE = 5.8594898E-02

(STATE 4) COMPUTED = 7.7160159E-02

WRITE PERFORMANCE EVALUATION DATA TO 'SAVE' FILE (Y OR N)>Y

PERFORMANCE EVALUATION DATA, NO. 1, WRITTEN TO 'SAVE ' FILE

CONTROLLER DESIGN (Y OR N) >N

(10)

FILTER DESIGN (Y OR N) >N

END DESIGN RUNS (Y OR N) >Y

REG/PI GAINS WRITTEN TO 'SAVE' FILE

PROGRAM EXECUTION STOP

STOP

065400 MAXIMUM EXECUTION FL.

5.323 CP SECONDS EXECUTION TIME.

COMMAND- FILES

--LOCAL FILES--

\$OUTPUT	PLOT	\$INPUT	CGTPIQ	SAVE
LIST	DATA			

COMMAND- CATALOG,SAVE,DATA

INITIAL CATALOG

RP = 008 DAYS

CT ID= T830287 PFN=DATA

CT CY= 001 SN=AFIT 0000000576 WORDS.

COMMAND- RETURN,DATA

COMMAND- COPYBF,SAVE,DATA

COMMAND- RT,LIST

LIST SENT TO PRINTER( AF ) WITH JPM.

COMMAND- RETURN,SAVE,PLOT,LIST,DATA

COMMAND- LOGOUT

CPA 6.471 SEC. 5.273 ADJ.

IO 79.214 SEC. 23.447 ADJ.

CRUS 34.486

CONNECT TIME 0 HRS. 40 MIN.

11/09/83 LOGGED OUT AT 22.06.48.

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### B.13 CGTPIQ Output to LIST File

The first output is a heading with date and time identical to that printed at the terminal. Next the sample period of the controller is identified. A series of outputs related to the design model then follow; these are identified by a heading "DESIGN MODEL". First the matrices defining the continuous-time representation are printed, then the matrices of the discrete-time representation are printed. An additional output is the matrix  $P_i$  under a heading of "CONTROLLER SETUP".

Output relating to the design of the PI controller is identified by a heading of "REG/PI DESIGN". The quadratic weighting matrices are printed ( $Y$ ,  $UQ$ ,  $X$  and  $UM$ ), followed by the controller gain solution GCS. Finally, the individual PI gains  $G_{C1}$  and  $G_{C2}$  are printed, as well as the intermediate product  $E$ . The proportional  $K_P$  and integral  $K_I$  gains are then printed. (Note, if implicit model following is requested, there are the additional outputs as discussed in Section B.8.5 of this guide.)

The truth model description is identified by the heading "TRUTH MODEL". The matrices of the continuous-time system are listed first. The eigenvalues of the matrix  $A_t$  are then printed. The matrices of the discrete-time representation are then listed.

Outputs due to the PI controller evaluation routines are identified by a heading of "CONTROLLER EVALUATION" and begin with the mapped eigenvalues of the closed-loop system with PI controller. The time-response plots are then output

with each plot labeled with the title specified by the user. The plots run from 0 to 2 seconds at the controller sample period specified by the user (maximum 101 character positions).

The CGT/PI design path begins with definition of the command model, with relevant output identified by the heading "COMMAND MODEL". The continuous-time system matrices are printed, follow by the eigenvalues of the matrix  $A_m$ . The discrete-time matrices are then printed. Output due to the CGT design computations is identified by the heading "CGT DESIGN". The  $A_{ij}$  matrices are then printed followed by the CGT/PI control gain matrices KXM, KXU and KXN.

The evaluation of the CGT/PI controller is also identified by the header "CONTROLLER EVALUATION". The closed-loop CGT/PI time response plots are then printed.

Output due to the Kalman filter design routine is identified by the heading "FILTER DESIGN", and includes the noise strength matrices  $Q$  and  $R$  and the Kalman filter gain matrix  $K_F$ . The output of the filter evaluation routines is identified by the heading "FILTER EVALUATION". First, the mapped poles of the filter system matrix are printed. During the covariance analysis, the full error covariance matrix is printed at each time sample. Finally, the plots are printed: each plot includes the standard deviations of the "true" and filter-computed estimation error for each design model state for 50 consecutive time samples taken at the controller/filter sample period.

B.14      Summary

Appendix B has given the user of the program CGTPIQ an in-depth look at the operations of the program. This appendix was written to be a stand-alone document for normal program operation and hopefully has met that goal.



## Appendix C

### CGTPIQ Program Listing

#### C.1 Complete Listing

The following program listing includes all routines of CGTPIQ. Routines of the 'LIBRARY' object file are not listed (Ref 13).

CGTPIQ is composed of three parts: a 'MAIN' routine, an optional set of user-provided routines, and a large set of invariant routines referred to as 'CGTPIQ SUBS'. In this listing, routines 'DSND', 'DSNM', 'TRTHD', 'TRTHM', 'ACDATA', 'GUSTS', and 'TBLUP1' are the optional routines. These optional routines are used to establish the design model AFTI(S3,A2,G3) for the pitch-pointing controller, and the truth model AFTI(S4,A2,G3), both as described in Chapter VI of Floyd's thesis (Ref 9).

Included at the end of this main listing are listings of the subroutines that were changed for each of the CGT/PI formulations 2, 3 and 4 (See Section 3.3.2).

```

100=   PROGRAM MAIN(INPUT=64,OUTPUT=64,LIST=64,
110=   1 SAVE=64,DATA=64,PLOT=64,
120=   1 TAPE5=INPUT,TAPE6=OUTPUT,TAPE25=SAVE,TAPE50=DATA,
130=   2 TAPE99=PLOT,TAPE16=LIST)
140=   COMMON/MAIN1/NDIM,NDIM1,COM1(400)
150=   COMMON/MAIN2/COM2(400)
160=   COMMON/INOI/KIN,KOUT,KPUNCH
170=   COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
180=   COMMON/SYSMTX/NVSM,SM(2125)
190=   COMMON/ZMTX1/NVZM,ZM1(1225)
200=   COMMON/ZMTX2/ZM2(1225)
210=   COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1750)
220=   COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(225)
230=   COMMON/TRUMTX/NVTM,TM(1725)
240=   COMMON/CONTROL/NVCTL,CTL(900)
250=   COMMON/CREGPI/NVRPI,RPI(675)
260=   COMMON/CCGT/NVCGT,CGT(400)
270=   COMMON/CKF/NVFLT,FLT(690)
280=   COMMON/AMC/AM(100)
290=   COMMON/BDG/BD(75)
300=   NDIM=400
310=   NVSM=2125
320=   NVZM=1225
330=   NVDM=1750
340=   NVCM=225
350=   NVTM=1725
360=   NVCTL=900
370=   NVRPI=675
380=   NVCGT=400
390=   NVFLT=690
400=   KIN=5
410=   KSAVE=25
420=   KDATA=50
430=   KPLOT=99
440=   KLIST=16
450=   KTERM=6
460=   CALL CGTXQ
470=   STOP
480=C END MAIN
490=   END
500=   SUBROUTINE DSND(ND)
510=   DIMENSION ND(1)
520=   ND(1)=8
530=   ND(2)=2
540=   ND(3)=2
550=   ND(4)=3
560=   ND(5)=0
570=   ND(6)=1
580=   ND(7)=0
590=   RETURN
600=C END SUBROUTINE DSND
610=   END
620=   SUBROUTINE DSNM(A,B,EX,G,Q,C,DY,EY,H,HN,R,AN,GN,QN)
630=   DIMENSION A(8,8),B(8,2),C(2,8),G(8),DY(2,2),H(3,8),R(3,3)

```

```

640= DATA GRAVY,DEGTRD,PI/32.174,.01745329,3.1415927/
650= CALL ACDATA(LEVEL,VT,ALT,ALPHA,ZA,ZAD,ZQ,ZU,ZDE,ZDF,
660= 1 PMA,PMAD,PMQ,PMU,PMDE,PMDF,XA,XAD,XQ,XU,XDE,XDF,
670= 2 TE,DLX,BSPAN)
680= 10 ALPHAR=DEGTRD*ALPHA
690= UO=VT*COS(ALPHAR)
700= WO=VT*SIN(ALPHAR)
710= A(1,3)=1.
720= A(2,1)=-GRAVY*SIN(ALPHAR)/UO
730= A(2,2)=ZA
740= A(2,3)=1.+ZQ
750= A(3,2)=PMA
760= A(3,3)=PMQ
770= A(2,7)=ZA
780= A(2,8)=ZQ
790= A(3,7)=PMA
800= A(3,8)=PMQ
810= A(2,4)=ZDE
820= A(2,5)=ZDF
830= A(3,4)=PMDE
840= A(3,5)=PMDF
850= A(4,4)=-TE
860= A(5,5)=-TE
870= B(4,1)=TE
880= B(5,2)=TE
890= CALL GUSTS(LEVEL,ALT,SLU,SLW,SIGU,SIGW)
900= A(6,6)=-VT/SLW
910= A(7,6)=(1.-SQRT(3.))*SIGW*SQRT(-A(6,6))/SLW
920= A(7,7)=A(6,6)
930= A(8,8)=-VT*PI/4./BSPAN
940= A(8,6)=-A(8,8)*A(7,6)
950= A(8,7)=-A(8,8)*A(7,7)
960= G(6)=1.
970= G(7)=SIGW*SQRT(3.*VT/SLW)/VT
980= G(8)=-A(8,8)*G(7)
990= Q=1.
1000= C(1,1)=1.
1010= C(2,1)=1.
1020= C(2,2)=-1.
1030= H(1,1)=1.
1040= H(2,2)=1.
1050= H(3,3)=1.
1060= H(2,7)=1.
1070= R(1,1)=4.76E-6
1080= R(2,2)=1.22E-5
1090= R(3,3)=3.22E-5
1100= RETURN
1110=C END SUBROUTINE DSNM
1120= END
1130= SUBROUTINE TRTHD(ND)
1140= DIMENSION ND(1)
1150= ND(1)=9
1160= ND(2)=2
1170= ND(3)=3
1180= ND(4)=1

```

```

1190=      RETURN
1200=C END SUBROUTINE TRTHD
1210=      END
1220=      SUBROUTINE TRTHM(AT,BT,GT,QT,HT,RT,TD,TNT)
1230=      DIMENSION AT(9,9),BT(9,2),GT(9),HT(3,9),RT(3,3),TD(8,9)
1240=      DATA GRAVTY,DEGTRD,PI/32.174,.01745329,3.1415927/
1250=      CALL ACDATA(LEVEL,VT,ALT,ALPHA,ZA,ZAD,ZQ,ZU,ZDE,ZDF,
1260=      1 PMA,PMAD,PMQ,PMU,PMDE,PMDF,XA,XAD,XQ,XU,XDE,XDF,
1270=      2 TE,DLX,BSPAN)
1280=  10   ALPHAR=DEGTRD*ALPHA
1290=      UO=VT*COS(ALPHAR)
1300=      WO=VT*SIN(ALPHAR)
1310=      RZAD=1./(1.-ZAD)
1320=      AT(1,3)=1.
1330=      AT(2,1)=-GRAVTY*SIN(ALPHAR)/UO
1340=      AT(2,2)=ZA
1350=      AT(2,3)=1.+ZQ
1360=      AT(2,4)=ZU
1370=      AT(3,2)=PMA
1380=      AT(3,3)=PMQ
1390=      AT(3,4)=PMU
1400=      AT(4,1)=-GRAVTY*COS(ALPHAR)
1410=      AT(4,2)=XA
1420=      AT(4,3)=XQ-WO
1430=      AT(4,4)=XU
1440=      AT(2,5)=ZDE
1450=      AT(2,6)=ZDF
1460=      AT(3,5)=PMDE
1470=      AT(3,6)=PMDF
1480=      AT(4,5)=XDE
1490=      AT(4,6)=XDF
1500=      AT(5,5)=-TE
1510=      AT(6,6)=-TE
1520=      AT(2,8)=ZA
1530=      AT(2,9)=ZQ
1540=      AT(3,8)=PMA
1550=      AT(3,9)=PMQ
1560=      AT(4,8)=XA
1570=      AT(4,9)=XQ
1580=      CALL GUSTS(LEVEL,ALT,SLU,SLW,SIGU,SIGW)
1590=      AT(7,7)=-VT/SLW
1600=      AT(8,7)=(1.-SQRT(3.))*SIGW*SQRT(-AT(7,7))/SLW
1610=      AT(8,8)=AT(7,7)
1620=      AT(9,9)=-VT*PI/4./BSPAN
1630=      AT(9,7)=-AT(9,9)*AT(8,7)
1640=      AT(9,8)=-AT(9,9)*AT(8,8)
1650=      GT(7)=1.
1660=      GT(8)=SIGW*SQRT(3.*VT/SLW)/VT
1670=      GT(9)=-AT(9,9)*GT(8)
1680=      QT=1.
1690=      DO 20 I=1,9
1700=      AT(2,I)=AT(2,I)*RZAD
1710=      AT(3,I)=AT(3,I)+PMAD*AT(2,I)
1720=  20   AT(4,I)=AT(4,I)+XAD*AT(2,I)
1730=      BT(5,1)=TE

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1740=      BT(6,2)=TE
1750=      HT(1,1)=1.
1760=      HT(2,2)=1.
1770=      HT(3,3)=1.
1780=      HT(2,8)=1.
1790=      RT(1,1)=4.76E-6
1800=      RT(2,2)=1.22E-5
1810=      RT(3,3)=3.22E-5
1820=      TDT(1,1)=1.
1830=      TDT(2,2)=1.
1840=      TDT(3,3)=1.
1850=      TDT(4,5)=1.
1860=      TDT(5,6)=1.
1870=      TDT(6,7)=1.
1880=      TDT(7,8)=1.
1890=      TDT(8,9)=1.
1900=      RETURN
1910=C END SUBROUTINE TRTHM
1920=      END
1930=      SUBROUTINE ACDATA(LEVEL,VT,ALT,ALPHA,ZA,ZAD,ZQ,ZU,ZDE,ZDF,
1940=      1 PMA,PMAD,PMQ,PMU,PMDE,PMDF,XA,XAD,XQ,XU,XDE,XDF,
1950=      2 TE,DLX,BSPAN)
1960=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
1970=      DATA NENTRY/1/
1980= 5      WRITE 101
1990=      READ*,LEVEL
2000=      IF((LEVEL.GT.3).OR.(LEVEL.LT.1)) GO TO 5
2010=      WRITE 102
2020=      READ*,VT,ALT,ALPHA
2030=      WRITE 103
2040=      READ*,ZA,ZAD,ZQ,ZU,ZDE,ZDF
2050=      WRITE 104
2060=      READ*,PMA,PMAD,PMQ,PMU,PMDE,PMDF
2070=      WRITE 105
2080=      READ*,XA,XAD,XQ,XU,XDE,XDF
2090=      WRITE(KLIST,101)
2100=      WRITE(KLIST,109) LEVEL
2110=      WRITE(KLIST,102)
2120=      WRITE(KLIST,110) VT,ALT,ALPHA
2130=      WRITE(KLIST,103)
2140=      WRITE(KLIST,110) ZA,ZAD,ZQ,ZU,ZDE,ZDF
2150=      WRITE(KLIST,104)
2160=      WRITE(KLIST,110) PMA,PMAD,PMQ,PMU,PMDE,PMDF
2170=      WRITE(KLIST,105)
2180=      WRITE(KLIST,110) XA,XAD,XQ,XU,XDE,XDF
2190=      IF(NENTRY.EQ.0) GO TO 10
2200=      BSPAN=30.
2210=      DLX=13.798
2220=      TE=20.
2230=      RETURN
2240= 10     WRITE 106
2250=      READ*,TE
2260=      WRITE 107
2270=      READ*,DLX
2280=      WRITE 108

```

```

2290=      READ*,BSPAN
2300= 101  FORMAT(" ENTER TURBULENCE LEVEL (1,2,3) >")
2310= 102  FORMAT(" ENTER TRIM VELOCITY, ALTITUDE, AND ALPHA >")
2320= 103  FORMAT(" ENTER ZA, ZAD, ZQ, ZU, ZDE, ZDF >")
2330= 104  FORMAT(" ENTER MA, MAD, MQ, MU, MDE, MDF >")
2340= 105  FORMAT(" ENTER XA, XAD, XQ, XU, XDE, XDF >")
2350= 106  FORMAT(" ENTER TIME CONSTANT FOR ELEVATOR >")
2360= 107  FORMAT(" ENTER DISTANCE FROM CG TO ACCELEROMETER >")
2370= 108  FORMAT(" ENTER WING SPAN >")
2380= 109  FORMAT(6X,I1)
2390= 110  FORMAT(6(6X1PE15.7))
2400=      RETURN
2410=C END  SUBROUTINE ACDATA
2420=      END
2430=      SUBROUTINE GUSTS(LEVEL,ALT,SLU,SLW,SIGU,SIGW)
2440=      DIMENSION ATRB1(4),ATRB2(4),ATRB3(4),SIGT1(4),SIGT2(4),SIGT3(4)
2450=      DATA ATRB1/2000.,2750.,10000.,30000./
2460=      DATA ATRB2/2000.,2750.,10000.,45000./
2470=      DATA ATRB3/2000.,5000.,20000.,70000./
2480=      DATA SIGT1/4.5,5.,5.,0./
2490=      DATA SIGT2/8.5,10.,10.,0./
2500=      DATA SIGT3/12.,21.,21.,0./
2510=      DATA IT1,IT2,IT3/1,1,1/
2520=      IF(ALT-1750.) 5,15,15
2530= 5     IF(ALT-1000.) 8,10,10
2540= 8     ALTT=ALT
2550=      GO TO 12
2560= 10    ALTT=1000.
2570= 12    SIGW=2.5*FLOAT(LEVEL)
2580=      SIGU=1./(.177+8.23E-4*ALTT)**.4
2590=      SLW=ALTT
2600=      SLU=ALTT*SIGU**3
2610=      SIGU=SIGU*SIGW
2620=      GO TO 100
2630= 15    SLU=1750.
2640=      SLW=1750.
2650=      IF(LEVEL-2) 17,18,16
2660= 16    CALL TBLUP1(ATRB3,SIGT3,4,IT3,ALT,SIGU)
2670=      GO TO 19
2680= 17    CALL TBLUP1(ATRB1,SIGT1,4,IT1,ALT,SIGU)
2690=      GO TO 19
2700= 18    CALL TBLUP1(ATRB2,SIGT2,4,IT2,ALT,SIGU)
2710= 19    SIGW=SIGU
2720= 100   RETURN
2730=C END  SUBROUTINE GUSTS
2740=      END
2750=      SUBROUTINE TBLUP1(X,Y,N,IXP,XP,YP)
2760=      DIMENSION X(1),Y(1)
2770=      IF(IXP) 15,15,1
2780= 1     IF(IXP-N) 10,10,5
2790= 5     IXP=N
2800=      GO TO 18
2810= 10    IF(XP-X(IXP)) 12,18,20
2820= 12    IXP=IXP-1
2830=      IF(IXP) 15,15,10

```

```

2840= 15   IXP=1
2850= 18   YP=Y(IXP)
2860=      RETURN
2870= 20   IF(IXP-N) 21,18,5
2880= 21   IXPP1=IXP+1
2890= 22   IF(XP-X(IXPP1)) 25,30,30
2900= 25   YP=Y(IXP)+(XP-X(IXP))/(X(IXPP1)-X(IXP))*(Y(IXPP1)-Y(IXP))
2910=      RETURN
2920= 30   IXP=IXPP1
2930=      GO TO 20
2940=C END SUBROUTINE TBLUP1
2950=      END
2960=      SUBROUTINE CGTXQ
2970=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
2980=      COMMON/MAIN2/COM2(1)
2990=      COMMON/INO/KIN,KOUT,KPUNCH
3000=      COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
3010=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
3020=      COMMON/SYSMTX/NVSM,SM(1)
3030=      COMMON/ZMTX1/NVZM,ZM1(1)
3040=      COMMON/ZMTX2/ZM2(1)
3050=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
3060=      COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
3070=      COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
3080=      COMMON/NDIMC/NNC,NRC,NPC
3090=      COMMON/LOCC/LPHC,LBDC,LCC,LDC
3100=      COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
3110=      COMMON/NDIMT/NNT,NRT,NMT,NWT
3120=      COMMON/LOCT/LPHT,LBDT,LQDT,LHT,LRT,LTDT,LTNT
3130=      COMMON/TRUMTX/NVTM,TM(1)
3140=      COMMON/LCCTRL/LPI11,LPI12,LPI21,LPI22,LPHDL,LBDL
3150=      COMMON/CONTROL/NVCTL,CTL(1)
3160=      COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
3170=      COMMON/CREGPI/NVRPI,RPI(1)
3180=      COMMON/LCGT/LA11,LA13,LA21,LA23,LA12,LA22,LELA11,LELA12,LELA13
3190=      COMMON/CCGT/NVCGT,CGT(1)
3200=      COMMON/LKF/LEADSN,LFLTRK,LFCOV
3210=      COMMON/CKF/NVFLT,FLT(1)
3220=      COMMON/AMC/AM(1)
3230=      COMMON/BDG/BD(1)
3240=      DIMENSION LD(15),ND(15)
3250=      DATA NPLTZM/606/
3260=      DATA IE0I,NO/-1,1HN/
3270=      REWIND KLIST
3280=      WRITE(KLIST,115) DATE(DUM),TIME(DUM)
3290=      WRITE(KTERM,115) DATE(DUM),TIME(DUM)
3300= 115  FORMAT(*1",27X,"* * * CGTPIQ * * **"/14X,
3310=      1 "PROGRAM TO DESIGN A COMMAND GENERATOR TRACKER"/8X,
3320=      2 "USING A REGULATOR WITH PROPORTIONAL PLUS INTEGRAL CONTROL"/13X,
3330=      3 "BASED ON THE INTEGRAL OF THE REGULATION ERROR,"/16X,
3340=      4 "AND A KALMAN FILTER FOR STATE ESTIMATION."/28X,
3350=      5 "* * * CGTPIQ * * **"/11X,"DATE : ",A10//,11X,
3360=      6 "TIME : ",A10////)
3370=      REWIND KSAVE

```

```

3380=      REWIND KDATA
3390=      WRITE(KSAVE,112) IEOL,NPLTZM
3400=      DO 10 I=1,15
3410= 10   ND(I)=0
3420=      DO 12 I=1,15
3430= 12   LD(I)=1
3440=      LFLRPI=0
3450=      LFLCGT=0
3460=      LFLKF=0
3470=      LTEVAL=0
3480=      LABORT=0
3490=      IPI=0
3500=      ICGT=0
3510=      ITRU=0
3520=      IFLTR=0
3530=      ICODE=4
3540=      LFAVAL=0
3550=      LGCGT=0
3560=      NVCOM=MINO (NDIM,NVZM)
3570=      KOUT=KLIST
3580=      KPUNCH=KPLOT
3590=      IF(NVSM.GE.NPLTZM) GO TO 50
3600=      WRITE 101,NPLTZM
3610=      GO TO 1000
3620= 50   WRITE 102
3630=      READ*,TSAMP
3640=      IF(TSAMP.LE.0.) GO TO 50
3650=      WRITE(KLIST,103) TSAMP
3660= 103  FORMAT("OSAMPLE PERIOD IS ",F5.3," SECONDS")
3670=      CALL SETUP(ND,LD,ICGT,ITRU,1)
3680=      IF(LABORT) 1000,100,1000
3690= 100  LABORT=0
3700=      IMPLIC=0
3710=      WRITE 104
3720= 104  FORMAT("OCONTROLLER DESIGN (Y OR N) >")
3730=      READ 111,IAN5
3740=      IF(IAN5.EQ.NO) GO TO 500
3750=      LFLKF=0
3760=      CALL PIMTX(IPI)
3770=      IF(LABORT) 1000,125,1000
3780= 125  WRITE 105
3790= 105  FORMAT("ODESIGN REG/PI (Y OR N) >")
3800=      READ 111,IAN5
3810=      IF(IAN5.EQ.NO) GO TO 150
3820=      WRITE 400
3830= 400  FORMAT("OINCORPORATE IMPLICIT MODEL (Y OR N) >")
3840=      READ 111,IAN5
3850=      IF(IAN5.EQ.NO) GO TO 490
3860=      IMPLIC=1
3870=      CALL SETUP(ND,LD,ICGT,ITRU,4)
3880=      IF(ICGT.NE.0) GO TO 460
3890=      IMPLIC=0
3900=      GO TO 480
3910= 460  IF(NPD.EQ.NNC) GO TO 480
3920=      WRITE 470

```



```

3930= 470  FORMAT("OCOMMAND MODEL STATE DIM MUST EQUAL SYSTEM OUTPUT DIM")
3940=      LABORT=-1
3950= 480  IF(LABORT) 100,490,1000
3960= 490  CALL SREGPI(IMPPLIC)
3970=      IF(LABORT) 1000,200,1000
3980= 150  WRITE 106
3990= 106  FORMAT("ODESIGN CGT (Y OR N) >")
4000=      READ 111, IANS
4010=      IF(IANS.EQ.NO) GO TO 100
4020=      CALL SETUP(ND,LD,ICGT,ITRU,2)
4030=      IF(ICGT) 155,100,155
4040= 155  IF(LABORT) 100,160,1000
4050= 160  CALL SCGT
4060=      IF(LABORT) 100,170,1000
4070= 170  IF(LFLCGT.LE.0) GO TO 125
4080= 200  LABORT=0
4090=      WRITE 107
4100= 107  FORMAT("OCONTROLLER EVALUATION WRT TRUTH MODEL (Y OR N) >")
4110=      READ 111, IANS
4120=      IF(IANS.EQ.NO) GO TO 250
4130=      CALL SETUP(ND,LD,ICGT,ITRU,3)
4140=      IF(LABORT) 200,260,1000
4150= 250  LTEVAL=0
4160= 260  CALL CEVAL
4170=      IF(LFLCGT.EQ.1) LGCGT=1
4180=      IF(LFAVAL.EQ.0.OR.LGCGT.EQ.0) GO TO 100
4190= 270  WRITE 600
4200= 600  FORMAT("OWRITE PERFORMANCE EVALUATION DATA TO 'SAVE' FILE (Y OR N)
4210=      +>")
4220=      READ 111, IANS
4230=      IF(IANS.EQ.NO) GO TO 100
4240=      ICODE=ICODE+1
4250=      CALL PFDATA(ICODE,ND)
4260=      INUM=ICODE-4
4270=      WRITE 605,INUM
4280= 605  FORMAT("OPERFORMANCE EVALUATION DATA, NO. "I2," WRITTEN TO 'SAVE
4290=      +' FILE")
4300=      GO TO 100
4310= 500  LABORT=0
4320=      WRITE 108
4330= 108  FORMAT("OFILTER DESIGN (Y OR N) >")
4340=      READ 111, IANS
4350=      IF(IANS.EQ.NO) GO TO 900
4360=      CALL FLTRK(IFLTR)
4370=      IF(IFLTR.EQ.0) GO TO 900
4380=      IF(LABORT) 1000,510,1000
4390= 510  CALL SETUP(ND,LD,ICGT,ITRU,3)
4400=      IF(LABORT) 500,525,1000
4410= 525  CALL FEVAL
4420= 530  IF(LABORT) 1000,540,1000
4430= 540  LFAVAL=1
4440=      IF(LGCGT.EQ.1) GO TO 270
4450=      GO TO 500
4460= 900  WRITE 109
4470= 109  FORMAT("OEND DESIGN RUNS (Y OR N) >")

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4480=      READ 111, IANS
4490=      IF(IANS.EQ.NO) GO TO 100
4500=      IF(LFLRPI.EQ.0) GO TO 1000
4510=      NPNTS=NRD*(NNPR+NND)
4520=      ND(1)=NPNTS
4530=      ND(2)=LGC1
4540=      ND(3)=LGC2
4550=      ND(4)=LEL
4560=      CALL WFILED(4, NPNTS, ND, RPI(LGC1))
4570=      WRITE 113
4580= 1000 CONTINUE
4590=      WRITE(KLIST, 110)
4600=      REWIND KSAVE
4610=      REWIND KDATA
4620=      REWIND KLIST
4630=      WRITE 110
4640= 101  FORMAT("OINSUFFICIENT MEMORY /SYSMTX/, NEED: ", I4)
4650= 102  FORMAT("OENTER SAMPLE PERIOD FOR DIGITAL CONTROLLER >")
4660= 110  FORMAT("OPROGRAM EXECUTION STOP")
4670= 111  FORMAT(A3)
4680= 112  FORMAT(2I4)
4690= 113  FORMAT(6X, "REG/PI GAINS WRITTEN TO 'SAVE' FILE")
4700=      RETURN
4710=C END SUBROUTINE CGTXQ
4720=      END
4730=      SUBROUTINE SETUP(ND, LD, ICGT, ITRU, ITYPE)
4740=      DIMENSION ND(1), LD(1)
4750=      GO TO (10, 15, 20, 15) ITYPE
4760= 10   CALL SDSN(ND, LD)
4770=      RETURN
4780= 15   CALL SCMD(ND, LD, ICGT, ITYPE)
4790=      RETURN
4800= 20   CALL STRTH(ND, LD, ITRU)
4810=      RETURN
4820=C END SUBROUTINE SETUP
4830=      END
4840=      SUBROUTINE SDSN(ND, LD)
4850=      COMMON/DESIGN/NVCOM, TSAMP, LFLRPI, LFLCGT, LFLKF, LTEVAL, LABORT
4860=      COMMON/SYSMTX/NVSM, SM(1)
4870=      COMMON/ZMTX1/NVZM, ZM1(1)
4880=      COMMON/ZMTX2/ZM2(1)
4890=      COMMON/NDIMD/NND, NRD, NPD, NMD, NDD, NWD, NWDD, NPLD, NWPWD, NNPR
4900=      DIMENSION ND(1), LD(1)
4910=      NSIZE=0
4920=      CALL RSYS(SM, LD, ND, 1, NSIZE)
4930=      IF(LABORT.GT.0) RETURN
4940=      NSIZE=NNPR
4950=      IF(NPLD.GT.NSIZE) NSIZE=NPLD
4960=      NSIZE=NSIZE*NSIZE
4970=      IF(NSIZE.LE.NVCOM) GO TO 5
4980=      WRITE 101, NSIZE
4990= 101  FORMAT("OINSUFFICIENT MEMORY /MAIN1/, /MAIN2/, /ZMTX1/, /ZMTX2/, NEED
5000=      1: ", I4)
5010=      LABORT=NSIZE
5020=      RETURN

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AD-A138 453

COMMAND GENERATOR TRACKER SYNTHESIS METHODS USING AN  
LAG (LINEAR SYSTEM M. (U) AIR FORCE INST OF TECH  
WRIGHT-PATTERSON AFB OH SCHOOL OF ENGI. J P MCMILLIAN  
DEC 83 AFIT/GE/EE/83D-46 F/G 9/2

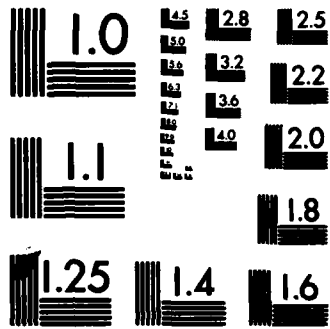
4/4

UNCLASSIFIED

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END

FILED



MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

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5030= 5   IF(NRD.EQ.NPD) GO TO 10
5040=     WRITE 102
5050= 102  FORMAT(*"NUMBER OF INPUTS AND OUTPUTS MUST BE EQUAL FOR DESIGN")
5060=     LABORT=-1
5070=     RETURN
5080= 10   CALL DSCR TD(LD,ZM1,ZM2)
5090=     RETURN
5100=C END SUBROUTINE SDSN
5110=     END
5120=     SUBROUTINE DSCR TD(LD,ZM1,ZM2)
5130=     COMMON/MAIN1/NDIM,NDIM1,COM1(1)
5140=     COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
5150=     COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
5160=     COMMON/SYSMTX/NVSM,SM(1)
5170=     COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
5180=     COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
5190=     COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
5200=     COMMON/LKF/LEADSN,LFLTRK,LFCOV
5210=     COMMON/CKF/NVFLT,FLT(1)
5220=     DIMENSION LD(1),ZM1(1),ZM2(1)
5230=     NDIM=NPLD
5240=     NDIM1=NDIM+1
5250=     CALL POLES(SM,NND,1,ZM1,ZM2)
5260=     DO 1 I=1,NND
5270= 1     IF(ZM1(I).GT.0.) LFLCGT=-1
5280=     CALL TFRMTX(SM,DM,NND,NND,2)
5290=     LAP=1
5300=     LGP=LAP+NPLD*NPLD
5310=     IF(NWD.EQ.0) GO TO 5
5320=     CALL TFRMTX(SM(LD(4)),DM(LGP),NND,NWD,2)
5330= 5     IF(NDD.EQ.0) GO TO 10
5340=     L1=LADDR(NPLD,NND+1,1)
5350=     L2=LADDR(NPLD,1,NND+1)
5360=     L3=LADDR(NPLD,NND+1,NND+1)
5370=     CALL ZPART(DM(L1),NDD,NMD,NPLD)
5380=     CALL TFRMTX(SM(LD(3)),DM(L2),NND,NDD,2)
5390=     CALL TFRMTX(SM(LD(12)),DM(L3),NDD,NDD,2)
5400=     IF(NWD.EQ.0) GO TO 8
5410=     L1=L1+LGP-1
5420=     CALL ZPART(DM(L1),NDD,NWD,NPLD)
5430= 8     L2=LADDR(NPLD,1,NWD+1)+LGP-1
5440=     L3=LADDR(NPLD,NND+1,NWD+1)+LGP-1
5450=     CALL ZPART(DM(L2),NND,NWDD,NPLD)
5460=     CALL TFRMTX(SM(LD(13)),DM(L3),NDD,NWDD,2)
5470= 10    LPHI=LGP+NPLD*NWPND
5480=     LEADSN=1
5490=     CALL NDCR TD(DM,NDIM,NT)
5500=     CALL DSCR TD(NPLD,DM,TSAMP,FLT,ZM1,NT)
5510=     LFLTRK=LEADSN+NPLD*NPLD
5520=     CALL TFRMTX(DM(LPHI),FLT,NND,NND,1)
5530=     LBD=LPHI+NND*NND
5540=     CALL TFRMTX(SM,ZM1,NND,NND,1)
5550=     CALL FMMUL(SM,SM(LD(2)),NND,NND,NRD,DM(LBD))
5560=     LEX=LBD+NND*NRD
5570=     IF(NDD.EQ.0) GO TO 15

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5580=      L1=LADDR(NPLD,1,NND+1)
5590=      CALL TFRMTX(DM(LEX),FLT(L1),NND,NDD,1)
5600=      LPHD=LEX+NND*NDD
5610=      L1=LADDR(NPLD,NND+1,NND+1)
5620=      CALL TFRMTX(DM(LPHD),FLT(L1),NDD,NDD,1)
5630=      LQ=LPHD+NDD*NDD
5640=      GO TO 20
5650= 15   LQ=LEX
5660= 20   IF(NWD.EQ.0) GO TO 25
5670=      CALL FTMTX(SM(LD(5)),DM(LQ),NWD,NWD)
5680=      LQN=LQ+NWD*NWD
5690=      GO TO 28
5700= 25   LQN=LQ
5710= 28   IF(NWDD.EQ.0) GO TO 33
5720=      CALL FTMTX(SM(LD(14)),DM(LQN),NWDD,NWDD)
5730=      LQD=LQN+NWDD*NWDD
5740=      GO TO 35
5750= 33   LQD=LQN
5760=      IF(NWPWD.GT.0) GO TO 35
5770=      LC=LQD
5780=      GO TO 36
5790= 35   CALL QDSCRT(DM(LQ),DM(LQN),ZM1,ZM2)
5800=      LC=LQD+NPLD*NPLD
5810= 36   LDY=LC+NPD*NND
5820=      LEY=LDY+NPD*NRD
5830=      LHP=LEY+NPD*NDD
5840=      LR=LHP+NMD*NPLD
5850=      L1=LR+NMD*NMD-LC
5860=      CALL FTMTX(SM(LD(6)),DM(LC),L1,1)
5870=      L1=LEY-1
5880=      NODY=1
5890=      DO 40 I=LDY,L1
5900=      IF(DM(I).EQ.0.) GO TO 40
5910=      NODY=0
5920=      GO TO 45
5930= 40   CONTINUE
5940= 45   NOEY=1
5950=      IF(NDD.LT.1) GO TO 55
5960=      L1=LHP-1
5970=      DO 50 I=LEY,L1
5980=      IF(DM(I).EQ.0.) GO TO 50
5990=      NOEY=0
6000=      GO TO 55
6010= 50   CONTINUE
6020= 55   CALL MATLST(DM(LPHI),NND,NND,"PHI",KLIST)
6030=      CALL MATLST(DM(LBD),NND,NRD,"BD",KLIST)
6040=      IF(NWPWD.GT.0) CALL MATLST(DM(LQD),NPLD,NPLD,"QD",KLIST)
6050=      IF(NMD.GT.0) CALL MATLST(DM(LHP),NMD,NPLD,"HA",KLIST)
6060=      IF(NDD.EQ.0) RETURN
6070=      CALL MATLST(DM(LEX),NND,NDD,"EXD",KLIST)
6080=      CALL MATLST(DM(LPHD),NDD,NDD,"PHN",KLIST)
6090=      RETURN
6100=C END SUBROUTINE DSCRTD
6110=      END

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6120= SUBROUTINE QDSCRT(Q,QN,ZM1,ZM2)
6130= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
6140= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
6150= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPNUD,NNPR
6160= COMMON/LOCN/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
6170= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
6180= DIMENSION Q(1),QN(1),ZM1(1),ZM2(1)
6190= IF(NWD.EQ.0) GO TO 5
6200= CALL TFRMTX(Q,ZM1,NWD,NWD,2)
6210= 5 IF(NWDD.EQ.0) GO TO 10
6220= L1=LADDR(NPLD,NWD+1,NWD+1)
6230= CALL TFRMTX(QN,ZM1(L1),NWDD,NWDD,2)
6240= IF(NWD.EQ.0) GO TO 10
6250= L1=LADDR(NPLD,1,NWD+1)
6260= CALL ZPART(ZM1(L1),NWD,NWDD,NPLD)
6270= L1=LADDR(NPLD,NWD+1,1)
6280= CALL ZPART(ZM1(L1),NWDD,NWD,NPLD)
6290= 10 CALL MAT3(NPLD,NWPNUD,DM(LGP),ZM1,ZM2)
6300= CALL INTEG(NPLD,DM(LAP),ZM2,DM(LQD),TSAMP)
6310= RETURN
6320=C END SUBROUTINE QDSCRT
6330= END
6340= SUBROUTINE SCMD(ND,LD,ICGT,ITYPE)
6350= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
6360= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
6370= COMMON/SYSMTX/NVSM,SM(1)
6380= COMMON/ZMTX1/NVZM,ZM1(1)
6390= COMMON/ZMTX2/ZM2(1)
6400= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPNUD,NNPR
6410= COMMON/NDIMC/NNC,NRC,NPC
6420= COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
6430= COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
6440= COMMON/CREGPI/NVRPI,RPI(1)
6450= DIMENSION ND(1),LD(1)
6460= DATA NO/1HN/
6470= IF(ITYPE.EQ.4) GO TO 10
6480= WRITE(KLIST,110)
6490= 110 FORMAT(/////11X,5(" "),"CGT DESIGN",5(" ")/)
6500= IF(LFLRPI) 10,5,10
6510= 5 WRITE 102
6520= READ 111,IANS
6530= IF(IANS.EQ.NO) GO TO 8
6540= CALL READFS(SM,ND,4,IERR)
6550= NSIZE=ND(1)
6560= LGC1=ND(2)
6570= LGC2=ND(3)
6580= LEL=ND(4)
6590= CALL FTMTX(SM,RPI(LGC1),NSIZE,1)
6600= IF(IERR.NE.0) RETURN
6610= CALL MATLST(RPI(LGC1),NRD,NND,"GC1",KLIST)
6620= CALL MATLST(RPI(LGC2),NRD,NRD,"GC2",KLIST)
6630= LFLRPI=-1
6640= GO TO 10
6650= 8 IF(LFLCGT.GE.0) GO TO 9

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6660= WRITE 103
6670= 103 FORMAT("OSYSTEM UNSTABLE - - OPEN-LOOP CGT NOT FEASIBLE")
6680= RETURN
6690= 9 LGC1=1
6700= LGC2=1
6710= LEL=1
6720= NSIZE=NRD*NND
6730= CALL ZPART(RPI(LGC1),1,NSIZE,1)
6740= 10 IF(ICGT.EQ.0) GO TO 12
6750= WRITE 108
6760= 108 FORMAT(" MODIFY COMMAND MODEL (Y OR N) >")
6770= READ 111, IANS
6780= IF(IANS.EQ.NO) RETURN
6790= 12 CALL RSYS(SM,LD,ND,2,ICGT)
6800= IF(LABORT.NE.0) RETURN
6810= NEWCM=1
6820= CALL POLES(SM,NNC,2,ZM1,ZM2)
6830= IF(NPC.EQ.NPD) GO TO 15
6840= WRITE 104
6850= LABORT=-1
6860= RETURN
6870= 15 CALL DSCRTC(LD,ZM1)
6880= 102 FORMAT(" READ REG/PI GAINS FROM 'DATA' FILE (Y OR N) >")
6890= 104 FORMAT("OCOMMAND AND DESIGN MODEL OUTPUTS NOT EQUAL IN NUMBER")
6900= 111 FORMAT(A3)
6910= RETURN
6920=C END SUBROUTINE SCMD
6930= END
6940= SUBROUTINE DSCRTC(LD,ZM1)
6950= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
6960= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
6970= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
6980= COMMON/SYSMTX/NVSM,SM(1)
6990= COMMON/NDIMC/NNC,NRC,NPC
7000= COMMON/LOCC/LPHC,LBDC,LCC,LDC
7010= COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
7020= DIMENSION LD(1),ZM1(1)
7030= NDIM=NNC
7040= NDIM1=NDIM+1
7050= CALL NDSCRT(SM,NDIM,NT)
7060= CALL DSCRT(NDIM,SM,TSAMP,CM,ZM1,NT)
7070= LPHC=1
7080= LBDC=LPHC+NNC*NNC
7090= CALL MMUL(ZM1,SM(LD(2)),NDIM,NDIM,NRC,CM(LBDC))
7100= LCC=LBDC+NNC*NRC
7110= LDC=LCC+NPC*NNC
7120= L1=LDC+NPC*NRC-LCC
7130= CALL FTMTX(SM(LD(3)),CM(LCC),L1,1)
7140= NODC=1
7150= L1=L1+LCC-1
7160= DO 10 I=LDC,L1
7170= IF(CM(I).EQ.0.) GO TO 10
7180= NODC=0
7190= GO TO 15
7200= 10 CONTINUE

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7210= 15 CALL MATLST(CM, NNC, NNC, "PHM", KLIST)
7220= CALL MATLST(CM(LBDC), NNC, NRC, "BDM", KLIST)
7230= CALL MATLST(CM(LCC), NPC, NNC, "CM", KLIST)
7240= CALL MATLST(CM(LDC), NPC, NRC, "DM", KLIST)
7250= RETURN
7260=C END SUBROUTINE DSCRTC
7270= END
7280= SUBROUTINE STRTH(ND, LD, ITRU)
7290= COMMON/DESIGN/NVCOM, TSAMP, LFLRPI, LFLCGT, LFLKF, LTEVAL, LABORT
7300= COMMON/SYSMTX/NVSM, SM(1)
7310= COMMON/ZMTX1/NVZM, ZM1(1)
7320= COMMON/ZMTX2/ZM2(1)
7330= COMMON/NDIMD/NND, NRD, NPD, NMD, NDD, NWD, NWDD, NPLD, NWPWWD, NNPR
7340= COMMON/NDIMT/NNT, NRT, NMT, NWT
7350= DIMENSION ND(1), LD(1)
7360= DATA NO/1HN/
7370= IF(ITRU.EQ.0) GO TO 5
7380= WRITE 103
7390= 103 FORMAT(" MODIFY TRUTH MODEL (Y OR N) >")
7400= READ 111, IANS
7410= 111 FORMAT(A3)
7420= IF(IANS.EQ.NO) GO TO 20
7430= 5 CALL RSYS(SM, LD, ND, 3, ITRU)
7440= IF(LABORT.GT.0) RETURN
7450= NSIZE=NNT*NNT
7460= IF(NSIZE.LE.NVCOM) GO TO 8
7470= WRITE 101, NSIZE
7480= 101 FORMAT("INSUFFICIENT MEMORY /MAIN1/, /MAIN2/, /ZMTX1/, /ZMTX2/, NEED
7490= 1: ", I2)
7500= LABORT=NSIZE
7510= RETURN
7520= 8 IF((NRT.EQ.NRD).AND.(NMT.EQ.NMD)) GO TO 10
7530= WRITE 102
7540= 102 FORMAT("OINPUTS AND MEASUREMENTS MUST BE EQUAL IN NUMBER FOR DESIG
7550= 1N AND TRUTH MODELS")
7560= LABORT=-1
7570= RETURN
7580= 10 CALL POLES(SM, NNT, 3, ZM1, ZM2)
7590= CALL DSCRTT(LD, ZM1)
7600= 20 LTEVAL=1
7610= RETURN
7620=C END SUBROUTINE STRTH
7630= END
7640= SUBROUTINE DSCRTT(LD, ZM1)
7650= COMMON/MAIN1/NDIM, NDIM1, COM1(1)
7660= COMMON/DESIGN/NVCOM, TSAMP, LFLRPI, LFLCGT, LFLKF, LTEVAL, LABORT
7670= COMMON/SYSMTX/NVSM, SM(1)
7680= COMMON/FILES/KSAVE, KDATA, KPLOT, KLIST, KTERM
7690= COMMON/NDIMD/NND, NRD, NPD, NMD, NDD, NWD, NWDD, NPLD, NWPWWD, NNPR
7700= COMMON/NDIMT/NNT, NRT, NMT, NWT
7710= COMMON/LOCT/LPHT, LBDT, LQDT, LHT, LRT, LTDT, LTNT
7720= COMMON/TRUMTX/NVTM, TM(1)
7730= DIMENSION LD(1), ZM1(1)
7740= NDIM=NNT
7750= NDIM1=NDIM+1

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7760=      CALL NDCRT(SM,NDIM,NT)
7770=      CALL DSCRT(NDIM,SM,TSAMP,TM,ZM1,NT)
7780=      LPHT=1
7790=      LBDT=LPHT+NNT*NNT
7800=      CALL MMUL(ZM1,SM(LD(2)),NDIM,NDIM,NRT,TM(LBDT))
7810=      LQDT=LBDT+NNT*NRT
7820=      IF(NWT.GT.0) GO TO 10
7830=      LHT=LQDT
7840=      GO TO 15
7850= 10   CALL MAT3(NDIM,NWT,SM(LD(3)),SM(LD(4)),ZM1)
7860=      CALL INTEG(NDIM,SM,ZM1,TM(LQDT),TSAMP)
7870=      LHT=LQDT+NNT*NNT
7880= 15   LRT=LHT+NNT*NNT
7890=      LTD=LRT+NNT*NNT
7900=      LTNT=LTD+NND*NNT
7910=      L1=LTNT+NDD*NNT-LHT
7920=      CALL FTMTX(SM(LD(5)),TM(LHT),L1,1)
7930=      CALL MATLST(TM,NNT,NNT,"PHT",KLIST)
7940=      CALL MATLST(TM(LBDT),NNT,NRT,"BDT",KLIST)
7950=      IF(NWT.GT.0) CALL MATLST(TM(LQDT),NNT,NNT,"QDT",KLIST)
7960=      RETURN
7970=C END SUBROUTINE DSCRT
7980=      END
7990=      SUBROUTINE PIMTX(IPI)
8000=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
8010=      COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
8020=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
8030=      COMMON/ZMTX1/NVZM,ZM1(1)
8040=      COMMON/ZMTX2/ZM2(1)
8050=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
8060=      COMMON/LOC/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
8070=      COMMON/DSMTX/NVDM,NODY,NOEY,DM(1)
8080=      COMMON/LC/NTRL/LPI11,LPI12,LPI21,LPI22,LPHDL,LBDL
8090=      COMMON/CONTROL/NVCTL,CTL(1)
8100=      IF(IPI.EQ.1) RETURN
8110=      WRITE(KLIST,110)
8120= 110  FORMAT(////11X,5(" * "), "CONTROLLER SET-UP",5(" *")////)
8130=      NDIM=NNPR
8140=      NSIZE=NDIM*(2*NDIM+NPD)
8150=      IF(NSIZE.LE.NVCTL) GO TO 10
8160=      WRITE 101,NSIZE
8170= 101  FORMAT("OINSUFFICIENT MEMORY /CONTROL/, NEED: ",I4)
8180=      LABORT=NSIZE
8190=      RETURN
8200= 10   NDIM1=NDIM+1
8210=      LPI11=1
8220=      LPI12=LPI11+NND*NND
8230=      LPI21=LPI12+NND*NRD
8240=      LPI22=LPI21+NPD*NND
8250=      LPHDL=LPI22+NPD*NRD
8260=      CALL TFRMTX(DM(LPHI),ZM1,NND,NND,2)
8270=      CALL SUBI(ZM1,NND,NDIM)
8280=      L2=LADDR(NDIM,1,NND+1)
8290=      CALL TFRMTX(DM(LBD),ZM1(L2),NND,NRD,2)
8300=      L3=LADDR(NDIM,NND+1,1)

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8310= CALL TFRMTX(DM(LC),ZM1(L3),NPD,NND,2)
8320= L4=LADDR(NDIM,NND+1,NND+1)
8330= CALL TFRMTX(DM(LDY),ZM1(L4),NPD,NRD,2)
8340= CALL GMINV(NDIM,NDIM,ZM1,ZM2,MR,1)
8350= IF(MR.EQ.NDIM) GO TO 15
8360= WRITE 102
8370= WRITE(KLIST,102)
8380= 102 FORMAT("OPI MATRIX IS RANK DEFECTIVE")
8390= 15 CALL MATLST(ZM2,NNPR,NNPR,"PI",KLIST)
8400= CALL TFRMTX(CTL(LPI11),ZM2,NND,NND,1)
8410= CALL TFRMTX(CTL(LPI12),ZM2(L2),NND,NRD,1)
8420= CALL TFRMTX(CTL(LPI21),ZM2(L3),NPD,NND,1)
8430= CALL TFRMTX(CTL(LPI22),ZM2(L4),NPD,NRD,1)
8440= CALL CDIF
8450= IPI=1
8460= RETURN
8470=C END SUBROUTINE PIMTX
8480= END
8490= SUBROUTINE CDIF
8500= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
8510= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
8520= COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
8530= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
8540= COMMON/LCCTRL/LPI11,LPI12,LPI21,LPI22,LPHDL,LBDL
8550= COMMON/CONTROL/NVCTL,CTL(1)
8560= CALL TFRMTX(DM(LPHI),CTL(LPHDL),NND,NND,2)
8570= L1=LADDR(NDIM,1,NND+1)+LPHDL-1
8580= CALL ZPART(CTL(L1),NND,NPD,NDIM)
8590= L1=LADDR(NDIM,NND+1,1)+LPHDL-1
8600= CALL TFRMTX(DM(LC),CTL(L1),NPD,NND,2)
8610= L1=LADDR(NDIM,NND+1,NND+1)+LPHDL-1
8620= CALL IDNT(NRD,CTL(L1),1.)
8630= LBDL=LPHDL+NDIM*NDIM
8640= CALL TFRMTX(DM(LBD),CTL(LBDL),NND,NRD,2)
8650= L1=LADDR(NDIM,NND+1,1)+LBDL-1
8660= CALL TFRMTX(DM(LDY),CTL(L1),NPD,NRD,2)
8670= RETURN
8680=C END SUBROUTINE CDIF
8690= END
8700= SUBROUTINE SREGPI(IMPIC)
8710= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
8720= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
8730= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
8740= COMMON/SYSMTX/NVSM,SM(1)
8750= COMMON/ZMTX1/NVZM,ZM1(1)
8760= COMMON/ZMTX2/ZM2(1)
8770= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
8780= COMMON/LCCTRL/LPI11,LPI12,LPI21,LPI22,LPHDL,LBDL
8790= COMMON/CONTROL/NVCTL,CTL(1)
8800= COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
8810= COMMON/CREGPI/NVRPI,RPI(1)
8820= COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
8830= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
8840= WRITE(KLIST,110)
8850= 110 FORMAT(////11X,5(" * "), "REG/PI DESIGN",5(" *")////)

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8860=      NSIZE=NRD*(5*NRD+2*NND)+NNPR*NNPR
8870=      IF(NSIZE.LE.NVRPI) GO TO 5
8880=      WRITE 101,NSIZE
8890= 101  FORMAT("OINSUFFICIENT MEMORY /CREGPI/, NEED: ",I4)
8900=      GO TO 8
8910= 5    NSIZE=NNPR*(3*NNPR+NRD)
8920=      IF(NSIZE.LE.NVSM) GO TO 10
8930=      WRITE 102,NSIZE
8940= 102  FORMAT("OINSUFFICIENT MEMORY /SYSMTX/, NEED: ",I4)
8950= 8    LABORT=NSIZE
8960=      RETURN
8970= 10   LX=1
8980=      LU=LX+NNPR*NNPR
8990=      CALL WXUS(SM(LX),SM(LU),COM1,ZM1,ZM2,IMPLIC)
9000=      LUIST=LU+NNPR*NRD
9010=      LPHP=LUIST+NNPR*NNPR
9020=      CALL PXUP(CTL(LPHDL),CTL(LBDL),SM(LX),SM(LU),COM1,ZM2,
9030= 1 SM(LUIST),SM(LPHP),SM(LX),ZM1)
9040=      CALL DRIC(NDIM,SM(LPHP),ZM2,SM(LX),ZM1,RPI(LPHCL))
9050=      CALL GCSTAR(SM(LPHP),CTL(LBDL),SM(LU),ZM1,SM(LUIST),SM(LX),ZM2)
9060=      CALL TFRMTX(RPI(LGC1),SM(LX),NRD,NND,1)
9070=      L3=LADDR(NDIM,1,NND+1)+LX-1
9080=      CALL TFRMTX(RPI(LGC2),SM(L3),NRD,NRD,1)
9090=      L1=LADDR(NNPR,NND+1,NND+1)
9100=      L2=LADDR(NNPR,1,NND+1)
9110=      CALL GMINV(NRD,NRD,ZM1(L1),ZM1(L2),MR,1)
9120=      L1=LADDR(NNPR,NND+1,1)
9130=      CALL MMUL(ZM1(L2),ZM1(L1),NRD,NRD,NND,ZM1)
9140=      CALL MMUL(SM(L3),ZM1,NRD,NRD,NND,ZM1(L1))
9150=      CALL MADD1(NRD,NND,SM(LX),ZM1(L1),ZM1,-1.)
9160=      CALL TFRMTX(RPI(LEL),ZM1,NRD,NND,1)
9170=      CALL FMMUL(RPI(LEL),CTL(LPI12),NRD,NND,NRD,RPI(LEE))
9180=      CALL FMADD(RPI(LEE),CTL(LPI22),NRD,NRD,RPI(LEE))
9190=      CALL MATLST(RPI(LGC1),NRD,NND,"GC1",KLIST)
9200=      CALL MATLST(RPI(LGC1),NRD,NND,"GC1",KTERM)
9210=      CALL MATLST(RPI(LGC2),NRD,NRD,"GC2",KLIST)
9220=      CALL MATLST(RPI(LGC2),NRD,NRD,"GC2",KTERM)
9230=      CALL MATLST(RPI(LEE),NRD,NRD,"E",KLIST)
9240=      IF(NODY.EQ.1)GO TO 15
9250=      CALL FMMUL(RPI(LEE),DM(LDY),NRD,NRD,NRD,ZM1)
9260=      CALL SUBI(ZM1,NRD,NRD)
9270=      NR2=NRD*NRD
9280=      DO 12 I=1,NR2
9290= 12   ZM1(I)=-ZM1(I)
9300=      NDIM=NRD
9310=      NDIM1=NDIM+1
9320=      CALL GMINV(NRD,NRD,ZM1,ZM2,MR,1)
9330=      CALL FMMUL(ZM2,RPI(LEE),NRD,NRD,NRD,ZM1)
9340=      CALL MATLST(ZM1,NRD,NRD,"KP",KLIST)
9350=      CALL FMMUL(ZM2,RPI(LGC2),NRD,NRD,NRD,ZM1)
9360=      CALL MATLST(ZM1,NRD,NRD,"KI",KLIST)
9370=      GO TO 20
9380= 15  WRITE(KLIST,103)

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9390= 103 FORMAT("OKP = E AND KI = GC2")
9400= 20 CONTINUE
9410= LFLRPI=1
9420= LFLCGT=0
9430= RETURN
9440=C END SUBROUTINE SREGPI
9450= END
9460= SUBROUTINE WXUS(X,U,S,ZM1,ZM2,IMPLIC)
9470= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
9480= COMMON/MAIN2/COM2(1)
9490= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
9500= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
9510= COMMON/SYSMTX/NVSM,SM(1)
9520= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
9530= COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
9540= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
9550= COMMON/LCNTRL/LPI11,LPI12,LPI21,LPI22,LPHDL,LBDL
9560= COMMON/CONTROL/NVCTL,CTL(1)
9570= COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
9580= COMMON/CREGPI/NVRPI,RPI(1)
9590= DIMENSION X(1),U(1),S(1),ZM1(1),ZM2(1)
9600= DATA NO/1HN/
9610= IF(IMPLIC.EQ.0) GO TO 2
9620= CALL IMPLEX(ZM1)
9630= 2 IF(LFLRPI) 5,5,10
9640= 5 LXDW=1
9650= LUDW=LXDW+2*NRD*NRD
9660= LPHCL=LUDW+NRD*NRD
9670= LGC1=LPHCL+NNPR*NNPR
9680= LGC2=LGC1+NRD*NND
9690= LEL=LGC2+NRD*NRD
9700= LEE=LEL+NRD*NND
9710= L1=LPHCL-1
9720= CALL ZPART(RPI,1,L1,1)
9730= 10 LUX=NRD*NRD+1
9740= WRITE 101,NPD
9750= 101 FORMAT(" ENTER WEIGHTS ON OUTPUT DEVIATIONS: ",I2)
9760= CALL RQWGT(S(RPI,NPD,0)
9770= WRITE 102,NRD
9780= 102 FORMAT(" ENTER WEIGHTS ON INTEGRAL OF REGULATION ERROR: ",I2)
9790= CALL RQWGT(S(RPI(LUX),NRD,1)
9800= WRITE 103,NRD
9810= 103 FORMAT(" ENTER WEIGHTS ON CONTROL MAGNITUDES: ",I2)
9820= CALL RQWGT(S(RPI(LUDW),NRD,1)
9830= CALL MATLST(RPI,NPD,NPD,"Y",KLIST)
9840= CALL DVCTOR(NPD,RPI,ZM1)
9850= CALL MATLST(ZM1,NPD,1,"Y",KTERM)
9860= CALL DVCTOR(NRD,RPI(LUX),ZM1)
9870= CALL MATLST(ZM1,NRD,1,"UQ",KTERM)
9880= CALL MATLST(RPI(LUX),NRD,NRD,"UQ",KLIST)
9890= NDIM=NNPR
9900= NDIM1=NDIM+1
9910= CALL FORMXU(RPI,RPI(LUX),RPI(LUDW),DM(LC),DM(LDY),ZM2,ZM1,COM1)
9920= WRITE(KTERM,104)
9930= 104 FORMAT("OMODIFY ELEMENTS OF 'X' MATRIX (Y OR N) >")

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994C= READ 111, IANS
9950= 111 FORMAT(A3)
9960= IF(IANS.EQ.NO) GO TO 20
9970= WRITE(KTERM, 105)
9980= 105 FORMAT(" LIST 'X' MATRIX TO TERMINAL (Y OR N) >")
9990= READ 111, IANS
10000= IF(IANS.EQ.NO) GO TO 12
10010= CALL MATLST(ZM2, NNPR, NNPR, "X", KTERM)
10020= 12 CALL ZMATIN(ZM2, NNPR, NNPR, -1)
10030= 20 CALL MATLST(ZM2, NNPR, NNPR, "X", KLIST)
10040= CALL MATLST(RPI(LUDW), NRD, NRD, "UM", KLIST)
10050= CALL DVCTOR(NRD, RPI(LUDW), ZM1)
10060= CALL MATLST(ZM1, NRD, 1, "UM", KTERM)
10070= IF(IMPPLIC.EQ.0) GO TO 260
10080= CALL MODXU(ZM2, RPI(LUDW))
10090= 260 CONTINUE
10100= T1=.25*TSAMP
10110= CALL MSCALE(ZM1, ZM2, NDIM, NDIM, T1)
10120= CALL DIAG(NDIM, COM1, CTL(LPHDL), 1., 1.)
10130= CALL MAT3A(NDIM, NDIM, COM1, ZM1, X)
10140= CALL MAT3A(NRD, NDIM, CTL(LBDL), ZM1, U)
10150= CALL MAT4A(COM1, ZM1, NDIM, NDIM, NDIM, ZM2)
10160= CALL FMUL(ZM2, CTL(LBDL), NDIM, NDIM, NRD, S)
10170= T1=.5*TSAMP
10180= CALL MSCALE(COM2, COM2, NNPR, NRD, T1)
10190= CALL MAT4A(COM1, COM2, NDIM, NDIM, NRD, ZM1)
10200= CALL MADD1(NDIM, NRD, ZM1, S, S, 1.)
10210= CALL FTMUL(CTL(LBDL), COM2, NDIM, NRD, NRD, COM1)
10220= NRD2=NRD*NRD
10230= DO 25 I=1, NRD
10240= K=(I-1)*NRD
10250= JK=K+LUDW
10260= DO 25 J=I, NRD2, NRD
10270= K=K+1
10280= COM2(K)=COM1(K)+COM1(J)+RPI(JK)*TSAMP
10290= 25 JK=JK+1
10300= CALL TFRMTX(COM2, ZM1, NRD, NRD, 2)
10310= CALL MADD1(NRD, NRD, U, ZM1, U, 1.)
10320= RETURN
10330=C END SUBROUTINE WXUS
10340= END
10350= SUBROUTINE FORMXU(QY, RY, RU, C, D, X, Z1, Z2)
10360= COMMON/NDIMD/NND, NRD, NPD, NMD, NDD, NWD, NWDD, NPLD, NWPND, NNPR
10370= COMMON/MAIN2/COM2(1)
10380= DIMENSION QY(1), RY(1), C(1), D(1), X(1), Z1(1), Z2(1)
10390= CALL ZPART(X, NNPR, NNPR, NNPR)
10400= CALL FTMUL(C, QY, NPD, NND, NPD, Z1)
10410= CALL FMUL(Z1, C, NND, NPD, NND, Z2)
10420= CALL TFRMTX(Z2, X, NND, NND, 2)
10430= L1=LADDR(NNPR, NND+1, NND+1)
10440= CALL TFRMTX(RY, X(L1) NRD, NRD, 2)
10450= L2=LADDR(NRD, NND, NND, 1)
10460= CALL ZPART(COM2(L2, , NRD, NRD, NNPR)
10470= IF(NODY.EQ.0) GO TO 5
10480= CALL ZPART(COM2, NND, NRD, NNPR)

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10490=      RETURN
10500= 5    CALL FMMUL(Z1,D,NND,NPD,NRD,Z2)
10510=      CALL TFRMTX(Z2,COM2,NND,NRD,2)
10520=      CALL FMMUL(QY,D,NPD,NPD,NRD,Z1)
10530=      CALL FTMUL(D,Z1,NPD,NRD,NRD,Z2)
10540=      CALL FMADD(Z2,RU,NRD,NRD,RU)
10550=      RETURN
10560=C END SUBROUTINE FORMXU
10570=      END
10580=      SUBROUTINE PXUP(PHIDL,BDEL,X,U,S,BUIBT,UIST,PHIP,XP,ZM1)
10590=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
10600=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPNWD,NNPR
10610=      DIMENSION PHIDL(1),BDEL(1),X(1),U(1),S(1),BUIBT(1),UIST(1),
10620= 1 PHIP(1),XP(1),ZM1(1)
10630=      CALL EQUATE(PHIP,U,NRD,NRD)
10640=      CALL GMINV(NRD,NRD,PHIP,ZM1,MR,1)
10650=      CALL MAT3(NDIM,NRD,BDEL,ZM1,BUIBT)
10660=      CALL MAT5(ZM1,S,NRD,NRD,NDIM,UIST)
10670=      CALL MMUL(BDEL,UIST,NDIM,NRD,NDIM,ZM1)
10680=      CALL MADD1(NDIM,NDIM,PHIDL,ZM1,PHIP,-1.)
10690=      CALL MMUL(S,UIST,NDIM,NRD,NDIM,ZM1)
10700=      CALL MADD1(NDIM,NDIM,X,ZM1,XP,-1.)
10710=      RETURN
10720=C END SUBROUTINE PXUP
10730=      END
10740=      SUBROUTINE GCSTAR(PHIP,BDEL,U,RK,UIST,GCS,ZM1)
10750=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
10760=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
10770=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPNWD,NNPR
10780=      DIMENSION PHIP(1),BDEL(1),U(1),RK(1),UIST(1),GCS(1),ZM1(1)
10790=      CALL MAT3A(NRD,NDIM,BDEL,RK,ZM1)
10800=      CALL MADD1(NRD,NRD,ZM1,U,ZM1,1.)
10810=      CALL GMINV(NRD,NRD,ZM1,U,MR,1)
10820=      CALL MAT5(U,BDEL,NRD,NRD,NDIM,ZM1)
10830=      CALL MAT1(ZM1,RK,NRD,NDIM,NDIM,GCS)
10840=      CALL MMUL(GCS,PHIP,NRD,NDIM,NDIM,ZM1)
10850=      CALL MADD1(NRD,NDIM,ZM1,UIST,GCS,1.)
10860=      WRITE(KLIST,101)
10870= 101  FORMAT("OREG/PI GAIN MATRIX--GCS"/)
10880=      CALL MATIO(GCS,NRD,NDIM,3)
10890=      RETURN
10900=C END SUBROUTINE GCSTAR
10910=      END
10920=      SUBROUTINE SCGT
10930=      COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
10940=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
10950=      COMMON/ZMTX1/NVZM,ZM1(1)
10960=      COMMON/ZMTX2/ZM2(1)
10970=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPNWD,NNPR
10980=      COMMON/NDIMC/NNC,NRC,NPC
10990=      COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
11000=      COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
11010=      COMMON/CREGPI/NVRPI,RPI(1)
11020=      COMMON/LCGT/LA11,LA13,LA21,LA23,LA12,LA22,LELA11,LELA12,LELA13
11030=      COMMON/CCGT/NVCGT,CGT(1)

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11040=      IF(NEWCM) 20,20,15
11050= 15   NSIZE=(NND+2*NPD)*(NNC+NRC+NDD)
11060=      IF(NSIZE.LE.NVCGT) GO TO 16
11070=      WRITE 106,NSIZE
11080=      LABORT=NSIZE
11090=      RETURN
11100= 16   IF(NND.GE.NNC) GO TO 17
11110=      WRITE 107
11120=      GO TO 18
11130= 17   IF(NND.GE.NDD) GO TO 19
11140=      WRITE 108
11150= 18   LABORT=-1
11160=      RETURN
11170= 19   NEWCM=0
11180=      LA11=1
11190=      LA13=LA11+NND*NNC
11200=      LA21=LA13+NND*NDD
11210=      LA23=LA21+NPD*NNC
11220=      LA12=LA23+NPD*NDD
11230=      LA22=LA12+NND*NRC
11240=      LELA11=LA22+NPD*NRC
11250=      LELA12=LELA11+NPD*NNC
11260=      LELA13=LELA12+NPD*NRC
11270=      CALL CGTA(CGT(LA11),CGT(LA13),CGT(LA21),CGT(LA23),CGT(LA12),
11280= 1 CGT(LA22),ZM1,ZM2)
11290= 20   CALL CGTKX(CGT(LA11),CGT(LA13),CGT(LA21),CGT(LA23),CGT(LA12),
11300= 1 CGT(LA22),CGT(LELA11),CGT(LELA12),CGT(LELA13),RPI(LEL))
11310=      LFLCGT=1
11320= 106  FORMAT("OINSUFFICIENT MEMORY /CCGT/, NEED: ",I4)
11330= 107  FORMAT("OFEWER DESIGN MODEL THAN COMMAND MODEL STATES")
11340= 108  FORMAT("FEWER DESIGN MODEL THAN DISTURBANCE MODEL STATES")
11350=      RETURN
11360=C END SUBROUTINE SCGT
11370=      END
11380=      SUBROUTINE CGTA(A11,A13,A21,A23,A12,A22,ZM1,ZM2)
11390=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
11400=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
11410=      COMMON/SYSMTX/NVSM,SM(1)
11420=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
11430=      COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
11440=      COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
11450=      COMMON/NDIMC/NNC,NRC,NPC
11460=      COMMON/LOCC/LPHC,LBDC,LCC,LDC
11470=      COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
11480=      COMMON/LCCTRL/LPI11,LPI12,LPI21,LPI22,LPHDL,LBDL
11490=      COMMON/CONTROL/NVCTL,CTL(1)
11500=      DIMENSION A11(1),A13(1),A21(1),A23(1),A12(1),A22(1),ZM1(1),ZM2(1)
11510=      NDIM=NND
11520=      NDIM1=NDIM+1
11530=      CALL TFRMTX(CM,ZM1,NNC,NNC,2)
11540=      CALL SUBI(ZM1,NNC,NDIM)
11550=      CALL FMMUL(CTL(LPI12),CM(LCC),NND,NRD,NNC,ZM2)
11560=      CALL MSCALE(ZM2,ZM2,NND,NNC,-1.)
11570=      NB=MAXO(NDD,NNC)
11580=      L2=1+NND*NND

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11590=      L3=L2+NND*NB
11600=      L4=L3+NND*NB
11610=      L5=L4+NND*NND
11620=      L6=L5+NND*NND
11630=      NSIZE=L6+NPD*NNC-1
11640=      IF(NSIZE.LE.NVSM) GO TO 1
11650=      WRITE 102,NSIZE
11660= 102  FORMAT("OINSUFFICIENT MEMORY /SYSMTX/, NEED: ",I4)
11670=      LABORT=NSIZE
11680=      RETURN
11690= 1    CALL AXBMXC(CTL(LPI11),NND,ZM1,NNC,ZM2,A11,SM,
11700=      1 SM(L2),SM(L3),SM(L4),SM(L5))
11710=      CALL MMUL(A11,ZM1,NND,NNC,NNC,ZM2)
11720=      CALL FMMUL(CTL(LPI21),ZM2,NPD,NND,NNC,A21)
11730=      CALL FMMUL(CTL(LPI22),CM(LCC),NPD,NRD,NNC,SM(L6))
11740=      CALL FMMUL(A11,CM(LBDC),NND,NNC,NRC,SM)
11750=      CALL FMMUL(CTL(LPI11),SM,NND,NND,NRC,A12)
11760=      CALL FMMUL(CTL(LPI21),SM,NPD,NND,NRC,A22)
11770=      IF(NODC.EQ.1) GO TO 2
11780=      CALL FMMUL(CTL(LPI12),CM(LDC),NND,NRD,NRC,SM(L2))
11790=      CALL FMADD(A12,SM(L2),NND,NRC,A12)
11800=      CALL FMMUL(CTL(LPI22),CM(LDC),NPD,NRD,NRC,SM(L2))
11810=      CALL FMADD(A22,SM(L2),NPD,NRC,A22)
11820= 2    IF(NDD.EQ.0) GO TO 15
11830=      CALL MMUL(CTL(LPI11),DM(LEX),NND,NND,NDD,ZM2)
11840=      IF(NOEY.EQ.1) GO TO 5
11850=      CALL FMMUL(CTL(LPI12),DM(LEY),NND,NRD,NDD,ZM1)
11860=      CALL MADD1(NND,NDD,ZM1,ZM2,ZM2,1.)
11870= 5    CALL TFRMTX(DM(LPHD),ZM1,NDD,NDD,2)
11880=      CALL SUBI(ZM1,NDD,NDIM)
11890=      CALL AXBMXC(CTL(LPI11),NND,ZM1,NDD,ZM2,A13,SM,
11900=      1 SM(L2),SM(L3),SM(L4),SM(L5))
11910=      CALL MMUL(A13,ZM1,NND,NDD,NDD,ZM2)
11920=      CALL MADD1(NND,NDD,ZM2,DM(LEX),ZM2,-1.)
11930=      CALL FMMUL(CTL(LPI21),ZM2,NPD,NND,NDD,A23)
11940= 15   NDIM=NPD
11950=      NDIM1=NDIM+1
11960=      CALL MADD1(NPD,NNC,A21,SM(L6),A21,1.)

11970=      IF(NOEY.EQ.1) GO TO 20
11980=      CALL MMUL(CTL(LPI22),DM(LEY),NPD,NRD,NDD,ZM1)
11990=      CALL MADD1(NPD,NDD,A23,ZM1,A23,-1.)
12000= 20   CALL MATLST(A11,NND,NNC,"A11",KLIST)
12010=      CALL MATLST(A21,NPD,NNC,"A21",KLIST)
12020=      CALL MATLST(A12,NND,NRC,"A12",KLIST)
12030=      CALL MATLST(A22,NPD,NRC,"A22",KLIST)
12040=      IF(NDD.GT.0) GO TO 25
12050=      WRITE(KLIST,101)
12060= 101  FORMAT("OMATRICES A13 AND A23 ARE ZERO")
12070=      RETURN
12080= 25   CALL MATLST(A13,NND,NDD,"A13",KLIST)
12090=      CALL MATLST(A23,NPD,NDD,"A23",KLIST)
12100=      RETURN
12110=C END SUBROUTINE CGTA
12120=      END

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12130= SUBROUTINE AXBMXC(A,NA,B,NB,C,X,AU,BU,R,Z1,Z2)
12140= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
12150= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
12160= DIMENSION A(1),B(1),C(1),X(1),AU(1),BU(1),R(1),Z1(1),Z2(1)
12170= DATA EMAX,ITMAX/1.E-6,3/
12180= CALL TRANS1(NA,A,Z1)
12190= CALL EIGEN(NA,Z1,Z2,Z2(NDIM1),AU,1)
12200= CALL TRANS1(NA,COM1,Z1)
12210= CALL EIGEN(NB,B,Z2,Z2(NDIM1),BU,1)
12220= CALL EQUATE(R,C,NA,NB)
12230= IT=0
12240= 10 CALL MAT4A(AU,R,NA,NA,NB,Z2)
12250= CALL MAT1(Z2,BU,NA,NB,NB,R)
12260= CALL SLVSHR(Z1,NA,COM1,NB,R,NDIM)
12270= CALL MAT4(R,BU,NA,NB,NB,Z2)
12280= CALL MAT1(AU,Z2,NA,NA,NB,R)
12290= IF(IT.GT.0) GO TO 15
12300= CALL EQUATE(X,R,NA,NB)
12310= GO TO 30
12320= 15 CALL MADD1(NA,NB,X,R,X,1.)
12330= CALL ENORM(R,NA,NB,EN)
12340= IF(EN.LE.EMAX) RETURN
12350= IF(IT.LT.ITMAX) GO TO 30
12360= WRITE(KLIST,101) EN
12370= WRITE(KTERM,101) EN
12380= 101 FORMAT(*OSOLUTION ERROR FOR 'A'(CGT) AFTER 3 ITERATIONS = ",1PE15.
12390= 17)
12400= RETURN
12410= 30 CALL MAT1(A,X,NA,NA,NB,Z2)
12420= CALL MAT1(Z2,B,NA,NB,NB,R)
12430= CALL MADD1(NA,NB,X,R,R,-1.)
12440= CALL MADD1(NA,NB,R,C,R,1.)
12450= IT=IT+1
12460= GO TO 10
12470=C END SUBROUTINE AXBMXC
12480= END
12490= SUBROUTINE SLVSHR(A,NA,B,NB,C,ND)
12500= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
12510= COMMON/INOU/KIN,KOUT,KPUNCH
12520= DIMENSION A(ND,1),B(ND,1),C(ND,1),V(16),W(4)
12530= L=1
12540= 5 LM1=L-1
12550= DL=1
12560= IF(L.EQ.NB) GO TO 8
12570= IF(B(L+1,L).NE.0.) DL=2
12580= 8 LL=LM1+DL
12590= K=1
12600= 10 KM1=K-1
12610= DK=1
12620= IF(K.EQ.NA) GO TO 12
12630= IF(A(K,K+1).NE.0.) DK=2
12640= 12 KK=KM1+DK
12650= AKK=A(K,K)
12660= BLL=B(L,L)
12670= IF(DL.EQ.2) GO TO 35

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12680=      IF(DK.EQ.2) GO TO 20
12690=      IF(L.EQ.1) GO TO 13
12700=      C(K,L)=C(K,L)-AKK*DOT3(LM1,C(K,1),B(1,L))
12710= 13   IF(K.EQ.1) GO TO 18
12720=      DO 15 I=1,KM1
12730= 15   C(K,L)=C(K,L)-A(K,I)*DOT3(L,C(I,1),B(1,L))
12740= 18   V(1)=AKK*BLL-1.
12750=      IF(V(1).EQ.0.) GO TO 99
12760=      C(K,L)=C(K,L)/V(1)
12770=      GO TO 95
12780= 20   IF(L.EQ.1) GO TO 22
12790=      I1=K
12800=      I2=KK
12810=      I3=LM1
12820=      GO TO 24
12830= 22   IF(K.EQ.1) GO TO 30
12840=      I1=1
12850=      I2=KM1
12860=      I3=L
12870= 24   DO 28 I=I1,I2
12880=      V(1)=DOT3(I3,C(I,1),B(1,L))
12890=      C(K,L)=C(K,L)-A(K,I)*V(1)
12900= 28   C(KK,L)=C(KK,L)-A(KK,I)*V(1)
12910=      IF(I1.EQ.K) GO TO 22
12920= 30   V(1)=AKK*BLL-1.
12930=      V(2)=A(KK,K)*BLL
12940=      V(3)=A(K,KK)*BLL
12950=      V(4)=A(KK,KK)*BLL-1.
12960=      V(5)=1./(V(1)*V(4)-V(2)*V(3))
12970=      V(6)=V(5)*(C(K,L)*V(4)-V(3)*C(KK,L))
12980=      C(KK,L)=V(5)*(V(1)*C(KK,L)-V(2)*C(K,L))
12990=      C(K,L)=V(6)
13000=      GO TO 95
13010= 35   IF(DK.EQ.2) GO TO 50
13020=      IF(L.EQ.1) GO TO 38
13030=      I1=K
13040=      I2=K
13050=      I3=LM1
13060=      GO TO 40
13070= 38   IF(K.EQ.1) GO TO 45
13080=      I1=1
13090=      I2=KM1
13100=      I3=LL
13110= 40   DO 42 I=I1,I2
13120=      C(K,L)=C(K,L)-A(K,I)*DOT3(I3,C(I,1),B(1,L))
13130= 42   C(K,LL)=C(K,LL)-A(K,I)*DOT3(I3,C(I,1),B(1,LL))
13140=      IF(I1.EQ.K) GO TO 38
13150= 45   V(1)=AKK*BLL-1.
13160=      V(2)=AKK*B(L,LL)
13170=      V(3)=AKK*B(LL,L)
13180=      V(4)=AKK*B(LL,LL)-1.
13190= 48   V(5)=1./(V(1)*V(4)-V(2)*V(3))
13200=      V(6)=V(5)*(C(K,L)*V(4)-V(3)*C(K,LL))
13210=      C(K,LL)=V(5)*(V(1)*C(K,LL)-V(2)*C(K,L))
13220=      C(K,L)=V(6)

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13230=      GO TO 95
13240= 50   IF(L.EQ.1) GO TO 55
13250=      V(1)=DOT3(LM1,C(K,1),B(1,L))
13260=      V(2)=DOT3(LM1,C(KK,1),B(1,L))
13270=      V(3)=DOT3(LM1,C(K,1),B(1,LL))
13280=      V(4)=DOT3(LM1,C(KK,1),B(1,LL))
13290=      C(K,L)=C(K,L)-AKK*V(1)-A(K,KK)*V(2)
13300=      C(KK,L)=C(KK,L)-A(KK,K)*V(1)-A(KK,KK)*V(2)
13310=      C(K,LL)=C(K,LL)-AKK*V(3)-A(K,KK)*V(4)
13320=      C(KK,LL)=C(KK,LL)-A(KK,K)*V(3)-A(KK,KK)*V(4)
13330= 55   IF(K.EQ.1) GO TO 65
13340=      DO 60 I=1,KM1
13350=      V(1)=DOT3(LL,C(I,1),B(1,L))
13360=      V(2)=DOT3(LL,C(I,1),B(1,LL))
13370=      C(K,L)=C(K,L)-A(K,I)*V(1)
13380=      C(KK,L)=C(KK,L)-A(KK,I)*V(1)
13390=      C(K,LL)=C(K,LL)-A(K,I)*V(2)
13400= 60   C(KK,LL)=C(KK,LL)-A(KK,I)*V(2)
13410= 65   V(1)=AKK*BLL-1.
13420=      V(2)=A(KK,K)*BLL
13430=      V(3)=AKK*B(L,LL)
13440=      V(4)=A(KK,K)*B(L,LL)
13450=      V(5)=A(K,KK)*BLL
13460=      V(6)=A(KK,KK)*BLL-1.
13470=      V(7)=A(K,KK)*B(L,LL)
13480=      V(8)=A(KK,KK)*B(L,LL)
13490=      V(9)=AKK*B(LL,L)
13500=      V(10)=A(KK,K)*B(LL,L)
13510=      V(11)=AKK*B(LL,LL)-1.
13520=      V(12)=A(KK,K)*B(LL,LL)
13530=      V(13)=A(K,KK)*B(LL,L)
13540=      V(14)=A(KK,KK)*B(LL,L)
13550=      V(15)=A(K,KK)*B(LL,LL)
13560=      V(16)=A(KK,KK)*B(LL,LL)-1.
13570=      W(1)=C(K,L)
13580=      W(2)=C(KK,L)
13590=      W(3)=C(K,LL)
13600=      W(4)=C(KK,LL)
13610=      NDS=NDIM
13620=      NDIM=4
13630=      NDIM1=NDIM+1
13640=      CALL DOOLIT(4,V,W,1,ISG)
13650=      NDIM=NDS
13660=      NDIM1=NDIM+1
13670= 95   K=K+DK
13680=      IF(K.LE.NA) GO TO 10
13690=      L=L+DL
13700=      IF(L.LE.NB) GO TO 5
13710=      RETURN
13720= 99   WRITE(KOUT,101)
13730=      RETURN
13740= 101  FORMAT(*0* * * ERROR IN CGT SOLUTION: A11->A23*)
13750=C END SUBROUTINE SLVSHR
13760=      END

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13770= SUBROUTINE ENORM(A, NR, NC, ENRM)
13780= COMMON/MAIN1/NDIM, NDIM1, COM1(1)
13790= DIMENSION A(1)
13800= ENRM=0.
13810= NE=NC*NDIM
13820= DO 10 I=1, NR
13830= DO 10 J=I, NE, NDIM
13840= 10 ENRM=ENRM+A(J)*A(J)
13850= ENRM=SQRT(ENRM)
13860= RETURN
13870=C END SUBROUTINE ENORM
13880= END
13890= SUBROUTINE CGTKX(A11, A13, A21, A23, A12, A22, REL11, REL12, REL13, REL)
13900= COMMON/MAIN1/NDIM, NDIM1, COM1(1)
13910= COMMON/FILES/KSAVE, KDATA, KPLOT, KLIST, KTERM
13920= COMMON/NDIMD/NND, NRD, NPD, NMD, NDD, NWD, NWDD, NPLD, NWPND, NNPR
13930= COMMON/NDIMC/NNC, NRC, NPC
13940= DIMENSION A11(1), A13(1), A21(1), A23(1), A12(1), A22(1),
13950= 1 REL11(1), REL12(1), REL13(1), REL(1)
13960= NDIM=NRD
13970= NDIM1=NDIM+1
13980= CALL FMMUL(REL, A11, NRD, NND, NNC, REL11)
13990= CALL MADD1(NRD, NNC, REL11, A21, REL11, 1.)
14000= CALL MATLST(REL11, NRD, NNC, "KXM", KLIST)
14010= CALL MATLST(REL11, NRD, NNC, "KXM", KTERM)
14020= CALL FMMUL(REL, A12, NRD, NND, NRC, REL12)
14030= CALL MADD1(NRD, NRC, REL12, A22, REL12, 1.)
14040= CALL MATLST(REL12, NRD, NRC, "KXU", KLIST)
14050= CALL MATLST(REL12, NRD, NRC, "KXU", KTERM)
14060= IF(NDD.LT.1) RETURN
14070= CALL FMMUL(REL, A13, NRD, NND, NDD, REL13)
14080= CALL MADD1(NRD, NDD, REL13, A23, REL13, 1.)
14090= CALL MATLST(REL13, NRD, NDD, "KXN", KLIST)
14100= CALL MATLST(REL13, NRD, NDD, "KXN", KTERM)
14110= RETURN
14120=C END SUBROUTINE CGTKX
14130= END
14140= SUBROUTINE CEVAL
14150= COMMON/MAIN1/NDIM, NDIM1, COM1(1)
14160= COMMON/INO/KIN, KOUT, KPUNCH
14170= COMMON/DESIGN/NVCOM, TSAMP, LFLRPI, LFLCGT, LFLKF, LTEVAL, LABORT
14180= COMMON/FILES/KSAVE, KDATA, KPLOT, KLIST, KTERM
14190= COMMON/SYSMTX/NVSM, SM(1)
14200= COMMON/ZMTX1/NVZM, ZM1(1)
14210= COMMON/ZMTX2/ZM2(1)
14220= COMMON/NDIMD/NND, NRD, NPD, NMD, NDD, NWD, NWDD, NPLD, NWPND, NNPR
14230= COMMON/NDIMC/NNC, NRC, NPC
14240= COMMON/LREGPI/LXDW, LUDW, LPHCL, LGC1, LGC2, LEL, LEE
14250= COMMON/CREGPI/NVRPI, RPI(1)
14260= DIMENSION NPLD(2), NVPLD(10), NS(6), LSCL(2), ITITLE(5)
14270= DATA NO/1HN/
14280= WRITE(KLIST, 110)
14290= 110 FORMAT(////11X, 5(" " ), "CONTROLLER EVALUATION", 5(" ")////)
14300= IPOLE=1
14310= 10 NVOUT=NRD+NPD+1

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14320=      IF(LFLCGT) 17, 17, 15
14330= 15   WRITE 106
14340=      READ*, IUM, VUM
14350=      IF(IUM.LT.1) GO TO 70
14360=      IF(IUM.GT.NRC) GO TO 15
14370=      NVOUT=NVOUT+NPC
14380=      NP=NMC
14390=      GO TO 18
14400= 17   IF(IPOLE.EQ.1) CALL POLES(RPI(LPHCL), NNPR, 4, ZM1, ZM2)
14410=      NP=0
14420= 18   CALL VOUTIC(SM, NVPLOT, NPLOT, NVOUT, LSCL)
14430=      IF(NVOUT.EQ.0) GO TO 70
14440= 20   WRITE 108
14450=      READ*, TEND
14460=      IF(TEND) 20, 20, 25
14470= 25   LVX0=NVOUT+1
14480=      LX0=LVX0+NVOUT
14490=      LX1=LX0+NPLD
14500=      LXMO=LX1+NPLD
14510=      LXM1=LXMO+NP
14520=      NP=LXM1+NP
14530=      DO 26 I=LVX0, NP
14540= 26   SM(I)=0.
14550=      CALL CTRESP(SM(LVX0), SM, SM(LX0), SM(LX1), SM(LXMO), SM(LXM1),
14560= 1 ZM1, NVOUT, TEND, IUM, VUM, NST)
14570=      WRITE(KTERM, 101)
14580=      READ(KIN, 102) ITITLE
14590=      M=50*NST
14600=      DO 40 I=1, 2
14610=      NS(1)=1
14620=      DO 28 J=2, 6
14630= 28   NS(J)=NS(J-1)+51
14640=      NP=NPLOT(I)
14650=      IF(NP.EQ.0) GO TO 40
14660=      NPP1=NP+1
14670=      REWIND KPLOT
14680=      NSV=5*I-4
14690=      CALL RPLOTF(ZM1, NVOUT, IERR)
14700=      CALL STRPLT(SM, ZM1, NS, NVPLOT(NSV), NP, NVOUT)
14710=      DO 35 J=1, M
14720=      CALL RPLOTF(ZM1, NVOUT, IERR)
14730=      IF(IERR.EQ.1) GO TO 40
14740=      IF(MOD(J, NST).NE.0) GO TO 35
14750=      DO 30 K=1, NPP1
14760= 30   NS(K)=NS(K)+1
14770=      CALL STRPLT(SM, ZM1, NS, NVPLOT(NSV), NP, NVOUT)
14780= 35   CONTINUE
14790=      CALL PLOTLP(51, NP, SM, LSCL(I), 1, 0, KTERM, ITITLE)
14800= 40   CONTINUE
14810=      NVM=NVOUT-1
14820=      M=NVM/5
14830=      NE=5*M
14840=      IF(M.EQ.0) GO TO 56
14850=      DO 55 I=1, NE, 5
14860=      NS(1)=1

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14870= DO 42 J=2,6
14880= 42 NS(J)=NS(J-1)+101
14890= REWIND KPLOT
14900= NVS=I-1
14910= DO 45 J=1,5
14920= 45 NVPLOT(J)=NVS+J
14930= DO 50 J=1,101
14940= CALL RPLOT(ZM1,NVOUT,IERR)
14950= IF(IERR.EQ.1) GO TO 55
14960= CALL STRPLT(SM,ZM1,NS,NVPLOT,5,NVOUT)
14970= DO 48 K=1,6
14980= 48 NS(K)=NS(K)+1
14990= 50 CONTINUE
15000= CALL PLOTLP(101,5,SM,1,1,1,KLIST,ITITLE)
15010= 55 CONTINUE
15020= 56 NVM=NVM-NE
15030= IF(NVM.LT.1) GO TO 70
15040= NPP1=NVM+1
15050= NS(1)=1
15060= DO 57 I=2,6
15070= 57 NS(I)=NS(I-1)+101
15080= DO 58 I=1,NVM
15090= 58 NVPLOT(I)=NE+I
15100= REWIND KPLOT
15110= DO 65 I=1,101
15120= CALL RPLOT(ZM1,NVOUT,IERR)
15130= IF(IERR.EQ.1) GO TO 70
15140= CALL STRPLT(SM,ZM1,NS,NVPLOT,NVM,NVOUT)
15150= DO 60 J=1,NPP1
15160= 60 NS(J)=NS(J)+1
15170= 65 CONTINUE
15180= CALL PLOTLP(101,NVM,SM,1,1,1,KLIST,ITITLE)
15190= 70 WRITE 104
15200= READ 111,IANS
15210= IF(IANS.EQ.NO) RETURN
15220= IPOLE=0
15230= GO TO 10
15240= 101 FORMAT(" +",10(" -")," ENTER TITLE IN GIVEN FIELD ",10(" -"),"+"/)
15250= 102 FORMAT(5A10)
15260= 104 FORMAT("OMORE TIME RESPONSE RUNS (Y OR N) >")
15270= 106 FORMAT("OENTER MODEL INPUT AND STEP VALUE : 1 >")
15280= 108 FORMAT(" ENTER TIME DURATION FOR RESPONSE, IN SECONDS >")
15290= 111 FORMAT(A3)
15300=C END SUBROUTINE CEVAL
15310= END
15320= SUBROUTINE VOUTIC(VIC,NVPLOT,NPLOT,NVOUT,LSCL)
15330= COMMON/DESIGN/NVCOM,TSAMP,LPLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
15340= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
15350= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
15360= COMMON/NDIMC/NNC,NRC,NPC
15370= COMMON/NDIMT/NNT,NRT,NMT,NWT
15380= DIMENSION NPLOT(1),NVPLOT(1),VIC(1),IOUT(5),LSCL(2)
15390= DATA IOUT/1HX,1HY,1HU,1HM,1HD/
15400= IF(LTEVAL) 2,2,5
15410= 2 NVS=NND

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15420=      NV=NPLD
15430=      GO TO 8
15440=  5    NV=NNT
15450=      NVS=NV
15460=  8    NVOUT=NVOUT+NV
15470=      DO 9 I=1,NVOUT
15480=  9    VIC(I)=0.
15490=      NVU=NV+NPD
15500=      NVM=NVU+NRD
15510=  10   WRITE 101,NVS
15520=  101  FORMAT("OENTER STATE AND IC VALUE (O/ TERMINATES): ",I2," >")
15530=  12   READ*,IV,V
15540=      IF(IV.LT.1) GO TO 15
15550=      IF(IV.GT.NVS) GO TO 10
15560=      VIC(IV)=V
15570=      GO TO 12
15580=  15   IF((LFLCGT.LT.1).OR.(LTEVAL.EQ.1).OR.(NDD.LT.1)) GO TO 25
15590=      LD=1
15600=  18   WRITE 102,NDD
15610=  102  FORMAT(" ENTER DISTURBANCE IC VALUE (O/ TERMINATES): ",I2," >")
15620=  20   READ*,IV,V
15630=      IF(IV.LT.1) GO TO 26
15640=      IF(IV.GT.NDD) GO TO 18
15650=      VIC(NND+IV)=V
15660=      GO TO 20
15670=  25   LD=0
15680=  26   WRITE 103
15690=  103  FORMAT(" 2 PLOTS OF 5 VARIABLES MAY BE PRINTED AT THE TERMINAL --
15700= 1SPECIFY NUMBER FOR EACH (N1,N2) >")
15710=      READ*,NPLOT(1),NPLOT(2)
15720=      IF(NPLOT(1).GT.5) NPLOT(1)=5
15730=      IF(NPLOT(2).GT.5) NPLOT(2)=5
15740=      IF((NPLOT(1).GT.0).OR.(NPLOT(2).GT.0)) GO TO 27
15750=      NVOUT=0
15760=      RETURN
15770=  27   WRITE 104
15780=  104  FORMAT(" ENTER OUTPUTS BY TYPE AND INDEX IN 2 ENTRIES--TYPES ARE"/
15790= 1 " STATE : 'X'"/" OUTPUT : 'Y'"/" INPUT : 'U'")
15800=      IF(LFLCGT) 30,30,28
15810=  28   WRITE 105
15820=  105  FORMAT(" MODEL : 'M'")
15830=      IF(LD.EQ.1) WRITE 106
15840=  106  FORMAT(" DISTURBANCE : 'D'")
15850=  30   DO 40 I=1,2
15860=      NC=NPLOT(I)
15870=      IF(NC.LT.1) GO TO 40
15880=      LSCL(I)=1
15890=      NS=5*(I-1)
15900=      WRITE 107,I
15910=  107  FORMAT("O PLOT ",I2)
15920=      DO 39 J=1,NC
15930=      NSP=NS+J
15940=  31   WRITE 108,J
15950=  108  FORMAT(" OUTPUT ",I2," >")
15960=      READ 111,IV

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15970= WRITE 113
15980= 113 FORMAT(11X,">")
15990= READ*,IO
16000= IF(IV.NE.IOOUT(1)) GO TO 32
16010= IF(IO.GT.NVS) GO TO 38
16020= NVPLOT(NSP)=IO
16030= GO TO 39
16040= 32 IF(IV.NE.IOOUT(2)) GO TO 321
16050= IF(IO.GT.NPD) GO TO 38
16060= NVPLOT(NSP)=NV+IO
16070= GO TO 39
16080= 321 IF(IV.NE.IOOUT(3)) GO TO 33
16090= IF(IO.GT.NRD) GO TO 38
16100= NVPLOT(NSP)=NVU+IO
16110= GO TO 39
16120= 33 IF(LFLCGT.LT.1) GO TO 31
16130= IF(IV.NE.IOOUT(4)) GO TO 34
16140= IF(IO.GT.NPC) GO TO 38
16150= NVPLOT(NSP)=NVM+IO
16160= LSCL(I)=-1
16170= GO TO 39
16180= 34 IF(LD.NE.1) GO TO 31
16190= IF(IV.NE.IOOUT(5)) GO TO 31
16200= IF(IO.GT.NDD) GO TO 38
16210= NVPLOT(NSP)=NVS+IO
16220= GO TO 39
16230= 38 WRITE 109
16240= 109 FORMAT(" INDEX TOO LARGE")
16250= GO TO 31
16260= 39 CONTINUE
16270= 40 CONTINUE
16280= NVM1=NVOUT-1
16290= NP=0
16300= DO 50 I=1,NVM1
16310= M=MOD((I-1),5)+1
16320= IF(M.GT.1) GO TO 41
16330= NP=NP+1
16340= WRITE(KLIST,110) NP
16350= 110 FORMAT("O PLOT ",I2)
16360= 41 IF(I.GT.NVS) GO TO 42
16370= IV=IOOUT(1)
16380= IO=I
16390= GO TO 45
16400= 42 IF(I.GT.NV) GO TO 43
16410= IV=IOOUT(5)
16420= IO=I-NVS
16430= GO TO 45
16440= 43 IF(I.GT.NVU) GO TO 441
16450= IV=IOOUT(2)
16460= IO=I-NV
16470= GO TO 45
16480= 441 IF(I.GT.NVM) GO TO 44
16490= IV=IOOUT(3)
16500= IO=I-NVU
16510= GO TO 45

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16520= 44 IV=IOUT(4)
16530= IO=I-NVM
16540= 45 WRITE(KLIST,112) M,IV,IO
16550= 50 CONTINUE
16560= RETURN
16570= 111 FORMAT(A1)
16580= 112 FORMAT(" OUTPUT ",I2," : ",A1,I2)
16590=C END SUBROUTINE VOUTIC
16600= END
16610= SUBROUTINE CTRESP(VX0,VX1,X0,X1,XMO,XM1,ZM1,NVOUT,TEND,IUM,VUM,
16620= 1 NST)
16630= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
16640= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
16650= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
16660= COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
16670= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
16680= COMMON/NDIMC/NNC,NRC,NPC
16690= COMMON/LOCC/LPHC,LBDC,LCC,LDC
16700= COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
16710= COMMON/LOCT/LPHT,LBDT,LQDT,LHT,LRT,LTDT,LTNT
16720= COMMON/TRUMTX/NVTM,TM(1)
16730= COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
16740= COMMON/CREGPI/NVRPI,RPI(1)
16750= DIMENSION VX0(1),VX1(1),X0(1),X1(1),XMO(1),XM1(1),ZM1(1)
16760= NSTPO=.01*TEND/TSAMP+.5
16770= NST=2
16780= IF(NSTPO.GE.1) GO TO 1
16790= NSTPO=1
16800= NST=1
16810= 1 NSTEPS=100*NSTPO
16820= IF(LFLCGT.EQ.0) GO TO 2
16830= LMO=NVOUT-NPC
16840= IF(NDD.EQ.0) GO TO 4
16850= LDCGT=1
16860= GO TO 5
16870= 2 LMO=NVOUT
16880= 4 LDCGT=0
16890= 5 LU=LMO-NRD
16900= LSO=LU-NPD
16910= NVX=LSO-1
16920= IF(LTEVAL)6,6,10
16930= 6 DO 7 I=1,NVX
16940= 7 X1(I)=VX1(I)
16950= GO TO 12
16960= 10 CALL XPDT(VX1,X1,LDCGT)
16970= 12 NNDP1=NND+1
16980= REWIND KPLOT
16990= CALL YDSN(X1,VX1(LU),DM(LC),DM(LDY),LDCGT,VX1(LSO))
17000= IF(LFLCGT.EQ.1) CALL YCMD(XM1,IUM,VUM,CM(LCC),CM(LDC),
17010= 1 VX1(LMO))
17020= CALL WPLOTF(VX1,NVOUT)
17030= DO 100 IT=1,NSTEPS
17040= CALL URPI(RPI(LGC1),RPI(LGC2),DM(LC),DM(LDY),X0,X1,VX0(LU),
17050= 1 VX1(LU))
17060= IF(LFLCGT) 20,20,15

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17070= 15 CALL UCGT(VX0(LU), VX1(LU), XMO, XM1, XO(NNDP1), ZM1, IUM, VUM, IT)
17080= CALL CUPDAT(XMO, XM1, IUM, VUM)
17090= 20 CALL FTMTX(VX1(LU), VX0(LU), NRD, 1)
17100= CALL FTMTX(X1, XO, NPLD, 1)
17110= IF(LTEVAL) 25, 25, 30
17120= 25 CALL DUPDAT(DM(LPHI), DM(LBD), DM(LPHD), DM(LEX), XO, X1,
17130= 1 VX1, VX0(LU), LDCGT, NNDP1)
17140= GO TO 35
17150= 30 CALL TUPDAT(TM(LPHT), TM(LBDT), VX0, VX1, VX0(LU))
17160= CALL XFDT(VX1, X1, LDCGT)
17170= 35 IF(MOD(IT, NSTPO).NE.0) GO TO 100
17180= VX1(NVOUT)=TSAMP*FLOAT(IT)
17190= CALL YDSN(X1, VX1(LU), DM(LC), DM(LDY), LDCGT, VX1(LSO))
17200= IF(LFLCGT.EQ.1) CALL YCMD(XM1, IUM, VUM, CM(LCC), CM(LDC),
17210= 1 VX1(LMO))
17220= CALL WPLOT(F(VX1, NVOUT))
17230= 100 CONTINUE
17240= ENDFILE KPLOT
17250= RETURN
17260=C END SUBROUTINE CTRESP
17270= END
17280= SUBROUTINE DUPDAT(PHI, BD, PHID, EX, XO, X1, VX1, UO, LDCGT, NNDP1)
17290= COMMON/MAIN1/NDIM, NDIM1, COM1(1)
17300= COMMON/NDIMD/NND, NRD, NPD, NMD, NDD, NWD, NWDD, NPLD, NWPND, NNPR
17310= DIMENSION PHI(1), BD(1), PHID(1), EX(1), XO(1), X1(1), VX1(1), UO(1)
17320= NDIM=NND
17330= NDIM1=NDIM+1
17340= CALL FMMUL(BD, UO, NND, NRD, 1, X1)
17350= CALL MMULS(PHI, XO, NND, NND, 1, X1)
17360= IF(LDCGT.EQ.0) GO TO 10
17370= CALL FMMUL(PHID, XO(NNDP1), NDD, NDD, 1, X1(NNDP1))
17380= CALL MMULS(EX, X1(NNDP1), NND, NDD, 1, X1)
17390= 10 CALL FTMTX(X1, VX1, NPLD, 1)
17400= RETURN
17410=C END SUBROUTINE DUPDAT
17420= END
17430= SUBROUTINE CUPDAT(XMO, XM1, IUM, VUM)
17440= COMMON/MAIN1/NDIM, NDIM1, COM1(1)
17450= COMMON/NDIMC/NNC, NRC, NPC
17460= COMMON/LOCC/LPHC, LBDC, LCC, LDC
17470= COMMON/CMDMTX/NVCM, NEWCM, NODC, CM(1)
17480= DIMENSION XMO(1), XM1(1)
17490= NDIM=NNC
17500= NDIM1=NDIM+1
17510= CALL FTMTX(XM1, XMO, NNC, 1)
17520= L1=LADDR(NNC, 1, IUM)+LBDC-1
17530= CALL VSCALE(XM1, CM(L1), NNC, VUM)
17540= CALL MMULS(CM(LPHC), XMO, NNC, NNC, 1, XM1)
17550= RETURN
17560=C END SUBROUTINE CUPDAT
17570= END
17580= SUBROUTINE TUPDAT(PHI, BD, VX0, VX1, UO)
17590= COMMON/MAIN1/NDIM, NDIM1, COM1(1)
17600= COMMON/NDIMT/NNT, NRT, NMT, NWT
17610= DIMENSION PHI(1), BD(1), VX0(1), VX1(1), UO(1)

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17620=      NDIM=NNT
17630=      NDIM1=NDIM+1
17640=      CALL FTMTX(VX1,VX0,NNT,1)
17650=      CALL FMMUL(BD,U0,NNT,NRT,1,VX1)
17660=      CALL MMULS(PHI,VX0,NNT,NNT,1,VX1)
17670=      RETURN
17680=C END SUBROUTINE TUPDAT
17690=      END
17700=      SUBROUTINE XFDT(V,X,LDCGT)
17710=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPNWD,NNPR
17720=      COMMON/NDIMT/NNT,NRT,NMT,NWT
17730=      COMMON/LOCT/LPHT,LBDT,LQDT,LHT,LRT,LTDT,LTNT
17740=      COMMON/TRUMTX/NVTM,TM(1)
17750=      DIMENSION V(1),X(1)
17760=      CALL FMMUL(TM(LTDT),V,NND,NNT,1,X)
17770=      IF(LDCGT.EQ.0) RETURN
17780=      CALL FMMUL(TM(LTNT),V,NDD,NNT,1,X(NND+1))
17790=      RETURN
17800=C END SUBROUTINE XFDT
17810=      END
17820=      SUBROUTINE URPI(RGC1,RGC2,C,DY,X0,X1,U0,U1)
17830=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
17840=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPNWD,NNPR
17850=      DIMENSION RGC1(1),RGC2(1),C(1),DY(1),X0(1),X1(1),U0(1),U1(1)
17860=      CALL YDSN(X0,U0,C,DY,0,U1)
17870= 10    CALL VSCALE(U1,U1,NRD,-1.)
17880=      CALL MMULS(RGC2,U1,NRD,NRD,1,U0)
17890=      DO 12 I=1,NPLD
17900= 12    XO(I)=X0(I)-X1(I)
17910=      CALL FMMUL(RGC1,X0,NRD,NND,1,U1)
17920=      CALL VADD(NRD,1.,U1,U0)
17930=      RETURN
17940=C END SUBROUTINE URPI
17950=      END

17960=      SUBROUTINE UCGT(U0,U1,XM0,XM1,DDIF,ZM1,IUM,VUM,IT)
17970=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
17980=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPNWD,NNPR
17990=      COMMON/NDIMC/NNC,NRC,NPC
18000=      COMMON/LOCC/LPHC,LBDC,LCC,LDC
18010=      COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
18020=      COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
18030=      COMMON/CREGPI/NVRPI,RPI(1)
18040=      COMMON/LCGT/LA11,LA13,LA21,LA23,LA12,LA22,LELA11,LELA12,LELA13
18050=      COMMON/CCGT/NVCGT,CGT(1)
18060=      DIMENSION U0(1),U1(1),XM0(1),XM1(1),DDIF(1),ZM1(1)
18070=      CALL YCMD(XM0,IUM,VUM,CM(LCC),CM(LDC),U0)
18080=      IF(IT.GT.1) GO TO 10
18090=      I=LELA12+LADDR(NPD,1,IUM)-1
18100=      CALL MADD1(NPD,1,U1,CGT(I),U1,VUM)
18110= 10    CALL MMULS(RPI(LGC2),U0,NDIM,NDIM,1,U1)
18120=      DO 12 I=1,NNC
18130= 12    XM0(I)=XM1(I)-XM0(I)
18140=      CALL FMMUL(CGT(LELA11),XM0,NPD,NNC,1,U0)
18150=      CALL VADD(NDIM,1.,U1,U0)

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18160=      IF(NDD.EQ.0) RETURN
18170=      DO 14 I=1,NDD
18180= 14    DDIF(I)=-DDIF(I)
18190=      CALL MMULS(CGT(LELA13),DDIF,NPD,NDD,1,U1)
18200=      RETURN
18210=C END  SUBROUTINE UCGT
18220=      END
18230=      SUBROUTINE YDSN(X,U,C,D,LDCGT,Y)
18240=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
18250=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
18260=      COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
18270=      COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
18280=      DIMENSION X(1),U(1),C(1),D(1),Y(1)
18290=      NDIM=NPD
18300=      NDIM1=NDIM+1
18310=      CALL FMMUL(C,X,NPD,NND,1,Y)
18320=      IF(NODY.EQ.1) GO TO 10
18330=      CALL MMULS(D,U,NPD,NRD,1,Y)
18340= 10    IF((LDCGT.EQ.0).OR.(NOEY.EQ.1)) RETURN
18350=      CALL MMULS(DM(LEY),X(NND+1),NPD,NDD,1,Y)
18360=      RETURN
18370=C END  SUBROUTINE YDSN
18380=      END
18390=      SUBROUTINE YCMD(X,IU,VU,C,D,Y)
18400=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
18410=      COMMON/NDIMC/NNC,NRC,NPC
18420=      COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
18430=      DIMENSION X(1),C(1),D(1),Y(1)
18440=      NDIM=NPC
18450=      NDIM1=NDIM+1
18460=      CALL FMMUL(C,X,NPC,NNC,1,Y)
18470=      IF(NODC.EQ.1) RETURN
18480=      L1=LADDR(NPC,1,IU)
18490=      CALL MADD1(NPC,1,Y,D(L1),Y,VU)
18500=      RETURN
18510=C END  SUBROUTINE YCMD
18520=      END
18530=      SUBROUTINE FLTRK(IFLTR)
18540=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
18550=      COMMON/MAIN2/COM2(1)
18560=      COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
18570=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
18580=      COMMON/SYSMTX/NVSM,SM(1)
18590=      COMMON/ZMTX1/NVZM,ZM1(1)
18600=      COMMON/ZMTX2/ZM2(1)
18610=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
18620=      COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
18630=      COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
18640=      COMMON/LKF/LEADSN,LFLTRK,LFCOV
18650=      COMMON/CKF/NVFLT,FLT(1)
18660=      IF(NWPND.GT.0) GO TO 1
18670=      WRITE(KTERM,108)
18680= 108    FORMAT("ONO DRIVING NOISES - - FILTER DESIGN ABORT")
18690=      RETURN
18700= 1    IF(NMD.GT.0) GO TO 2

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18710= WRITE(KTERM,109)
18720= 109 FORMAT("ONO MEASUREMENTS - - FILTER DESIGN ABORT")
18730= RETURN
18740= 2 WRITE(KLIST,110)
18750= 110 FORMAT(////11X,5(" # "), "FILTER DESIGN",5(" #")////)
18760= NSIZE=NPLD*(1+NPLD+NMD)
18770= IF(NSIZE.LE.NVFLT) GO TO 3
18780= WRITE 101,NSIZE
18790= 101 FORMAT("OINSUFFICIENT MEMORY /CKF/, NEED: ",I4)
18800= LABORT=NSIZE
18810= RETURN
18820= 3 NDIM=NPLD
18830= NDIM1=NDIM+1
18840= 5 IF(NWD.EQ.0) GO TO 12
18850= IF(IFLTR.LE.0) GO TO 6
18860= WRITE 105,NWD
18870= 105 FORMAT(" ENTER STATE NOISE STRENGTHS: ",I2)
18880= CALL RQWGT(DM(LQ),NWD,0)
18890= 6 CALL DVCTOR(NWD,DM(LQ),ZM1)
18900= CALL MATLST(ZM1,NWD,1,"Q",KTERM)
18910= 10 CALL MATLST(DM(LQ),NWD,NWD,"Q",KLIST)
18920= 12 IF(NWDD.EQ.0) GO TO 18
18930= IF(IFLTR.LE.0) GO TO 13
18940= WRITE 106,NWDD
18950= 106 FORMAT(" ENTER DISTURBANCE NOISE STRENGTHS: ",I2)
18960= CALL RQWGT(DM(LQN),NWDD,0)
18970= 13 CALL DVCTOR(NWDD,DM(LQN),ZM1)
18980= CALL MATLST(ZM1,NWDD,1,"QN",KTERM)
18990= 15 CALL MATLST(DM(LQN),NWDD,NWDD,"QN",KLIST)
19000= 18 CALL QDSCRT(DM(LQ),DM(LQN),ZM1,ZM2)
19010= IF(IFLTR.LE.0) GO TO 19
19020= WRITE 107,NMD
19030= 107 FORMAT(" ENTER MEASUREMENT NOISE STRENGTHS: ",I2)
19040= CALL RQWGT(DM(LR),NMD,0)
19050= 19 CALL DVCTOR(NMD,DM(LR),ZM1)
19060= CALL MATLST(ZM1,NMD,1,"R",KTERM)
19070= 20 CALL MATLST(DM(LR),NMD,NMD,"R",KLIST)
19080= 25 CALL TFRMTX(DM(LHP),SM,NMD,NDIM,2)
19090= CALL TRANS2(NMD,NDIM,SM,ZM1)
19100= LFCOV=LFLTRK+NDIM*NMD
19110= CALL DVCTOR(NMD,DM(LR),FLT(LFCOV))
19120= CALL KFLTR(NDIM,NMD,FLT,ZM1,DM(LQD),FLT(LFCOV),ZM2,
19130= 1 FLT(LFLTRK),SM)
19140= CALL TFRMTX(SM,COM2,NDIM,NDIM,2)
19150= IA=1
19160= DO 30 I=1,NPLD
19170= FLT(LFCOV-1+I)=SQRT(ZM2(IA))
19180= 30 IA=IA+NDIM1
19190= CALL MATLST(FLT(LFLTRK),NDIM,NMD,"KF",KLIST)
19200= CALL MATLST(FLT(LFLTRK),NDIM,NMD,"KF",KTERM)
19210= IFLTR=1
19220= LFLKF=1
19230= 111 FORMAT(A3)
19240= RETURN
19250=C END SUBROUTINE FLTRK

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19260=      END
19270=      SUBROUTINE FEVAL
19280=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
19290=      COMMON/MAIN2/COM2(1)
19300=      COMMON/INO/KIN,KOUT,KPUNCH
19310=      COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
19320=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
19330=      COMMON/SYSMTX/NVSM,SM(1)
19340=      COMMON/ZMTX1/NVZM,ZM1(1)
19350=      COMMON/ZMTX2/ZM2(1)
19360=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
19370=      COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
19380=      COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
19390=      COMMON/NDIMT/NNT,NRT,NMT,NWT
19400=      COMMON/LOCT/LPHT,LBDT,LQDT,LHT,LRT,LTDT,LTNT
19410=      COMMON/TRUMTX/NVTM,TM(1)
19420=      COMMON/LKF/LEADSN,LFLTRK,LFCOV
19430=      COMMON/CKF/NVFLT,FLT(1)
19440=      DIMENSION ITITLE(5),NS(3),NVPLT(2)
19450=      IF(NWT.GT.0) GO TO 1
19460=      WRITE(KTERM,108)
19470= 108  FORMAT(*ONO TRUTH MODEL DRIVING NOISE - - FILTER EVALUATION ABORTE
19480=      1D*)
19490=      RETURN
19500= 1    WRITE(KLIST,110)
19510= 110  FORMAT(////11X,5(* *),"FILTER EVALUATION",5(" *")////)
19520=      CALL FMMUL(COM2,FLT(LEADSN),NPLD,NPLD,NPLD,SM)
19530=      CALL POLES(SM,NPLD,5,ZM1,ZM2)
19540=      NA=NNT+NPLD
19550=      NSIZE=NA*NA
19560=      IF(NSIZE.LE.NVSM) GO TO 8
19570=      WRITE 101,NSIZE
19580= 101  FORMAT(*OINSUFFICIENT MEMORY /SYSMTX/, NEED: ",I4)
19590=      GO TO 9
19600= 8    IF(NSIZE.LE.NVZM) GO TO 10
19610=      WRITE 103,NSIZE
19620= 103  FORMAT(*OINSUFFICIENT MEMORY /ZMTX1/,/ZMTX2/, NEED: ",I4)
19630= 9    LABORT=NSIZE
19640=      RETURN
19650= 10   CALL ZPART(SM,1,NSIZE,1)
19660=      NDIM=NPLD
19670=      NDIM1=NDIM+1
19680=      CALL TFRMTX(TM(LRT),ZM1,NMD,NMD,2)
19690=      CALL MAT3(NPLD,NMD,FLT(LFLTRK),ZM1,COM1)
19700=      NVOUT=2*NPLD+1
19710=      REWIND KPLOT
19720=      CALL DACOV(SM,FLT(LFCOV),ZM1,ZM2,NA,NVOUT,0.)
19730=      DO 20 IT=1,50
19740=      TIME=TSAMP*FLOAT(IT)
19750=      CALL ACOVUD(SM,TM(LQDT),COM1,TM(LPHT),FLT(LEADSN),
19760=      1 COM2,ZM1,ZM2)
19770=      CALL DACOV(SM,FLT(LFCOV),ZM1,ZM2,NA,NVOUT,TIME)
19780= 20   CONTINUE
19790=      ENDFILE KPLOT
19800=      WRITE(KTERM,104)

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19810= READ(KIN,102) ITITLE
19820= DO 50 I=1,NPLD
19830= REWIND KPLOT
19840= NS(1)=1
19850= NS(2)=52
19860= NS(3)=103
19870= NVPLOT(1)=I+I-1
19880= NVPLOT(2)=I+I
19890= DO 40 J=1,51
19900= CALL RPLOTF(ZM1,NVOUT,IERR)
19910= IF(IERR.EQ.1) GO TO 50
19920= CALL STRPLT(SM,ZM1,NS,NVPLOT,2,NVOUT)
19930= DO 35 K=1,3
19940= 35 NS(K)=NS(K)+1
19950= 40 CONTINUE
19960= WRITE 107,ZM1(NVPLOT(1)),I,ZM1(NVPLOT(2))
19970= 107 FORMAT("OFINAL RMS ERRORS : TRUE = ",1PE15.7/" (STATE",I3,
19980= 1 ")",4X,"COMPUTED = ",1PE15.7)
19990= CALL PLOTLP(51,2,SM,-1,1,0,KLIST,ITITLE)
20000= WRITE(KLIST,106) I
20010= 106 FORMAT("0 STATE : ",I2//4X,"SYMBOL 1 : TRUE ERROR"/
20020= 1 4X,"SYMBOL 2 : COMPUTED ERROR "/)
20030= 50 CONTINUE
20040= RETURN
20050= 104 FORMAT(" +",10("-")," ENTER TITLE IN GIVEN FIELD ",10("-"),"+"/)
20060= 102 FORMAT(5A10)
20070=C END SUBROUTINE FEVAL
20080= END
20090= SUBROUTINE DACOV(PCA,PC,ZM1,ZM2,NA,NVOUT,TIME)
20100= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
20110= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
20120= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
20130= COMMON/NDIMT/NNT,NRT,NMT,NWT
20140= COMMON/LOCT/LPHT,LBDT,LQDT,LHT,LRT,LTDT,LTNT
20150= COMMON/TRUMTX/NVTM,TM(1)
20160= DIMENSION PCA(1),PC(1),ZM1(1),ZM2(1)
20170= NDIM=NA
20180= NDIM1=NDIM+1
20190= CALL TFRMTX(TM(LTDT),ZM1,NND,NNT,2)
20200= IF(NDD.LT.1) GO TO 5
20210= IA=LADDR(NA,NND+1,1)
20220= CALL TFRMTX(TM(LTNT),ZM1(IA),NDD,NNT,2)
20230= 5 CALL MSCALE(ZM1,ZM1,NPLD,NNT,-1.)
20240= IA=LADDR(NA,1,NNT+1)
20250= CALL IDNT(NPLD,ZM1(IA),1.)
20260= CALL MAT3(NPLD,NA,ZM1,PCA,ZM2)
20270= WRITE(KLIST,101) TIME
20280= 101 FORMAT("0'TRUE' DESIGN ERROR COVARIANCE AT TIME = ",F6.4)
20290= CALL MATIO(ZM2,NPLD,NPLD,3)
20300= IA=1
20310= DO 10 I=1,NPLD
20320= NS=I+I
20330= ZM1(NS-1)=SQRT(ZM2(IA))
20340= ZM1(NS)=PC(I)
20350= 10 IA=IA+NDIM1

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20360=      ZM1(NVOUT)=TIME
20370=      CALL WPLOTF(ZM1,NVOUT)
20380=      RETURN
20390=C END SUBROUTINE DACOV
20400=      END
20410=      SUBROUTINE ACOVUD(PC,QD,RKRKT,PHIT,PHI,RIMKH,ZM1,ZM2)
20420=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)
20430=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPWWD,NNPR
20440=      COMMON/NDIMT/NNT,NRT,NMT,NWT
20450=      COMMON/LOCT/LPHT,LBDT,LQDT,LHT,LRT,LTDT,LTNT
20460=      COMMON/TRUMTX/NVTM,TM(1)
20470=      COMMON/LKF/LEADSN,LFLTRK,LFCOV
20480=      COMMON/CKF/NVFLT,FLT(1)
20490=      DIMENSION PC(1),QD(1),RKRKT(1),PHIT(1),PHI(1),RIMKH(1),
20500=      1 ZM1(1),ZM2(1)
20510=      L1=LADDR(NDIM,1,NNT+1)
20520=      CALL ZPART(ZM2(L1),NNT,NPLD,NDIM)
20530=      CALL TFRMTX(PHIT,ZM2,NNT,NNT,2)
20540=      L1=LADDR(NDIM,NNT+1,NNT+1)
20550=      CALL TFRMTX(PHI,ZM2(L1),NPLD,NPLD,2)
20560=      L2=LADDR(NDIM,NNT+1,1)
20570=      CALL ZPART(ZM2(L2),NPLD,NNT,NDIM)
20580=      CALL MAT3(NDIM,NDIM,ZM2,PC,ZM1)
20590=      CALL FPADD(ZM1,NDIM,QD,NNT,NNT,1,PC)
20600=      CALL IDNT(NNT,ZM2,1.)
20610=      CALL FMMUL(FLT(LFLTRK),TM(LHT),NPLD,NMD,NNT,ZM1)
20620=      CALL TFRMTX(ZM1,ZM2(L2),NPLD,NNT,2)
20630=      CALL TFRMTX(RIMKH,ZM2(L1),NPLD,NPLD,2)
20640=      CALL MAT3(NDIM,NDIM,ZM2,PC,ZM1)
20650=      CALL FPADD(ZM1,NDIM,RKRKT,NPLD,NPLD,L1,PC)
20660=      RETURN
20670=C END SUBROUTINE ACOVUD
20680=      END
20690=      SUBROUTINE FPADD(X,NX,Y,NRY,NCY,LADDR,Z)
20700=      DIMENSION X(1),Z(1),Y(NRY,NCY)
20710=      CALL FTMTX(X,Z,NX,NX)
20720=      LAM1=LADDR-1
20730=      DO 10 I=1,NCY
20740=      LA1=LAM1+NX*(I-1)
20750=      DO 10 J=1,NRY
20760=      LA1=LA1+1
20770= 10 Z(LA1)=Z(LA1)+Y(J,I)
20780=      RETURN
20790=C END SUBROUTINE FPADD
20800=      END
20810=      SUBROUTINE RSYS(A,L,ND,ITYPE,IWRT)
20820=      COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
20830=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
20840=      COMMON/SYSMTX/NVSM,SM(1)
20850=      COMMON/AMC/AM(1)
20860=      COMMON/BDG/BD(1)
20870=      DIMENSION A(1),L(1),ND(1),NAD(14,2),IND(7,3),NTYP(2,3),NTITLE(3),
20880=      1 NMAT(14,3)
20890=      DATA NTYP/7,14,3,4,4,8/
20900=      DATA NO/1HN/

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20910= DATA IND/1HN,1HR,1HP,1HM,1HD,1HW,2HWD,2HNM,2HRM,2HPM,4(1H ),
20920= 1 2HNT,2HRT,2HMT,2HWT,1H ,1H ,1H /
20930= DATA NTITLE/6HDESIGN,7HCOMMAND,5HTRUTH/
20940= DATA NMAT/1HA,1HB,2HEX,1HG,1HQ,1HC,2HDY,2HEY,1HH,2HHN,1HR,2HAN,
20950= 1 2HGN,2HQN,2HAM,2HBM,2HCM,2HDM,10(1H ),2HAT,2HBT,2HGT,2HQT,2HHT,
20960= 2 2HRT,3HTDT,3HTNT,6(1H )/
20970= NDM=NTYP(1,ITYPE)
20980= NAR=NTYP(2,ITYPE)
20990= NT=NTITLE(ITYPE)
21000= WRITE(KLIST,110) NT
21010= 110 FORMAT(////11X,5(" " ),A7," MODEL",5(" " )////)
21020= 5 WRITE 101,NT
21030= 101 FORMAT("OREAD ",A7," MODEL FROM 'DATA' FILE (Y OR N) >")
21040= READ 111,IANS
21050= IF(IANS.EQ.NO) GO TO 10
21060= IF=1
21070= CALL READFS(A,ND,ITYPE,IERR)
21080= IF(IERR.EQ.0) GO TO 201
21090= 10 WRITE 102,NT
21100= 102 FORMAT(" ENTER ",A7," MODEL FROM TERMINAL (Y OR N) >")
21110= READ 111,IANS
21120= IF(IANS.EQ.NO) GO TO 15
21130= IF=2
21140= DO 12 I=1,NDM
21150= WRITE 112,IND(I,ITYPE)
21160= 112 FORMAT(" ENTER ",A2," >")
21170= 12 READ*,ND(I)
21180= GO TO 201
21190= 15 IF=3
21200= IF(ITYPE-2) 16,17,18
21210= 16 CALL DSND(ND)
21220= GO TO 20
21230= 17 CALL CMDD(ND)
21240= GO TO 20
21250= 18 CALL TRTHD(ND)
21260= 20 IF(ND(1).GT.0) GO TO 201
21270= WRITE 114,NT
21280= 114 FORMAT("0",A7," MODEL SUBROUTINE NON-EXISTENT")
21290= GO TO 5
21300= 201 IF(ITYPE-2) 21,22,23
21310= 21 CALL DSNDM(ND,NAD)
21320= GO TO 25
21330= 22 CALL CMDDM(ND,NAD)
21340= GO TO 25
21350= 23 CALL TRTHDM(ND,NAD)
21360= 25 IF(LABORT.EQ.0) GO TO 26
21370= WRITE 103,NT,LABORT
21380= 103 FORMAT("OINSUFFICIENT MEMORY FOR ",A7," MODEL, NEED: ",I4)
21390= RETURN
21400= 26 L(1)=1
21410= DO 30 I=2,NAR
21420= 30 L(I)=L(I-1)+NAD(I-1,1)*NAD(I-1,2)
21430= NPNTS=L(NAR)+NAD(NAR,1)*NAD(NAR,2)-1
21440= IF(NPNTS.LE.NVSM) GO TO 34
21450= WRITE 104,NPNTS

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21460= 104  FORMAT("OINSUFFICIENT MEMORY /SYSMTX/, NEED: ",I4)
21470=      LABORT=NPNTS
21480=      RETURN
21490= 34   IF(IF-2) 75,35,50
21500= 35   IZ=1
21510=      DO 40 I=1,NAR
21520=      N1=NAD(I,1)
21530=      N2=NAD(I,2)
21540=      IF((N1.EQ.0).OR.(N2.EQ.0)) GO TO 40
21550=      WRITE 113,NMAT(I,ITYPE)
21560= 113  FORMAT("OENTER ",A3)
21570=      CALL ZMATIN(A(L(I)),N1,N2,IZ)
21580= 40   CONTINUE
21590=      GO TO 75
21600= 50   CALL ZPART(A,1,NPNTS,1)
21610=      IF(ITYPE-2) 55,60,65
21620= 55   CALL DSNM(A(L(1)),A(L(2)),A(L(3)),A(L(4)),A(L(5)),A(L(6)),A(L(7)),
21630= 1 A(L(8)),A(L(9)),A(L(10)),A(L(11)),A(L(12)),A(L(13)),A(L(14)))
21640=      GO TO 75
21650= 60   CALL CMDM(A(L(1)),A(L(2)),A(L(3)),A(L(4)))
21660=      GO TO 75
21670= 65   CALL TRTHM(A(L(1)),A(L(2)),A(L(3)),A(L(4)),A(L(5)),A(L(6)),
21680= 1 A(L(7)),A(L(8)))
21690= 75   IZ=0
21700= 77   WRITE 105
21710= 105  FORMAT("OMODIFY MATRIX ELEMENTS (Y OR N) >")
21720=      READ 111, IANS
21730=      IF(IANS.EQ.NO) GO TO 88
21740=      WRITE 106,(NMAT(I,ITYPE),I=1,NAR)
21750= 106  FORMAT(1X,14(2X,A3))
21760= 78   WRITE 107
21770= 107  FORMAT(" ENTER MATRIX NAME >")
21780=      READ 111, IANS
21790=      DO 80 I=1,NAR
21800=      IF(IANS.EQ.NMAT(I,ITYPE)) GO TO 81
21810= 80   CONTINUE
21820=      GO TO 78
21830= 81   WRITE 116
21840= 116  FORMAT(" LIST MATRIX TO TERMINAL (Y OR N) >")
21850=      READ 111, IANS
21860=      IF(IANS.EQ.NO) GO TO 83
21870=      CALL MATLST(A(L(I)),NAD(I,1),NAD(I,2),NMAT(I,ITYPE),KTERM)
21880= 83   CALL ZMATIN(A(L(I)),NAD(I,1),NAD(I,2),IZ)
21890=      GO TO 77
21900= 88   IF(ITYPE.EQ.2)CALL FTMTX(A(L(1)),AM,ND(1),ND(1))
21910=      IF(ITYPE.EQ.1)CALL FTMTX(A(L(2)),BD,ND(1),ND(2))
21920=      IF(IWRT) 95,92,93
21930= 92   IWRT=1
21940= 93   WRITE 115,NT
21950= 115  FORMAT("OWRITE ",A7," MODEL TO 'SAVE' FILE (Y OR N) >")
21960=      READ 111, IANS
21970=      IF(IANS.EQ.NO) GO TO 95
21980=      CALL WFILED(ITYPE,NPNTS,ND,A)
21990=      IWRT=-1
22000=      WRITE 109,NT

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22010= 109  FORMAT(6X,A7," MODEL WRITTEN TO 'SAVE' FILE")
22020= 95   DO 100 I=1,NAR
22030=      N1=NAD(I,1)
22040=      N2=NAD(I,2)
22050=      IF((N1.EQ.0).OR.(N2.EQ.0)) GO TO 100
22060=      CALL MATLST(A(L(I)),N1,N2,NMAT(I,ITYPE),KLIST)
22070= 100  CONTINUE
22080= 111  FORMAT(A3)
22090=      RETURN
22100=C END  SUBROUTINE RSYS
22110=      END
22120=      SUBROUTINE DSND(ND)
22130=      DIMENSION ND(1)
22140=      ND(1)=0
22150=      RETURN
22160=C END  SUBROUTINE DSND
22170=      END
22180=      SUBROUTINE CMDD(ND)
22190=      DIMENSION ND(1)
22200=      ND(1)=0
22210=      RETURN
22220=C END  SUBROUTINE CMDD
22230=      END
22240=      SUBROUTINE TRTHD(ND)
22250=      DIMENSION ND(1)
22260=      ND(1)=0
22270=      RETURN
22280=C END  SUBROUTINE TRTHD
22290=      END
22300=      SUBROUTINE DSNM(A,B,EX,G,Q,C,DY,EY,H,HD,R,AD,GD,QD)
22310=      RETURN
22320=C END  SUBROUTINE DSNM
22330=      END
22340=      SUBROUTINE CMDM(AM,BM,CM,DM)
22350=      RETURN
22360=C END  SUBROUTINE CMDM
22370=      END
22380=      SUBROUTINE TRTHM(AT,BT,GT,QT,HT,RT,TDT,TNT)
22390=      RETURN
22400=C END  SUBROUTINE TRTHM
22410=      END
22420=      SUBROUTINE DSNDM(ND,NAD)
22430=      COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
22440=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
22450=      COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
22460=      DIMENSION ND(1),NAD(14,2)
22470=      NND=ND(1)
22480=      NRD=ND(2)
22490=      NPD=ND(3)
22500=      NMD=ND(4)
22510=      NDD=ND(5)
22520=      NWD=ND(6)
22530=      NWDD=ND(7)
22540=      NPLD=NND+NDD
22550=      NWPND=NWD+NWDD

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22560=      NNPR=NND+NRD
22570=      NAD(1,1)=NND
22580=      NAD(2,1)=NND
22590=      NAD(3,1)=NND
22600=      NAD(4,1)=NND
22610=      NAD(5,1)=NWD
22620=      NAD(6,1)=NPD
22630=      NAD(7,1)=NPD
22640=      NAD(8,1)=NPD
22650=      NAD(9,1)=NMD
22660=      NAD(10,1)=NMD
22670=      NAD(11,1)=NMD
22680=      NAD(12,1)=NDD
22690=      NAD(13,1)=NDD
22700=      NAD(14,1)=NWDD
22710=      NAD(1,2)=NND
22720=      NAD(2,2)=NRD
22730=      NAD(3,2)=NDD
22740=      NAD(4,2)=NWD
22750=      NAD(5,2)=NWD
22760=      NAD(6,2)=NND
22770=      NAD(7,2)=NRD
22780=      NAD(8,2)=NDD
22790=      NAD(9,2)=NND
22800=      NAD(10,2)=NDD
22810=      NAD(11,2)=NMD
22820=      NAD(12,2)=NDD
22830=      NAD(13,2)=NWDD
22840=      NAD(14,2)=NWDD
22850=      NSIZE=NPLD*(2*NPLD+NND+NMD+NPD+NWPND)+NRD*(NND+NPD)+
22860=      1 NDD*NDD+NMD*NMD+NWD*NWD+NWDD*NWDD
22870=      IF(NSIZE.GT.NVDM) LABORT=NSIZE
22880=      RETURN
22890=C END SUBROUTINE DSNDM
22900=      END
22910=      SUBROUTINE CMDDM(ND,NAD)
22920=      COMMON/NDIMC/NNC,NRC,NPC
22930=      COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
22940=      COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
22950=      DIMENSION ND(1),NAD(14,2)
22960=      NNC=ND(1)
22970=      NRC=ND(2)
22980=      NPC=ND(3)
22990=      NAD(1,1)=NNC
23000=      NAD(2,1)=NNC
23010=      NAD(3,1)=NPC
23020=      NAD(4,1)=NPC
23030=      NAD(1,2)=NNC
23040=      NAD(2,2)=NRC
23050=      NAD(3,2)=NNC
23060=      NAD(4,2)=NRC
23070=      NSIZE=NNC*(NNC+NRC+NPC)+NPC*NRC
23080=      IF(NSIZE.GT.NVCM) LABORT=NSIZE
23090=      RETURN
23100=C END SUBROUTINE CMDDM

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23110=      END
23120=      SUBROUTINE TRTHDM(ND,NAD)
23130=      COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
23140=      COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPNWD,NNPR
23150=      COMMON/NDIMT/NNT,NRT,NMT,NWT
23160=      COMMON/TRUMTX/NVTM,TM(1)
23170=      DIMENSION ND(1),NAD(14,2)
23180=      NNT=ND(1)
23190=      NRT=ND(2)
23200=      NMT=ND(3)
23210=      NWT=ND(4)
23220=      NAD(1,1)=NNT
23230=      NAD(2,1)=NNT
23240=      NAD(3,1)=NNT
23250=      NAD(4,1)=NWT
23260=      NAD(5,1)=NMT
23270=      NAD(6,1)=NMT
23280=      NAD(7,1)=NND
23290=      NAD(8,1)=NDD
23300=      NAD(1,2)=NNT
23310=      NAD(2,2)=NRT
23320=      NAD(3,2)=NWT
23330=      NAD(4,2)=NWT
23340=      NAD(5,2)=NNT
23350=      NAD(6,2)=NMT
23360=      NAD(7,2)=NNT
23370=      NAD(8,2)=NNT
23380=      NSIZE=NNT*(2*NNT+NMD+NRD+NPLD)+NMD*NMD
23390=      IF(NSIZE.GT.NVTM) LABORT=NSIZE
23400=      RETURN
23410=C END SUBROUTINE TRTHDM
23420=      END
23430=      SUBROUTINE ZMATIN(A,NR,NC,IZ)
23440=      DIMENSION A(NR,NC)
23450=      IF(IZ) 10,10,1
23460= 1      DO 5 I=1,NR
23470=      DO 5 J=1,NC
23480= 5      A(I,J)=0.
23490= 10     WRITE 101,NR,NC
23500= 15     READ*,I,J,V
23510=      IF(I.EQ.0) RETURN
23520=      IF((I.LE.NR).AND.(J.LE.NC)) GO TO 20
23530=      WRITE 102
23540=      GO TO 10
23550= 20     A(I,J)=V
23560=      IF(IZ.LT.0) A(J,I)=V
23570=      GO TO 15
23580= 101    FORMAT(" ENTER I,J AND M(I,J)--(0/ WHEN COMPLETE) : "I2," BY "I2,
23590= 1 " >")
23600= 102    FORMAT(" ERROR IN ARRAY INDEX")
23610=C END SUBROUTINE ZMATIN
23620=      END
23630=      SUBROUTINE WFILED(NT,NP,ND,A)
23640=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
23650=      DIMENSION ND(15),A(NP)

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23660= DATA IEOI/-1/
23670= BACKSPACE KSAVE
23680= WRITE(KSAVE,101) NT,NP
23690= WRITE(KSAVE,101) (ND(I),I=1,15)
23700= WRITE(KSAVE,102) (A(I),I=1,NP)
23710= WRITE(KSAVE,101) IEOI,NP
23720= RETURN
23730= 101 FORMAT(2I4)
23740= 102 FORMAT(E20.10)
23750=C END SUBROUTINE WFILED
23760= END
23770= SUBROUTINE READFS(A,ND,NT,IERR)
23780= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
23790= DIMENSION A(1),ND(15)
23800= DATA IEOI/-1/
23810= REWIND KDATA
23820= 5 READ(KDATA,102) IT,NP
23830= IF(IT.NE.IEOI) GO TO 10
23840= WRITE 101
23850= IERR=1
23860= RETURN
23870= 10 CALL FARRAY(A,ND,NP)
23880= IF(IT.NE.NT) GO TO 5
23890= IERR=0
23900= 101 FORMAT(*ODATA NOT IN 'DATA' FILE . . .")
23910= 102 FORMAT(2I4)
23920= RETURN
23930=C END SUBROUTINE READFS
23940= END
23950= SUBROUTINE FARRAY(A,ND,NP)
23960= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
23970= DIMENSION A(NP),ND(15)
23980= READ(KDATA,101) (ND(I),I=1,15)
23990= READ(KDATA,102) (A(I),I=1,NP)
24000= RETURN
24010= 101 FORMAT(2I4)
24020= 102 FORMAT(E20.10)
24030=C END SUBROUTINE FARRAY
24040= END
24050= SUBROUTINE TFRMTX(X1,X2,NR,NC,ITX)
24060= COMMON/MAIN1/NDIM
24070= DIMENSION X1(1),X2(1)
24080= IF(ITX.EQ.2) GO TO 20
24090= J=NC*NDIM
24100= KK=0
24110= DO 10 I=1,J,NDIM
24120= L=I+NR-1
24130= DO 10 JJ=I,L
24140= KK=KK+1
24150= 10 X1(KK)=X2(JJ)
24160= RETURN
24170= 20 KK=NR*NC+1
24180= DO 30 I=1,NC
24190= L=(NC-I)*NDIM+1
24200= DO 30 J=1,NR

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24210=      KK=KK-1
24220=      JJ=L+NR-J
24230= 30   X2(JJ)=X1(KK)
24240=      RETURN
24250=      END
24260=      SUBROUTINE MATLST(A,NR,NC,NT,KDEV)
24270=      DIMENSION A(NR,NC)
24280=      WRITE(KDEV,101) NT
24290=      DO 10 I=1,NR
24300= 10   WRITE(KDEV,102) (A(I,J),J=1,NC)
24310= 101  FORMAT(1H0,A3," MATRIX"/)
24320= 102  FORMAT(1X1P10G13.4)
24330=      RETURN
24340=C END SUBROUTINE MATLST
24350=      END
24360=      SUBROUTINE NDSCRT(A,N,NTERMS)
24370=      COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
24380=      DIMENSION A(1)
24390=      NTERMS=IFIX(6.+3.*TSAMP*XNORM(N,A))
24400=      IF(NTERMS.GT.30) NTERMS=30
24410=      RETURN
24420=C END SUBROUTINE NDSCRT
24430=      END
24440=      SUBROUTINE RQWGTS(W,ND,NP)
24450=      DIMENSION W(1)
24460= 10   WRITE 101
24470= 101  FORMAT(" ENTER I AND QW(I,I)--(0/ WHEN COMPLETE) >")
24480= 15   READ*,I,V
24490=      IF(I.EQ.0) RETURN
24500=      IF(I.LE.ND) GO TO 20
24510=      WRITE 102
24520= 102  FORMAT(" ERROR IN ARRAY INDEX")
24530=      GO TO 10
24540= 20   IF(V) 25,30,40
24550= 25   WRITE 103
24560= 103  FORMAT(" ELEMENTS MUST BE NON-NEGATIVE")
24570=      GO TO 15
24580= 30   IF(NP) 35,40,35
24590= 35   WRITE 104
24600= 104  FORMAT(" ELEMENTS MUST BE POSITIVE")
24610=      GO TO 15
24620= 40   L1=LADDR(ND,I,I)
24630=      W(L1)=V
24640=      GO TO 15
24650=C END SUBROUTINE RQWGTS
24660=      END
24670=      SUBROUTINE DVCTOR(N,A,V)
24680=      DIMENSION A(1),V(1)
24690=      NP1=N+1
24700=      N2=N*N
24710=      J=0
24720=      DO 10 I=1,N2,NP1
24730=      J=J+1
24740= 10   V(J)=A(I)
24750=      RETURN

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24760=C END SUBROUTINE DVCTOR
24770= END
24780= SUBROUTINE POLES(A,N,ITYPE,ZM1,ZM2)
24790= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
24800= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
24810= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
24820= DIMENSION NTYP(5),A(1),ZM1(1),ZM2(1)
24830= DATA NTYP/6HDESIGN,7HCOMMAND,5HTRUTH,5HREGPI,6HFILTER/
24840= NDS=NDIM
24850= NDIM=N
24860= NDIM1=NDIM+1
24870= CALL EIGEN(NDIM,A,ZM1,ZM1(NDIM1),ZM2,0)
24880= IF(ITYPE.LT.4) GO TO 10
24890= CALL MAPOLE(N,ZM1,ZM1(NDIM1),TSAMP)
24900= 10 WRITE(KLIST,102) NTYP(ITYPE)
24910= WRITE(KTERM,102) NTYP(ITYPE)
24920= WRITE(KLIST,101) (ZM1(I),ZM1(NDIM+I),I=1,N)
24930= WRITE(KTERM,101) (ZM1(I),ZM1(NDIM+I),I=1,N)
24940= NDIM=NDS
24950= NDIM1=NDIM+1
24960= 101 FORMAT(6X,1PE15.7," +J(",1PE15.7,")")
24970= 102 FORMAT("OPOLES OF ",A7," MATRIX"/)
24980= RETURN
24990=C END SUBROUTINE POLES
25000= END
25010= SUBROUTINE MAPOLE(N,ZR,ZI,T)
25020= DIMENSION ZR(1),ZI(1)
25030= RT=1./T
25040= DO 10 I=1,N
25050= ZM=SQRT(ZR(I)**2+ZI(I)**2)
25060= SIGMA=RT*ALOG(ZM)
25070= ZI(I)=RT*ATAN2(ZI(I),ZR(I))
25080= 10 ZR(I)=SIGMA
25090= RETURN
25100=C END SUBROUTINE MAPOLE
25110= END
25120= FUNCTION LADDR(NR,I,J)
25130= LADDR=I+NR*(J-1)
25140= RETURN
25150=C END FUNCTION LADDR
25160= END
25170= SUBROUTINE FTMTX(X,Y,NR,NC)
25180= DIMENSION X(1),Y(1)
25190= NE=NR*NC
25200= DO 10 I=1,NE
25210= 10 Y(I)=X(I)
25220= RETURN
25230=C END SUBROUTINE FTMTX
25240= END

25250= SUBROUTINE FMMUL(X,Y,NR1,NC1,NC2,Z)
25260= DIMENSION X(NR1,NC1),Y(NC1,NC2),Z(NR1,NC2)
25270= DOUBLE PRECISION TD
25280= DO 10 I=1,NR1
25290= DO 10 J=1,NC2

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25300=      TD=0.D00
25310=      DO 5 K=1,NC1
25320= 5    TD=TD+X(I,K)*Y(K,J)
25330= 10   Z(I,J)=TD
25340=      RETURN
25350=C END SUBROUTINE FMMUL
25360=      END
25370=      SUBROUTINE FTMUL(X,Y,NR1,NC1,NC2,Z)
25380=      DIMENSION X(NR1,NC1),Y(NR1,NC2),Z(NC1,NC2)
25390=      DOUBLE PRECISION TD
25400=      DO 10 I=1,NC1
25410=      DO 10 J=1,NC2
25420=      TD=0.D00
25430=      DO 5 K=1,NR1
25440= 5    TD=TD+X(K,I)*Y(K,J)
25450= 10   Z(I,J)=TD
25460=      RETURN
25470=C END SUBROUTINE FTMUL
25480=      END
25490=      SUBROUTINE FMADD(X,Y,NR,NC,Z)
25500=      DIMENSION X(1),Y(1),Z(1)
25510=      NE=NR*NC
25520=      DO 10 I=1,NE
25530= 10   Z(I)=X(I)+Y(I)
25540=      RETURN
25550=C END SUBROUTINE FMADD
25560=      END
25570=      SUBROUTINE ZPART(A,NR,NC,ND)
25580=      DIMENSION A(1)
25590=      NE=NC*ND
25600=      DO 10 I=1,NR
25610=      DO 10 J=I,NE,ND
25620= 10   A(J)=0.
25630=      RETURN
25640=C END SUBROUTINE ZPART
25650=      END
25660=      SUBROUTINE SUBI(A,NR,ND)
25670=      DIMENSION A(1)
25680=      ND1=ND+1
25690=      NE=NR*ND
25700=      DO 10 I=1,NE,ND1
25710= 10   A(I)=A(I)-1.
25720=      RETURN
25730=C END SUBROUTINE SUBI
25740=      END
25750=      SUBROUTINE WPLOT(V,N)
25760=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
25770=      DIMENSION V(N)
25780=      WRITE(KPLOT,101) (V(I),I=1,N)
25790=      RETURN
25800= 101  FORMAT(E20.10)
25810=C END SUBROUTINE WPLOT
25820=      END
25830=      SUBROUTINE RPLOT(V,N,IERR)
25840=      COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM

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25850=      DIMENSION V(N)
25860=      READ(KPLOT,101) (V(I),I=1,N)
25870=      IF(EOF(KPLOT)) 5,10
25880= 5     IERR=1
25890=      RETURN
25900= 10    IERR=0
25910=      RETURN
25920= 101  FORMAT(E20.10)
25930=C END SUBROUTINE RPLOTF
25940=      END
25950=      SUBROUTINE STRPLT(A,V,NS,NV,NP,NVO)
25960=      DIMENSION A(1),NS(1),NV(1),V(1)
25970=      A(NS(1))=V(NVO)
25980=      DO 5 I=1,NP
25990= 5     A(NS(I+1))=V(NV(I))
26000=      RETURN
26010=C END SUBROUTINE STRPLT
26020=      END
26030=      SUBROUTINE PLOTLP(N,M,A,IPSC,ISCL,LPTERM,NDEV,ITITLE)
26040=C * * * * *
26050=C * N = NUMBER OF POINTS TO BE PLOTTED
26060=C * M = NUMBER OF OUTPUTS TO BE PLOTTED
26070=C * A = VECTOR OF SAMPLE POINTS FOR PLOTTING : DIMENSION = N*M
26080=C *     ELEMENTS 1 TO N ARE THE INDEPENDENT VARIABLE
26090=C *     ELEMENTS (N+1) TO 2*N, (2*N+1) TO 3*N, AND SO ON ARE
26100=C *     THE DEPENDENT VARIABLES--EACH VARIABLE IS IN CONSECUTIVE
26110=C *     STORAGE WITH CORRESPONDING SAMPLE POINTS FOR EACH
26120=C *     SEPARATED BY MULTIPLES OF N
26130=C * IPSC = -1 => SCALE ALL VARIABLES TOGETHER (1 PLOT)
26140=C *     = 0 => SCALE TOGETHER AND SEPARATELY (2 PLOTS)
26150=C *     = +1 => SCALE SEPARATELY (1 PLOT)
26160=C * ISCL = 0 => PLOT OVER EXACT RANGE OF VARIABLE
26170=C *     = 1 => PLOT USING EVEN SCALING
26180=C * LPTERM = 0 => PLOT IS TO TERMINAL (50 CHARACTERS WIDE)
26190=C *     = 1 => PLOT IS TO LINE PRINTER (100 CHARACTERS WIDE)
26200=C * NDEV = DEVICE NUMBER FOR PLOT OUTPUT
26210=C * ITITLE = VECTOR(DIMENSIONED 5) WITH 50 CHARACTER TITLE
26220=C * * * * *
26230=      DIMENSION YSCAL(6),YMIN(6),IBLNK(6),YPR(11),A(1)
26240=      INTEGER OUT(101),SYMBOL(6),BLANK,PLUS,GRID,ITITLE(5)
26250=      DATA BLANK,PLUS,COLON,SYMBOL/1H ,1H+,1H:,1H1,1H2,1H3,1H4,1H5,1H6/
26260= 1     FORMAT(1H )
26270= 2     FORMAT(1H1,11X,5A10/)
26280= 10    FORMAT(1H ,F11.2,6X,101A1)
26290= 12    FORMAT(11H0 SCALE ,A1,1X,11F10.4)
26300=      IPAPER=5*(1+LPTERM)
26310=      ISPAC=10*IPAPER
26320=      RISPAC=FLOAT(ISPAC)
26330=      ISPAC=ISPAC+1
26340=      IPRT1=IPAPER+1
26350=      RMIN=A(N+1)
26360=      RMAX=RMIN
26370= 25    DO 41 ISC=1,M
26380=      M1=ISC*N+1
26390=      YL=A(M1)

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26400=      YH=YL
26410=      M2=N*(ISC+1)
26420=      DO 40 J=M1,M2
26430=      IF(A(J).LT.YL) GO TO 30
26440=      IF(A(J).GT.YH) YH=A(J)
26450=      GO TO 40
26460= 30   YL=A(J)
26470= 40   CONTINUE
26480=      IF(YL.LT.RMIN)RMIN=YL
26490=      IF(YH.GT.RMAX) RMAX=YH
26500=      IF(IPSC.GE.0) CALL VARSCL(YL,YH,YSCAL(ISC),RISPAC,ISCL)
26510= 41   YMIN(ISC)=YL
26520=      IF(IPSC.LE.0)CALL VARSCL(RMIN,RMAX,SCAL,RISPAC,ISCL)
26530=      IC=2-IABS(IPSC)
26540=      DO 45 IX=1,ISPAC
26550= 45   OUT(IX)=BLANK
26560=      DO 100 ICO=1,IC
26570=      WRITE(NDEV,2) (ITITLE(I),I=1,5)
26580=      DO 60 I=1,N
26590=      XPR=A(I)
26600=      IF(MOD(I,10).EQ.0) GO TO 458
26610=      GRID=BLANK
26620=      GO TO 460
26630= 458  GRID=COLON
26640= 460  DO 461 IX=2,ISPAC,2
26650= 461  OUT(IX)=GRID
26660=      DO 46 IX=1,ISPAC,10
26670= 46   OUT(IX)=PLUS
26680=      DO 55 J=1,M
26690=      IL=I+J*N
26700=      IF(IPSC) 48,47,49
26710= 47   IPSCT=IPSC+ICO
26720=      IF(IPSCT.EQ.2) GO TO 49
26730= 48   JP=IFIX((A(IL)-RMIN)/SCAL)+1
26740=      GO TO 50
26750= 49   JP=IFIX((A(IL)-YMIN(J))/YSCAL(J))+1
26760= 50   OUT(JP)=SYMBOL(J)
26770= 55   IBLNK(J)=JP
26780=      WRITE(NDEV,10) XPR,(OUT(IX),IX=1,ISPAC)
26790=      DO 59 J=1,M
26800=      ITEMP=IBLNK(J)
26810= 59   OUT(ITEMP)=BLANK
26820= 60   CONTINUE
26830=      IF(IPSC) 68,67,72
26840= 67   IF(IPSCT.EQ.2) GO TO 72
26850= 68   YPR(1)=RMIN
26860=      DO 70 I=1,IPAPER
26870= 70   YPR(I+1)=YPR(I)+10.*SCAL
26880=      WRITE(NDEV,12) BLANK,(YPR(I),I=1,IPRT1)
26890=      GO TO 100
26900= 72   DO 76 ISC=1,M
26910=      YPR(1)=YMIN(ISC)
26920=      DO 74 I=1,IPAPER
26930= 74   YPR(I+1)=YPR(I)+10.*YSCAL(ISC)
26940= 76   WRITE(NDEV,12) SYMBOL(ISC),(YPR(IX),IX=1,IPRT1)

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26950= 100 WRITE(NDEV,1)
26960= RETURN
26970=C END SUBROUTINE PLOTLP
26980= END
26990= SUBROUTINE VARSCL(XMIN,XMAX,SCALE,RSPACE,ISCL)
27000= IF(XMAX.EQ.XMIN) XMIN=.9*XMIN-10.
27010= SCALE=XMAX-XMIN
27020= IF(ISCL.EQ.0) GO TO 25
27030= EXP=IFIX(100.+ALOG10(SCALE))-100.
27040= FACTOR=10.**(.9-EXP)
27050= XMINT=XMIN*FACTOR
27060= XMAXT=XMAX*FACTOR
27070= IF(XMAXT.GE.0.) XMAXT=XMAXT+.9
27080= IF(XMINT.LE.0.) XMINT=XMINT-.9
27090= XMINT=AIN(T, XMINT)
27100= ISCAL=XMAXT-XMINT
27110= IF(MOD(ISCAL,5).NE.0) ISCAL=ISCAL+5-MOD(ISCAL,5)
27120= FACTOR=10.**(.9-EXP)
27130= XMIN=XMINT*FACTOR
27140= SCALE=FACTOR*FLOAT(ISCAL)
27150= 25 SCALE=SCALE/RSPACE
27160= RETURN
27170=C END SUBROUTINE VARSCL
27180= END
27190= SUBROUTINE PFDATA(ICODE,ND)
27200= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
27210= COMMON/MAIN2/COM2(1)
27220= COMMON/INO/KIN,KOUT,KPUNCH
27230= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
27240= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
27250= COMMON/SYSMTX/NVSM,SM(1)
27260= COMMON/ZMTX1/NVZM,ZM1(1)
27270= COMMON/ZMTX2/ZM2(1)
27280= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
27290= COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
27300= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
27310= COMMON/NDIMC/NNC,NRC,NPC
27320= COMMON/LOCC/LPHC,LBDC,LCC,LDC
27330= COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
27340= COMMON/NDIMT/NNT,NRT,NMT,NWT
27350= COMMON/LOCT/LPHT,LBDT,LQDT,LHT,LRT,LTDT,LTNT
27360= COMMON/TRUMTX/NVTM,TM(1)
27370= COMMON/LCNTRL/LPI11,LPI12,LPI21,LPI22,LPHDL,LBDL
27380= COMMON/CONTROL/NVCTL,CTL(1)
27390= COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
27400= COMMON/CREGPI/NVRPI,RPI(1)
27410= COMMON/LCGT/LA11,LA13,LA21,LA23,LA12,LA22,LELA11,LELA12,LELA13
27420= COMMON/CCGT/NVCGT,CGT(1)
27430= COMMON/LKF/LEADSN,LFLTRK,LFCOV
27440= COMMON/CKF/NVFLT,FLT(1)
27450= DIMENSION ND(1)
27460= ND(1)=NND
27470= ND(2)=NRD
27480= ND(3)=NPD
27490= ND(4)=NMD

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27500= ND(5)=NDD  
 27510= ND(6)=NPLD  
 27520= ND(7)=NNC  
 27530= ND(8)=NRC  
 27540= ND(9)=NPC  
 27550= ND(10)=NNT  
 27560= ND(11)=NRT  
 27570= ND(12)=NMT  
 27580= ND(13)=NODY  
 27590= ND(14)=NOEY  
 27600= NVZMS=NVZM  
 27610= CALL FTMTX(DM(LPHI), SM, NND, NND)  
 27620= LL=NND\*NND+1  
 27630= CALL FTMTX(DM(LBD), SM(LL), NND, NRD)  
 27640= LL=NND\*NRD+LL  
 27650= IF(NDD.EQ.0) GO TO 100  
 27660= CALL FTMTX(DM(LEX), SM(LL), NND, NDD)  
 27670= LL=NND\*NDD+LL  
 27680= CALL FTMTX(DM(LPHD), SM(LL), NDD, NDD)  
 27690= LL=NDD\*NDD+LL  
 27700= IF(NODY.EQ.1) GO TO 90  
 27710= CALL FTMTX(DM(LDY), SM(LL), NPD, NRD)  
 27720= LL=NPD\*NRD+LL  
 27730= 90 IF(NOEY.EQ.1) GO TO 95  
 27740= CALL FTMTX(DM(LEY), SM(LL), NPD, NDD)  
 27750= LL=NPD\*NDD+LL  
 27760= 95 CALL FTMTX(DM(LHP), SM(LL), NMD, NPLD)  
 27770= LL=NMD\*NPLD+LL  
 27780= GO TO 200  
 27790= 100 CONTINUE  
 27800= IF(NODY.EQ.1) GO TO 105  
 27810= CALL FTMTX(DM(LDY), SM(LL), NPD, NRD)  
 27820= LL=NPD\*NRD+LL  
 27830= 105 CALL FTMTX(DM(LHP), SM(LL), NMD, NND)  
 27840= LL=NMD\*NND+LL  
 27850= 200 CALL FTMTX(DM(LC), SM(LL), NPD, NND)  
 27860= LL=NPD\*NND+LL  
 27870= CALL FTMTX(CM(LPHC), SM(LL), NNC, NNC)  
 27880= LL=NNC\*NNC+LL  
 27890= CALL FTMTX(CM(LBDC), SM(LL), NNC, NRC)  
 27900= LL=NNC\*NRC+LL  
 27910= CALL FTMTX(CM(LCC), SM(LL), NPC, NNC)  
 27920= LL=NPC\*NNC+LL  
 27930= CALL FTMTX(TM(LPHT), SM(LL), NNT, NNT)  
 27940= LL=NNT\*NNT+LL  
 27950= CALL FTMTX(TM(LBDT), SM(LL), NNT, NRT)  
 27960= LL=NNT\*NRT+LL  
 27970= CALL FTMTX(TM(LQDT), SM(LL), NNT, NNT)  
 27980= LL=NNT\*NNT+LL  
 27990= CALL FTMTX(TM(LHT), SM(LL), NMT, NNT)  
 28000= LL=NMT\*NNT+LL  
 28010= CALL FTMTX(TM(LRT), SM(LL), NMT, NMT)  
 28020= LL=NMT\*NMT+LL  
 28030= CALL FTMTX(RPI(LGC1), SM(LL), NRD, NND)  
 28040= LL=NRD\*NND+LL

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28050= CALL FTMTX(RPI(LGC2),SM(LL),NRD,NPD)
28060= LL=NRD*NPD+LL
28070= CALL FTMTX(CGT(LELA11),SM(LL),NRC,NNC)
28080= LL=NRC*NNC+LL
28090= IF(NDD.EQ.0) GO TO 300
28100= CALL FTMTX(CGT(LELA13),SM(LL),NRD,NDD)
28110= LL=NRD*NDD+LL
28120= CALL FTMTX(FLT(LFLTRK),SM(LL),NPLD,NMD)
28130= LL=NPLD*NMD+LL
28140= CALL FTMTX(TM(LTDT),SM(LL),NND,NNT)
28150= LL=NND*NNT+LL
28160= CALL FTMTX(TM(LTNT),SM(LL),NDD,NNT)
28170= LL=NDD*NNT+LL
28180= GO TO 310
28190= 300 CONTINUE
28200= CALL FTMTX(FLT(LFLTRK),SM(LL),NND,NMD)
28210= LL=NND*NMD+LL
28220= CALL FTMTX(TM(LTDT),SM(LL),NND,NNT)
28230= LL=NND*NNT+LL
28240= 310 SM(LL)=TSAMP
28250= ND(15)=LL
28260= CALL WFILED(ICODE,LL,ND,SM)
28270= NVZM=NVZMS
28280= RETURN
28290=C END SUBROUTINE PFDATA
28300= END
28310= SUBROUTINE IMPLEX(A)
28320= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
28330= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
28340= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
28350= COMMON/SYSMTX/NVSM,SM(1)
28360= COMMON/ZMTX1/NVZM,ZM1(1)
28370= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
28380= COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
28390= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
28400= COMMON/NDIMC/NNC,NRC,NPC
28410= COMMON/AMC/AM(1)
28420= COMMON/BDG/BD(1)
28430= DIMENSION A(1)
28440= DATA NO/1HN/
28450= 215 WRITE(KLIST,126)
28460= 126 FORMAT(5(" "),"COMBINED IMPLICIT/EXPLICIT CONTROL",5(" "))
28470= LQI=1
28480= LRII=LQI+NPD*NPD
28490= LRRI=LRII+NRD*NRD
28500= NPDNRD=NPD+NRD
28510= 120 CALL ZPART(A,NPDNRD,NPDNRD,NPDNRD)
28520= WRITE 122,NPD
28530= 122 FORMAT(" ENTER WEIGHTS ON IMPLICIT OUTPUT DERIVATIVES: ",I2)
28540= CALL RQWGT(A,NPD,0)
28550= WRITE 124,NRD
28560= 124 FORMAT(" ENTER WEIGHTS ON IMPLICIT CONTROL MAGNITUDES: ",I2)
28570= CALL RQWGT(A(LRII),NRD,1)
28580= L1=1
28590= L2=L1+NND*NND

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28600=      L3=L2+NPD*NND
28610=      L4=L3+NPD*NND
28620=      L5=L4+NPD*NND
28630=      L6=L5+NND*NPD
28640=      L7=L6+NPD*NND
28650=      IF(NDD.EQ.0) GO TO 5
28660=          NDIM=NPLD
28670=          NDIM1=NDIM+1
28680=          GO TO 10
28690= 5      NDIM=NND
28700=      NDIM1=NDIM+1
28710= 10     CALL TFRMTX(SM(L1),DM(LAP),NND,NND,1)
28720=      CALL FMMUL(DM(LC),SM(L1),NPD,NND,NND,SM(L2))
28730=      CALL FMMUL(AM,DM(LC),NPD,NPD,NND,SM(L3))
28740=      NDIM=NPD
28750=      NDIM1=NDIM+1
28760=      CALL MADD1(NPD,NND,SM(L2),SM(L3),SM(L4),-1.)
28770=      CALL FTRNSP(NPD,NND,SM(L4),SM(L5))
28780=      CALL FMMUL(A,SM(L4),NPD,NPD,NND,SM(L6))
28790=      CALL FMMUL(SM(L5),SM(L6),NND,NPD,NND,SM(L1))
28800=      CALL FTRNSP(NND,NRD,BD,SM(L2))
28810=      CALL FTRNSP(NPD,NND,DM(LC),SM(L3))
28820=      CALL FMMUL(SM(L2),SM(L3),NRD,NND,NPD,SM(L4))
28830=      CALL FMMUL(SM(L4),SM(L6),NRD,NPD,NND,SM(L5))
28840=      CALL FTMTX(SM(L5),SM(L2),NRD,NND)
28850=      CALL FMMUL(SM(L4),A,NRD,NPD,NPD,SM(L5))
28860=      CALL FMMUL(SM(L5),DM(LC),NRD,NPD,NND,SM(L6))
28870=      CALL FMMUL(SM(L6),BD,NRD,NND,NRD,SM(L7))
28880=      CALL MADD1(NRD,NRD,A(LRII),SM(L7),SM(L5),1.)
28890=      CALL FTMTX(SM(L5),SM(L3),NRD,NRD)
28900=      WRITE 400
28910= 400    FORMAT("OLIST 'QIH' MATRIX TO TERMINAL (Y OR N) >")
28920=      READ 410,IANS
28930= 410    FORMAT(A3)
28940=      IF (IANS.EQ.NO)GO TO 490
28950=      CALL MATLST(SM(L1),NND,NND,"QIH",KTERM)
28960=      WRITE 420
28970= 420    FORMAT("OCHANGE IMPLICIT WEIGHTS (Y OR N) >")
28980=      READ 410,IANS
28990=      IF(IANS.EQ.NO)GO TO 490
29000=      GO TO 120
29010= 490    CALL MATLST(A,NPD,NPD,"QI",KLIST)
29020=      CALL DVCTOR(NPD,A,A(LRRI))
29030=      CALL MATLST(A(LRRI),NPD,1,"QI",KTERM)
29040=      CALL MATLST(A(LRII),NRD,NRD,"RI",KLIST)
29050=      CALL DVCTOR(NRD,A(LRII),A(LRRI))
29060=      CALL MATLST(A(LRRI),NRD,1,"RI",KTERM)
29070=      CALL MATLST(SM(L1),NND,NND,"QIH",KLIST)
29080=      CALL MATLST(SM(L2),NRD,NND,"SIH",KLIST)
29090=      CALL MATLST(SM(L3),NRD,NRD,"RIH",KLIST)
29100=      RETURN
29110=C END  SUBROUTINE IMPLEX
29120=      END
29130=      SUBROUTINE MODXU(X,U)
29140=      COMMON/MAIN1/NDIM,NDIM1,COM1(1)

```



```

29150= COMMON/MAIN2/COM2(1)
29160= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
29170= COMMON/SYSMTX/NVSM,SM(1)
29180= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
29190= COMMON/NDIMC/NNC,NRC,NPC
29200= DIMENSION X(1),U(1)
29210= L1=1
29220= L2=L1+NND*NND
29230= L3=L2+NRD*NND
29240= L4=L3+NRD*NRD
29250= L5=L4+NND*NND
29260= L6=L5+NND*NND
29270= NDIM=NNPR
29280= NDIM1=NDIM+1
29290= CALL TFRMTX(SM(L4),X,NND,NND,1)
29300= CALL FMADD(SM(L4),SM,NND,NND,SM(L5))
29310= CALL TFRMTX(SM(L5),X,NND,NND,2)
29320= DO 10 I=1,NRD
29330=     LA=NNPR*(I-1)
29340=     LB=L2+I-1
29350=     LE=LB+NRD*(NND-1)
29360=     DO 10 J=LB,LE,NRD
29370=     LA=LA+1
29380= 10 COM2(LA)=COM2(LA)+SM(J)
29390= CALL FMADD(SM(L3),U,NRD,NRD,U)
29400= CALL MATLST(X,NNPR,NNPR,"XIE",KLIST)
29410= RETURN
29420=C END SUBROUTINE MODXU
29430= END
29440= SUBROUTINE FTRNSP(NR,NC,A,B)
29450= DIMENSION A(1),B(1)
29460= DO 10 I=1,NR
29470=     DO 20 J=1,NC
29480=         B((I-1)*NC+J)=A((J-1)*NR+I)
29490= 20 CONTINUE
29500= 10 CONTINUE
29510= RETURN
29520=C END SUBROUTINE FTRNSP
29530= END
29540=*EOR

```

C.2      Subroutine Changes for CGT/PI Formulation 2

Subroutines CGTXQ, SREGPI, SCGT, and CGTKX were changed to produce the program based on CGT/PI formulation 2. These subroutines are listed on the following pages. Changed lines are marked.

```

2960= SUBROUTINE CGTXQ
2970= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
2980= COMMON/MAIN2/COM2(1)
2990= COMMON/INO/KIN,KOUT,KPUNCH
3000= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
3010= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
3020= COMMON/SYSMTX/NVSM,SM(1)
3030= COMMON/ZMTX1/NVZM,ZM1(1)
3040= COMMON/ZMTX2/ZM2(1)
3050= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
3060= COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
3070= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
3080= COMMON/NDIMC/NNC,NRC,NPC
3090= COMMON/LOCC/LPHC,LBDC,LCC,LDC
3100= COMMON/CHDMTX/NVCM,NEWCM,NODC,CM(1)
3110= COMMON/NDIMT/NNT,NRT,NMT,NWT
3120= COMMON/LOCT/LPHT,LBDT,LQDT,LHT,LRT,LTDT,LTNT
3130= COMMON/TRUMTX/NVTM,TM(1)
3140= COMMON/LCNTRL/LPI11,LPI12,LPI21,LPI22,LPHDL,LBDL
3150= COMMON/CONTROL/NVCTL,CTL(1)
3160= COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
3170= COMMON/CREGPI/NVRPI,RPI(1)
3180= COMMON/LCGT/LA11,LA13,LA21,LA23,LA12,LA22,LELA11,LELA12,LELA13
3190= COMMON/CCGT/NVCGT,CGT(1)
3200= COMMON/LKF/LEADSN,LFLTRK,LFCOV
3210= COMMON/CKF/NVFLT,FLT(1)
3220= COMMON/AMC/AM(1)
3230= COMMON/BDG/BD(1)
3240= DIMENSION LD(15),ND(15)
3250= DATA NPLTZM/606/
3260= DATA IEOI,NO/-1,1HN/
3270= REWIND KLIST
3280= WRITE(KLIST,115) DATE(DUM),TIME(DUM)
3290= WRITE(KTERM,115) DATE(DUM),TIME(DUM)
3300= 115 FORMAT(*1*,27X,** * * CGTPIQ * * **/14X,
3310= 1 "PROGRAM TO DESIGN A COMMAND GENERATOR TRACKER"/8X,
3320= 2 "USING A REGULATOR WITH PROPORTIONAL PLUS INTEGRAL CONTROL"/13X,
3330= 3 "BASED ON THE INTEGRAL OF THE REGULATION ERROR,"/16X,
3340= 4 "AND A KALMAN FILTER FOR STATE ESTIMATION."/28X,
3350= 5 ** * * CGTPIQ * * **//11X,"DATE : ",A10//,11X,
3360= 6 "TIME : ",A10////)
3370= REWIND KSAVE
3380= REWIND KDATA
3390= WRITE(KSAVE,112) IEOI,NPLTZM
3400= DO 10 I=1,15
3410= 10 ND(I)=0
3420= DO 12 I=1,15
3430= 12 LD(I)=1
3440= LFLRPI=0
3450= LFLCGT=0
3460= LFLKF=0
3470= LTEVAL=0
3480= LABORT=0
3490= IPI=0

```

```

3500=      ICGT=0
3510=      ITRU=0
3520=      IFLTR=0
3530=      ICODE=4
3540=      LFAVAL=0
3550=      LGCGT=0
3560=      NVCOM=MINO(NDIM,NVZM)
3570=      KOUT=KLIST
3580=      KPUNCH=KPLOT
3590=      IF(NVSM.GE.NPLTZM) GO TO 50
3600=      WRITE 101,NPLTZM
3610=      GO TO 1000
3620= 50   WRITE 102
3630=      READ*,TSAMP
3640=      IF(TSAMP.LE.0.) GO TO 50
3650=      WRITE(KLIST,103) TSAMP
3660= 103  FORMAT("OSAMPLE PERIOD IS ",F5.3," SECONDS")
3670=      CALL SETUP(ND,LD,ICGT,ITRU,1)
3680=      IF(LABORT) 1000,100,1000
3690= 100  LABORT=0
3700=      IMPLIC=0
3710=      WRITE 104
3720= 104  FORMAT("OCONTROLLER DESIGN (Y OR N) >")
3730=      READ 111, IANS
3740=      IF(IANS.EQ.NO) GO TO 500
3750=      LFLKF=0
3760=      CALL PIMTX(IPI)
3770=      IF(LABORT) 1000,125,1000
3780= 125  WRITE 105
3790= 105  FORMAT("ODESIGN REG/PI (Y OR N) >")
3800=      READ 111, IANS
3810=      IF(IANS.EQ.NO) GO TO 150
3820=      CALL SETUP(ND,LD,ICGT,ITRU,4)
3830=      IF(ICGT.EQ.0) GO TO 125
3840=      WRITE 400
3850= 400  FORMAT("OINCORPORATE IMPLICIT MODEL (Y OR N) >")
3860=      READ 111, IANS
3870=      IF(IANS.EQ.NO) GO TO 490
3880=      IMPLIC=1
3890=      CALL SETUP(ND,LD,ICGT,ITRU,4)
3900=      IF(ICGT.NE.0) GO TO 460
3910=      IMPLIC=0
3920=      GO TO 480
3930= 460  IF(NPD.EQ.NNC) GO TO 480
3940=      WRITE 470
3950= 470  FORMAT("OCOMMAND MODEL STATE DIM MUST EQUAL SYSTEM OUTPUT DIM")
3960=      LABORT=-1
3970= 480  IF(LABORT) 100,490,1000
3980= 490  CALL SREGPI(IMPLIC)
3990=      IF(LABORT) 1000,200,1000
4000= 150  WRITE 106
4010= 106  FORMAT("ODESIGN CGT (Y OR N) >")
4020=      READ 111, IANS
4030=      IF(IANS.EQ.NO) GO TO 100
4040=      CALL SETUP(ND,LD,ICGT,ITRU,2)

```

```

4050=      IF(ICGT) 155,100,155
4060= 155  IF(LABORT) 100,160,1000
4070= 160  CALL SCGT
4080=      IF(LABORT) 100,170,1000
4090= 170  IF(LFLCGT.LE.0) GO TO 125
4100= 200  LABORT=0
4110=      WRITE 107
4120= 107  FORMAT("OCONTROLLER EVALUATION WRT TRUTH MODEL (Y OR N) >")
4130=      READ 111, IANS
4140=      IF(IANS.EQ.NO) GO TO 250
4150=      CALL SETUP(ND,LD,ICGT,ITRU,3)
4160=      IF(LABORT) 200,260,1000
4170= 250  LTEVAL=0
4180= 260  CALL CEVAL
4190=      IF(LFLCGT.EQ.1) LGCGT=1
4200=      IF(LFAVAL.EQ.0.OR.LGCGT.EQ.0) GO TO 100
4210= 270  WRITE 600
4220= 600  FORMAT("OWRITE PERFORMANCE EVALUATION DATA TO 'SAVE' FILE (Y OR N)
4230=      +>")
4240=      READ 111, IANS
4250=      IF(IANS.EQ.NO) GO TO 100
4260=      ICODE=ICODE+1
4270=      CALL PFDATA(ICODE,ND)
4280=      INUM=ICODE-4
4290=      WRITE 605, INUM
4300= 605  FORMAT("OPERFORMANCE EVALUATION DATA, NO. "I2," WRITTEN TO 'SAVE
4310=      +' FILE")
4320=      GO TO 100
4330= 500  LABORT=0
4340=      WRITE 108
4350= 108  FORMAT("OFILTER DESIGN (Y OR N) >")
4360=      READ 111, IANS
4370=      IF(IANS.EQ.NO) GO TO 900
4380=      CALL FLTRK(IFLTR)
4390=      IF(IFLTR.EQ.0) GO TO 900
4400=      IF(LABORT) 1000,510,1000
4410= 510  CALL SETUP(ND,LD,ICGT,ITRU,3)
4420=      IF(LABORT) 500,525,1000
4430= 525  CALL FEVAL
4440= 530  IF(LABORT) 1000,540,1000
4450= 540  LFAVAL=1
4460=      IF(LGCGT.EQ.1) GO TO 270
4470=      GO TO 500
4480= 900  WRITE 109
4490= 109  FORMAT("OEND DESIGN RUNS (Y OR N) >")
4500=      READ 111, IANS
4510=      IF(IANS.EQ.NO) GO TO 100
4520=      IF(LFLRPI.EQ.0) GO TO 1000
4530=      NPNTS=NRD*(NNPR+NND)
4540=      ND(1)=NPNTS
4550=      ND(2)=LGC1
4560=      ND(3)=LGC2
4570=      ND(4)=LEL
4580=      CALL WFILED(4, NPNTS, ND, RPI(LGC1))
4590=      WRITE 113

```

```

4600= 1000 CONTINUE
4610= WRITE(KLIST,110)
4620= REWIND KSAVE
4630= REWIND KDATA
4640= REWIND KLIST
4650= WRITE 110
4660= 101 FORMAT("OINSUFFICIENT MEMORY /SYSMTX/, NEED: ",I4)
4670= 102 FORMAT("OENTER SAMPLE PERIOD FOR DIGITAL CONTROLLER >")
4680= 110 FORMAT("OPROGRAM EXECUTION STOP")
4690= 111 FORMAT(A3)
4700= 112 FORMAT(2I4)
4710= 113 FORMAT(6X,"REG/PI GAINS WRITTEN TO 'SAVE' FILE")
4720= RETURN
4730=C END SUBROUTINE CGTXQ
4740= END

```

```

8720= SUBROUTINE SREGPI(IMPLOC)
8730= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
8740= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
8750= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
8760= COMMON/SYSMTX/NVSM,SM(1)
8770= COMMON/ZMTX1/NVZM,ZM1(1)
8780= COMMON/ZMTX2/ZM2(1)
8790= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
8800= COMMON/LCCTRL/LPI11,LPI12,LPI21,LPI22,LPHDL,LBDL
8810= COMMON/CONTROL/NVCTL,CTL(1)
8820= COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
8830= COMMON/CREGPI/NVRPI,RPI(1)
8840= COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
8850= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)

```

```

8860= COMMON/NDIMC/NNC,NRC,NPC
8870= COMMON/LOCC/LPHC,LBDC,LCC,LDC
8880= COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)

```

```

8890= WRITE(KLIST,110)
8900= 110 FORMAT(////11X,5(" * "), "REG/PI DESIGN",5(" *")////)
8910= NSIZE=NRD*(5*NRD+2*NND)+NNPR*NNPR
8920= IF(NSIZE.LE.NVRPI) GO TO 5
8930= WRITE 101,NSIZE
8940= 101 FORMAT("OINSUFFICIENT MEMORY /CREGPI/, NEED: ",I4)
8950= GO TO 8
8960= 5 NSIZE=NNPR*(3*NNPR+NRD)
8970= IF(NSIZE.LE.NVSM) GO TO 10
8980= WRITE 102,NSIZE
8990= 102 FORMAT("OINSUFFICIENT MEMORY /SYSMTX/, NEED: ",I4)
9000= 8 LABORT=NSIZE
9010= RETURN
9020= 10 LX=1
9030= LU=LX+NNPR*NNPR
9040= CALL WXUS(SM(LX),SM(LU),COM1,ZM1,ZM2,IMPLOC)
9050= LUIST=LU+NNPR*NRD
9060= LPHP=LUIST+NNPR*NNPR
9070= CALL PXUP(CTL(LPHDL),CTL(LBDL),SM(LX),SM(LU),COM1,ZM2,
9080= 1 SM(LUIST),SM(LPHP),SM(LX),ZM1)

```

```

9090= CALL DRIC(NDIM,SM(LPHP),ZM2,SM(LX),ZM1,RPI(LPHCL))
9100= CALL GCSTAR(SM(LPHP),CTL(LBDL),SM(LU),ZM1,SM(LUIST),SM(LX),ZM2)
9110= CALL TFRMTX(RPI(LGC1),SM(LX),NRD,NND,1)
9120= L3=LADDR(NDIM,1,NND+1)+LX-1
9130= CALL TFRMTX(RPI(LGC2),SM(L3),NRD,NRD,1)
9140= L1=LADDR(NNPR,NND+1,NND+1)
9150= L2=LADDR(NNPR,1,NND+1)
9160= CALL GMINV(NRD,NRD,ZM1(L1),ZM1(L2),MR,1)
9170= L1=LADDR(NNPR,NND+1,1)
9180= CALL MMUL(ZM1(L2),ZM1(L1),NRD,NRD,NND,ZM1)
9190= CALL MMUL(SM(L3),ZM1,NRD,NRD,NND,ZM1(L1))
9200= CALL TFRMTX(COM1,ZM1(L1),NRD,NND,1)
9210= CALL MADD1(NRD,NND,SM(LX),ZM1(L1),ZM1,-1.)
9220= CALL TFRMTX(RPI(LEL),ZM1,NRD,NND,1)
9230= CALL FMMUL(RPI(LEL),CTL(LPI12),NRD,NND,NRD,RPI(LEE))
9240= CALL FMADD(RPI(LEE),CTL(LPI22),NRD,NRD,RPI(LEE))
9250= CALL MATLST(RPI(LGC1),NRD,NND,"GC1",KLIST)
9260= CALL MATLST(RPI(LGC1),NRD,NND,"GC1",KTERM)
9270= CALL MATLST(RPI(LGC2),NRD,NRD,"GC2",KLIST)
9280= CALL MATLST(RPI(LGC2),NRD,NRD,"GC2",KTERM)
9290= CALL MATLST(RPI(LEE),NRD,NRD,"E",KLIST)
9300= IF(NODY.EQ.1)GO TO 15
9310= CALL FMMUL(RPI(LEE),DM(LDY),NRD,NRD,NRD,ZM1)
9320= CALL SUBI(ZM1,NRD,NRD)
9330= NR2=NRD*NRD
9340= DO 12 I=1,NR2
9350= 12 ZM1(I)=-ZM1(I)
9360= NDIM=NRD
9370= NDIM1=NDIM+1
9380= CALL GMINV(NRD,NRD,ZM1,ZM2,MR,1)
9390= CALL FMMUL(ZM2,RPI(LEE),NRD,NRD,NRD,ZM1)
9400= CALL MATLST(ZM1,NRD,NRD,"KP",KLIST)
9410= CALL FMMUL(ZM2,RPI(LGC2),NRD,NRD,NRD,ZM1)
9420= CALL MATLST(ZM1,NRD,NRD,"KI",KLIST)
9430= GO TO 20
9440= 15 WRITE(KLIST,103)
9450= 103 FORMAT("OKP = E AND KI = GC2")
9460= 20 CONTINUE
9470= CALL FMMUL(COM1,CTL(LPI12),NRD,NND,NRD,ZM2)
9480= CALL FTMTX(CM(LPHC),ZM1,NNC,NNC)
9490= CALL SUBI(ZM1,NNC,NNC)
9500= NR2=NNC*NNC
9510= DO 25 I=1,NR2
9520= 25 ZM1(I)=-ZM1(I)
9530= NDIM=NNC
9540= NDIM1=NDIM+1
9550= CALL GMINV(NNC,NNC,ZM1,COM1,MR,1)
9560= CALL FMMUL(CM(LCC),COM1,NPC,NNC,NNC,ZM1)
9570= CALL FMMUL(ZM1,CM(LBDC),NPC,NNC,NRC,COM1)
9580= CALL FMADD(COM1,CM(LDC),NPC,NRC,ZM1)
9590= CALL FMMUL(ZM2,ZM1,NRD,NRD,NRC,RPI(LEL))
9600= LFLRPI=1
9610= LFLCGT=0
9620= RETURN
9630=C END SUBROUTINE SREGPI

```

```

9640=      END

11110=     SUBROUTINE SCGT
11120=     COMMON/DESIGN/NVCOM, TSAMP, LFLRPI, LFLCGT, LFLKF, LTEVAL, LABORT
11130=     COMMON/FILES/KSAVE, KDATA, KPLOT, KLIST, KTERM
11140=     COMMON/ZMTX1/NVZM, ZM1(1)
11150=     COMMON/ZMTX2/ZM2(1)
11160=     COMMON/NDIMD/NND, NRD, NPD, NMD, NDD, NWD, NWDD, NPLD, NWPND, NNPR
11170=     COMMON/NDIMC/NNC, NRC, NPC
11180=     COMMON/CMDMTX/NVCM, NEWCM, NODC, CM(1)
11190=     COMMON/LREGPI/LXDW, LUDW, LPHCL, LGC1, LGC2, LEL, LEE
11200=     COMMON/CREGPI/NVRPI, RPI(1)
11210=     COMMON/LCGT/LA11, LA13, LA21, LA23, LA12, LA22, LELA11, LELA12, LELA13
11220=     COMMON/CCGT/NVCGT, CGT(1)
11230=     IF(NEWCM) 20,20,15
11240= 15   NSIZE=(NND+2*NPD)*(NNC+NRC+NDD)
11250=     IF(NSIZE.LE.NVCGT) GO TO 16
11260=     WRITE 106, NSIZE
11270=     LABORT=NSIZE
11280=     RETURN
11290= 16   IF(NND.GE.NNC) GO TO 17
11300=     WRITE 107
11310=     GO TO 18
11320= 17   IF(NND.GE.NDD) GO TO 19
11330=     WRITE 108
11340= 18   LABORT=-1
11350=     RETURN
11360= 19   NEWCM=0
11370=     LA11=1
11380=     LA13=LA11+NND*NNC
11390=     LA21=LA13+NND*NDD
11400=     LA23=LA21+NPD*NNC
11410=     LA12=LA23+NPD*NDD
11420=     LA22=LA12+NND*NRC
11430=     LELA11=LA22+NPD*NRC
11440=     LELA12=LELA11+NPD*NNC
11450=     LELA13=LELA12+NPD*NRC
11460=     CALL CGTA(CGT(LA11),CGT(LA13),CGT(LA21),CGT(LA23),CGT(LA12),
11470=     1 CGT(LA22),ZM1,ZM2)
11480= 20   CALL CGTKX(CGT(LA11),CGT(LA13),CGT(LA21),CGT(LA23),CGT(LA12),
11490= 1 CGT(LA22),CGT(LELA11),CGT(LELA12),CGT(LELA13),RPI(LEL),RPI(LGC1))
11500=     LFLCGT=1
11510= 106  FORMAT(*OINSUFFICIENT MEMORY /CCGT/, NEED: ",I4)
11520= 107  FORMAT(*OFEWER DESIGN MODEL THAN COMMAND MODEL STATES*)
11530= 108  FORMAT(*FEWER DESIGN MODEL THAN DISTURBANCE MODEL STATES*)
11540=     RETURN
11550=C END SUBROUTINE SCGT
11560=     END

```

```

14080=     SUBROUTINE CGTKX(A11,A13,A21,A23,A12,A22,RELA11,RELA12,RELA13,REL,
14090= 1 RGC)

```



```

14100= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
14110= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
14120= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
14130= COMMON/NDIMC/NNC,NRC,NPC
14140= DIMENSION A11(1),A13(1),A21(1),A23(1),A12(1),A22(1),
14150= 1 RELA11(1),RELA12(1),RELA13(1),REL(1),RGC(1)
14160= NDIM=NRD
14170= NDIM1=NDIM+1
14180= CALL FMMUL(RGC,A11,NRD,NND,NNC,RELA11)
14190= CALL MADD1(NRD,NNC,RELA11,A21,RELA11,1.)
14200= CALL MATLST(RELA11,NRD,NNC,"KXM",KLIST)
14210= CALL MATLST(RELA11,NRD,NNC,"KXM",KTERM)
14220= CALL FMMUL(RGC,A12,NRD,NND,NRC,RELA12)
14230= CALL MADD1(NRD,NRC,RELA12,A22,RELA12,1.)
14240= CALL MADD1(NRD,NRC,RELA12,REL,RELA12,-1.)
14250= CALL MATLST(RELA12,NRD,NRC,"KXU",KLIST)
14260= CALL MATLST(RELA12,NRD,NRC,"KXU",KTERM)
14270= IF(NDD.LT.1) RETURN
14280= CALL FMMUL(RGC,A13,NRD,NND,NDD,RELA13)
14290= CALL MADD1(NRD,NDD,RELA13,A23,RELA13,1.)
14300= CALL MATLST(RELA13,NRD,NDD,"KXN",KLIST)
14310= CALL MATLST(RELA13,NRD,NDD,"KXN",KTERM)
14320= RETURN
14330=C END SUBROUTINE CGTKX
14340= END

```

C.3      Subroutine Changes for CGT/PI Formulation 3

Subroutines CTRESP, UCGT, SREGPI, SCGT, and CGTKX were changed to produce the program based on CGT/PI formulation 3. These subroutines are listed on the following pages. Changed lines are marked.

```

8700= SUBROUTINE SREGPI(IMPPLIC)
8710= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
8720= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
8730= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
8740= COMMON/SYSMTX/NVSM,SM(1)
8750= COMMON/ZMTX1/NVZM,ZM1(1)
8760= COMMON/ZMTX2/ZM2(1)
8770= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
8780= COMMON/LCCTRL/LPI11,LPI12,LPI21,LPI22,LPHDL,LBDL
8790= COMMON/CONTROL/NVCTL,CTL(1)
8800= COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
8810= COMMON/CREGPI/NVRPI,RPI(1)
8820= COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
8830= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
8840= WRITE(KLIST,110)
8850= 110 FORMAT(////11X,5(" * "), "REG/PI DESIGN",5(" *")////)
8860= NSIZE=NRD*(5*NRD+2*NND)+NNPR*NNPR
8870= IF(NSIZE.LE.NVRPI) GO TO 5
8880= WRITE 101,NSIZE
8890= 101 FORMAT("INSUFFICIENT MEMORY /CREGPI/, NEED: ",I4)
8900= GO TO 8
8910= 5 NSIZE=NNPR*(3*NNPR+NRD)
8920= IF(NSIZE.LE.NVSM) GO TO 10
8930= WRITE 102,NSIZE
8940= 102 FORMAT("INSUFFICIENT MEMORY /SYSMTX/, NEED: ",I4)
8950= 8 LABORT=NSIZE
8960= RETURN
8970= 10 LX=1
8980= LU=LX+NNPR*NNPR
8990= CALL WXUS(SM(LX),SM(LU),COM1,ZM1,ZM2,IMPPLIC)
9000= LUIST=LU+NNPR*NRD
9010= LPHP=LUIST+NNPR*NNPR
9020= CALL PXUP(CTL(LPHDL),CTL(LBDL),SM(LX),SM(LU),COM1,ZM2,
9030= 1 SM(LUIST),SM(LPHP),SM(LX),ZM1)
9040= CALL DRIC(NDIM,SM(LPHP),ZM2,SM(LX),ZM1,RPI(LPHCL))
9050= CALL GCSTAR(SM(LPHP),CTL(LBDL),SM(LU),ZM1,SM(LUIST),SM(LX),ZM2)
9060= CALL TFRMTX(RPI(LGC1),SM(LX),NRD,NND,1)
9070= L3=LADDR(NDIM,1,NND+1)+LX-1
9080= CALL TFRMTX(RPI(LGC2),SM(L3),NRD,NRD,1)
9090= L1=LADDR(NNPR,NND+1,NND+1)
9100= L2=LADDR(NNPR,1,NND+1)
9110= CALL GMINV(NRD,NRD,ZM1(L1),ZM1(L2),MR,1)
9120= L1=LADDR(NNPR,NND+1,1)
9130= CALL MMUL(ZM1(L2),ZM1(L1),NRD,NRD,NND,ZM1)
9140= CALL MMUL(SM(L3),ZM1,NRD,NRD,NND,ZM1(L1))
9150= CALL MADD1(NRD,NND,SM(LX),ZM1(L1),ZM1,-1.)
9160= CALL TFRMTX(RPI(LEL),ZM1,NRD,NND,1)
9170= CALL FMMUL(RPI(LEL),CTL(LPI12),NRD,NND,NRD,RPI(LEE))
9180= CALL FMADD(RPI(LEE),CTL(LPI22),NRD,NRD,RPI(LEE))
9190= CALL FTMTX(RPI(LEE),RPI(LEL),NRD,NRD)
9200= CALL MATLST(RPI(LGC1),NRD,NND,"GC1",KLIST)
9210= CALL MATLST(RPI(LGC1),NRD,NND,"GC1",KTERM)
9220= CALL MATLST(RPI(LGC2),NRD,NRD,"GC2",KLIST)
9230= CALL MATLST(RPI(LGC2),NRD,NRD,"GC2",KTERM)

```

```

9240=      CALL MATLST(RPI(LEE),NRD,NRD,"E",KLIST)
9250=      IF(NODY.EQ.1)GO TO 15
9260=      CALL FMMUL(RPI(LEE),DM(LDY),NRD,NRD,NRD,ZM1)
9270=      CALL SUBI(ZM1,NRD,NRD)
9280=      NR2=NRD*NRD
9290=      DO 12 I=1,NR2
9300= 12    ZM1(I)=-ZM1(I)
9310=      NDIM=NRD
9320=      NDIM1=NDIM+1
9330=      CALL GMINV(NRD,NRD,ZM1,ZM2,MR,1)
9340=      CALL FMMUL(ZM2,RPI(LEE),NRD,NRD,NRD,ZM1)
9350=      CALL MATLST(ZM1,NRD,NRD,"KP",KLIST)
9360=      CALL FMMUL(ZM2,RPI(LGC2),NRD,NRD,NRD,ZM1)
9370=      CALL MATLST(ZM1,NRD,NRD,"KI",KLIST)
9380=      GO TO 20
9390= 15    WRITE(KLIST,103)
9400= 103   FORMAT("OKP = E AND KI = GC2")
9410= 20    CONTINUE
9420=      LFLRPI=1
9430=      LFLCGT=0
9440=      RETURN
9450=C END SUBROUTINE SREGPI

```

```

10930=     SUBROUTINE SCGT
10940=     COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
10950=     COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
10960=     COMMON/ZMTX1/NVZM,ZM1(1)
10970=     COMMON/ZMTX2/ZM2(1)
10980=     COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
10990=     COMMON/NDIMC/NNC,NRC,NPC
11000=     COMMON/CMDMX/NVCM,NEWCM,NODC,CM(1)
11010=     COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
11020=     COMMON/CREGPI/NVRPI,RPI(1)
11030=     COMMON/LCGT/LA11,LA13,LA21,LA23,LA12,LA22,LELA11,LELA12,LELA13
11040=     COMMON/CCGT/NVCGT,CGT(1)
11050=     IF(NEWCM) 20,20,15
11060= 15    NSIZE=(NND+2*NPD)*(NNC+NRC+NDD)
11070=     IF(NSIZE.LE.NVCGT) GO TO 16
11080=     WRITE 106,NSIZE
11090=     LABORT=NSIZE
11100=     RETURN
11110= 16    IF(NND.GE.NNC) GO TO 17
11120=     WRITE 107
11130=     GO TO 18
11140= 17    IF(NND.GE.NDD) GO TO 19
11150=     WRITE 108
11160= 18    LABORT=-1
11170=     RETURN
11180= 19    NEWCM=0
11190=     LA11=1
11200=     LA13=LA11+NND*NNC
11210=     LA21=LA13+NND*NDD
11220=     LA23=LA21+NPD*NNC

```

```

11230= LA12=LA23+NPD*NDD
11240= LA22=LA12+NND*NRC
11250= LELA11=LA22+NPD*NRC
11260= LELA12=LELA11+NPD*NNC
11270= LELA13=LELA12+NPD*NRC
11280= CALL CGTA(CGT(LA11),CGT(LA13),CGT(LA21),CGT(LA23),CGT(LA12),
11290= 1 CGT(LA22),ZM1,ZM2)
11300= 20 CALL CGTKX(CGT(LA11),CGT(LA13),CGT(LA21),CGT(LA23),CGT(LA12),
11310= 1 CGT(LA22),CGT(LELA11),CGT(LELA12),CGT(LELA13),RPI(LGC1))
11320= LFLCGT=1
11330= 106 FORMAT(*OINSUFFICIENT MEMORY /CCGT/, NEED: ",I4)
11340= 107 FORMAT(*OFEWER DESIGN MODEL THAN COMMAND MODEL STATES*)
11350= 108 FORMAT(*FEWER DESIGN MODEL THAN DISTURBANCE MODEL STATES*)
11360= RETURN
11370=C END SUBROUTINE SCGT
11380= END

```

```

13900= SUBROUTINE CGTKX(A11,A13,A21,A23,A12,A22,RELA11,RELA12,RELA13,RGC)
13910= COMMON/MAIN1/NDIM,NDIM1,COM1(1)
13920= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
13930= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
13940= COMMON/NDIMC/NNC,NRC,NPC
13950= DIMENSION A11(1),A13(1),A21(1),A23(1),A12(1),A22(1),
13960= 1 RELA11(1),RELA12(1),RELA13(1),RGC(1)
13970= NDIM=NRD
13980= NDIM1=NDIM+1
13990= CALL FMMUL(RGC,A11,NRD,NND,NNC,RELA11)
14000= CALL MADD1(NRD,NNC,RELA11,A21,RELA11,1.)
14010= CALL MATLST(RELA11,NRD,NNC,"KXM",KLIST)
14020= CALL MATLST(RELA11,NRD,NNC,"KXM",KTERM)
14030= CALL FMMUL(RGC,A12,NRD,NND,NRC,RELA12)
14040= CALL MADD1(NRD,NRC,RELA12,A22,RELA12,1.)
14050= CALL MATLST(RELA12,NRD,NRC,"KXU",KLIST)
14060= CALL MATLST(RELA12,NRD,NRC,"KXU",KTERM)
14070= IF(NDD.LT.1) RETURN
14080= CALL FMMUL(RGC,A13,NRD,NND,NDD,RELA13)
14090= CALL MADD1(NRD,NDD,RELA13,A23,RELA13,1.)
14100= CALL MATLST(RELA13,NRD,NDD,"KXN",KLIST)
14110= CALL MATLST(RELA13,NRD,NDD,"KXN",KTERM)
14120= RETURN
14130=C END SUBROUTINE CGTKX
14140= END

```

```

16620= SUBROUTINE CTRESP(VX0,VX1,X0,X1,XM0,XM1,ZM1,NVOUT,TEND,IUM,VUM,
16630= 1 NST)
16640= COMMON/DESIGN/NVCOM,TSAMP,LFLRPI,LFLCGT,LFLKF,LTEVAL,LABORT
16650= COMMON/FILES/KSAVE,KDATA,KPLOT,KLIST,KTERM
16660= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPND,NNPR
16670= COMMON/LOCD/LAP,LGP,LPHI,LBD,LEX,LPHD,LQ,LQN,LQD,LC,LDY,LEY,LHP,LR
16680= COMMON/DSNMTX/NVDM,NODY,NOEY,DM(1)
16690= COMMON/NDIMC/NNC,NRC,NPC
16700= COMMON/LOCC/LPHC,LBDC,LCC,LDC

```

```

16710= COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)
16720= COMMON/LOCT/LPHT,LBDT,LQDT,LHT,LRT,LTDT,LTNT
16730= COMMON/TRUMTX/NVTM,TM(1)
16740= COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE
16750= COMMON/CREGPI/NVRPI,RPI(1)
16760= DIMENSION VX0(1),VX1(1),X0(1),X1(1),XMO(1),XM1(1),ZM1(1)
16770= NSTPO=.01*TEND/TSAMP+.5
16780= NST=2
16790= IF(NSTPO.GE.1) GO TO 1
16800= NSTPO=1
16810= NST=1
16820= 1 NSTEPS=100*NSTPO
16830= IF(LFLCGT.EQ.0) GO TO 2
16840= LMO=NVOUT-NPC
16850= IF(NDD.EQ.0) GO TO 4
16860= LDCGT=1
16870= GO TO 5
16880= 2 LMO=NVOUT
16890= 4 LDCGT=0
16900= 5 LU=LMO-NRD
16910= LSO=LU-NPD
16920= NVX=LSO-1
16930= IF(LTEVAL)6,6,10
16940= 6 DO 7 I=1,NVX
16950= 7 X1(I)=VX1(I)
16960= GO TO 12
16970= 10 CALL XFDT(VX1,X1,LDCGT)
16980= 12 NNDP1=NND+1
16990= REWIND KPLOT
17000= CALL YDSN(X1,VX1(LU),DM(LC),DM(LDY),LDCGT,VX1(LSO))
17010= IF(LFLCGT.EQ.1) CALL YCMD(XM1,IUM,VUM,CM(LCC),CM(LDC),
17020= 1 VX1(LMO))
17030= CALL WPLOT(VX1,NVOUT)
17040= DO 100 IT=1,NSTEPS
17050= CALL URPI(RPI(LGC1),RPI(LGC2),DM(LC),DM(LDY),X0,X1,VX0(LU),
17060= 1 VX1(LU))
17070= IF(LFLCGT) 20,20,15
17080= 15 CALL UCGT(VX0(LU),VX1(LU),XMO,XM1,X0(NNDP1),ZM1,IUM,VUM,IT,
17090= 1 VX1(LMO))
17100= CALL CUPDAT(XMO,XM1,IUM,VUM)
17110= 20 CALL FTMTX(VX1(LU),VX0(LU),NRD,1)
17120= CALL FTMTX(X1,X0,NPLD,1)
17130= IF(LTEVAL) 25,25,30
17140= 25 CALL DUPDAT(DM(LPHI),DM(LBD),DM(LPHD),DM(LEX),X0,X1,
17150= 1 VX1,VX0(LU),LDCGT,NNDP1)
17160= GO TO 35
17170= 30 CALL TUPDAT(TM(LPHT),TM(LBDT),VX0,VX1,VX0(LU))
17180= CALL XFDT(VX1,X1,LDCGT)
17190= 35 IF(MOD(IT,NSTPO).NE.0) GO TO 100
17200= VX1(NVOUT)=TSAMP*FLOAT(IT)
17210= CALL YDSN(X1,VX1(LU),DM(LC),DM(LDY),LDCGT,VX1(LSO))
17220= IF(LFLCGT.EQ.1) CALL YCMD(XM1,IUM,VUM,CM(LCC),CM(LDC),
17230= 1 VX1(LMO))
17240= CALL WPLOT(VX1,NVOUT)
17250= 100 CONTINUE

```

17260= ENDFILE KPLOT  
17270= RETURN  
17280=C END SUBROUTINE CTRESP  
17290= END

17980= SUBROUTINE UCGT(UO,U1,XMO,XM1,DDIF,ZM1,IUM,VUM,IT,YC)  
17990= COMMON/MAIN1/NDIM,NDIM1,COM1(1)  
18000= COMMON/NDIMD/NND,NRD,NPD,NMD,NDD,NWD,NWDD,NPLD,NWPWWD,NNPR  
18010= COMMON/NDIMC/NNC,NRC,NPC  
18020= COMMON/LOCC/LPHC,LBDC,LCC,LDC  
18030= COMMON/CMDMTX/NVCM,NEWCM,NODC,CM(1)  
18040= COMMON/LREGPI/LXDW,LUDW,LPHCL,LGC1,LGC2,LEL,LEE  
18050= COMMON/CREGPI/NVRPI,RPI(1)  
18060= COMMON/LCGT/LA11,LA13,LA21,LA23,LA12,LA22,LELA11,LELA12,LELA13  
18070= COMMON/CCGT/NVCGT,CGT(1)  
18080= DIMENSION UO(1),U1(1),XMO(1),XM1(1),DDIF(1),ZM1(1)  
18090= CALL YCMD(XMO,IUM,VUM,CM(LCC),CM(LDC),UO)  
18100= IF(IT.GT.1) GO TO 8  
18110= I=LELA12+LADDR(NPD,1,IUM)-1  
18120= CALL MADD1(NPD,1,U1,CGT(I),U1,VUM)  
18130= CALL MMULS(RPI(LEL),UO,NDIM,NDIM,1,U1)  
18140= GO TO 10  
18150= 8 CALL MADD1(NPD,1,YC,UO,YC,-1.)  
18160= CALL MMULS(RPI(LEL),YC,NDIM,NDIM,1,U1)  
18170= 10 CALL MMULS(RPI(LGC2),UO,NDIM,NDIM,1,U1)  
18180= DO 12 I=1,NNC  
18190= 12 XMO(I)=XM1(I)-XMO(I)  
18200= CALL FMMUL(CGT(LELA11),XMO,NPD,NNC,1,UO)  
18210= CALL VADD(NDIM,1.,U1,UO)  
18220= IF(NDD.EQ.0) RETURN  
18230= DO 14 I=1,NDD  
18240= 14 DDIF(I)=-DDIF(I)  
18250= CALL MMULS(CGT(LELA13),DDIF,NPD,NDD,1,U1)  
18260= RETURN  
18270=C END SUBROUTINE UCGT  
18280= END

C.4      Subroutine Changes for CGT/PI Formulation 4

Subroutines SCGT and CGTKX were changed to produce the program based on CGT/PI formulation 4. These subroutines are listed on the following pages. Changed lines are marked.



```

10920= SUBROUTINE SCGT
10930= COMMON/DESIGN/NVCOM, TSAMP, LFLRPI, LFLCGT, LFLKF, LTEVAL, LABORT
10940= COMMON/FILES/KSAVE, KDATA, KPLOT, KLIST, KTERM
10950= COMMON/ZMTX1/NVZM, ZM1(1)
10960= COMMON/ZMTX2/ZM2(1)
10970= COMMON/NDIMD/NND, NRD, NPD, NMD, NDD, NWD, NWDD, NPLD, NWPND, NNPR
10980= COMMON/NDIMC/NNC, NRC, NPC
10990= COMMON/CMDMTX/NVCM, NEWCM, NODC, CM(1)
11000= COMMON/LREGPI/LXDW, LUDW, LPHCL, LGC1, LGC2, LEL, LEE
11010= COMMON/CREGPI/NVRPI, RPI(1)
11020= COMMON/LCGT/LA11, LA13, LA21, LA23, LA12, LA22, LELA11, LELA12, LELA13
11030= COMMON/CCGT/NVCGT, CGT(1)
11040= IF(NEWCM) 20, 20, 15
11050= 15 NSIZE=(NND+2*NPD)*(NNC+NRC+NDD)
11060= IF(NSIZE.LE.NVCGT) GO TO 16
11070= WRITE 106, NSIZE
11080= LABORT=NSIZE
11090= RETURN
11100= 16 IF(NND.GE.NNC) GO TO 17
11110= WRITE 107
11120= GO TO 18
11130= 17 IF(NND.GE.NDD) GO TO 19
11140= WRITE 108
11150= 18 LABORT=-1
11160= RETURN
11170= 19 NEWCM=0
11180= LA11=1
11190= LA13=LA11+NND*NNC
11200= LA21=LA13+NND*NDD
11210= LA23=LA21+NPD*NNC
11220= LA12=LA23+NPD*NDD
11230= LA22=LA12+NND*NRC
11240= LELA11=LA22+NPD*NRC
11250= LELA12=LELA11+NPD*NNC
11260= LELA13=LELA12+NPD*NRC
11270= CALL CGTA(CGT(LA11), CGT(LA13), CGT(LA21), CGT(LA23), CGT(LA12),
11280= 1 CGT(LA22), ZM1, ZM2)
11290= 20 CALL CGTKX(CGT(LA11), CGT(LA13), CGT(LA21), CGT(LA23), CGT(LA12),
11300= 1 CGT(LA22), CGT(LELA11), CGT(LELA12), CGT(LELA13), RPI(LGC1))
11310= LFLCGT=1
11320= 106 FORMAT("OINSUFFICIENT MEMORY /CCGT/, NEED: ", I4)
11330= 107 FORMAT("OFEWER DESIGN MODEL THAN COMMAND MODEL STATES")
11340= 108 FORMAT("FEWER DESIGN MODEL THAN DISTURBANCE MODEL STATES")
11350= RETURN
11360=C END SUBROUTINE SCGT
11370= END

```

```

13890= SUBROUTINE CGTKX(A11, A13, A21, A23, A12, A22, RELA11, RELA12, RELA13, RGC)
13900= COMMON/MAIN1/NDIM, NDIM1, COM1(1)
13910= COMMON/FILES/KSAVE, KDATA, KPLOT, KLIST, KTERM
13920= COMMON/NDIMD/NND, NRD, NPD, NMD, NDD, NWD, NWDD, NPLD, NWPND, NNPR
13930= COMMON/NDIMC/NNC, NRC, NPC

```

```

13940=      DIMENSION A11(1),A13(1),A21(1),A23(1),A12(1),A22(1),
13950=      1 RELA11(1),RELA12(1),RELA13(1),RGC(1)
13960=      NDIM=NRD
13970=      NDIM1=NDIM+1
13980=      CALL FMMUL(RGC,A11,NRD,NND,NNC,RELA11)
13990=      CALL MADD1(NRD,NNC,RELA11,A21,RELA11,1.)
14000=      CALL MATLST(RELA11,NRD,NNC,"KXM",KLIST)
14010=      CALL MATLST(RELA11,NRD,NNC,"KXM",KTERM)
14020=      CALL FMMUL(RGC,A12,NRD,NND,NRC,RELA12)
14030=      CALL MADD1(NRD,NRC,RELA12,A22,RELA12,1.)
14040=      CALL MATLST(RELA12,NRD,NRC,"KXU",KLIST)
14050=      CALL MATLST(RELA12,NRD,NRC,"KXU",KTERM)
14060=      IF(NDD.LT.1) RETURN
14070=      CALL FMMUL(RGC,A13,NRD,NND,NDD,RELA13)
14080=      CALL MADD1(NRD,NDD,RELA13,A23,RELA13,1.)
14090=      CALL MATLST(RELA13,NRD,NDD,"KXN",KLIST)
14100=      CALL MATLST(RELA13,NRD,NDD,"KXN",KTERM)
14110=      RETURN
14120=C END SUBROUTINE CGTKX
14130=      END

```

## Appendix D

### CGT/PI/KF Design Evaluation

#### D.1 Introduction

CGT/PI/KF design actually consists of three separate designs: the controller with PI control action, the open-loop CGT or closed-loop CGT/PI controller, and the Kalman filter. Each of these designs is best evaluated according to criteria specifically related to the task that each is to perform.

For the controller, relevant considerations include the closed-loop system poles, the values of the feedforward and/or feedback gains, and the time response of the controller system states, output, and control inputs in either unforced or forced input conditions. For the filter, relevant considerations include the poles of the filter, the values of the filter gains, and the filter's estimation error behavior. An overall evaluation of the system performance for the CGT/PI/KF closed-loop controller is necessary to tune the entire design properly and judge its ultimate performance. The true CGT/PI/KF controller will suffer some degree of degraded performance due to the dynamics of the Kalman filter's state estimation and also a slightly increased delay in control generation due to the needed filter computations. The necessary performance evaluation software for this entire CGT/PI/KF controller is contained in the program "PFEVAL" (Ref 21). This appendix

is taken from Chapter IV of Floyd's thesis (Ref 9).

## D.2 PI Controller Evaluation

The discrete-time poles of the closed-loop system incorporating the optimal gain  $G_C^*$  of Equation (III-52) and assuming perfect state knowledge are computed from the matrix

$$\underline{\lambda}_{fCL} = [\underline{\lambda}_f - B_f G_C^*] \quad (D-1)$$

with  $\underline{\lambda}_f$  and  $B_f$  as defined in Equations (III-42a) and (III-42b), respectively. The equivalent continuous-time poles are then computed using the inverse of the relation between the  $z$  and  $s$  transforms

$$z = e^{sT} \quad (D-2)$$

in which  $z$  and  $s$  are respectively the discrete and continuous-time complex poles and  $T$  is the controller sample period. This mapping is for the primary strip in the  $s$ -plane only and does not consider any possible aliasing effects (Ref 14).

Another important consideration in evaluating the controller design is the magnitudes of the gains  $G_{C1}^*$  and  $G_{C2}^*$ , but the most useful information can be determined from the system's time response to initial conditions on the states. The time response can be readily simulated using the discretized

deterministic state transition equations of either the design or the truth model and driven by the control input

$$\begin{aligned} \underline{u}^*(t_i) = & \underline{u}^*(t_{i-1}) - \underline{G}_{c1}^* [\underline{x}(t_i) - \underline{x}(t_{i-1})] \\ & - \underline{G}_{c2}^* \begin{bmatrix} \underline{C} & \underline{D}_y \\ \underline{x}(t_{i-1}) \\ \underline{u}^*(t_{i-1}) \end{bmatrix} \end{aligned} \quad (D-3)$$

obtained from Equation (III-75) by deleting terms due to the CGT feedforward control. Note that this controller form is valid only for the PI controller with zero reference input ( $\underline{y}_d = \underline{0}$ ) and in response to non-zero initial conditions on the states. Plots of the time histories of the states, the outputs, and the generated control inputs then may be made. These allow evaluation of the quality of the regulation achieved--speed and damping of the state and output response, and the magnitudes and rates of the control inputs actually required.

### D.3 CGT or CGT/PI Evaluation

As for the PI controller evaluation discussed above, consideration of the magnitudes of the feedforward gains may provide useful insights into the CGT design results. For the open-loop CGT the relevant gains are  $\underline{A}_{21}$  acting on the command model states and  $\underline{A}_{23}$  acting on the disturbance states in the open-loop CGT control law

$$\begin{aligned}
\underline{u}(t_i) = & \underline{u}(t_{i-1}) + \underline{A}_{21}[\underline{x}_m(t_i) - \underline{x}_m(t_{i-1})] \\
& + \underline{A}_{22}[\underline{u}_m(t_i) - \underline{u}_m(t_{i-1})] \\
& + \underline{A}_{23}[\underline{n}_d(t_i) - \underline{n}_d(t_{i-1})]
\end{aligned}
\tag{D-4}$$

obtained from Equation (III-75) by setting the PI controller gains  $\underline{G}_{c1}^*$  and  $\underline{G}_{c2}^*$  to zero. For the CGT/PI controller of Equation (III-75) the relevant gains are

$$\underline{K}_{xm} = \underline{L}\underline{A}_{11} + \underline{A}_{21} \tag{D-5a}$$

$$\underline{K}_{xu} = \underline{L}\underline{A}_{12} + \underline{A}_{22} \tag{D-5b}$$

$$\underline{K}_{xn} = \underline{L}\underline{A}_{13} + \underline{A}_{23} \tag{D-5c}$$

acting on the command model states and inputs, and disturbance states, respectively. (See Section 3.3.2 for changes for the CGT/PI formulations 2,3,4.)

#### D.4 Kalman Filter Evaluation

Without going into any detail, the state transition matrix for the filter estimate propagation is

$$\underline{\Phi}_{KF} = [\underline{I} - \underline{K}_F \underline{H}_a] \underline{\Phi}_a \tag{D-6}$$

The filter's discrete-time poles are computed as the eigenvalues of  $\underline{\Phi}_{KF}$  and their continuous-time equivalents computed by the method mentioned in Section D.2. The magnitudes of the Kalman filter gains may be evaluated from the standard  $\underline{K}_F$  matrix

$$\underline{K}_F = \underline{P}_a \underline{H}_a^T [\underline{H}_a \underline{P}_a \underline{H}_a^T + \underline{R}]^{-1} \quad (D-7)$$

The greatest insight into Kalman filter tuning is provided by a covariance analysis (Refs 11 and 17). In the covariance analysis, the covariance of the estimation errors of the Kalman filter when applied to the system truth model is propagated forward in time from the initial conditions on the covariances of the truth model states. In parallel with this estimate-error covariance propagation, the filter-computed covariance is itself propagated forward in time. The true and filter computed estimation error covariances may then be compared since the truth model state estimation error covariances can be transformed to errors for the design states using Equation (B-6c). The designer may then modify (tune) the dynamics noise and measurement noise strengths to achieve the desired filter performance: the duration of the initial estimation transient and the steady state error covariance obtained. The total development of this is given in Ref (17) and summarized in Ref (9).

## Vita

James Page McMillian was born on 2 February 1947 in Clinton, Missouri. He enlisted in the Air Force in June 1970 and received training as an Electronics Technician for the Precision Measuring Equipment Laboratories. Assignments included England AFB, La., Lowry AFB, Colo., Barksdale AFB, La., and Bitburg AFB, Germany. In September 1977 he attended Louisiana Tech University under the Airman Education and Commissioning Program, graduating in December 1977 with a degree of Bachelor of Science in Electrical Engineering. During his undergraduate education, he became a member of Eta Kappa Nu and Tau Beta Pi. He received his commission from Officer Training School in March 1980. From March 1980 until June 1982 he was assigned to HQ Electronic Security Command, Kelly AFB, San Antonio, Texas. He entered the School of Engineering of the Air Force Institute of Technology in June 1982 and has pursued the Guidance and Control curriculum of the Electrical Engineering Department.

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8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State and ZIP Code)		10. SOURCE OF FUNDING NOS.			
		PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
11. TITLE (Include Security Classification) See Box 19					
12. PERSONAL AUTHOR(S) James P. McMillian, B.S., B.S.E.E., 1Lt, USAF					
13a. TYPE OF REPORT MS Thesis	13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Yr., Mo., Day) 1983 December		15. PAGE COUNT 356
16. SUPPLEMENTARY NOTATION					
<p style="text-align: right;">Approved for public release: IAW AFM 190-17.  <i>Lynn E. Wolaver</i>          LYNN E. WOLAVER          Dept. for Research and Professional Development          Air Force Institute of Technology (AFIT)          Dayton, Ohio 45433-3909          7 Feb 84</p>					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and include block number)		
FIELD	GROUP	SUB. GR.			
01	03		Optimal Control, Model-Following Control, Proportional-Integral Control, Command Generator Tracker		

This study develops a computer program for interactive execution to aid in the design of Command Generator Tracker control systems employing Proportional Plus Integral inner loop controllers based on the integral of the regulation error and Kalman Filters for state estimation (CGT/PI/KF controllers). Sampled-data controller designs are based upon the Linear system model, Quadratic cost, and Gaussian noise process (LQG) assumptions of optimal control theory.

The report develops the CGT/PI/KF controller theory with the PI controller portion based upon the integral of the regulation error. Following a brief description of the computer program developed, results of applying it to an example aircraft-related controller design problem is presented. The CGT/PI/KF controller is found to be a technique particularly well suited to the aircraft control design problem but is a technique that may be applied to any general controller problem fitting the design criteria.

Use of the computer program is fully documented in the appendices of the report. Included are a brief "Programmer's Manual," a complete "User's Manual", and a program listing. These pertain to the computer program as implemented on a CDC CYBER computer system.

