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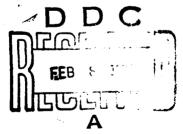


THE APPLICATION OF OUTPUT PREDICTIVE DIGITAL CONTROL TO WING FLUTTER SUPPRESSION AND TERRAIN FOLLOWING PROBLEMS

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AFIT/GE/EE/79-9 / David E./Chaffin / Captain USAF

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THE APPLICATION OF OUTPUT PREDICTIVE DIGITAL CONTROL TO WING FLUTTER SUPPRESSION AND TERRAIN FOLLOWING PROBLEMS

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
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in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

bу

David E. Chaffin

Captain USAF

Graduate Electrical Engineering

December 1979

Approved for public release; distribution unlimited.

Preface

This work is basically a continuation of Captain Howard Colson's thesis study (Ref 1). Output Predictive Control is a relatively new concept and little material has been published on the subject.

Guidance and clarification throughout the project was from Major J. G. Reid, my thesis advisor. Many thanks to him for his patience and indulgence. I am also obliged to Captains Silverthorn and Rader for their assistance during the research and in the preparation of the final document.

David E. Chaffin

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Abstract

This thesis is a study of a digital control technique known as Output Predictive Control (OPC) or Model Algorithmic Control (MAC). In OPC, the behavior of the system is predicted using its impulse response function and the desired response is characterized by a reference trajectory. Controls are computed iteratively to drive the system output along the desired trajectory.

In an earlier study, the system was made to follow the reference trajectory exactly, but only at the control application time; there were large oscillations of the output between control changes. In this study, the control calculation is reformulated as a least squares curve fit problem, allowing some deviation from the desired trajectory.

This approach is applied as a regulator for a very lightly damped fourth-order single-input/single-output system and as a pitch axis autopilot in a simplified terrain following problem. A qualitative discussion of robustness properties is included.

The design of the controller is difficult due to the interrelationships of the internal parameters; however, the results of the terrain following example indicate that this is a viable approach for this problem.

THE APPLICATION OF OUTPUT PREDICTIVE DIGITAL CONTROL TO WING FLUTTER SUPPRESSION AND TERRAIN FOLLOWING PROBLEMS

I Introduction

Background

A new control technique known as Output Predictive Control (OPC) or Model Algorithmic Control (MAC) has recently been developed (Ref 6,7, 8,11,12). The control technique differs from previous state variable methods in that it employs a discrete impulse response model rather than a "state space model." Also, rather than employing "feedback," OPC uses an explicit prediction of the future response, thus trying to find the future input which best matches a desired future response.

This technique is conceptually pleasing in that it approximates a human "controller" in some tasks. As an example, consider a pilot attempting to maintain a particular course. This course can be referred to as a 'set path' and the control objective is to maintain the set path. If an error exists between the aircraft's actual course and the set path, the pilot formulates a control input (or series of control inputs) to return the aircraft to the set path. Some of the factors involved in his control calculation include:

1. The zero-input response of his aircraft, i.e., the path the aircraft will follow if no additional controls are applied.

- 2. The urgency of the error condition, i.e., how quickly must he get back to the set path? The pilot will want the error reduced rapidly if maintaining his present (incorrect) course leads to a hazard-ous situation (i.e., collision with a mountain or another aircraft).
- 3. Aircraft limitations, his desire for a smooth maneuver or passenger comfort, and the urgency of the situation will determine the trajectory to fly from his present position to a point on the set path. The most direct approach is to fly a heading perpendicular to the set path. This would, however, result in passing through the set path and an even larger deviation or overshoot on the other side. A more practical solution is to choose a trajectory which will reduce the course error more gradually and allow the pilot to roll out on the set path.
- 4. The "system model" of the aircraft (i.e., how the aircraft will react to a given control input). Through experience, the pilot knows his aircraft's response to a control change at a particular altitude, airspeed and aircraft configuration.

Based on these factors, the pilot formulates a control scheme to fly his aircraft to the set path. After the control has taken effect, he assesses the results and, if necessary, reformulates the problem.

During the landing phase, when course (and glide path) control is critical, the entire sequence can occur in less than a second.

OPC or MAC is an attempt to automate this type of process using a digital computer. The discrete impulse response model is used both to make an explicit prediction of future output responses using knowledge of past inputs and to compute alternative future control strategies. The one control strategy is then selected which gives the best match to

a desired future output trajectory. The output prediction and control computation are performed closed loop on a discrete sample by discrete sample basis.

Original applications included industrial process control where a priori models were not well understood (Ref 12). In these situations, on line identification of the discrete impulse response function model can be employed.

The control strategy has also been successfully applied to a number of aerospace problems (Ref 6,8) and theoretical investigations (Ref 7). In many of these aerospace applications, the system is very lightly damped, some nonminimum phase. In such situations, it was found that a direct application of the output predictive control strategy to force the output to follow the desired path exactly would lead to closed loop instability almost immediately (Ref 1). Specifically, it was found that the system could be made to follow the desired trajectory exactly, but only at the discrete sample times corresponding to a change in control. The response could be rapidly oscillating between control changes, leading to instability (Ref 1).

Problem and Scope

The objective of this thesis effort is to formulate and test a control strategy which will not only follow the desired trajectory at control change times, but also keep output oscillations within "acceptable" bounds between control changes.

Single-input/single-output (SISO) reduced order system models will be used to investigate the control technique for use as a regulator for a very lightly damped system and as a pitch controller for a fighter-type aircraft.

This report will not go deeply into the background theory of OPC; the interested reader is referred to References 6, 7, 8 and 12. This report will focus on the controller used to achieve the objective as listed above.

A complete computer program called IDCOM (Identification and Command) has been designed by the French company of Andersa/Gerbios to implement their version of the output predictive technique. IDCOM is not available for proprietary reasons, but the controller implemented in this thesis is conceptually similar.

Approach and Sequence of Presentation

The solution proposed in this report is to formulate the prediction/control computation so that the future output trajectory is calculated at a smaller sample spacing than the control switch times.

Trying to match the desired path at this finer spacing then creates an overdetermined, weighted least squares problem and allows prediction times into the future as long as are computationally feasible. The internal energy states (causing oscillations between control changes) are thus controlled indirectly by keeping the future output trajectory within a least squares "tube" rather than attempting to match the desired path exactly at only control switch times.

The theory and equations used in this scheme are presented in Chapter II. Internal parameters and the effect of their variations on the sampled output and control energy expended are discussed in Chapter III. A qualitative discussion of "robustness" in the presence of model mismatch is presented in Chapter IV. Application of the control scheme as a pitch controller for a reduced order model of a fighter aircraft is presented in Chapter V. Finally, conclusions and recommendations for further study are listed in Chapter VI.

II Theory

This chapter outlines the theory and equations underlying the output predictive controller that is developed. This development will be for the algorithm applied as a regulator. Modifications for application of the algorithm to the aircraft pitch controller and terrain following problems are discussed in Chapter V.

Figure 1 is a functional block diagram of the controller algorithm. In this formulation of OPC, a desired trajectory (y_d) is calculated from the point of the 'present' system output (y) to the set point (y_{set}) . A control input is calculated to zero out the difference (z) between the system's zero-input response (y_{zi}) and the desired trajectory (y_d) . The following sections explain each of the functional blocks in detail.

Discretization of System Model

This thesis treats the discrete time control of the nth order linear time invariant, single-input system represented as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \tag{1}$$

$$\underline{\mathbf{x}}(0) = \underline{\mathbf{x}}_0 \tag{2}$$

with single-output sampled at a constant sample time, T,

$$y(kT) = Cx(kT)$$
 (3)

Assuming a piecewise constant input, the discrete time model of the system (1) - (3) is then represented by

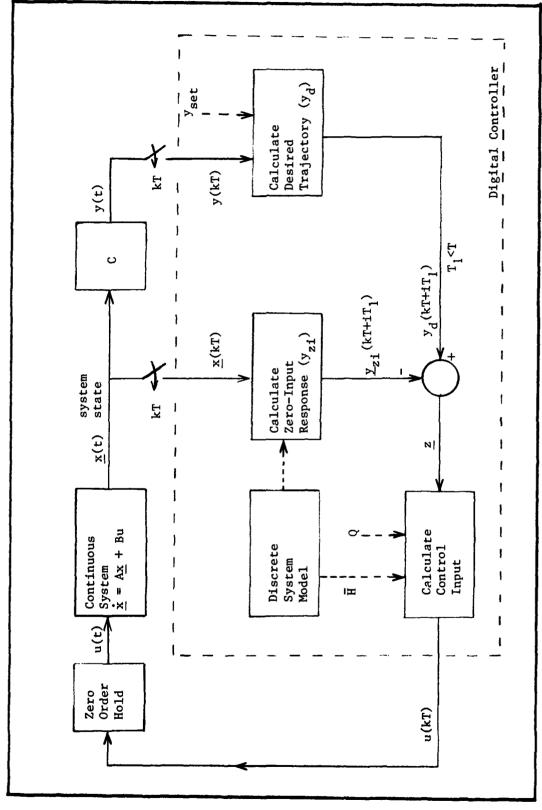


Fig 1. Functional Block Diagram of the Output Predictive Controller

$$\underline{\mathbf{x}}(\mathbf{k}+1) = F\underline{\mathbf{x}}(\mathbf{k}) + G\mathbf{u}(\mathbf{k}) \tag{4}$$

$$\underline{\mathbf{x}}(0) = \underline{\mathbf{x}}_0 \tag{5}$$

$$y(k) = Cx(k)$$
 (6)

where

$$\mathbf{F} \equiv \mathbf{e}^{\mathbf{A}\mathbf{T}} \tag{7}$$

$$G \equiv (\int_{0}^{T} e^{A\tau} d\tau) B$$
 (8)

The system (1) - (3) then has the discrete impulse response sequence (Ref 10,11) denoted as

$$\{h(1),h(2),h(3),\ldots\} = \{CG,CFG,CF^2G,\ldots\}$$
 (9)

or

$$h(i) = CF^{i-1}G \tag{10}$$

Control Objectives

The controller is first implemented as a regulator. As pictured in Figure 2, the system output is taken from an arbitrary initial point (state) along a reference output trajectory to a desired final value or set point. As an example, consider the pointing of a radar antenna aboard a ship rolling and tossing in rough water. If the desired antenna angle is constant at $\theta_{\mathbf{x}}$ (referenced to true north or some inertial reference) the set point for the regulator is $\theta_{\mathbf{x}}$. The controller's task then is to drive the antenna to, and keep it at, $\theta_{\mathbf{x}}$, regardless of the gyrations of the ship.

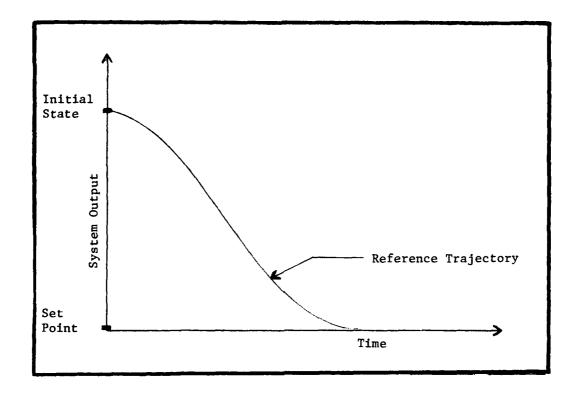


Fig 2. Controller Implemented as a Regulator

In the tracking application discussed in Chapter V, the controller is used as a pitch axis autopilot. Instead of a constant set point, the system is driven to a time varying commanded pitch angle as dictated by the requirement to fly along a given terrain profile.

Calculate Points Along Desired Trajectory

In the regulator implementation of the proposed controller, the reference or desired trajectory is chosen as a decreasing exponential with time constant Tau. Discrete points along the reference trajectory shown in Figure 2 can be calculated as

$$y_{d}(i) = y_{set} - \phi^{i}(y_{set} - y)$$
 (11)

where

 $y_d(i)$ = discrete point along desired path

 y_{set} = set point or where we want the system to go (for the regulator, $y_{set}^{=0}$)

y = 'present' output of the system

 \Rightarrow = exp ($-T_1/Tau$)

 $T_1 = \text{sample time at which } y_d(i) \text{ is calculated}$

Tau = time constant of first order decreasing exponential
 representing reference trajectory from y to y
set

Figure 2 illustrates the situation for initial start-up of the system.

For each subsequent iteration of the digital algorithm the "present"

system output is used for the initial state and a new reference trajectory is calculated for each iteration.

Zero-Input Response

The total system response can be represented as

$$y(t) = y_{zs}(t) + y_{zi}(t)$$
 (12)

where

 $y_{zs}(t) = zero-state response$

 $y_{zi}(t) = zero-input response$

If the system is started at rest (i.e., zero internal energy), the response to an input would be termed the system's zero-state response.

The system response at time k based solely on past inputs (i.e., all future inputs equal zero), is the zero-input response. The

zero-input response may be found in terms of the impulse response function (Ref 10,11) or in terms of the discrete system model equations as

$$y_{zi}(i) = CF^{i}\underline{x}(0)$$
 (13)

The algorithm is an iterative technique where the "present" time is always considered to be t=0. When the program is first started $\underline{x}(0)$ is the arbitrary initial state of the system. For each successive iteration $\underline{x}(0)$ is the actual system state, thereby closing the loop. It is beyond the scope of this thesis to consider the "state estimation problem," but clearly a closed loop estimator of the "state" is required for this particular implementation of the prediction calculation.

Control Calculation

It is desired that the system output match some reference path, or in equation form

$$y_d(i) = y(i)$$
; $i = 1, 2, ..., N$ (14)

where

 $y_d(i)$ = points along desired path

y(i) = system output

The discrete form of Eq (12) is substituted for the right side of Eq (14):

$$y_{d}(i) = y_{zi}(i) + y_{zs}(i)$$
 (15)

An expression relating $y_{zi}(i)$, the zero-input part of the response, to the current system "state" was given by Eq (13).

Using the ideas of a piecewise constant input and a discrete representation of the convolution integral (Ref 10) gives an expression for the zero-state response:

$$y_{zs}(i) = \sum_{j=1}^{i} h(j)u(i-j)$$
(16)

Substituting Eq (16) into Eq (15) and expanding yields

$$\begin{bmatrix} y_{d}(1) \\ y_{d}(2) \\ y_{d}(3) \\ \vdots \\ y_{d}(N) \end{bmatrix} = \begin{bmatrix} y_{zi}(1) \\ y_{zi}(2) \\ y_{zi}(3) \\ \vdots \\ y_{zi}(N) \end{bmatrix} + \begin{bmatrix} h(1)u(0) \\ h(2)u(0) + h(1)u(1) \\ h(3)u(0) + h(2)u(1) + h(1)u(2) \\ \vdots \\ N \\ \sum_{z} h(j)u(N-j) \\ j=1 \end{bmatrix}$$
(17)

This equation is solved, with no restrictions, in Ref 1 for the input as

$$u(0) = \frac{y_d(1) - y_{zi}(1)}{h(1)}$$
 (18)

This is, in effect, one step ahead prediction and led to instability.

If the problem is restricted to bring in the idea of "smoothing terms," or equivalently, if the input is held constant over NSM (number of smoothing terms) of the desired points ($y_d(i)$), an overdetermined least squares problem evolves. Figure 3 illustrates the concept of four smoothing terms within the span of one control input.

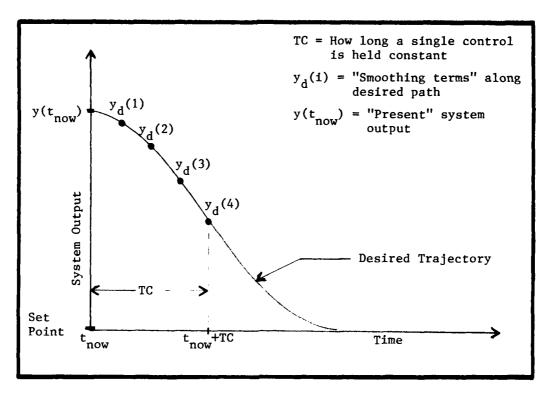


Fig 3. Four Smoothing Terms Within One Control Span (NSM=4)

A new set of controls can be defined as

where $\bar{u}(0)$ is not a row vector, but the value assigned to $u(0), u(1), \dots u(NSM)$.

Eq (19) can be substituted into Eq (17), then manipulated to yield

$$\underline{z} = \overline{\underline{H}\underline{u}} \tag{20}$$

$$\underline{\overline{u}} = \begin{bmatrix} \overline{u}(0) \\ \overline{u}(1) \\ \vdots \\ \overline{u}(L) \end{bmatrix}$$
(23)

Points along the desired trajectory, $y_d(i)$, and the zero-input response are still given by Eqs (11) and (13) respectively. $\overline{\underline{u}}$ is a vector of inputs with dimension "L," the number of future inputs to be calculated. \overline{H} is a matrix of impulse response functions, similar in information content to the Hankel matrix (Ref 11).

Eq (20) is a linear equation which can be solved for $\underline{\bar{u}}$. If the control problem is reformulated using the smoothing terms approach, the result is an overdetermined problem; the "best" solution for $\underline{\bar{u}}$ is a weighted least squares "curve fit." The cost function can be defined as

$$J = (z - \overline{H}\overline{u})'Q(z - \overline{H}\overline{u})$$
 (24)

where Q is a positive, semi-definite weighting matrix.

For computational simplicity, one can also choose for it to be diagonal. The influence of Q on the controller performance will be discussed in detail in Chapter III.

One way to solve the least squares approximation is to develop the Normal Equation (Ref 5:122-129; Ref 9:72,222-224). Taking the partial derivative of J with respect to $\underline{\bar{u}}$, setting the result equal to zero and solving for $\underline{\bar{u}}$ will yield the Normal Equation:

$$\frac{\partial J}{\partial \bar{u}} = -2(\underline{z} - \bar{H}\underline{u}) \hat{Q}\bar{H} = 0$$
 (25)

Taking the indicated transpose and solving the equation for $\overline{\underline{u}}$ yields

$$\underline{\mathbf{z}} \hat{\mathbf{Q}} \bar{\mathbf{H}} = \underline{\bar{\mathbf{u}}} \hat{\mathbf{H}} \hat{\mathbf{Q}} \bar{\mathbf{H}}$$
 (26)

$$\underline{\overline{u}}' = \underline{z}' Q \overline{H} (\overline{H}' Q \overline{H})^{-1}$$
 (27)

or

$$\underline{\bar{\mathbf{u}}} = (\bar{\mathbf{H}}' \mathbf{Q} \bar{\mathbf{H}})^{-1} \bar{\mathbf{H}}' \mathbf{Q} \underline{\mathbf{z}}$$
 (28)

The dimensions of the elements of Eq (28) are

 $\overline{\underline{\mathbf{u}}} = \mathbf{A}\mathbf{n}$ L dimension vector

 $\vec{H} = An \quad (NSM*L)XL \quad matrix$

Q = An (NSM*L)X(NSM*L) matrix

z = An (NSM*L) dimension vector

Due to the fact that $\,Q\,$ is a diagonal matrix and all of the real information contained in $\,\overline{H}\,$ is found in the first column, a memory saving FORTRAN coding technique was proposed by Dr. J. G. Reid and implemented by the author. This technique is illustrated by the solution of the normal equation for a simple example problem in Appendix A.

Eq (28) is used to solve for a vector of inputs $\underline{\underline{u}}$. In terms of on-line implementation, only the first element of $\underline{\underline{u}}$ is used. The problem is reformulated with each iteration and a new $\underline{\underline{u}}$ vector found.

Application of Control

After the control has been found, the system state is updated:

$$\underline{\mathbf{x}}(\mathbf{k}+1) = F\underline{\mathbf{x}}(\mathbf{k}) + G\overline{\mathbf{u}}(0) \tag{29}$$

 $\bar{u}(0)$ is the first element of the vector of controls found using Eq (28). The output of the system can now be found as

$$y(k) = C\underline{x}(k) \tag{30}$$

Summa: y

The general sample times and index of Figure 1 can now be defined. The overall sample time, T , is the control change time, TC . The system model is discretized at a sample time T_1 =TC/NSM . The desired trajectory (y_d) and zero input response function (y_{zi}) are predicted i=1,2,...NSM*L discrete points into the future.

The relationships developed in this chapter have been coded in FORTRAN. Appendix B contains a sample program. Embodied in the program listed are the options of adding zero-mean white Gaussian noise to the sampled input and/or control calculated. Model mismatch options are also provided. These features are discussed in Chapter IV.

A very lightly damped fourth order system (see Chapter III) is chosen as a test model for the regulator and the results of variations of the internal parameters used by the controller

TC = Time span of one control input

Tau = Time constant of reference trajectory

L = Number of future inputs calculated per iteration

Q = Weighting matrix

NSM = Number of smoothing terms calculated per control

NSM*L = Total number of output points predicted into the
 future

are recorded. The effect on the system output and control energy

required to drive the system to a zero set point for various combinations of internal parameters are the subjects of Chapter III.

III Internal Parameter Variation and Results

The hypothetical regulator described in Chapter II is applied to a lightly damped fourth order system. Throughout this chapter, the control objective is to take the system output from an arbitrary initial state, along an exponential path, to a zero set point. The results of variations of the internal parameters Tau, Q , NSM , L and TC were graphically recorded. Only a few of the infinite number of possible combinations are presented. Because of the interdependence of the parameters, only a general idea of the effects of variations of a particular parameter is possible.

An arbitrary initial state and C matrix are chosen as

$$\underline{\mathbf{x}}_{0}^{\prime} = [20 \quad 10 \quad 5 \quad 0]$$
 (31)

$$C = [1 \quad 0 \quad 0 \quad 0]$$
 (32)

for demonstration of the characteristics of the controller. A random number generator was used at one time to generate an initial state; however, the general characteristics exhibited by the controller were unchanged.

System Model

An all pole fourth order system, described by the differential equation

$$\ddot{y}$$
 (t) + 1.6 \ddot{y} (t) + 274 \ddot{y} (t) + 279 \dot{y} (t) + 8612 y (t) = u(t) (33)

is chosen as the system model. y(t) is defined as an arbitrary output and u(t) as an arbitrary input. The eigenvalues

$$\lambda_{1,2} = \sigma \pm j\omega_d = -0.25 \pm j15.4$$
 (34)

$$\lambda_{3,4} = \sigma \pm j\omega_{d} = -0.55 \pm j6.0$$
 (35)

are representative of the first and fifth aeroelastic modes of the B-52 Control Configured Vehicle airspeed root locus (Ref 1:8,18; Ref 2:2-20). Figure 4 shows the fourth order system's open loop time response for a unit step input.

Variation of Time Constant of the Exponential Reference Trajectory Tau

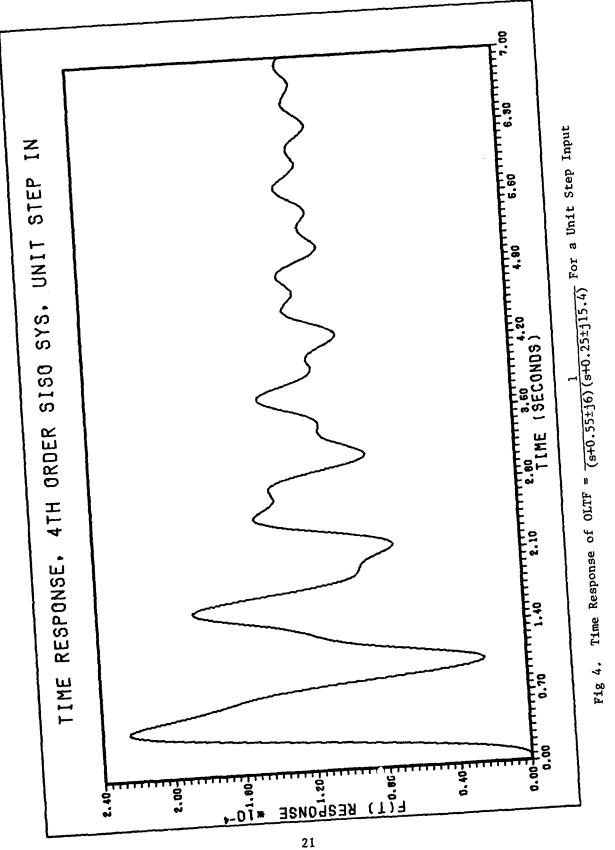
In the regulator application, an exponential path is chosen as the reference trajectory or desired path to the set point. Tau, the time constant of the exponential path, is a measure of how quickly the system output is driven to the set point.

Figure 5 shows the system output for Tau = 0.1 and Tau = 0.3.

Predictably, as the system output is brought to the set point more rapidly, the magnitude of the controls required increases. This is shown in Figures 6 and 7.

Variations in the Weighting Matrix -- Q

The Q matrix in Eq (28) is defined as a positive semi-definite, diagonal weighting matrix. In the overdetermined least squares problem



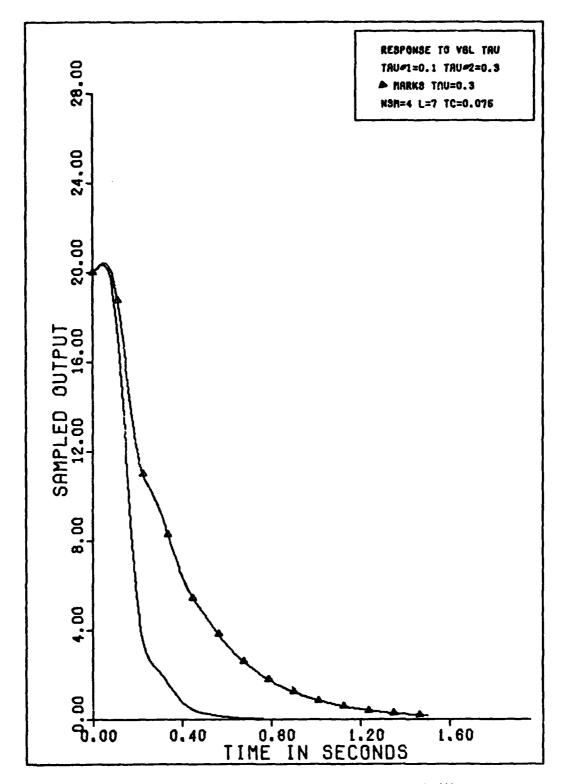


Fig 5. System Output for Tau=0.1 and Tau=0.3 (Δ)

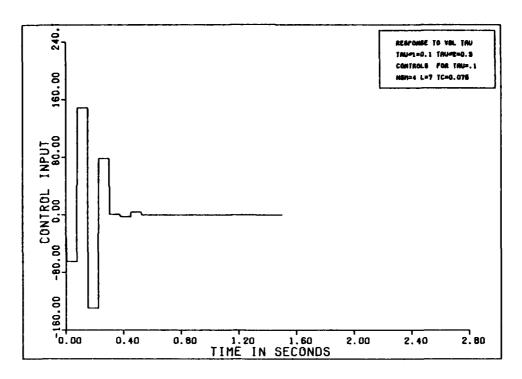


Fig 6. Controls Applied for Tau=0.1

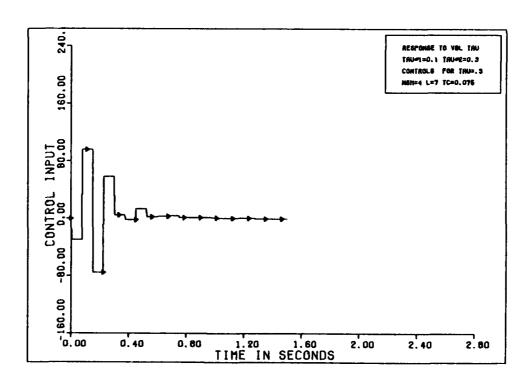


Fig 7. Controls Applied for Tau=0.3

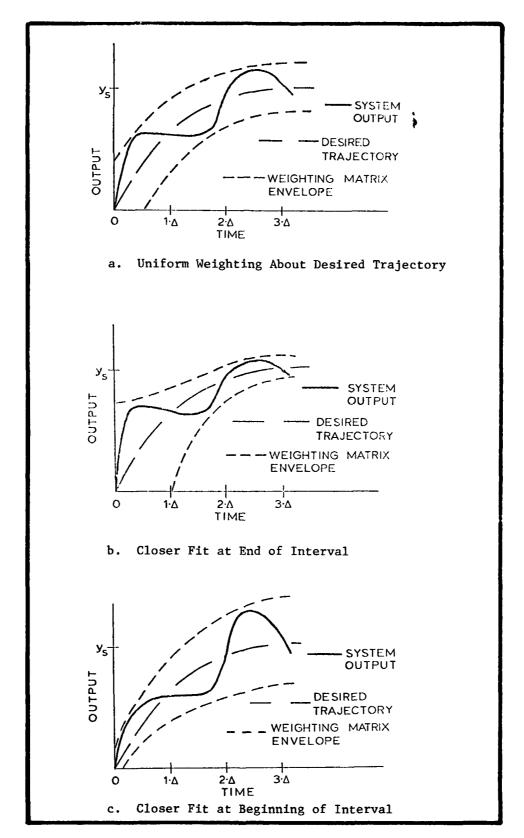


Fig 8. Different Possible Output Constraints Defined by the Weighting Matrix Q (Ref 1:79,81-82)

formulated to find the optimal control input, the relative sizes of the elements of the Q matrix define the shape of a tube (MIMO) or envelope (SISO) along the desired trajectory. In the least squares problem formulation, the output of the system is optimized to stay within the envelope (tube), as indicated in Figure 8.

The weighting matrix used to generate the envelope illustrated by Figure 8a is the identity matrix:

Q1 = Diagonal
$$[1,1,...,1]$$
 (NSM*L) $X(NSM*L)$ (36)

Several alternative matrices are used to achieve the general effect illustrated in Figure 8b.

where each sub-block is NSM elements long

Q3 = Diagonal[1,2,4,8,16,...] (NSM*L)
$$X(NSM*L)$$
 (38)

Q4 = Diagonal[1,1,..,1;
$$10^6$$
, 10^6 ,.., 10^6]_(NSM*L)X(NSM*L) (39)

The progressive application of Q2 , Q3 and Q4 results in the tube being squeezed tighter along the latter points of the interval (i.e., the oscillation of the system output about the desired trajectory is being progressively constrained). For the regulator applied to the fourth order system discussed earlier, the use of Q4 results in the output closely approximating the desired path.

The weighting matrix denoted as Q4 is used as a "bench mark" for comparison of the system output and controls required for variations

of the Q matrix. Figures 9 through 17 show the system output and control inputs required for Q1 , Q2 and Q3 versus Q4's use as the weighting matrix. In the parameter identification boxes (upper right corner of each graph), Q1 is referred to as "Identity Weighting," Q2 is referred to as "Block Weighting," Q3 as "Geometric Weighting" and Q4 as "MOD 2 Weighting."

A desire to have the system output initially follow the desired trajectory very closely and allow deviations from the desired path to increase with time is indicated in Figure 8c. The weighting matrix formulated to do this is

Q5 = Diagonal[...,32,16,8,4,2,1]
$$(NSM*L)X(NSM*L)$$
 (40)

Figures 18 and 19 show the system output and controls with Eq (40) as the weighting matrix. Scaling of the plots masks the fact that the system goes unstable almost immediately.

The choice of the weighting matrix to be utilized is, of course, application dependent. Natural damping of the system, allowable peak overshoot and specified settling time are all factors in the selection of Q . All of these specifications are reflected in the envelope (tube) shape selected from Figure 8. In this regulator application, with a very lightly damped system model, a trade-off between "nice" system response and the control energy required is apparent.

For the regulator applied to a very lightly damped system, utilization of a weighting matrix similar to Q3, Eq (38), or Q4, Eq (39), gives the best results. Use of Eq (40) is clearly a "bad" approach.

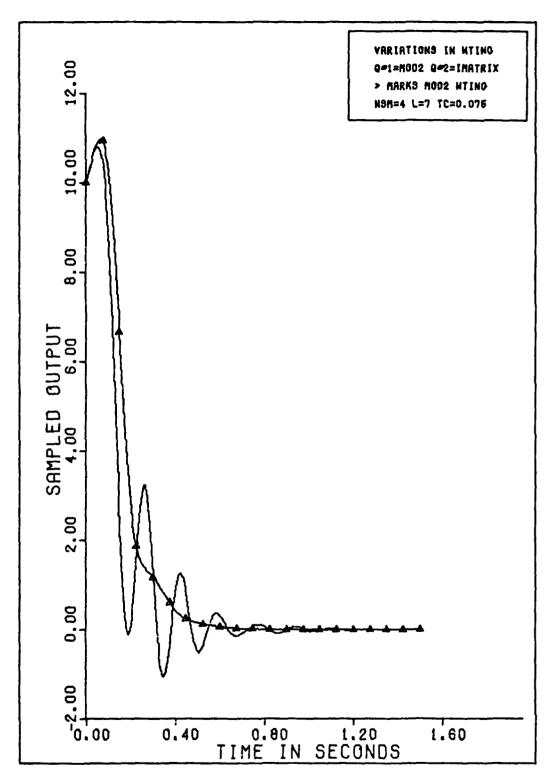


Fig 9. Sampled Output for Q4 (Δ) and Q1 Used as the Weighting Matrix

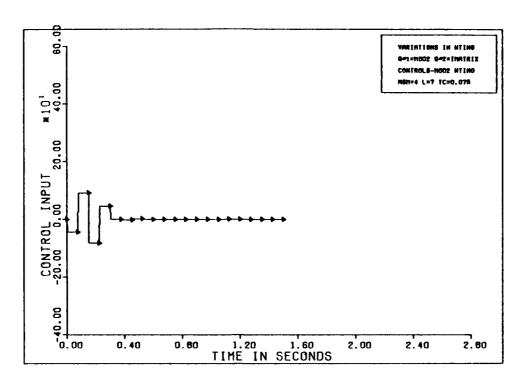


Fig 10. Controls Applied When Using Q4 as the Weighting Matrix

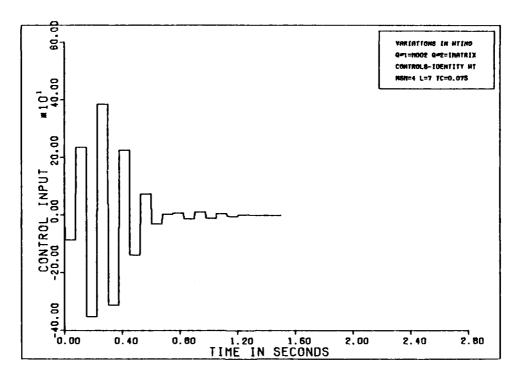


Fig 11. Controls Applied When Using Ql as the Weighting Matrix

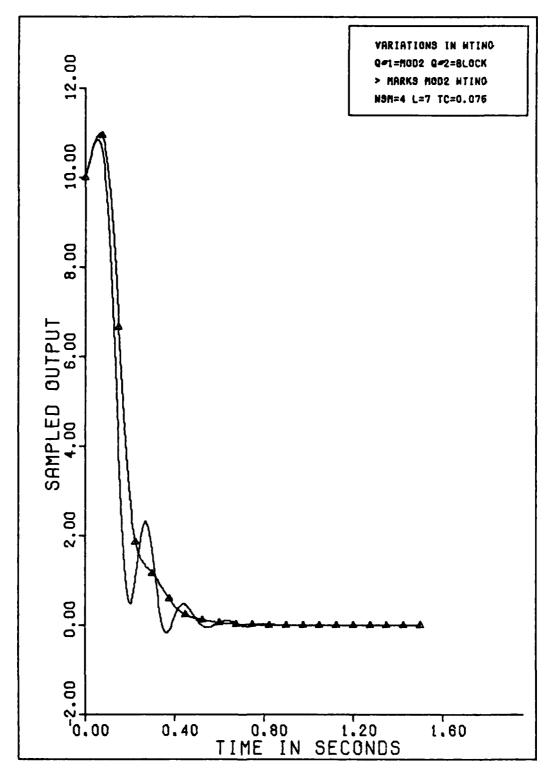


Fig 12. Sampled Output for Q4 (Δ) and Q2 Used as the Weighting Matrix

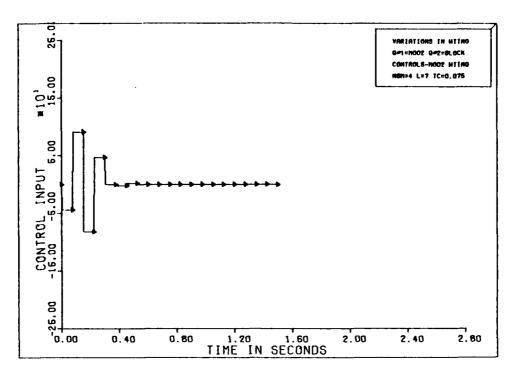


Fig 13. Controls Applied When Using Q4 as the Weighting Matrix

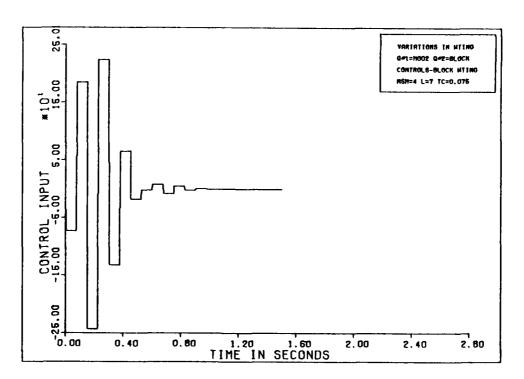


Fig 14. Controls Applied When Using Q2 as the Weighting Matrix

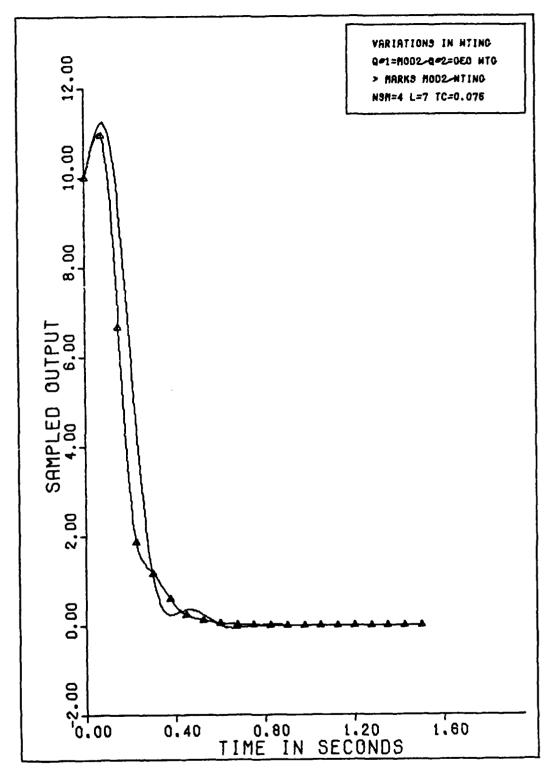


Fig 15. Sampled Output for Q4 (Δ) and Q3 Used as the Weighting Matrix

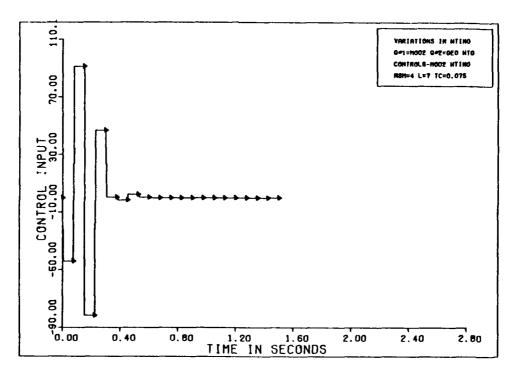


Fig 16. Controls Applied When Using Q4 as the Weighting Matrix

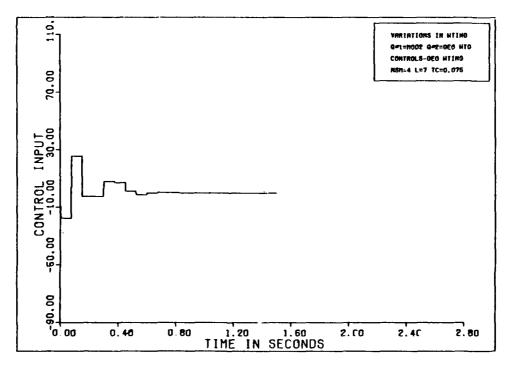


Fig 17. Controls Applied When Using Q3 as the Weighting Matrix

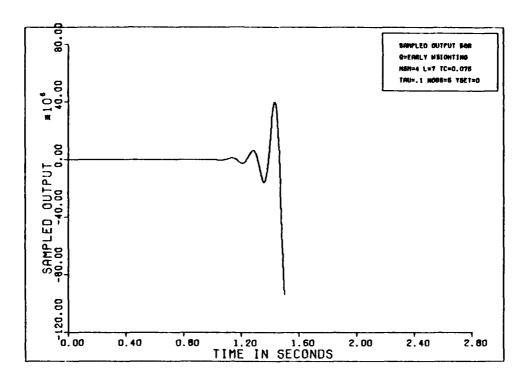


Fig 18. Sampled Output for Q5 Used as the Weighting Matrix

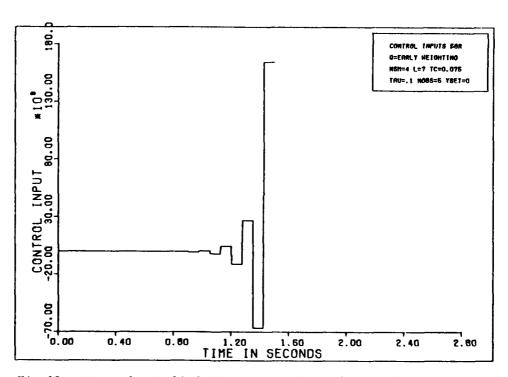


Fig 19. Controls Applied When Using Q5 as the Weighting Matrix

Variation of Number of Smoothing Terms -- NSM

As the number of smoothing terms per control change is increased, the system response time increases, as seen in Figure 20. The initial increase from NSM=2 to NSM=4 smooths the response. However, a further increase to NSM=10 reintroduces oscillations in the output.

Figures 21 through 23 show the controls applied for each case.

As NSM is increased, there is a substantial decrease (note factor of 10 on controls for NSM=2) in the control energy required to bring the system to the zero set point. As the number of smoothing terms increases (i.e., the reference trajectory becomes better defined), less control energy is expended in controlling overshoots.

Variation of Number of Future Controls Calculated -- L

The solution of the Normal Equation (28) is a vector of control inputs with length or dimension L . The quantity "L*TC" is a measure of how far in the future both prediction and calculations are carried out. The vector of controls could be sequentially applied; however, in this controller only the first element of the control vector is applied and the problem reformulated at each iteration. Figure 24 shows how variations in L affect the system output.

Increasing from L=3 to L=4 damps the large oscillations and increases the system response time. Also investigated (but not shown) is an increase to L=10 which further slows the system response and reintroduces some low amplitude oscillation.



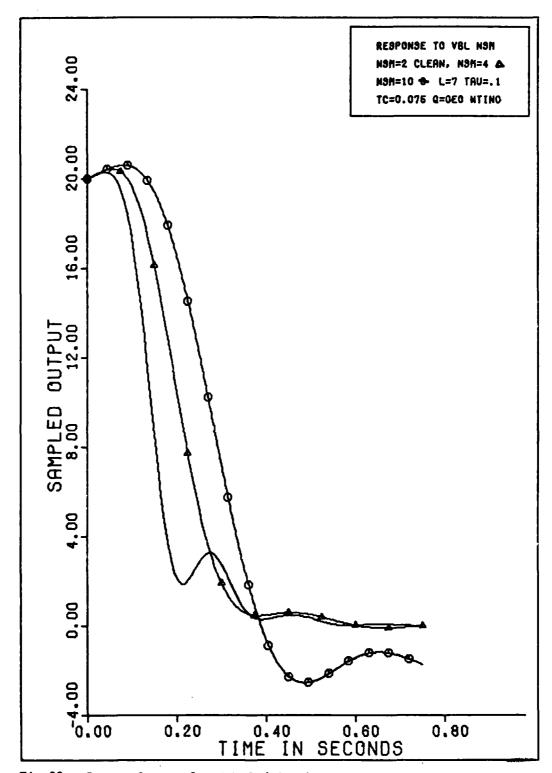


Fig 20. System Output for NSM=2 (Clean), NSM=4 (Δ) and NSM=10 (\emptyset)

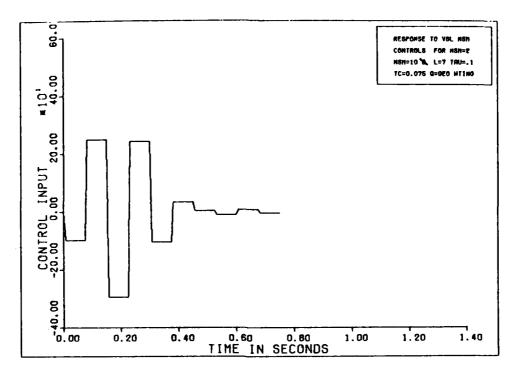


Fig 21. Controls Applied for NSM=2

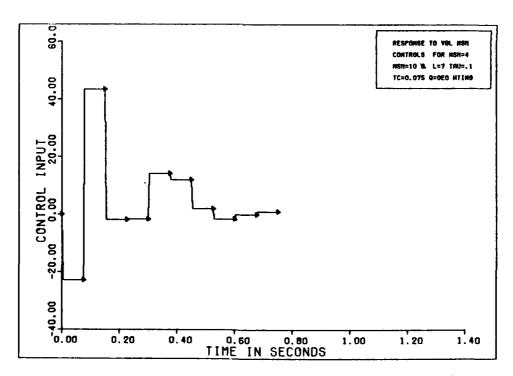


Fig 22. Controls Applied for NSM=4

-

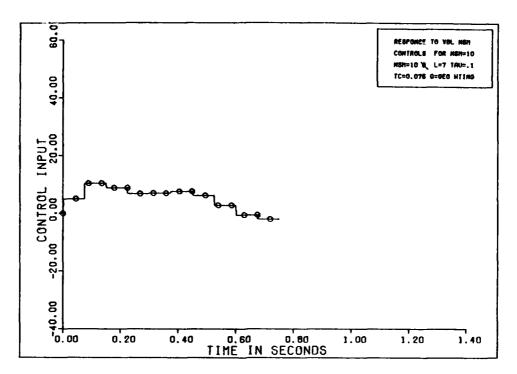


Fig 23. Controls Applied for NSM=10

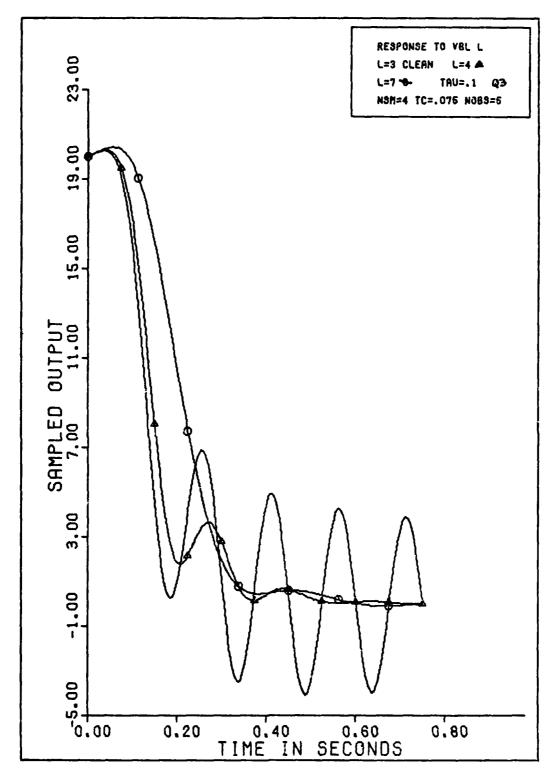


Fig 24. Sampled Output for L=3 (Clean), L=4 (Δ) and L=7 (\emptyset)

Figures 25 through 27 show that as L is increased, there is a decrease in the control energy required to bring the system to the zero set point.

The introduction of oscillations into the output for L>7 and large reduction in control energy required as L increases can be explained through an analysis of the weighting matrix (Eq (38)) utilized, and the fact that the time interval in question is increasing as L increases. Use of Q3 reflects a desire for a closer fit of the output to the desired trajectory toward the end of the time interval. This is indicated by Figure 8b. As the time interval of calculation is increased by increasing L , larger deviations are tolerated early in the time interval. As less weighting is given the early deviations, less control energy is spent trying to match the desired path during the period where it (the desired path) is rapidly changing.

A good initial guess for L is 2*N, where N is the dimension of the state vector. The final value of L chosen depends on the specifications for system response time and control input limitations.

Variations in the Time Span of Each Control -- TC

Other than a slight increase in system response time, Figure 28 indicates no real change in system output for variations in TC. There is, however, a dramatic change in control energy requirements as indicated by Figures 29 through 31.

A direct design procedure for selection of the "optimal" sample time to maximize closed loop robustness (robustness is discussed in Chapter IV) is developed in Ref 11. This technique was designed for

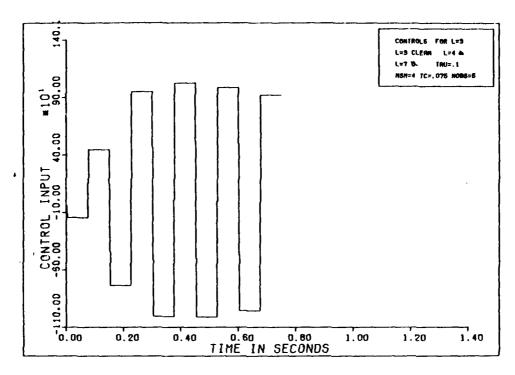


Fig 25. Controls Applied for L=3

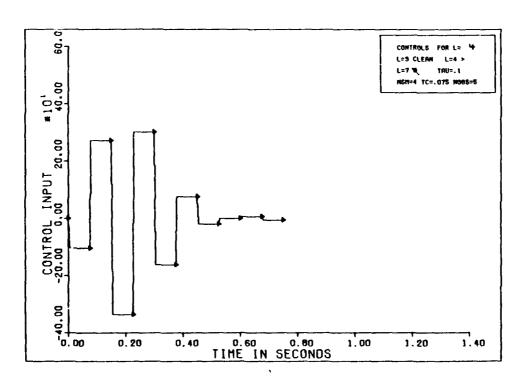


Fig 26. Controls Applied for L=4

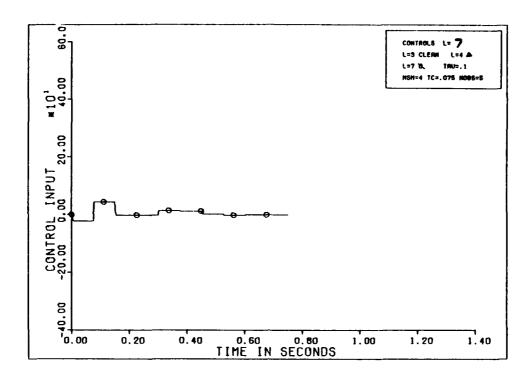


Fig 27. Controls Applied for L=7

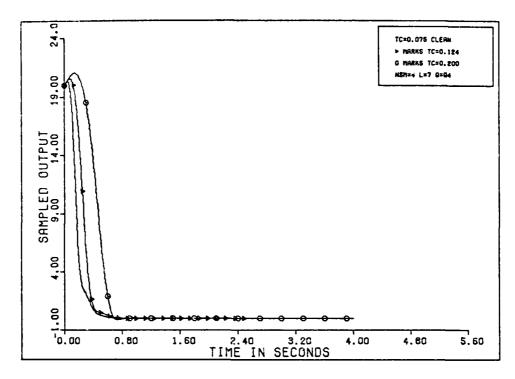


Fig 28. System Output for TC=0.075 (Clean), TC=0.124 (Δ) and TC=0.200 (\emptyset)

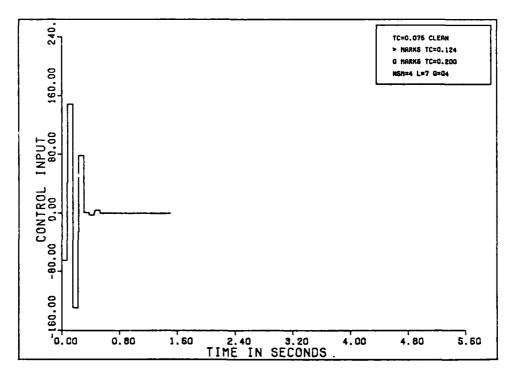


Fig 29. Controls Applied for TC=0.075

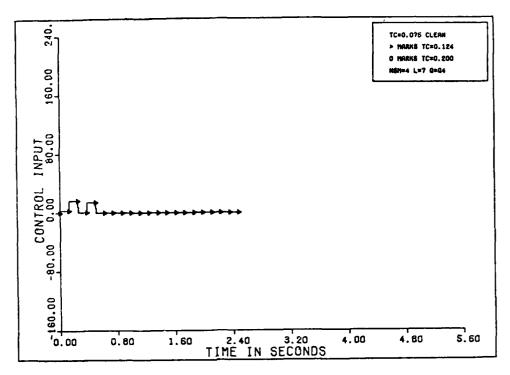


Fig 30. Controls Applied for TC=0.124

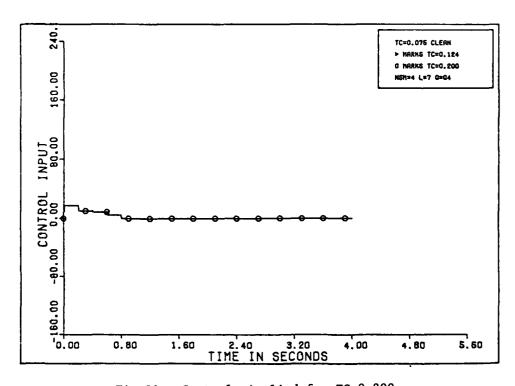


Fig 31. Controls Applied for TC=0.200

use with the Output Predictive Dead-Beat Controller (OPDEC) when investigating model mismatch. The basic procedure used is to investigate the reciprocal condition number, $1/\kappa$, of the Hankel matrix (H_n) as a function of sample time.

$$1/\kappa = \sigma_{\min}/\sigma_{\max} \tag{41}$$

where

 $1/\kappa$ = Reciprocal condition number

 σ_{\min} = Minimum singular value (minimum magnitude eigenvalue of $H_n^T H_n$) of the Hankel matrix

 σ_{max} = Maximum singular value of the Hankel matrix

Choice of the Hankel matrix for investigation stems from analyzing the equation used for calculation of the inputs for the OPDEC (Ref 11):

$$H_{n-} = -y_{zi} \tag{42}$$

where

H_n = Hankel matrix

u = Vector of control inputs

y_{zi} = Vector of zero-input responses

Using the same logic, the matrix in the Normal Equation to be investigated is $[\bar{H}'Q\bar{H}]$.

The sample time that maximizes $1/\kappa$ is hypothesized to be the "optimal" control change time (TC) for the minimization of perturbation effects (model mismatch, input and measurement noises) on the system. It is also a realistic initial choice for TC , without regard

to any perturbation of the original system. Figure 32 is a plot of $1/\kappa$ of $[\overline{H}'Q\overline{H}]$ for the system model. Relative peaks in $1/\kappa$ occur at approximately 0.088 and 0.124 with valleys at 0.075 and 0.200. Although Figure 28 shows no real change in system response for variance of TC , selection of TC=0.124 will yield a much better response when the "original" system model is in error (i.e., model mismatch). This will be shown in Chapter IV.

Nonminimum Phase Systems

A brief investigation of a nonminimum phase system (i.e., system zeroes in the right-half plan (RHP)) is discussed in this section. It is hypothesized that selection of Tau, Q and NSM is the same as for the basic system with no zeroes in the RHP; however, because of the inherent difficulty in controlling a nonminimum phase system, the controller should look further into the future (increase in L) for calculation of the controls. The reciprocal condition number of $[\overline{H}'Q\overline{H}]$ built from the nonminimum phase system's equation is used to find TC .

If a zero at S=+0.3 is added to the original system, the open loop transfer function (OLTF) becomes

OLTF =
$$\frac{(s-0.3)}{(s+0.55\pm j6)(s+0.25\pm j15.4)}$$
 (43)

Figure 33 is a plot of the reciprocal condition number of $[\widetilde{H}^{\prime}Q\widetilde{H}]$ for the system model of Eq (43). Initially the dimension of $\underline{\widetilde{u}}$ is fixed at L=7, the "best" value for the original (minimum phase) system model. Figures 34 through 37 show the system output and controls for TC=0.125 TC=0.180 (good sample times) and TC=0.205 (bad choice, according to

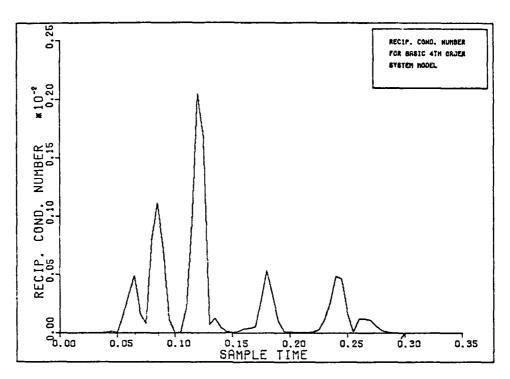


Fig 32. Reciprocal Condition Number of $[\overline{H}\,\,{}^{'}Q\overline{H}\,]$ Using the Basic System Model

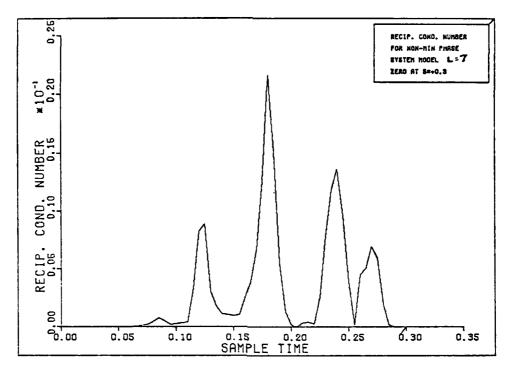


Fig 33. Reciprocal Condition Number of $[\overline{H}\,\,{}^{'}Q\overline{H}\,]$ Using the Nonminimum Phase System Model

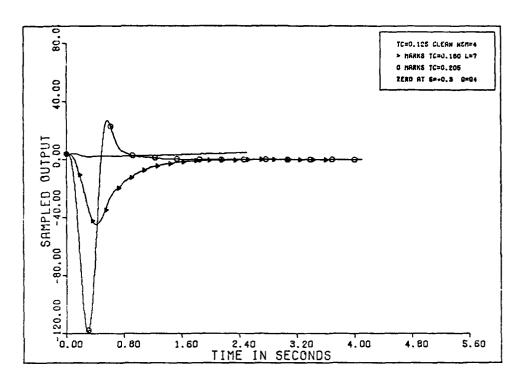


Fig 34. Sampled Output of Nonminimum Phase System for TC=0.125 (Clean), TC=0.180 (Δ) and TC=0.205 (\emptyset); L=7

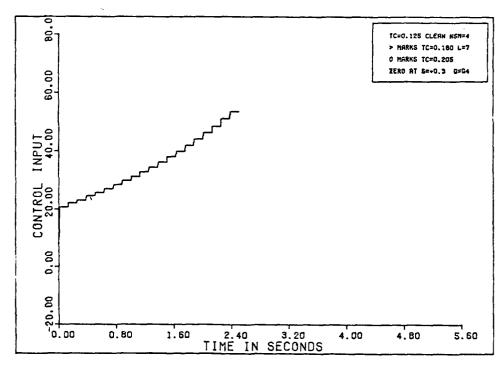


Fig 35. Controls for TC=0.125, L=7

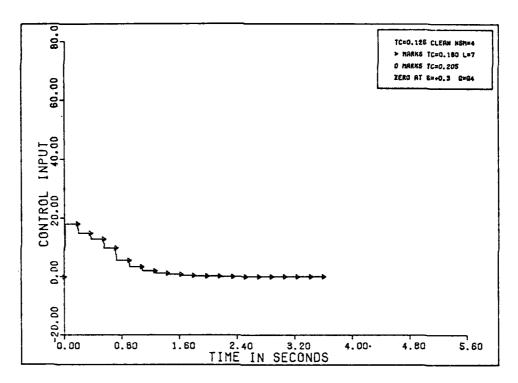


Fig 36. Controls for TC=0.180, L=7

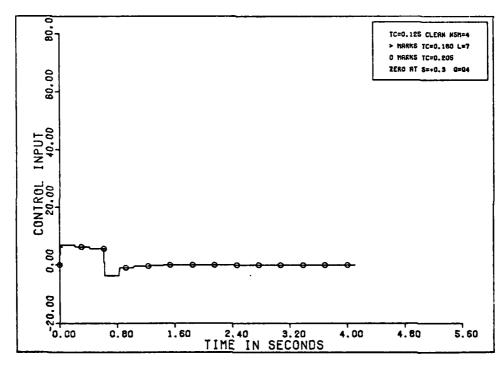


Fig 37. Controls for TC=0.205, L=7

Figure 33). An interesting observation is that for TC=0.125, a supposedly "good" sample time for minimization of the effect of perturbation of the system model, the system goes unstable. This is easier to see in Figure 35, a plot of the controls for TC=0.125. Although there is a large transient with TC=0.205, the output is driven to (and kept at) the zero set point.

It is hypothesized that control of the nonminimum phase system is improved by allowing the controller to look further into the future. Figures 38 through 41 show the results of using the same sample times as above, but increasing the dimension of \bar{u} to L=10. Instead of instability, using TC=0.125 results in the "best" response of the three sample times.

This limited analysis has not addressed all of the questions concerning control of the nonminimum phase system; however, the main factor in successful application of the hypothetical regulator to a nonminimum phase system is an increase in L over that used to control the basic all pole system.

Summary

An ironclad synthesis technique is not possible at this stage of development of the controller; however, the following guidelines are presented for selection of the internal parameters for control of the all pole system:

1. Specifications for settling time, response time and maximum allowable overshoot can be reflected in the tube shapes (Figure 8) defined by the elements of the weighting matrix. For the regulator

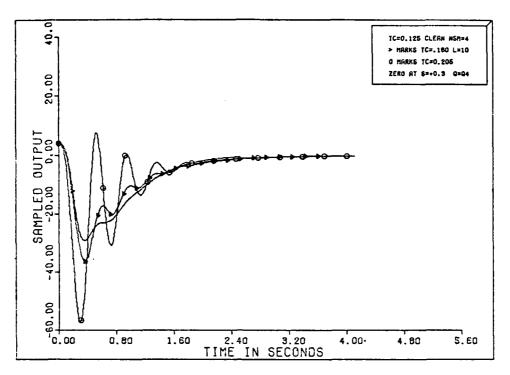


Fig 38. System Output of Nonminimum Phase System for TC=0.125 (Clean), TC=0.180 (Δ) and TC=0.205 (\emptyset); L=10

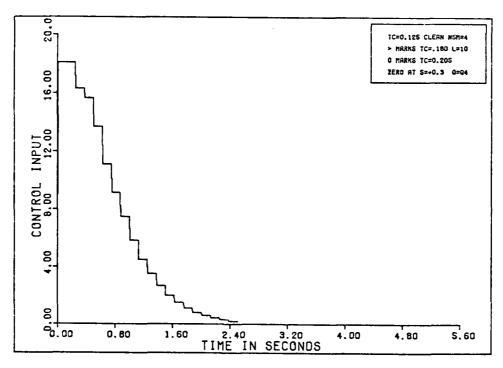


Fig 39. Controls for TC=0.125, L=10

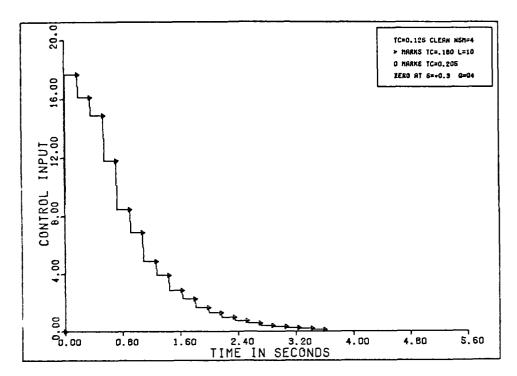


Fig 40. Controls for TC=0.180, L=10

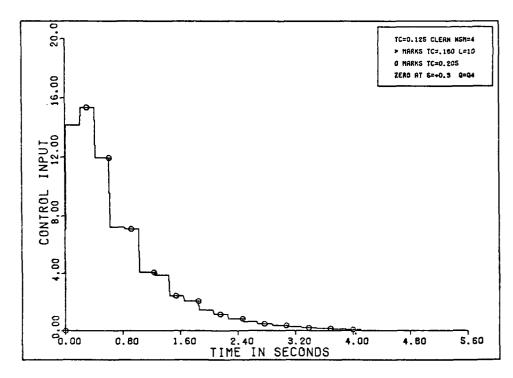


Fig 41. Controls for TC=0.205, L=10

applied to a lightly damped system, the weighting matrices identified in Eqs (38) and (39) gives a good system response. Eq (40), reflecting the tube shape indicated in Figure 8c is clearly a bad choice.

- 2. The sample time which maximizes the reciprocal condition number of $[\overline{H}^*Q\overline{H}]$ is chosen as TC , the length of time a control is held constant. Although this selection process may not result in the best TC for an unperturbed system model, it is a good initial choice.
- 3. Tau is a reflection of how quickly the error between the desired and actual paths is brought to zero. Selection of Tau is dependent on the specified system response time. Its value will affect the control energy expended in taking the system output to the desired set point.
- 4. The number of smoothing terms (NSM) utilized depends on the shape of the desired path. A sufficient number of smoothing terms must be utilized to characterize the reference trajectory. For the first order exponential trajectory utilized in the regulator application, few smoothing terms are needed. As NSM is increased, resulting in a better defined reference path for solution of the least squares problem, the controls needed to drive the system output to the set point decreases. For the regulator example, 2≤NSM≤7 works well.
- 5. An initial value for the number of future controls calculated (L) per iteration is 2n ; where 'n' is the order of the system model or dimension of the state vector. The final value of L chosen has a dramatic effect on control energy expenditures as well as system response time. L=7 is the choice for the regulator example. Variations from this introduces oscillations in the output.

For the nonminimum phase system, the same values for Tau, Q and NSM are applicable. The sample time which maximizes the reciprocal condition number of $[\overline{H}'Q\overline{H}]$ for the system equations is a good choice for TC . L must be increased over that used for the all pole system to facilitate control. Control of the nonminimum phase system is not fully understood at this point.

After an initial set of internal variables is selected, a scheme of parameter variation is necessary to get the best set of parameters for the particular application.

There are several interesting relationships between this "smoothing approach" and the Output Predictive Dead-beat Controller (OPDEC) discussed in Refs 3 and 11. Selection of L=2n and Q=Q4 given by Eq (39) for implementation of the "smoothing approach" is actually an approximation of the scheme used in the OPDEC approach and gives much the same kind of performance as OPDEC itself.

IV Perturbations of the System Model

For many practical problems, the true system model is unknown or the system dynamics change with environmental conditions. An example of such a system is an aircraft for which the flight characteristics change as a function of altitude, airspeed, attitude or some other parameter. Either of the above situations can be considered a case of model mismatch; that is, the actual system equations differ from the system model used in designing the controller. In this thesis, model mismatch is simulated by perturbation of the eigenvalues of the plant or "A" matrix. The technique for selection of the best value of TC (see Chapter III) for closed loop "robustness" is tested in the model mismatch simulation.

The original example system model developed in Chapter III is used in this chapter. The controller is applied as a regulator with the control objectives as listed in Chapter II. The initial state and output relationship are as given by Eqs (31) and (32).

Robustness

A robust controller is one that continues to perform properly despite system perturbations (i.e., model mismatch and noise corrupted information fed back to the controller). For an analytical discussion of robustness, see Refs 7 and 11. For this analysis robustness is measured in terms of stability only.

Model Mismatch

For discussion of model mismatch, several system models are defined - the Truth model and Delta models. The Truth model is the original system represented by Eq (33). A Delta model is formed by changing the natural frequencies associated with each of the eigenvalues of the original system by 10%, 20% or 30%. Table I lists the OLTFs for each model.

TABLE I

System Models Utilized in Model Mismatch Analysis

	 	
System Model	OLTF	
Truth	1 (s+0.55±j6) (s+0.25±j15.4)	
Delta l	1	
(+10% eigenvalue change)	(s+0.605±j6.6) (s+0.275±j16.94)	
Delta 2	1 (s+0.66±j7.2) (s+0.3±j18.4)	
(+20% eigenvalue change)		
Delta 3	1	
(+30% eigenvalue change)	(s+0.715±j7.8) (s+0.325±j20.2)	

The regulator is, of course, designed for use with the Truth model. Model mismatch occurs whenever the discrete matrix representation of one of the Delta models is used in calculation of the control and/or prediction of the zero-input response. One entry point into the control calculation is through the $\overline{\mathbb{H}}$ matrix, given by Eq (22). Each

element of H is given by

$$h(i) = CF^{i-1}G \tag{10}$$

The zero-input response prediction is given by

$$y_{zi}(i) = CF^{i}\underline{x}(0)$$
 (13)

Both \tilde{H} and y_{zi} are contained within the Normal Equation (28) used to find the input. In this analysis, however, they are considered separately as independent entry points for the discrete matrices describing the Delta models.

Model Mismatch Simulation Results

The basic regulator described in Chapter II is augmented with a series of logical switches (see Appendix A) allowing the Delta model matrices to be used for prediction of y_{zi} and/or calculation of \tilde{H} . Tables II and III summarize the results of the simulation for selected values of TC . Figures showing the system output and controls applied are in Appendix C. Figures are included for those cases where the system is slowly going unstable.

Selection of the various values of TC for the model mismatch simulation was made with Figure 42 in mind. In Chapter III it is hypothesized that the discrete time which maximizes $1/\kappa$ of $[\widetilde{H}^{\prime}Q\widetilde{H}]$ is the best TC for closed loop robustness of the controller. In relation to the value of TC , the following observations are made concerning Tables II and III:

TABLE II

Summary of Results for Perturbed or Delta Models Used to Calculate the Zero-Input Response

System Model	TC (sec)	Results
Delta l	0.075	stable (Figure C-1)
(10% eigenvalue change)	0.088	stable (Figure C-4)
	0.124	stable (Figure C-7)
	0.200	unstable
Delta 2	0.075	stable (Figure C-10)
(20% eigenvalue change)	0.088	stable (Figure C-13)
	0.124	unstable (Figure C-16)
ļ	0.200	unstable
Delta 3	0.075	stable (Figure C-19)
(30% eigenvalue change)	0.088	stable (Figure C-22)
	0.124	unstable
	0.200	unstable

TABLE III $\begin{tabular}{ll} \textbf{Summary of Results for Perturbed or Delta Models} \\ \textbf{Used to Find \widetilde{H}} \end{tabular}$

System Model	TC (sec)	Results
Delta 1	0.075	stable (Figure C-25)
(10% eigenvalue change)	0.088	stable (Figure C-28)
	0.124	stable (Figure C-31)
	0.200	unstable
Delta 2	0.075	unstable (Figure C-34)
(20% eigenvalue change)	0.088	stable (Figure C-37)
	0.124	stable (Figure C-40)
	0.200	unstable
Delta 3	0.075	unstable (Figure C-43)
(30% eigenvalue change)	0.088	stable (Figure C-46)
	0.124	stable (Figure C-49)
	0.200	unstable

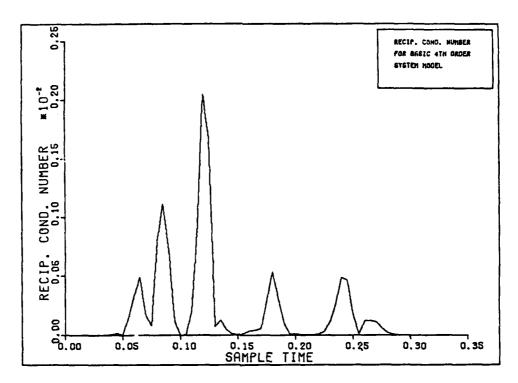


Fig 42. Reciprocal Condition Number of $[\overline{H}\,\,{}^{'}Q\overline{H}\,]$ for the "Truth" or Basic System Model

- From Table II, stability is maintained for all Delta models only with the smallest values of TC (0.075 and 0.088).
- 2. For TC=0.200 , the system is unstable for all Delta models to both $\bar{\rm H}$ and $y_{z,i}$.
- 3. From Table III, the only control change times for which stability is maintained for all Delta models correspond to the "peaks" in Figure 42.

As TC increases, the time span of the zero input response prediction also increases, thus amplifying the error involved when using a Delta model for prediction of y_{zi} . For any practical application of the controller, closed loop prediction would be accomplished through implementation of an observer or Kalman filter for use directly in the control law (17) or (28). This involves a transformation to an "output predictive state coordinate system," an idea developed by Dr. Reid in Ref 11. The new "state vector" is actually the predicted output (see Ref 11). When the zero input prediction responsibility is assumed by a Kalman filter, the results of Table II will be obviated. Selection of TC can be based on the information contained in Figure 42, substantiated by the results of Table III.

At TC=0.200, $1/\kappa$ is very small (see Figure 42), reflecting the fact that $[\overline{H}'Q\overline{H}]$ is ill-conditioned in terms of robustness. This is confirmed by Table III, in that for TC=0.200 the system is unstable for all Delta models sent to the calculation of \overline{H} .

TC=0.088 and TC=0.124 correspond to the two largest peaks in the reciprocal condition number, Figure 42. As seen in Table III, with these values of TC the system maintains stability with up to a

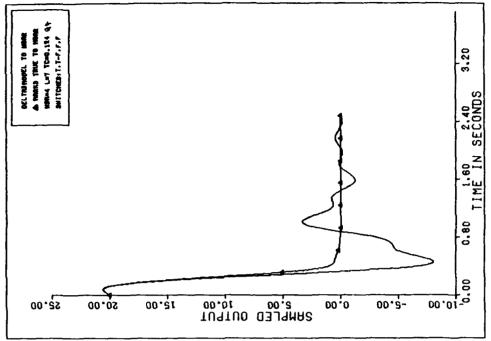
30% change in eigenvalues. Further, comparison of the system response for these two values of TC (Figures 43 and 44) indicates that the controller is "more robust" at the time which maximizes $1/\kappa$ (TC=0.124)

Summary

The model mismatch simulation points out two important factors to be considered in a "real world" application. The first is that to avoid the results indicated in Table II, a Kalman filter or observer should be implemented to perform the future state estimation function. Second, in applications calling for a robust controller, the selection of control change time (TC) is a critical design step. The best choice for TC is the discrete time which maximizes the reciprocal condition number of $[\vec{H}'Q\vec{H}]$. The results demonstrated in this chapter concerning the selection of TC corresponds to the same result derived analytically in Ref 11 for the case of OPDEC.

This chapter concludes the discussion of the regulator application of the "smoothing approach" to Output Predictive Control.

Chapter V discusses the technique implemented as a pitch controller on a modern aircraft in a terrain following problem.





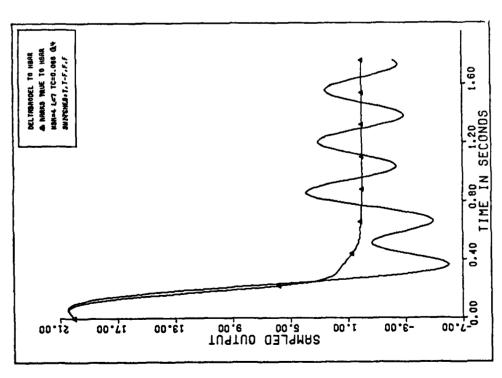


Fig 43. Sampled Output for Truth Model (Δ) and 30% Delta 3 Model to \bar{H} Calculation, TC=0.088

V Controller Algorithm Implemented as a Pitch Axis Autopilot

In this chapter the algorithm developed in Chapter II is modified clightly for implementation as a pitch axis autopilot for a terrain following problem. The control objectives and aircraft model are discussed first, followed by an explanation of the changes necessary to the algorithm developed in previous chapters. Two test cases are presented and the results discussed. Model mismatch was not investigated. This development is not an attempt to present an ideal solution to the terrain following problem, but is included in the thesis as an initial investigation into a possible application area for the smoothing approach to Output Predictive Control.

Control Objectives

In Chapters III and IV the smoothing approach to Output Predictive Control is implemented as a regulator. In that case the set point is constant at zero for all time. In this chapter, the controller is used as a pitch axis autopilot and the objective is to follow a desired altitude profile; the set point becomes a time varying "set path."

System Model

The equations of motion for an aircraft are nonlinear with time varying coefficients. By assuming small perturbations about a specific operating point, however, a linearized set of equations is obtained.

A linearized version of the longitudinal dynamics (called the short period approximation) for a modern fighter aircraft, linearized about a

straight and level operating point at 0.8 Mach, 10,000 feet altitude and υ_0 =constant=1077 fps , is given by

$$\begin{bmatrix} \dot{q} \\ \dot{\alpha} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -3.854 & -12.240 & 0 \\ 1 & -2.834 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ \alpha \\ \theta \end{bmatrix} + \begin{bmatrix} 34.170 \\ .331 \\ 0 \end{bmatrix} \varepsilon$$
(44)

where

q = Pitch rate (radians/sec)

 α = Angle of attack (radians)

 θ = Pitch angle (radians)

 ε = Elevator deflection (radians)

The elevator deflection is assumed limited to $-0.262 \text{ rads} \le \le 0.426 \text{ rads}$. For the short period approximation, $\zeta = 0.69$ and $w_n = 4.8 \text{ rad/sec}$. Figure 45 shows the angles listed above and includes the flight path angle (γ), the angle between the horizon and flight path.

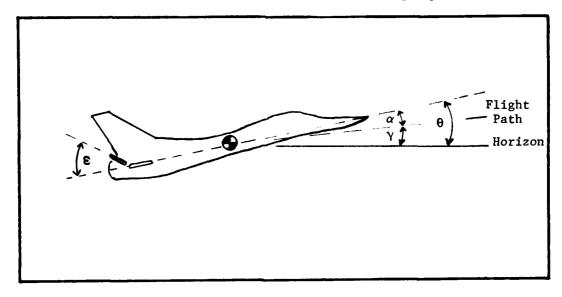


Fig 45. Perturbation Angles for Linearized Longitudinal Dynamics

With the forward velocity (υ_0 assumed constant in short period approximation) maintained constant through use of an automatic throttle system or pilot inputs, the additional state of altitude (h) is added through the relationship

$$\dot{h}(t) = v_0 \gamma(t) = v_0 [\theta(t) - \alpha(t)] \text{ fps}$$
 (45)

where

 $\dot{h}(t)$ = Vertical velocity (fps) v_o = Constant = 1077 fps

The system model becomes

$$\begin{bmatrix} \dot{q} \\ \dot{\alpha} \\ \dot{\theta} \\ \dot{h} \end{bmatrix} = \begin{bmatrix} -3.854 & -12.240 & 0 & 0 \\ 1 & -2.834 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & -1077 & 1077 & 0 \end{bmatrix} \begin{bmatrix} q \\ \alpha \\ \theta \\ h \end{bmatrix} + \begin{bmatrix} 34.170 \\ .331 \\ 0 \\ 0 \end{bmatrix} \varepsilon$$
(46)

The transfer function of interest is altitude change for a given elevator deflection

$$\frac{h(s)}{\epsilon(s)} = \frac{-356.81(s-14.93) (s+18.78)}{s^2(s+3.34\pm j3.46)}$$
(47)

The controller, then, will use Eq (46) as the system model to calculate the elevator deflection necessary to follow a desired altitude profile.

Implementation

The algorithm used for the regulator is modified slightly for the terrain following problem. These changes include the generation of a set path, a modification of how the system error is reduced, the addition of a control limiter and finally, selection of the internal parameters of the controller.

<u>Set Path</u>. Initially, the desired altitude profile or set path is chosen as a sinusoid with a variable frequency of oscillation:

$$y_{set}(i) = Asin\omega t_i$$
 (48)

From Figure 46, if A is fixed at 1000 feet, then the base or length of the "obstacle" can be calculated as

$$L = v_0 t = v_0 \frac{\pi}{\omega} \tag{49}$$

As the frequency of oscillation (ω) varies, the length (L) or base of the obstacle varies as given in Table IV. Figure 47 is a plot of the set path given by Eq (48) for A=1000 feet, ω =0.5 Hz and TC=0.5 sec .

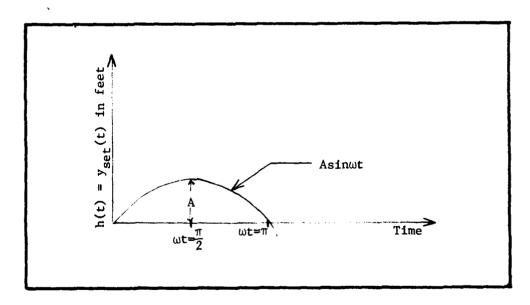


Fig 46. Asinwt as the Set Path

TABLE IV $\begin{tabular}{ll} Effective Size of Obstacle for Variation of the Frequency \\ (\omega) of the Sinusoidal Set Path \\ \end{tabular}$

Frequency of Oscillation (ω) Hz	Base of Obstacle (rt)	Height (Ft)
0.50	6772	1000
0.60	5643	1000
0.75	4515	1000
0.90	3762	1000
1.00	3386	1000

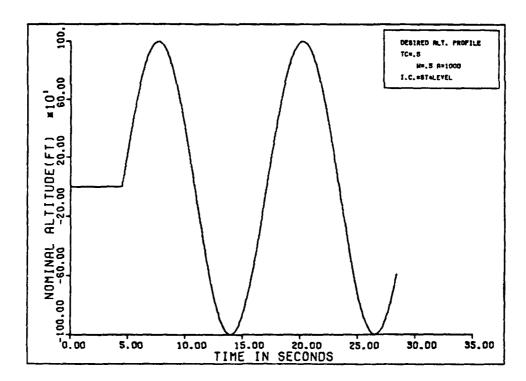


Fig 47. Set Path or Desired Altitude Profile for A=1000 ft, $\omega = 0.5 Hz \,,\,$ and TC=0.5 sec

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Modification of System Error Reduction Relationship. In Chapter II, Eq (11) is given as the relationship for calculation of points along the desired trajectory from present position (y) to the set point (y_{set} =0 for regulator):

$$y_d(i) = y_{set} - \dot{q}^i(y_{set} - y) ; i = 1,2,...NSM*L$$
 (11)

Eq (11) is based on the fact that, for the regulator application, the set point is constant for all time. A modification of this relationship is necessary because there is no longer a constant set point, but a time varying set path.

Assuming that an error exists between the actual system output and the set path, then $y_d(t)$ is a function of the present system output, present set point along the set path, future set points and how we wish to reduce the system error. If the error is to be exponentially reduced, then

where 🕏 is as given in Eq (11). Substituting into Eq (49)

$$y_d(t_{now}^{+iT_1}) - y_{set}(t_{now}^{+iT_1}) = *^{i}[y(t_{now}^{+iT_1}) - y_{set}(t_{now}^{+iT_1})]$$
 (51)

For the case of a constant set point where $y_{set}(t_{now}^{+iT}) = y_{set}(t_{now}^{-})$, Eq (52) reduces to Eq (11). Eq (51) is used for calculation of discrete points along the desired trajectory.

Selection of Internal Parameters. As discussed in Chapter III,

system. In this application of the algorithm, the parameters are chosen with physical restrictions in mind.

In an effort to use a physically realizable control change time, \mbox{TC} is chosen as $\mbox{TC=0.5}$.

Tau, the time constant of the decreasing exponential of Eqs (11) and (50), is a measure of how quickly the error between the desired and actual altitude profile is reduced. For this example, Tau is chosen as Tau=0.3 . As Tau is decreased from this number, aircraft accelerations become excessive.

A sufficient number of smoothing terms (NSM) to give a well defined characterization of the desired or set path must be utilized. Values over the range 3≤NSM≤8 were tried, with NSM=4 chosen. As the frequency of oscillation of the sine wave used as the set path increases, more smoothing terms per control are required to characterize this path.

Values of L , the number of future control changes calculated per iteration, over the range $4 \le L \le 10$ were tried. A value of L=7 is chosen to effect a good tradeoff between response time and the magnitude of the elevator deflections calculated.

The choice of a weighting matrix for the Normal Equation (28) is, of course, dependent on the values of L and TC. Each of the weighting matrices discussed in Chapter III and Eq (52) were tested as Q. Q6 is basically Q2 [Eq (37)] with the column order reversed and the nonzero elements moved to the principal diagonal:

Q6 = Diagonal
$$[64,64,64,64]$$
 32,32,32,32 $[16,...,1]$ 28X28 (52)

where each block is NSM=4 units long. The resulting average and peak altitude errors for each weighting matrix are listed in Table V. Based on this data Q3, Eq (38), is chosen as the weighting matrix to be utilized. Graphical results for the case of Q=Q4 and ω =0.5 are shown in Figures 48 through 49. It is interesting to note that although Q4 was the best choice for the regulator application, its use induces large altitude errors in this example.

Final Tests and Results

A sum of sinusoids is chosen as the set path or desired altitude profile for final testing of the controller:

$$y_{set}(i) = Asin\omega_1(iT_1) + Asin\omega_2(iT_1) + Asin\omega_3(iT_1)$$
 (53)

The results of two test cases are presented. For both tests, A=1000 feet and the aircraft is started from an initial condition of straight and level flight. For the first case ω_1 =0.5 , ω_2 =0.6 and ω_3 =0.2 ; for the second, ω_1 and ω_2 are unchanged and ω_3 =0.8 . Table VI summarizes the results of the tests.

Figures 50 through 57 show the results of the test cases.

Included for each test are plots of the desired and achieved altitude profiles, controls applied and pitch angle variations. Plots of the achieved altitude and control inputs show that the controller came to "steady state" tracking long before the inputs become steady state; this is considered a significant result.

Examination of the pitch angle history (Figures 53 and 57) for either case reveals angles well outside the range of "small perturbation"

TABLE V $\begin{tabular}{ll} Average and Peak Altitude Error for Variation of the Frequency of Oscillation (ω) of the Sinusoidal Set Path and Weighting Matrix Utilized \\ \end{tabular}$

Weighting Matrix	ω(Hz)	Peak Error (ft)	Average Error (ft)
Q1	0.50	66.42	35.61
·	0.60	79.49	40.65
Eq (36)	0.75	131.09	51.39
	0.90	263.81	74.42
	1.00	1051.37	160.80
Q2	0.50	68.17	35.38
4-	0.60	81.38	40.43
Eq (37)	0.75	164.04	51.84
	0.90	378.67	83.44
	1.00	1062.53	159.80
Q3	0.50	66.51	36.75
Ų3	0.60	76.96	42.35
Eq (38)	0.75	96.05	52.55
24 (30)	0.90	113.70	61.98
į	1.00	124.23	68.86
Q4	0.50	1007.79	100.04
Q4	0.60	1007.79	100.04
Eq (39)	0.75	1007.79	114.60
24 (3))	0.90	1007.79	126.70
	1.00	1007.79	136.03
O.F.	0.50	333.72	74.52
Q5	0.60	213.09	59.75
Eq (40)	0.75	1406.44	214.43
Eq (40)	0.75	1116.40	368.62
	1.00	6421.20	1766.51
Q6	0.50	67.52	36.01
Ų	0.60	81.02	41.10
Eq (52)	0.75	101.15	51.09
Pd (27)	0.90	162.67	62.93
	1.00	703.38	161.68

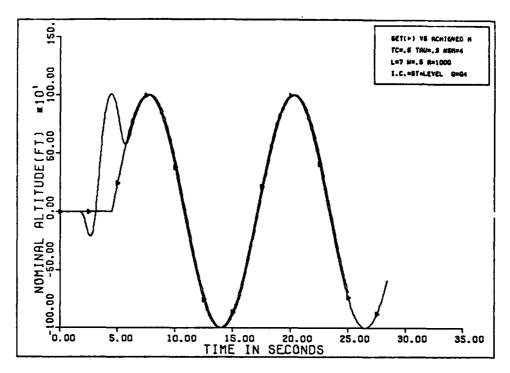


Fig 48. Set Altitude (Δ) and Achieved Altitude (Clean) for Q=Q4 and ω =0.5 Hz and TC=0.5 sec

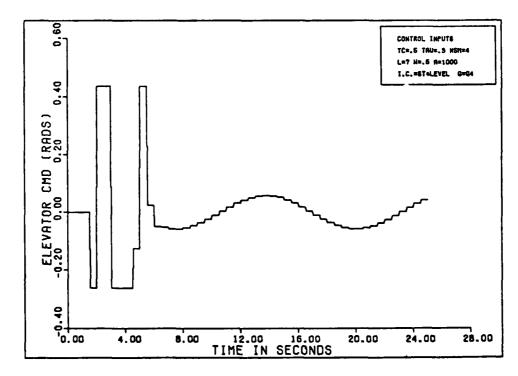


Fig 49. Control Inputs for Q=Q4 and ω =0.5 Hz and TC=0.5 sec

TABLE VI
Sinusoidal Frequencies Used and Peak and Average
Altitude Errors for the Test Cases

Variable	Test Case 1	Test Case 2
A(ft)	1000	1000
ω _l (Hz)	0.5	0.5
ω ₂ (Hz)	0.6	0.6
ω ₃ (Hz)	0.2	0.8
Average Error (ft)	69.31	82.18
Peak Error (ft)	171.59	254.96

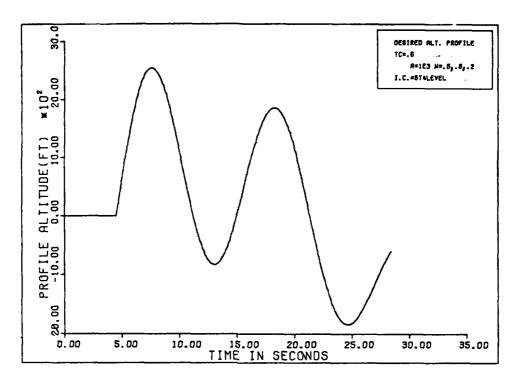


Fig 50. Set Path or Desired Altitude Profile for Test Case 1 (see Table VI)

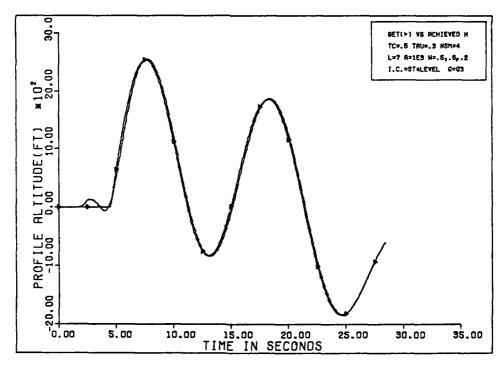


Fig 51. Desired Altitude (Δ) and Achieved Altitude (Clean) for Test Case 1 (see Table VI)

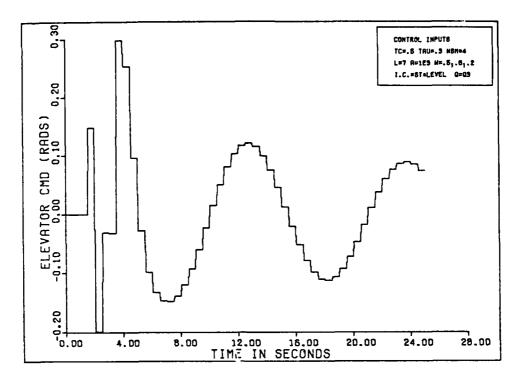


Fig 52. Control Inputs for Test Case 1 (see Table VI)

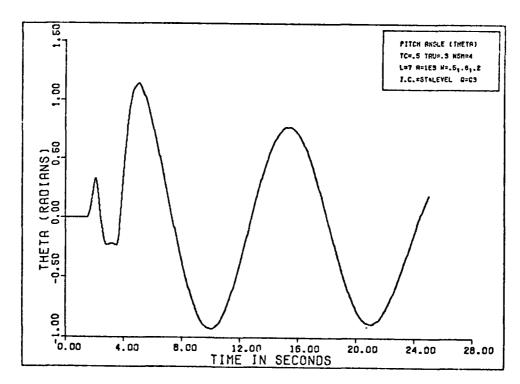


Fig 53. Pitch Angle (θ) for Test Case 1 (see Table VI)

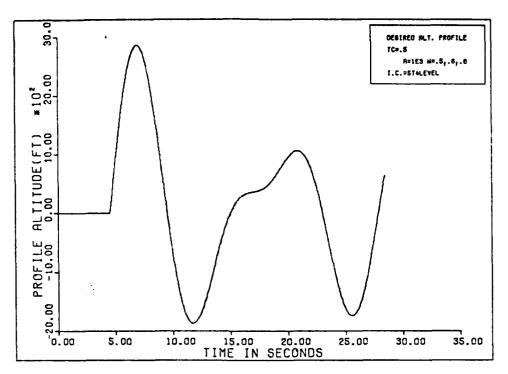


Fig 54. Set Path or Desired Altitude Profile for Test Case 2 (see Table VI)

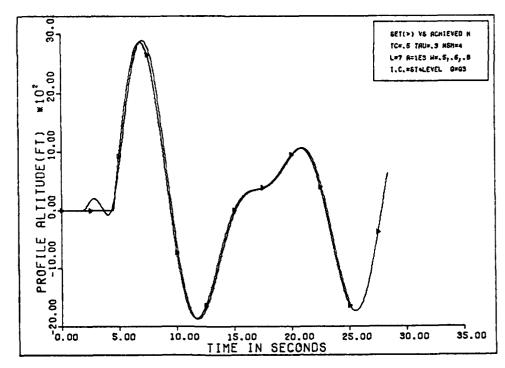


Fig 55. Desired Altitude (Δ) and Achieved Altitude (Clean) for Test Case 2 (see Table VI)

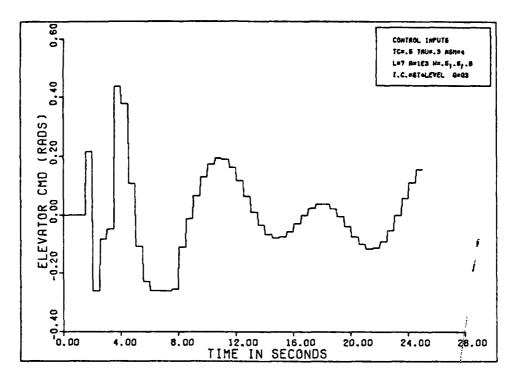


Fig 56. Control Inputs for Test Case 2 (see Table VI)

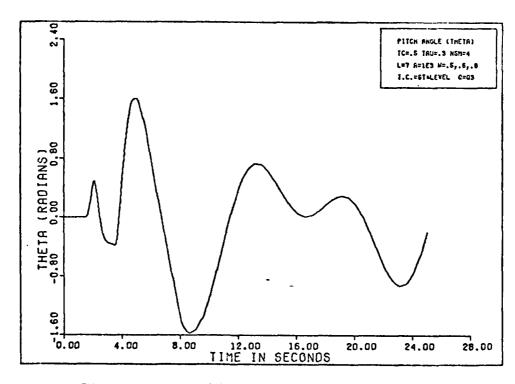


Fig 57. Pitch Angle (θ) for Test Case 2 (see Table VI)

angle for which the system model is valid. Although the altitude errors indicated in Figures 51 or 55 cannot be used to show that the controller/aircraft could actually fly the test profiles as indicated, the test results indicate that this controller algorithm is a viable one for the terrain following probles.

It is concluded that the algorithm is readily adaptable to a tracking problem. Limitations due to the linearized system model, however, make the results of the terrain following tests unusable except for comparison purposes. In order to get more meaningful results, the problem should be reformulated to run altitude as a function of down-range position and utilization of one of the following alternatives:

- 1. Go to on-line identification of the impulse function and use of a Kalman Filter for prediction purposes.
- 2. A series of linearized models can be stored, each to be used within the appropriate range of flight conditions (similar in concept to gain scheduling).
- 3. Make the controller so "robust" that the model mismatch has little effect.

Appendix D contains the FORTRAN code used for Test Case 1.

VI Conclusions and Recommendations

Chapter VI contains the conclusions drawn from this study of the smoothing approach to Output Predictive Control and some possible areas for further study.

Conclusions

In Ref 1, the control problem is formulated for exact matching (at control change time) of the system output to the desired trajectory and prediction of the zero input response is for one step ahead. For a system higher than second order the above formulation led to instability. This problem was corrected by looking further into the future for control calculation and by allowing some deviation of the output around the desired trajectory.

For the smoothing approach implemented as a regulator the results are good - even in the face of 30% model mismatch. The level of success or goodness, however, is dependent on the proper selection of the internal parameters of the regulator. The "best" set of parameters for the smoothing approach implementation approximates the Output Predictive Dead-Beat Controller (OPDEC) found in Refs 3 and 11. The most attractive feature of OPDEC is that there is only one internal parameter to be chosen, the control change time (TC), and a direct design procedure has been developed for the selection of TC.

Investigation of the terrain following application indicates
that the algorithm is easily adapted to a tracking task. Limitations
due to the linearized system model, however, make the current results

of the example inconclusive for a practical aircraft controller without the probable use of model adaption. However, this example illustrates good performance of the output predictive controller in a demanding tracking situation.

Recommendations for Further Study

Investigation in the following areas could provide further insights into the general area of Output Predictive Control:

- 1. Further development of the synthesis technique for selection of the internal parameters of the controller (i.e., TC , L , NSM , Q and Tau). A clearer understanding of the interrelationships of the parameters will facilitate application of the controller to new problems.
- 2. An indepth study of the robustness properties of the algorithm is necessary for quantification of these properties.
- 3. A reformulation of the tracking problem for more meaningful results would include running altitude as a function of downrange position and utilization of one of the following alternatives:
- a. Implementation of on-line identification of the impulse response function and use of a Kalman Filter for prediction.
- b. A series of linearized models can be stored, each to be used within the appropriate range of flight conditions (similar in concept to gain scheduling).
- c. Insure that the controller is so robust that the model mismatch introduced by using a linearized model outside its range has little effect on the closed loop performance.

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Appendix A

Procedure for Solution of the Normal Equation

The procedure for solving the Normal Equation for a simple example problem is presented to illustrate the dimensions of its components and to show a series of matrix manipulations which result in a savings of computer storage space. Eq (28), the Normal Equation, is repeated for convenience:

$$\bar{\mathbf{u}} = (\bar{\mathbf{H}}' \mathbf{Q} \bar{\mathbf{H}})^{-1} \bar{\mathbf{H}}' \mathbf{Q} \mathbf{z} \tag{28}$$

where

 $\frac{\overline{u}}{u}$ = An L dimension vector

 $\overline{H} = An (NSM*L) X L matrix$

Q = An (NSM*L) X (NSM*L) diagonal matrix

$$\underline{z} = \underline{y}_{d} - \underline{y}_{zi} \tag{21}$$

z = An (NSM*L) dimension vector

If three future control inputs per iteration are calculated (L=3), three smoothing terms per control input are used (NSM=3) and Q is chosen as Q3 , Eq (38), a weighting matrix discussed in Chapter III, then

$$\bar{H} = \begin{bmatrix} h(1) & 0 & 0 & 0 \\ h(1)+h(2) & 0 & 0 & 0 \\ h(1)+h(2)+h(3) & 0 & 0 \\ \vdots & h(1) & \vdots & \vdots & \vdots \\ h(1) & h(1)+h(2) & 0 \\ h(1)+h(2) & 0 & \vdots & \vdots \\ h(1) & h(1)+h(2)+h(3) & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ h(1) & \vdots & \vdots \\ h(1) & \vdots & \vdots & \vdots \\ h(1) & \vdots & \vdots & \vdots \\ h(1) & \vdots & \vdots \\ h(1) & \vdots & \vdots & \vdots \\ h(1) & \vdots & \vdots & \vdots \\ h(1) & \vdots & \vdots \\$$

$$Q = Q3 = Diagonal[1,2,4,8,16,32,...,256]$$
 (A-2)

(A-1)

The following vectors and matrices are defined:

$$\underline{x}_1 = \begin{bmatrix} h(1) \\ h(1)+h(2) \\ h(1)+h(2)+h(3) \end{bmatrix}$$
 (A-3)

$$\underline{x}_{2} = \begin{bmatrix} h(1)+h(2)+..+h(4) \\ h(1)+h(2)+..+h(5) \\ h(1)+h(2)+..+h(6) \end{bmatrix}$$
(A-4)

$$\underline{\mathbf{x}}_{3} = \underline{\mathbf{x}}_{L} = \begin{bmatrix} h(1) + h(2) + \dots + h(7) \\ h(1) + h(2) + \dots + h(8) \\ h(1) + h(2) + \dots + h(9) \end{bmatrix}$$
(A-5)

$$Q_1 = Diagonal[124]$$
 (A-6)

$$Q_2 = Diagonal[8 16 32]$$
 (A-7)

$$Q_3 = Diagonal[64 128 256]$$
 (A-8)

and a piece of the Normal Equation can be written as

$$\tilde{H}^{\prime}Q\tilde{H} = \begin{bmatrix}
\underline{x}_{1}^{\prime} & \underline{x}_{2}^{\prime} & \underline{x}_{3}^{\prime} \\
\underline{0}^{\prime} & \underline{x}_{1}^{\prime} & \underline{x}_{2}^{\prime} \\
\underline{0}^{\prime} & \underline{0}^{\prime} & \underline{x}_{3}^{\prime}
\end{bmatrix}
\begin{bmatrix}
Q_{1} & 0* & 0* \\
0* & Q_{2} & 0* \\
0* & 0* & Q_{3}
\end{bmatrix}
\begin{bmatrix}
\underline{x}_{1} & \underline{0} & \underline{0} \\
\underline{x}_{2} & \underline{x}_{1} & \underline{0} \\
\underline{x}_{3} & \underline{x}_{2} & \underline{x}_{1}
\end{bmatrix}$$
(A-9)

where

$$\underline{0} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{A-10}$$

$$0* = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$
 (A-11)

Carrying out the matrix multiplications indicated in Eq (A-9) and putting the result into a summation form yields

which is symmetric.

Equivalent matrices, containing all of the information found in the original $\bar{\rm H}$, Eq (22), and Q matrices can be formulated as

HEQ =
$$[\underline{x}_1, \underline{x}_2, ..., \underline{x}_L]_{NSMXL}$$
 (A-13)

QEQ =
$$[\underline{q}_1, \underline{q}_2, \dots, \underline{q}_L]_{NSMXL}$$
 (A-14)

where, for the example problem $\underline{x}_1,\underline{x}_2$ and $\underline{x}_3=\underline{x}_L$ are given by Eqs (A-3) through (A-5), and

$$\underline{q}_1 = \begin{bmatrix} 1 \\ 2 \\ 4 \end{bmatrix} \tag{A-15}$$

$$\underline{\mathbf{q}}_{2} = \begin{bmatrix} 8 \\ 16 \\ 32 \end{bmatrix} \tag{A-16}$$

$$\underline{q}_3 = \underline{q}_L = \begin{bmatrix} 64 \\ 128 \\ 256 \end{bmatrix}$$
(A-17)

Using these equivalent matrices (HEQ and QEQ) an inner product relationship can be used to produce $[\overline{H}^*Q\overline{H}]$ instead of the straightforward transpose and matrix multiplications of Eqs (A-1) and (A-2). The first column of the original \overline{H} matrix is formed using the relationship

$$h(i) = CF^{i-1}G$$
 (10)

These elements are put into \mbox{HFC} , an ($\mbox{NSM}{\star}\mbox{L}$) single dimension array. HEQ is dimensioned as an ($\mbox{NSM}{\times}\mbox{L}$) matrix and equivalenced to \mbox{HFC} .

The FORTRAN code used to find $[\widetilde{H}^{\prime}Q\widetilde{H}]$ using HEQ and QEQ is in Appendix B within Subroutine HBAR.

At this point the inverse of $[\bar{H}'Q\bar{H}]$ is required. The $[\bar{H}'Q\bar{H}]$ matrix may be less than full rank, requiring a generalized inverse. A library subroutine, GMINV, computes the generalized inverse through a process of column orthogonalization using a Gram-Schmidt procedure (Ref 13).

ZEQ , an (NSMXL) matrix is equivalenced to Z , an (NSM*L) single dimension array containing the elements found using Eq (21).

$$ZEQ = [\underline{z}_1, \underline{z}_2, \dots, \underline{z}_L]_{NSMXL}$$
 (A-18)

where, for the example problem

$$\underline{z}_{1} = \begin{bmatrix} y_{d}(1) - y_{zi}(1) \\ y_{d}(2) - y_{zi}(2) \\ y_{d}(3) - y_{zi}(3) \end{bmatrix}$$
(A-19)

$$\underline{z}_{2} = \begin{bmatrix} y_{d}(4) - y_{zi}(4) \\ y_{d}(5) - y_{zi}(5) \\ y_{d}(6) - y_{zi}(6) \end{bmatrix}$$
(A-20)

$$\underline{z}_{3} = \underline{z}_{L} = \begin{bmatrix} y_{d}(7) - y_{zi}(7) \\ y_{d}(8) - y_{zi}(8) \\ y_{d}(9) - y_{zi}(9) \end{bmatrix}$$
(A-21)

An expression similar to Eq (A-12) can be built and an inner product relationship similar to the one used to find $[\bar{H}'Q\bar{H}]$ can be used to calculate $[\bar{H}'Qz]$. The FORTRAN code used to find $[\bar{H}'Qz]$ using HEQ , QEQ and ZEQ is in Appendix B within Subroutine CONTROL.

As an indication of the savi.gs realized when using the HEQ , QEQ and ZEQ matrices versus \vec{H} , Q and \vec{z} , consider the solution of the Normal Equation for twenty step ahead prediction (L=20) and ten smoothing terms (NSM=10). Matrix dimensions are

[用] _{200X10}	versus	[HEQ] _{20X10}
[Q] _{200X200}	versus	[QEQ] _{20X10}

Core memory requirements (in base 10) for these two matrices alone are 42000 words required for $\overline{\rm H}$ and Q versus 400 words using HEQ and QEQ .

Appendix B

Sample FORTRAN Code Used in the Investigation of the Algorithm Implemented as a Regulator

The basic program in this Appendix follows the functional block diagram of Figure 1. Addition of a set of logical switches allows investigation of model mismatch (Chapter IV) and the effects of noisy measurements and inputs. Comment statements at the front of the program explain the use of these switches.

The only external to the program is a subroutine used to find the generalized inverse of a matrix (GMINV). This subroutine is on a functional library named CONTROL, ID=L 720033, SN=AFML. CONTROL must be attached and libraried before compilation of the program.

The output of this particular version of the algorithm is Figures 28 through 31 in Chapter III.

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DATA INUS(17)/SUHFIG . CONTROL VARIATIONS FOR VARIABLE TC
                                                                                                DATA YSZI,NI,NPUNI,NDF2/L,3(;),4,28/
DATA TG1,NCR3,VE,NO35,NSH/.075,7;7,20,5,4/
UATA TAU,NCR3,VE,NO35,NSH/.075,7;7,20,5,4/
UATA TAU,NCR3,VE,NO35,NSH/.075,7;7,20,5/
UATA IDYS(1)/20HY MARCS FC=U.12:

DATA IDYS(3)/20HY MARCS FC=U.250

DATA IDYS(7)/20HNSH=h L=7 Q=90

DATA IDYS(7)/20H TIMF IN SECONDS /

DATA IDYS(1)/20H SAMPLED OUTFUT /

DATA IDYS(1)/20HFIG . DUTFUT VALAFIONS FOR VARIABLE TC
DATA (C4(I), I=1,4) /1.2, 3+6./
DATA BT/3+6., 8611.769305/
DATA CT/1.0,3+6./
C=1 LEAST P,NOX2=AT FAST ML,NOK3=AT LEAST L
DATA YSST,NT,H,MOR1,NOF2/6.,3.,+9,4,28/
                                                                                  DATA YSST,NT,N,NOK1,NJR2/C.,30,4,4,28/
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        IF (IPESS.GE.4) GO TO 13 F
                                                                                                                                                                                                                                                                                                                                                                                                                                                          IF (IPASS.50.2) TC=.124
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  00 to I=1,1
IDUS (I)=INYS(I)
COALINUS
                                                                                                                                                                                                                                                                                                                                                                                                                SW3= FALSE.
SW+= FALS T-
IP453: IPASS+1
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IP453=(
NTPT=1203
SWI=1705
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                                                                                                  THIS ALL GIVE THE SAME INITIAL STATE VECTOR FOR ALL COMBIGATIONS OF SMITCH SETTINGS.

CALL PANSET(3)
                                                                                                                                                   HERE IS WHERE CAN READ IN RANDOM INITIAL STATES.
THESE WILL OF FEAU IN AND REIMITIALIZED
AS FOLLOWS
X(1) = 20.
                                                                                                                                                                                                                                                      PAINT: ""
PAINT: "SWITCH SETTINGS AKE AS FOLLOWS!"
WAITE(G, F) (10YS(1), I=1,3)
FORWAT((1H, 2A10,7))
                                                                                                                                                                                                                                                                                                                                T035=10/4H
ALPHA=5X2(-10ESIRE/TAJ)
AL=N3H L
XS=1
FORM Y(J)=54X(O)
                                                                                                                                                                                                                 X(4) =[...
PKINT', "INITIAL STATE"
CALL PRINTR(N, X, NOR1)
        0T(1)=0.
R1(2)=0.
BT(3)=f.
BT(4)=P511. 69806
BM(1)=0.
REINITIALITE X AND B
                                                                                                                                                                                                                                                                                                                                                                                              DO 57 K=19N
Y=Y+C4(K) X(K)
                                                          94(2)=(.
84(3)=1.
84(4)=.2466f5
                                                                                                                                                                                                                                                                                                             MURISH 409S
TOES IKE TOZISM
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                                                                                                                                                            "FOR THIS RUN TCOMTRUL=",TC,",1DESIRED=",TOESIRE",
                                                                                                                                                                                                                                                                                                CALL WEIGHT (WSM,L,ML,JC, lEQ)
IF (SW2) GO TO 61
CALL MIAK (CM,FLM,CFL,)FLK, GLM,MFC,MEQ,QEQ,MTQH,MTQHI,*N*L,*U,N3 M,NORI)
GO TO G2
                                                                                                                                                                                                                                                                                                                                                                          CALL "PARR (G) , FLT, CFL, JFLK, GLT, HFC, HEQ, DEQ, HTQH, HTQHI,
                                                                                                                                                                                                                                                                                                                                                                                                                          FINALLY THEOMGH WITH THE FRELIMINARIES, CAN NOW GET DOWN TO BUSINESS OF FINDING AN APPROPIATE CONTROL BY LOOKING AT THE DESIRED PATH, THE ZERO INPUT RESPONSE AND THE SET POINT.
                                                                                                                                                                                    PULINT',"TOACEKVE=",103S,",1AU=",1AU,",ALPHA=",ALPHA
                                                                                                                                                                                                                                                             CALL PISCOFT(AT,BT,AM,BM,TDESIRE,TOBS,N,NT,NDK1,+ELLNT,FLY,FLM,FSM,GSM)
                                                                                                                                                                                                                         PRINT', "NSMCOTH(NSN)=", NSh,", NOBS=", NOBS,", L=", L
                                                                                                                                                                                                                                                                                                                                                                                     +W+L, 4L, NSH, PDR1)
CC NITHUE
                                                                                                 1532(1)=7.
YS1(1) = Y
YS2(1) = Y
YS3(1) = Y
CO-41 TRUE
US1(1) = J
US2(1) = J
                                                                                     TSS1(1)=1.
                                                                         US $(1) = 0.
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DO 150 KO=1,KF

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                                                                                                                                                                                                                                                    NOW UPDATE STATES AND SAMPLE THE DUTPUT OF THE "ACTUAL" SYSTEM.
                                                  COPY C MATRIX INTO
                                                                                                                                                                                                                    CALL CONTROL (YD,YZ,ZC,ZEQ,HEO,DEO,HIQHI,HTQZ,UCOMP,+U,L,HL,HZH,HOR3)
                                                                                                                                                                                                                                                                                                                                                                      CALL STATE (X,FST,FS4,6ST,6SU,N,U,NDK1)
                                                                                                                                                                                                                                                                                                                                      CALL "TATE(X, FST, FSX, SST, GSU, N, UN, NOR1)
GU TO 123
        REMOVED HEADTRES FOR DESIRED DUTPUT PUINTS
                                                                                                                                            CALL YZZ(X, N, ML, YZ, 84, FLM, GFL, NDR1)
60 10 93
                                                                                                                                                                          COLL YZEKY,N,ML,YZ,BT,FLT,CFL,NOK1)
COLTINUS
                                                SUBROUTING YZI DESTROYS THE C MATRIX.
                            CALL YDESIRE(Y, YSET, A_PH1, ML, Y3)
                                                                                                                                                                                                                                                                                                                                                                                                    SALL OUTPUT(X,CM,Y,V)
LF(,W)T,SW() 60 TO 113
                                                                                                                                                                                                                                                                                                      IF(.NO1.5W3) GU TO 133
CALL POTSE(1.0,6.,MN)
                                                                                                                                  IF(SW1)60 Tr 80
                                                          THE 9 MAIRIX • DO 75 I=1, N 31 (1) =51 (5) 38 (1) = 52 (1)
                                                                                                                                                                                                                                                                                 Do 15. K0=1,48
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UNLY DIPPERBUGG BETWEEN FOST, TOSS, TSS IS THAT
SOME ANE CHOPPER FINEW THAN OTHERS.
                                                                                                                                                                                                                        IF(IPASS-E0.1)YS1(KS)*Y
IF(IPASS-E0.1)US1(KS)=U
IF(IPYSS-E0.1)TS1(KS)=TSS1(KS-1)+T09S
                                                                                                                  |F(|P0|S)+E0+2)|US|KS)=U
|F(|P4|SF+E0+2)|ISS2|KS|=TSS2|KS+1)+T09|S
                                                                                                                                                                       IF(IPASS. 80.3) TSS3 (KS) = FSS3 (KS-1) +T09S
                                                                                                                                                                                                                                                                                                                                                                                                                                        CALL PREAMPHISSI, YSI, 41P, 10YS, -1, up.)
                                                                                                                                                                                                                                                                                                       YC2 (2) = YS22
YS2 (4(F+1) = YS1 (NIPT+1)
YS2 (41 P+2) = YS1 (NIPT+2)
TS32 (41 P+1) = TSS3 (NIP+1)
TS32 (4TP+2) = TSS3 (NIP+2)
                                                                                                                                          IF(IP455.E0.3) YS3(KS):Y
IF(IP455.E0.3) US3(KS):U
                                                                                                       (F(1P4S3.EP.2) Y52(KS)=Y
                                                                                                                                                                                                                                                                                                                                                                                                              1831 (NTP+1) = TSS3 (NTP+1)
                                                                                                                                                                                                                                                                                                                                                                                                                             1551 (410+2) = 1553 (610+2)
                                                                                                                                                                                                                                                                                                                                                                                    YS1 ('1) P+1) = YST (N1 PT +1)
Y_1 ('1) P+?) = YS1 (N7 PT +2)
CALL NOISE(1.0,0., WN)
                                                                                                                                                                                                                                                                                                                                                                                                                                                      YS2(1)=Y321
                                                                                                                                                                                                CONTINUE
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                                                    KS=KS+1
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                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  SUBBOUTINE YDESIRE(Y, (SET, ALPHA, ML, YO) 
DIMENSIOA YE(1)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 GALL HGKAPH(1582, US2, VTP, I BUS, -1, 20,2)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            CALL 46217H(TSS3, US3, 4TP, IOUS, -1, 34,1)
                                                                                                                                                                                                                                                                                                                                                                                                              1531 (HTP+1) = TSS (NTP+1)
1531 (HTP+1) = TSS (NTP+1)
1531 (HTP+2) = TSS (NTP+2)
051 (HTP+1) = UST (NTP1+1)
051 (HFP+2) = UST (NTPT+2)
061L HGAPH (1551, US1, NTP, 10US, -1, 0, 0)
USZ (1) = USZ (2)
CALL HG2APH(1552, YS2, NT9, 10YS, 2, 20, 2)
                                                                             YS3(2)=YS32
CALL HG~1PH(1SS3,YS3,NTP,1DYS,2,36,1)
                                                                                                                                                                                     CALL SCALS(1853,7.,HT),1)
PAINT, "SCALED TSS3 FOK 46RAPH"
CALL SCALF (HST,5.,HFPF,1)
PHINT, "SCALED UST FOR HSKAPH"
US $1 = US $1 = US $2 = US
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      TSS2 (4TP+1)=TSS3(4TP+L)
TSS2 (4TP+2)=TSS3(8TP+2)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               US2(((1P+1)=((ST(N)PT+1)
US2((((P+2)=((ST(NTPT+2)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             SALL PLOTE(M)
STOP "EUD OF MAIN"
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               30 13 K=1, M.
                                             YS3(1) =YS31
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    US 3 (1) = U 5 71
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                                                                                                                                                                                                                                                                                                                        SUBROUTINE CONTROL (YD, Y7. ZC, ZEO, HEO, QEO, HTQHI, HTQZ, UCOMP, +U, L, +I, HSM, NDK3)

OIMERSTON YD(1), YZ(1), ZC(1), ZEO(NSM, 1), HEO(NSM, 1)

OIMERSTON YD(1), YZ(1), FINI (L, 1), HIQY(1), UCOMP(1)
                                                                                                                                                                                                                                                                                                                                                                                   THE "LOWBAL EDUATION" IS FRUGRAMED AS FOLLOWS: THE VECTOR OF INPUTS CALBULATED U= (HTGHI) * HTGZ*
                                                                           SU3mUJIJE YZI(X,N,ML,YZ,C,FL,CFL,NDQ1)
DIJETSIOJ X(1),YZ(1),FL(NDK1,1),CFL(1),G(1)
                                                                                                               EDUATION PROGRAMEDI YZIKI =C+(FL++K)+X
YD(K)=YSET-(ALPHA+*<)+(YSET-Y)
COJIINUT
KETURN
END
                                                                                                                                    DO 3) 1=1,ML

Y7(1)=1

CALL TVHAT(C,FL,H,N,CFL,NUR1)

30 15 J=1,N

Y7(1)=Y7(1)+CFL(1)*X(J)
                                                                                                                                                                                                                                                                                                                                                                                                                         DG 134 I=1, ML
2C(I)=Y7(I)-Y2(I)
40 CG4TINUS
FORM 4177
                                                                                                                                                                                                              OU 2: KEI+N
O(K) #OFL(K)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                           00 12, J=1,1
HT17(J)=0.
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CONFINER
RETURN
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00 11E K=J,L
HTG7(J)=70T3(HEO(1,K-J+1), 0EG(1,K),7EG(1,K),NSM)+HTG7(J)
                                                                                                                                                                                                                                                                                                                                                            FMAS SUR DESCRITIZES THE A AND B MATRICES USING KOUTLES ON A FACKAGE CALED "CONTRUL". THE STAPLE THE OF DUESTRE IS HOW OFTEN THE CONTROL INPUT IS CALCULATED. TIME TOPS IS THE DELIA T OF THE OUTPUT
                                                                                                                                                                                                                                                                          DIME 47 DW AT (NUKI,) J. FILL), AA(NOKI,), PH(1)
DLYEVSIOW FILMT (NUFI,), FIT (NFL,), GLT (1), FST (NUKI,1)
DIAENSIOW GST (1), FLM(VPKI,1), GLM(1), FSM (NDM1,1), GSM (1)
COMMONITALITY (NOIM, NOIMI, N), GLM(N), FSM (NDM1,1), GSM (1)
                                                                                                                                                                                                                                              SUBROUTINE PISCRET(AT, PT, & M, 8M, TRESIRE, TOBS, N, NT, NOR1,
                                                              C FURH JOSHP, THE CONTROL VECTOR
CALL MATY (HTGHI, HTGZ, JCO4P, L, L, 7, 7)
C PICK JF THE FTRST ELEMENT AS THE CONTROL TO
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HAFY (SAIN) 91, GLT, N, N, NDKI, NDRI)
DSORICE, AT, TOBS, FST, EALNI, NT)
NATY (FFINT, B1, GST, M, N, ADP1, NDRI)
TACT UAL. CYSTEM
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                                                                                                                                                                                                                                                             02:14:0
                                                                                                                                                                                                                  SUBMOUTINE "TATE(X,FS,FSX,GS,GSU,N,U,NDR)
DIMENSION X(1),FS(NDR,1),GS(1)
UIMENSION GSU(1),FSX(1)
                                       SUBKOUTINE WEIGHT(NSM,L,HL, QC, DFD)
DIMENSION OC(1),QSD(NSM,L)
HAS IS FOR HORM? GEO WINS
WILL DNLY SET A CLEAN MA.FSMALF BLOCK
DIVISION IF ML IS EVEN.
                                                                                                                                                                                                                                                                              DO 13 I=1, H

GSU(1) = GS(1) + U

GSU(1) = GS(1) + U

CALL MATV(FS, X, FSX, N, N, N, NDK)

C REPLACE X WITH THE NEW STATE

DO 2) J=1, N

X(1) =FSX(J) +GSU(J)

Zy GCUI IPUE
                                                                                                                                                                                                                                                            EQUALION CODED: X(K+1)=FS+X(K)+6S*U
                                                                                                                                                                                                                                                                                                                                                                                                         SURFAUTINE OUTPUT (X,C,Y,4)
                                                                                                                                            00 23 J=KK,PL
10(J)=1.0[+16
                                                                                                             30 13 Z=1,K
30 (f)=1,0
00 41 E-00
                                                                                                                                                               CONTENUE
REFURA
END
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ENJ
RETURN
END
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	DIMENSION X(1) (1)	005180
		305190
، د	EQUATION CODED: Y(K)=C*X(K)	305200
ى		0.521
		9,5220
	No. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1.	16546U
	(I) x → (1) 0 + k = k	042400
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	そい このかい	35550
	E14.)	362 300
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ပ		062300
	SUBJOUTING FRINGH(NR, 40, ORAT, NOR)	005 30 Q
	TOUR TOUR TOUR TOUR TOUR TOUR TOUR TOUR	116.300
	00 23 1=19(0)	325.326
	MELL E(3, 17) 1, (DMAT(1, J) , J=1, NC, 1)	385 400
3	FO (NAT (1H: \$12) (14)4(1PE134)))	148338
٠, د	3)11 In 10 -	300
	KETURY	3.5.5.C
	EX.D) / c d u u
، ب		105366
ပ		ったとうこつ
	SUBACHITE FUNDATION, ANATONE, NEW YEAT, NOR.)	004400
	OLTENSION RV(1), AMAT(NOR, 1), VMAT(1)	24.3500
	00 21 I=1,NF	02+300
	VNAT(I)=0.0	36 1973
	00 17 J=1,NC	はまがいっつ
	V4AT (I)=VMAT (I)+RV (J) + AMAT (J,1)	354300
10	CONTINUE	00-360
<u>၁</u>	CONTINUE	02:400
	RETURN	184550
	END	064400
ပ		[136n0
ပ		3555
	SUBLOUTE'45 FKINTK (NE, 2V, 4DR)	6.552d
	DIHENSION RV(NDR)	000000
	1=1	945466
	MART EL 179J9 (KV (I) »IR1,NE)	016618
J.	FORMAT (1H0, 12, (T4, 4 (1PF13, 4, 1X)))	1965-70
	RE TURB	076700

ENJ	042540
	005500
	30500
SUBROUTINE MATV(AMAT, J, AMATV, NR, NC, NOR, NOC)	0.5619
	025020
00 2) I=1,4E	06.56.50
AMAIV(I)=:0	0.59400
7 30 15 J=19NG	065650
AMATY (I)=ANATV (L)+BMAT (L, J) · V(J)	Jurion
00411495	ロンシベンロ
C0.41 IP.00	000000
RETURN	0.50.00
CNS	002350
	0.5714
	305750
÷	065730
DIMENSION X(1),Y(1),I)(1) \$ IF(NG.EG.2) GO TO 30	0.274.0
IF (40.LT.n) GO TO 13	00,500
5 CAL F (X , 7 . , 4 , 1)	395768
FLOT (2.5,0.,-3) ! C	0.1537.0
PLOT (-1.35,1.35,3)	30.5733
PLOT (-7 -15,1.30,2)	06/400
J(1).En.usu) GO TJ 25	00270
	Je5616
] I=1,7,2	0.5820
SYM30L(1*.1-0.5,7.5) ,.67,10(125634
PLOT(-1.55,7.55,2) S CALL	647400
FLOT (-1.05, 3.55, 2) 5 CALL	יו קטר ידר
PIOT(-7.15,3.65,3)	30.2500
CALL PLOF(-1.35,9.61,2) \$ CALL FLOT(-1.35,1.35,2)	01.5073
	0.55600
	067570
CALL AXIS(-1-85)2-15IS(11)-2095-9160-97(N+1)-7(N+2))	006600
	016300
$X(4+1) = X(3+2) - 2_{*}1 + X(3+2) - \xi - Y(3+1) = Y(3+1) + 1_{*}65 + Y(3+2)$	0.5920
	005933
X(4+1)=X(1+1)+2*1+X(1+2) { Y(N+1)=Y(1+1)-1*05+Y(N+2)	30.5 540
=-X(N+2)	150,400 150,400
RETURN S END	365960
SUBJOUTING VERAPH(X,Y,N,ID,NO,NP,NS)	ロイホいつつ

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	DIMENSION X(1), Y(1), T(1) & IFCNO.FO.2) GO TO 30	108086
		377420
	SCALE (Y, 4.9, N, 1)	136600
بد	FLOT (8.5,00,-3) 8 3A	000 .13
	PLOT (+4 - 35 - 1 - 35 - 7)	J. 6 v 2 t
	PLOT (-7.15,1.30,2)	30.5030
	PLOf (-1.35,9.00,2) \$	36.6643
	PLOT (-1.45,9.57,)	Subton
	06 21 7= 197,2	3.6.50
ن	SY430E (-3.15, 9.4-I*.1	J.16.070
	1 LOF (-7.45,9.5%;2) & CALL	00000
	PLOF (=1.45,0.50,2) 5	10.6093
	CALL PLUI(-1.35,9.60,3)	05t.13u
رت		J-6113
		276129
		U. t. 132
	CALL (XXIS(-(+4,1.40,1)(11),20,7.6,90.,7(N+1),4(N+2))	0 6140
٦ اع	X(1+1) = X(1+1) + 0 + 0 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1	000 100
		0.6150
	$X(1+1) = X(N+1) - C_{+} L^{-1} X(1+2) = 2 \cdot Y(N+1) = Y(N+1) + 1 + 3 S^{-1} Y(N+2)$	100170
	Katuya Tend	1 06150
		0.6130
	FUACTION DOT3(X,O,Y,NSM)	001 200
	D_1=NSJON X(1),Q(1),Y(1)	006213
	rof3=:.	3.6223
	DC 1 1=1, VS:	016233
	00(3=x(T)+u(1)+t(1)+0113	45664
_	Co ITINUE	0.16250
	KETU KN	u 3 5 5 0
	ENO	306270
		336200
		366233
	SUDMOUTING HEARIC, FL, SFL, CFLK, GL, HFC, HED, GEQ, HTOH, HTQAI,	006300
	+H+L+11,153470K1)	0.6310
	014ENSI01 G(1),FL(NDR1,1),GL(1),GFL(1),GFLK(1)	0.6320
	U145451513 4 HFG(1), HEG(NSM,1), 7F5 (NSM,1), HTGH(L,1), HTGHI(L,1)	006330
	CC 1MORZ-AXIN5 ZNDEM, NDEM1, DCMLZINOUZKIW, KOUT, KPUNCH	ປ ι 53 ὑ
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                                                         THIS BLOCKTHRU SNAW) CREATES AN EQUIVALENT OF HBAR WHEN SO TO 11MO JUST CAL, RIPAT
THE ELEMENTS OF THE FIRST COL OF HSAP, HFC, IS FORMED USING THE ALLATIONS 4IP HFC(1)=SUM OVER 1 OF (C°F* (I-1)*G).
                                                                                                                                                                                                                                                                                                                                                                                                                         WILL NOW FORM THE REST OF THE PIECES NEEDED FOR THE 'NORMAL' FOLLUSED IN CALCULATION OF THE CONTROL INPUT. FORM 4104
HIS IS 141 REID METHOD
DO 79 I=1, L
NOW GET THE PIECES OF THE "ADRHAL EDN", WHICH IS USED TO CALCULATE THE CONTROL USED TO DRIVE THE OJIPUT ALCHG THE DESTRED TRAJECTORY.
                                                                                                                                                                                                                                                                           CONFINITE COLUCTOR ()) - GL ())
CONFINITE COLUCTOR () - CFLSL
SALL SYNA (GFL,FL,N,N,GFLK,NDK1)
EQUATE THE TWO MATLICES SO SAN GO THRU INNER
                                                                                                                                 NDIM=L
HDIM1=L+1
CHANGE L TO NOF3 WHEN GO TO 1GTH OADER
                                                                                                                                                                                                                              CALL FV4AT (C, FL,N,N,C*L, HDR1)
NO 44 J=2, ML
                                                                                                                                                                 00 30 II=1,N
CFL(II)=CFLK(II)
SONTINUE
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                         00 50 K= 1,L
HT?H(T, 1)=DOT3(HEQ(1,<-I+1),QE2(1,K),HEQ(1,K-J+1),NSH)+HTQH(I,J)
                                               CONTINUE
CONTINUE
CONTINUE
HAVE FURKED
AND THE UPPER SCITION OF MED,OFF DIAGONAL TERMS
AND TRAMFFORSS. IN THE SISS CASE LLEMFILS AND SCALARS
SO THE OFF PIAGONAL TERMS ARE EDUAL. THIS BLUCK
URFINED THE LOWER ELEMENTS IN FRRNS OF THE UPPLA ONCS.
                                                                                                                                                                                                                                                                                                              SUB NJISE CALCULATES THE VALUES OF THE MEASUREHENT NOISE USING A FANDOM NOISE GENERATON MODELLED AS GAUSSIAM:
                                                                                                                                                                                                                                                                                     SUBROUTIVE NOISE (RMSNDIS, DUTHEAN, MN)
                                                                                                                                                                                                         DO41 TRUE
CALL GMI 1V (1, L, HIOH, HIOHE, MR, 1)
RETURA
END
                                                                                                                                                                                                                                                                                                                                                                                DO 1) I=1,12
SAUSS=SAUSS+KANF(DU4)
CO1TINUE
                                                                                                                                                                                                                                                                                                                                                                                                                     GA JSS=GA 188-6. +OUTMEAN WR=GA 188 * CMSNOIS
                                                                                                                                        00 9) I=19L
00 a) J=19L
IF(I.EC.) FO TO 80
HICH(J,1)=HTQH(I,J)
00 63 J=I,L
HTAH(I,J)=0.
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Appendix C

Graphical Results of Model Mismatch Simulation

Appendix C contains the graphical results corresponding to the cases listed in Table II and Table III in Chapter IV.

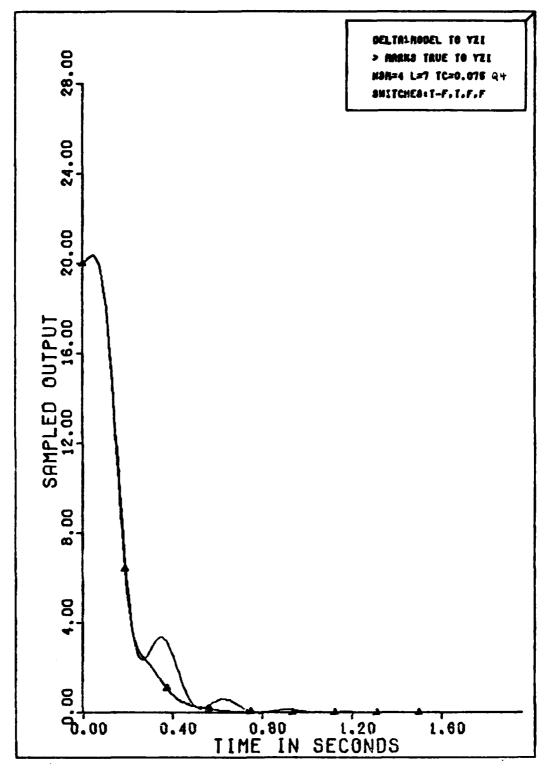


Fig C-1. System Output for Truth Model (Δ) and 10% Delta 1 Model to Zero-Input Response Calculation, TC=0.075

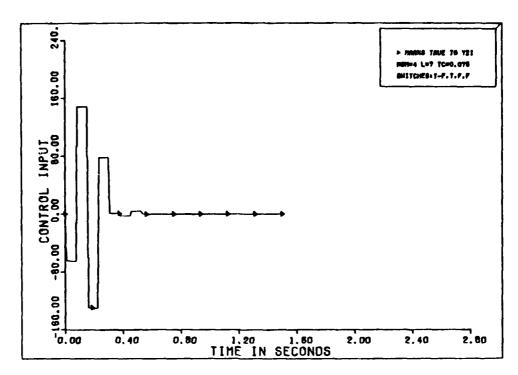


Fig C-2. Controls Applied for Truth Model to Zero-Input Response Calculation, TC=0.075

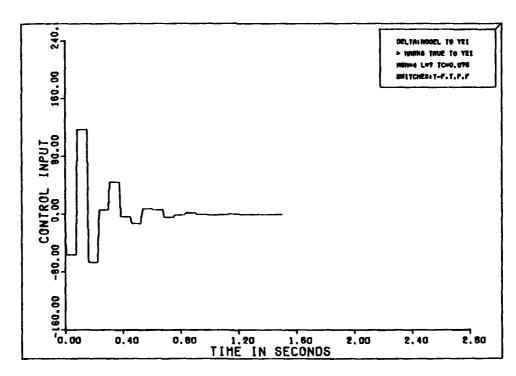


Fig C-3. Controls Applied for 10% Delta 1 Model to Zero-Input Response Calculation, TC=0.075

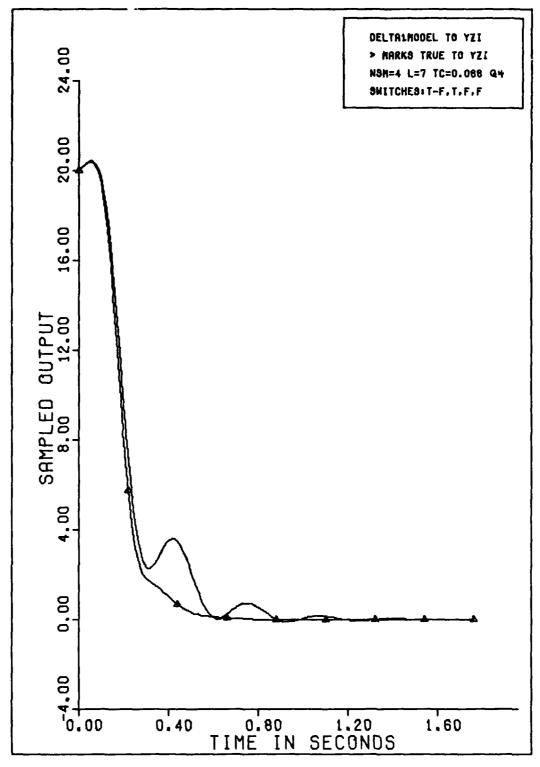


Fig C-4. System Output for Truth Model (Δ) and 10% Delta 1 Model to Zero-Input Response Calculation, TC=0.088

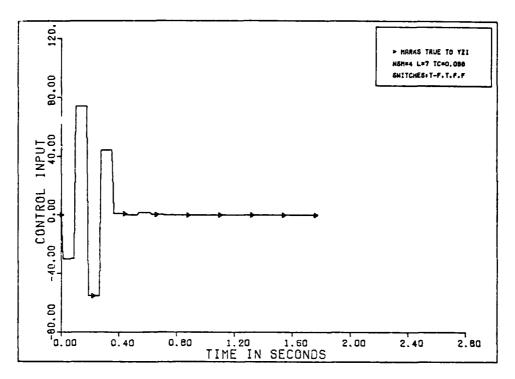


Fig C-5. Controls Applied for Truth Model to Zero-Input Response Calculation, TC=0.088

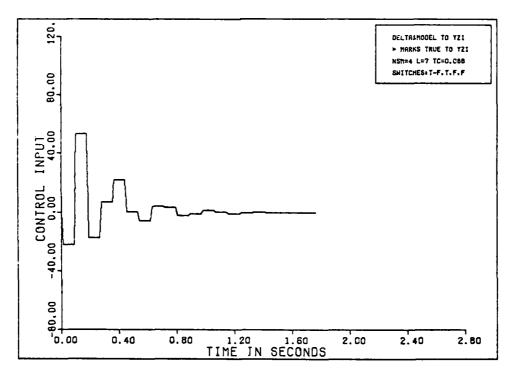


Fig C-6. Controls Applied for 10% Delta 1 Model to Zero-Input Response Calculation, TC=0.088

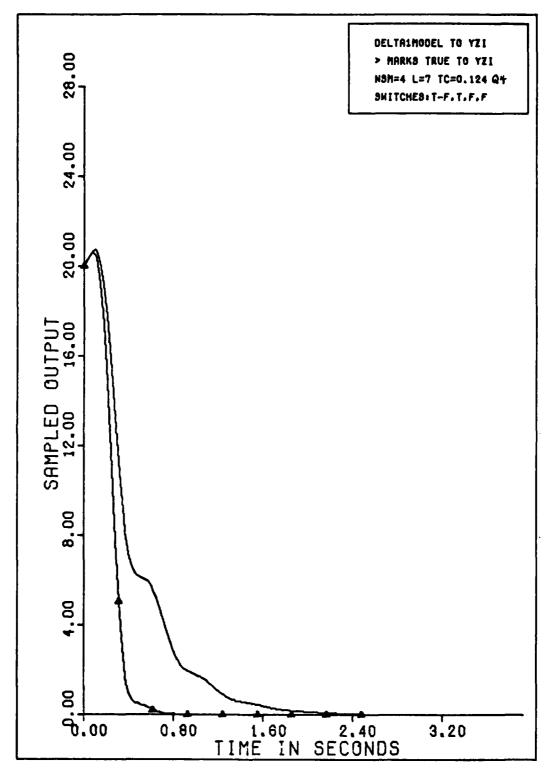


Fig C-7. System Output for Truth Model (Δ) and 10% Delta 1 Model to Zero-Input Response Calculation, TC=0.124

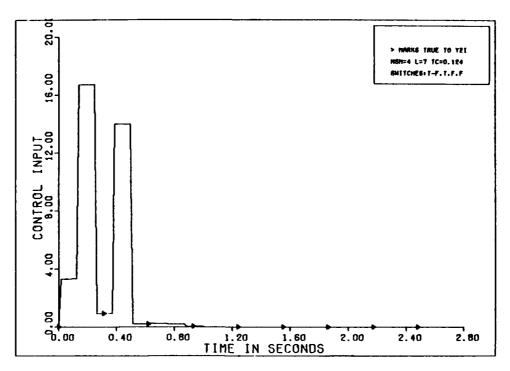


Fig C-8. Controls Applied for Truth Model to Zero-Input Response Calculation, TC=0.124

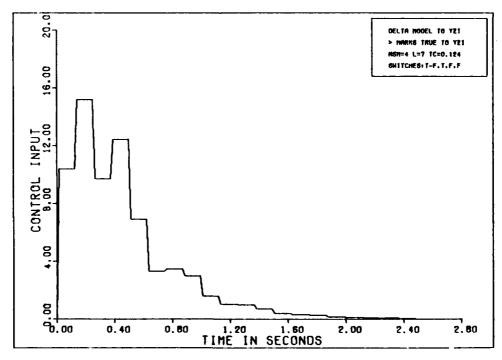


Fig C-9. Controls Applied for 10% Delta 1 Model to Zero-Input Response Calculation, TC=0.124

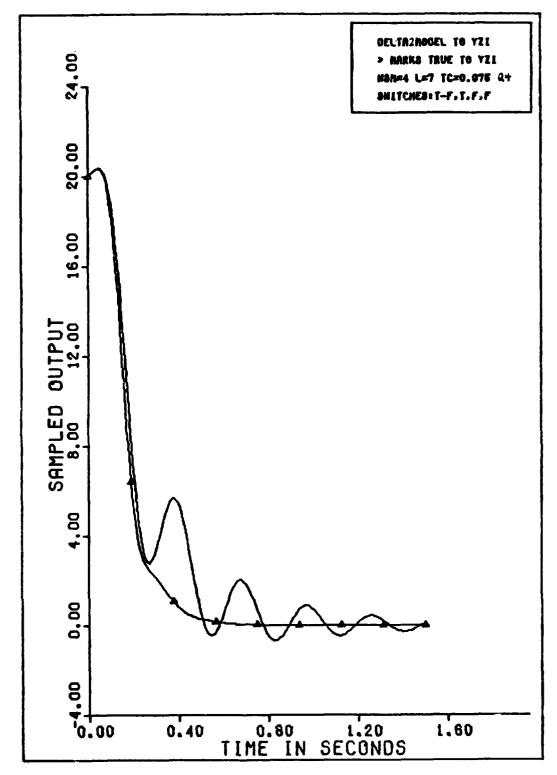


Fig C-10. System Output for Truth Model (Δ) and 20% Delta 2 Model to Zero-Input Response Calculation, TC=0.075

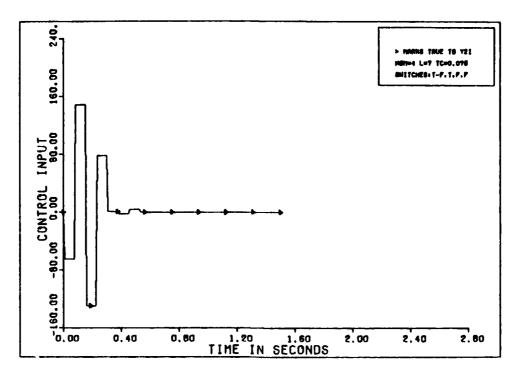


Fig C-11. Controls Applied for Truth Model to Zero-Input Response Calculation, TC=0.075

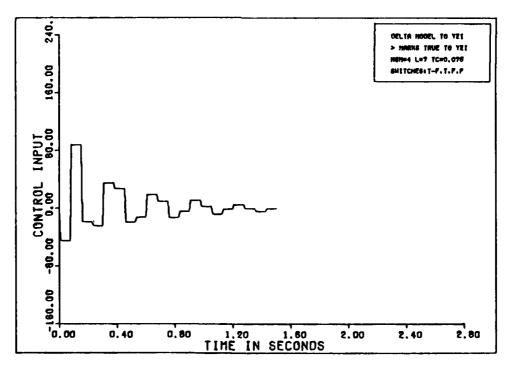


Fig C-12. Controls Applied for 20% Delta 2 Model to Zero-Input Response Calculations, TC=0.075

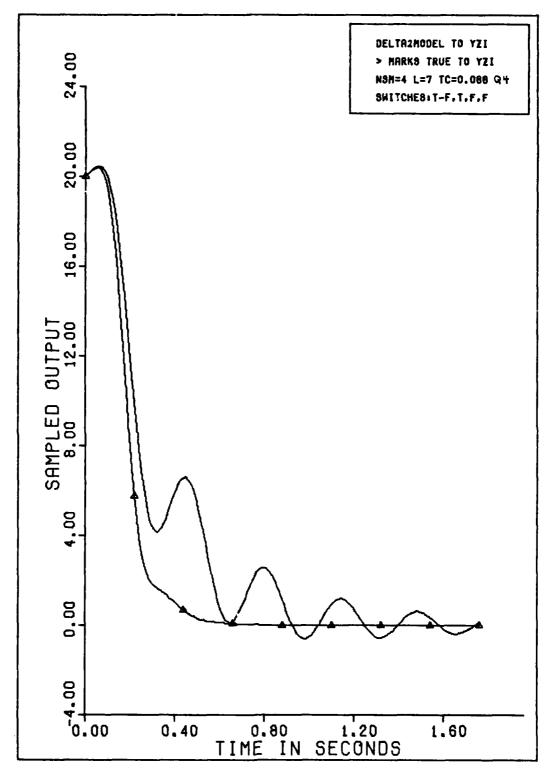


Fig C-13. System Output for Truth Model (Δ) and 20% Delta 2 Model to Zero-Input Response Calculation, TC=0.088

~ 6 10 6

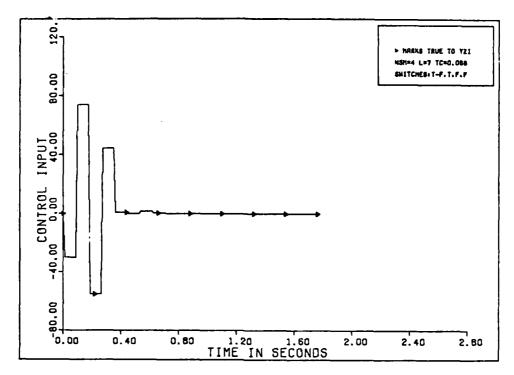


Fig C-14. Controls Applied for Truth Model to Zero-Input Response Calculation, TC=0.088

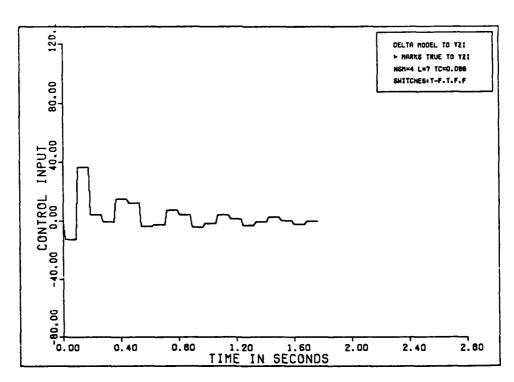


Fig C-15. Controls Applied for 20% Delta 2 Model to Zero-Input Response Calculation, TC=0.088

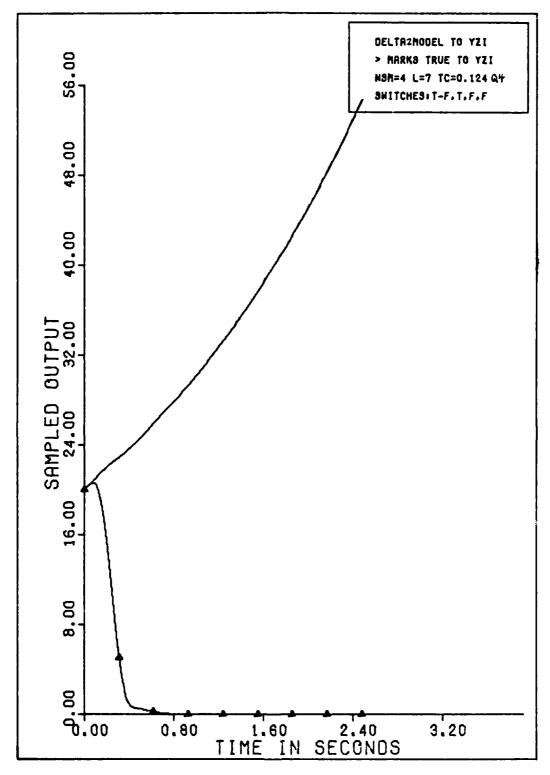


Fig C-16. System Output for Truth Model (Δ) and 20% Delta 2 Model to Zero-Input Response Calculation, TC=0.124

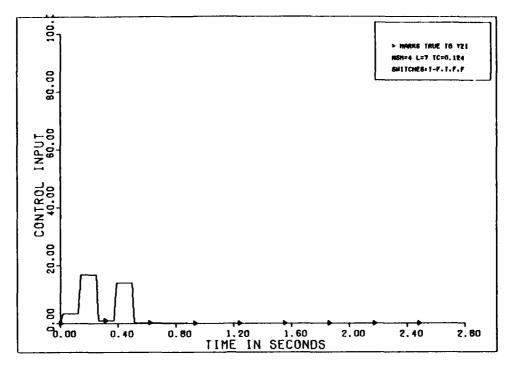


Fig C-17. Controls Applied for Truth Model to Zero-Input Response Calculation, TC=0.124

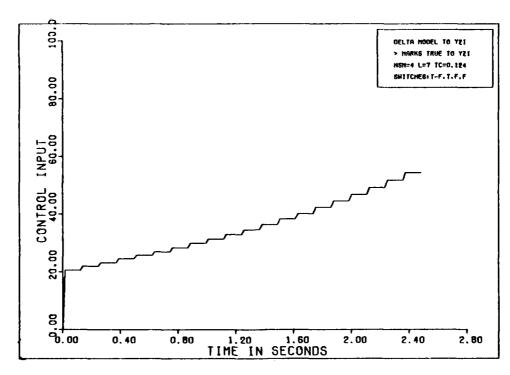


Fig C-18. Controls Applied for 20% Delta 2 Model to Zero-Input Response Calculation, TC=0.124

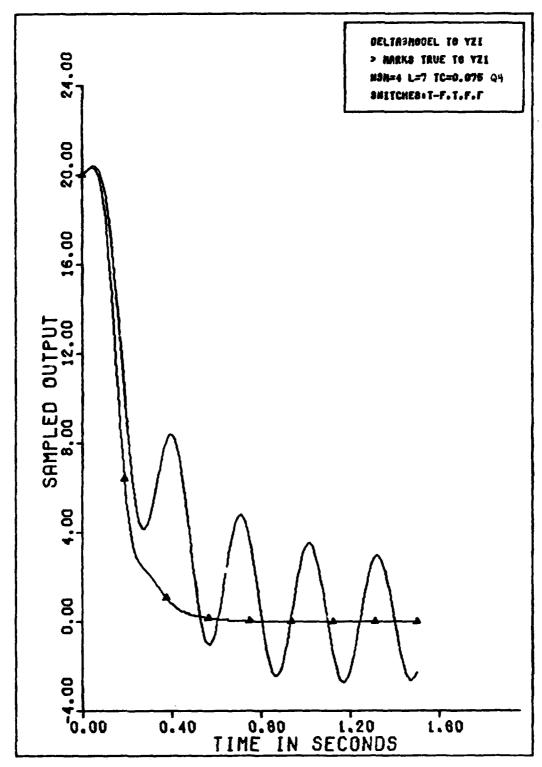


Fig C-19. System Output for Truth Model (Δ) and 30% Delta 3 Model to Zero-Input Response Calculation, TC=0.075

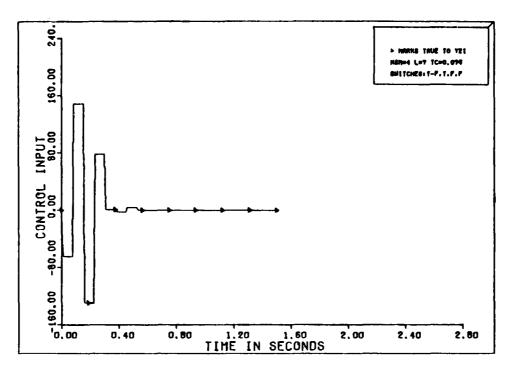


Fig C-20. Controls Applied for Truth Model to Zero-Input Response Calculation, TC=0.075

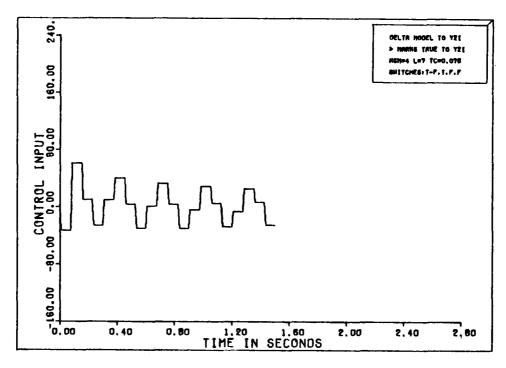


Fig C-21. Controls Applied for 30% Delta 3 Model to Zero-Input Response Calculation, TC=0.075

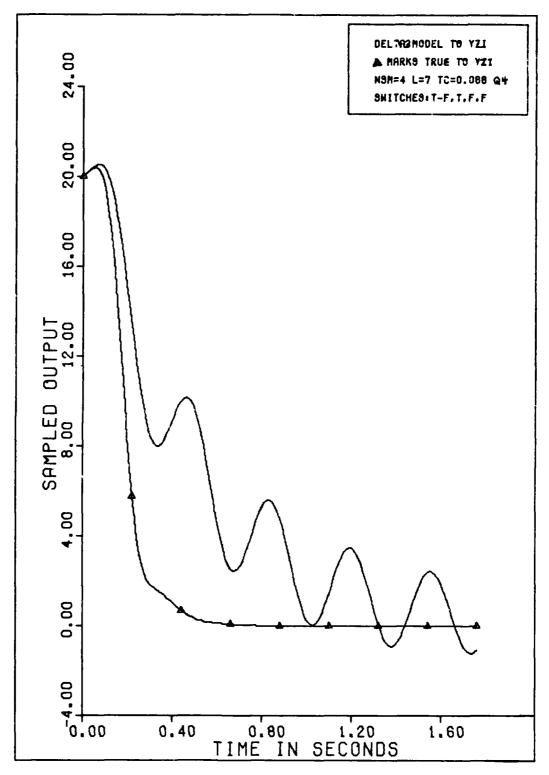


Fig C-22. System Output for Truth Model (Δ) and 30% Delta 3 Model to Zero-Input Calculation, TC=0.088

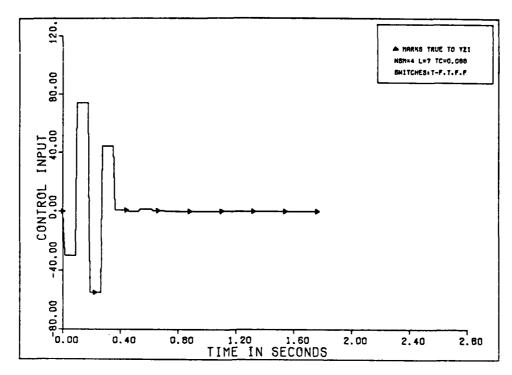


Fig C-23. Controls Applied for Truth Model to Zero-Input Response Calculation, TC=0.088

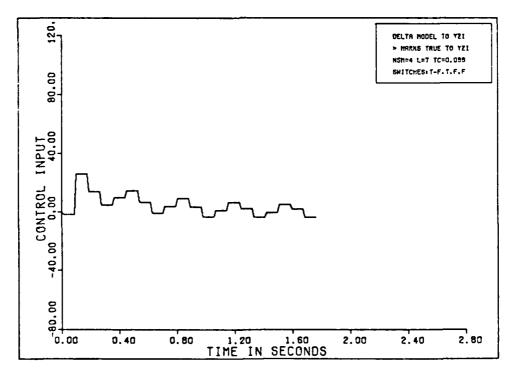


Fig C-24. Controls Applied for 30% Delta 3 Model to Zero-Input Response Calculation, TC=0.088

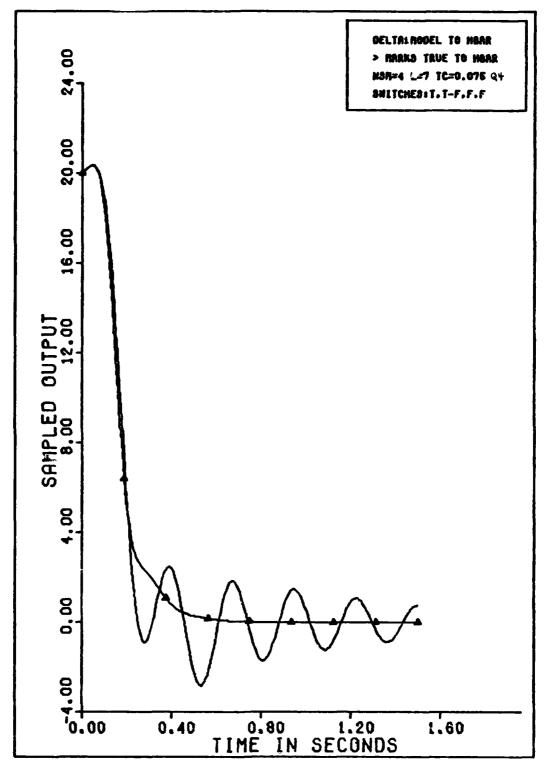


Fig C-25. System Output for Truth Model (Δ) and 10% Delta 1 Model to \overline{H} Calculation, TC=0.075

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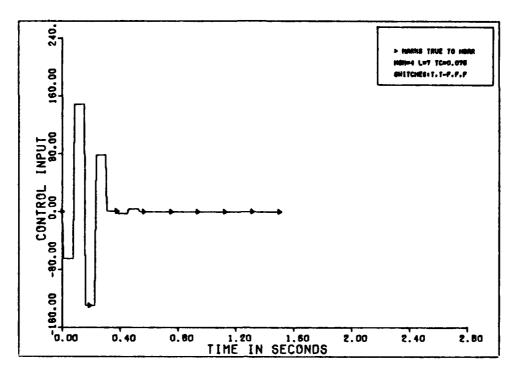


Fig C-26. Controls Applied for Truth Model to $\overline{\rm H}$ Calculation, TC=0.075

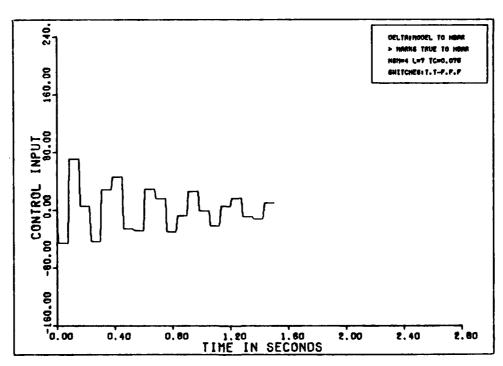


Fig C-27. Controls Applied for 10% Delta 1 Model to $\overline{\rm H}$ Calculation, TC=0.075

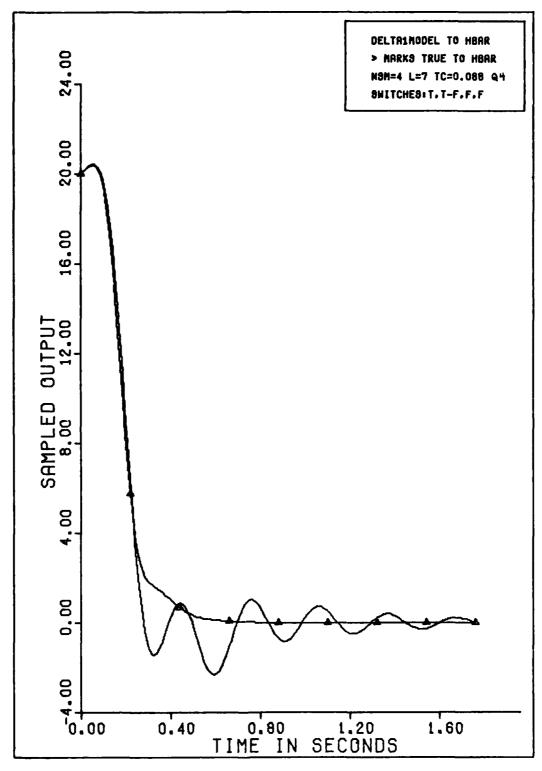


Fig C-28. System Output for Truth Model (Δ) and 10% Delta 1 Model to H Calculation, TC=0.088

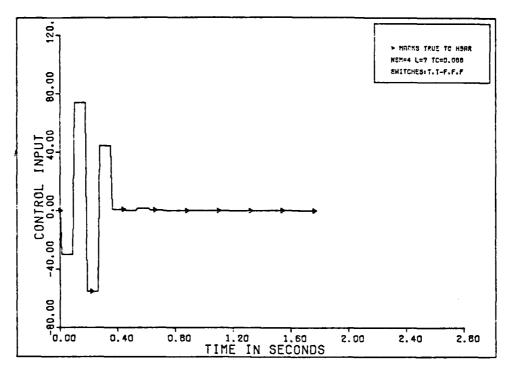


Fig C-29. Controls Applied for Truth Model to $\overline{\text{H}}$ Calculation, TC=0.088

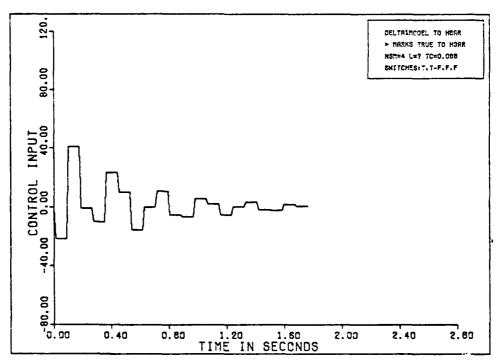


Fig C-30. Controls Applied for 10% Delta 1 Model to $\overline{\rm H}$ Calculation, TC = 0.088

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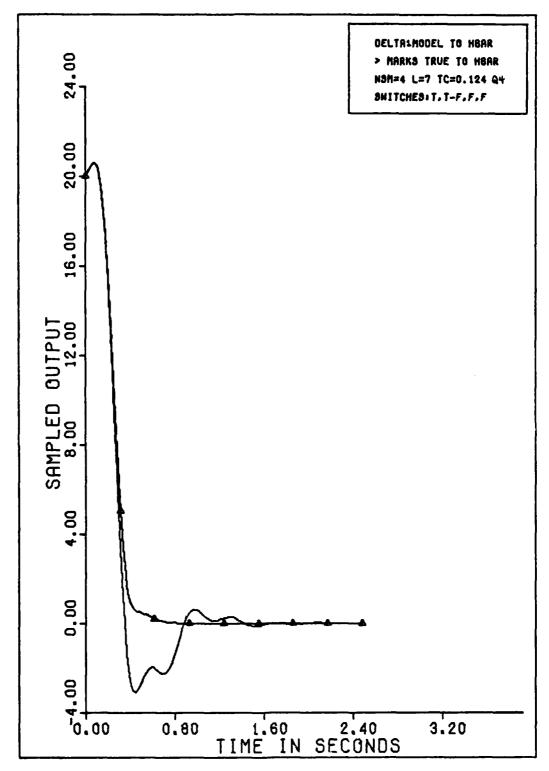


Fig C-31. System Output for Truth Model (Δ) and 10% Delta 1 Model to H Calculation, TC=0.124

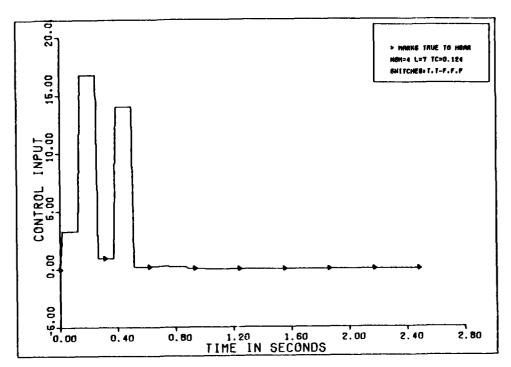


Fig C-32. Controls Applied for Truth Model to \overline{H} Calculation, TC = 0.124

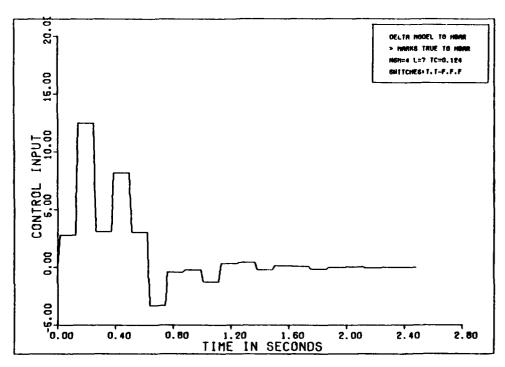


Fig C-33. Controls Applied for 10% Delta 1 Model to $\overline{\rm H}$ Calculation, TC=0.124

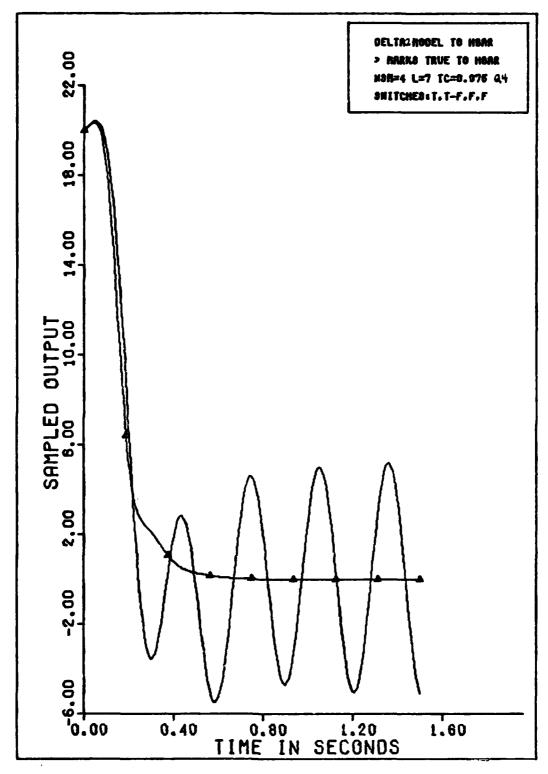


Fig C-34. System Output for Truth Model (Δ) and 20% Delta 2 Model to \overline{H} Calculation, TC=0.075

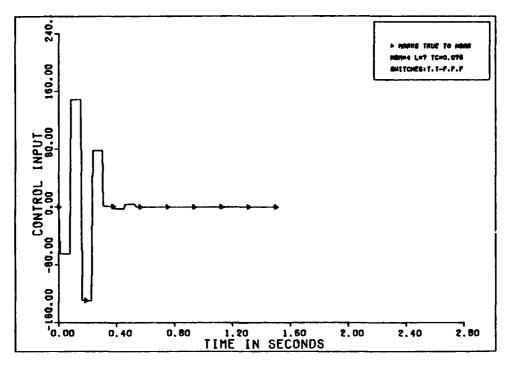


Fig C-35. Controls Applied for Truth Model to $\overline{\rm H}$ Calculation, TC=0.075

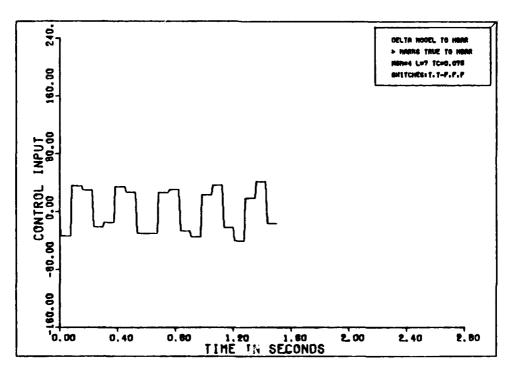


Fig C-36. Controls Applied for 20% Delta 2 Model to $\overline{\rm H}$ Calculation, TC=0.075

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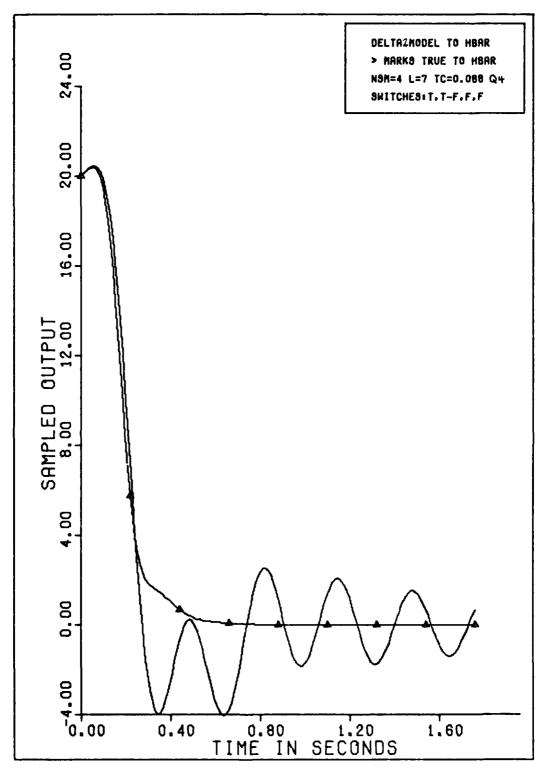


Fig C-37. System Output for Truth Model (Δ) and 20% Delta 2 Model to \overline{H} Calculation, TC=0.088

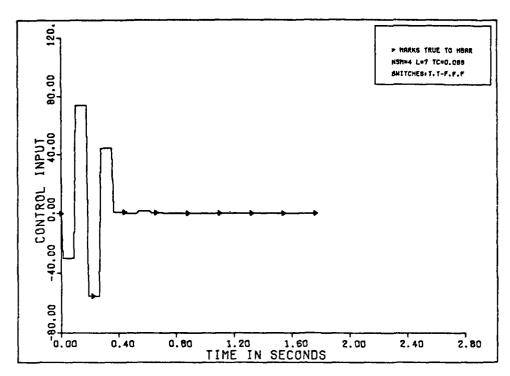


Fig C-38. Controls Applied for Truth Model to $\overline{\rm H}$ Calculation, TC=0.088

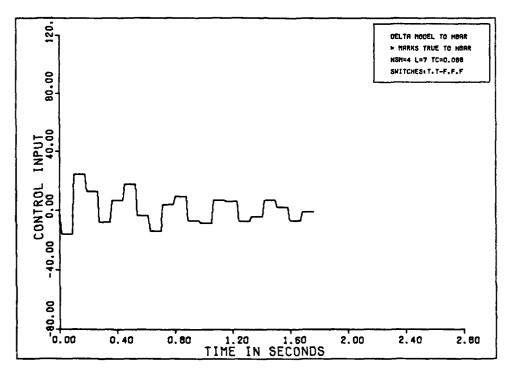


Fig C-39. Controls Applied for 20% Delta 2 Model to $\overline{\rm H}$ Calculation, TC=0.088

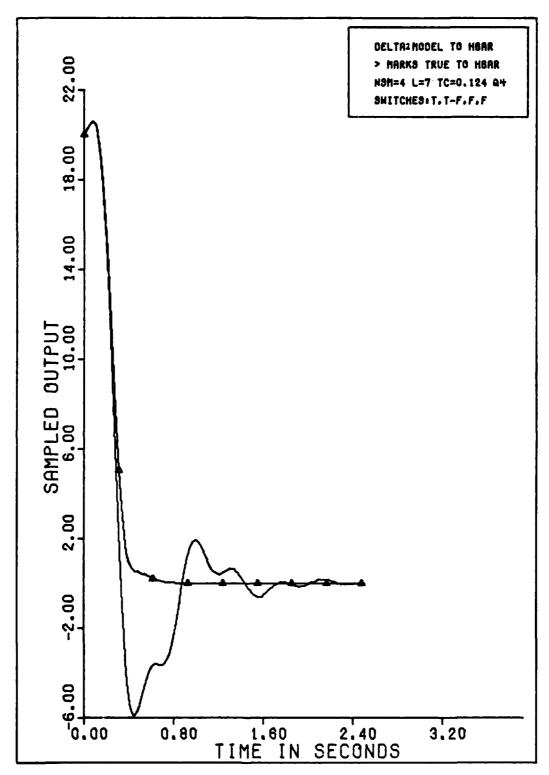


Fig C-40. System Output for Truth Model (Δ) and 20% Delta 2 Model to \bar{H} Calculation, TC=0.124

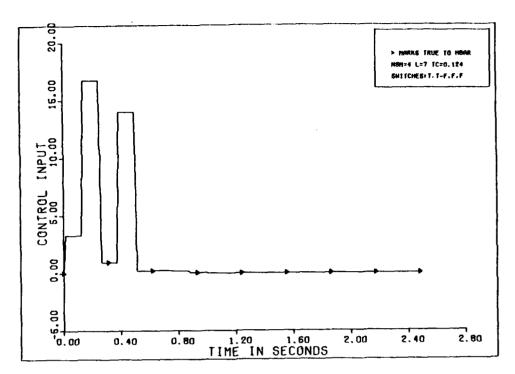


Fig C-41. Controls Applied for Truth Model to $\overline{\rm H}$ Calculation, TC=0.124

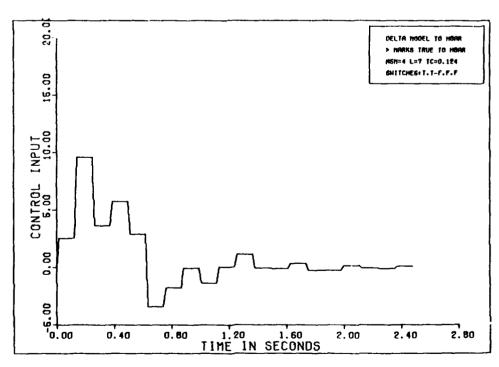


Fig C-42. Controls Applied for 20% Delta 2 Model to $\overline{\rm H}$ Calculation, TC=0.124

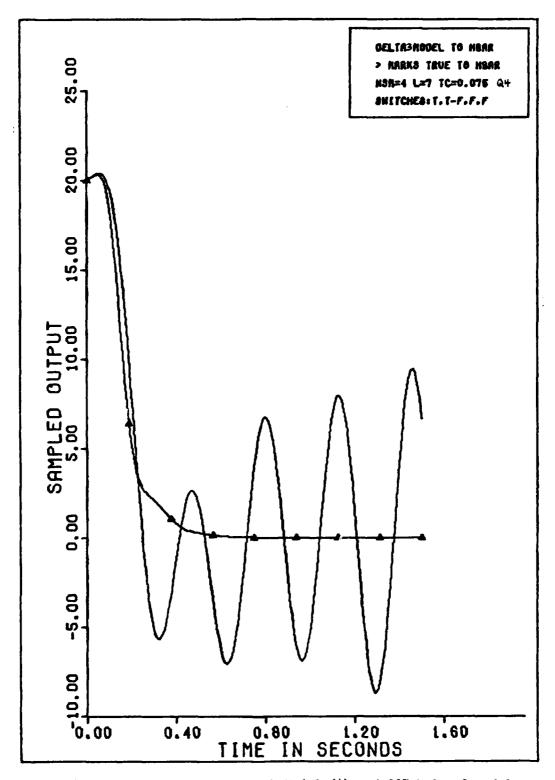


Fig C-43. System Output for Truth Model (Δ) and 30% Delta 3 Model to H̄ Calculation, TC=0.075

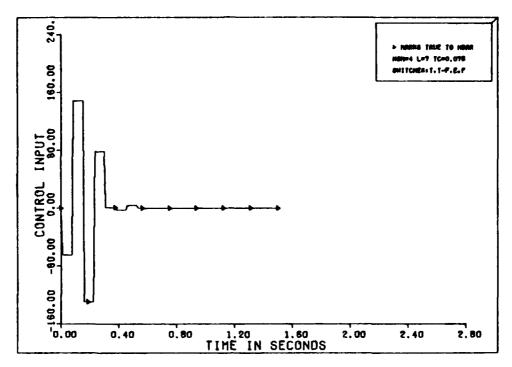


Fig C-44. Controls Applied for Truth Model to \overline{H} Calculation, TC=0.075

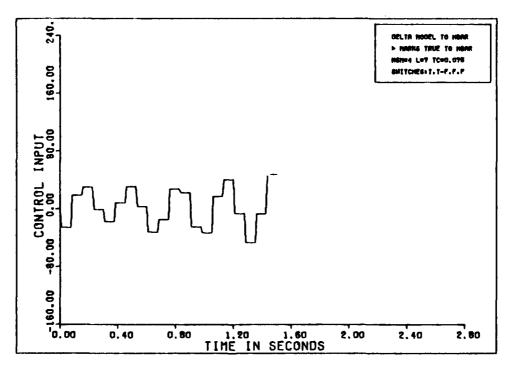


Fig C-45. Controls Applied for 30% Delta 3 Model to H Calculation, TC=0.075

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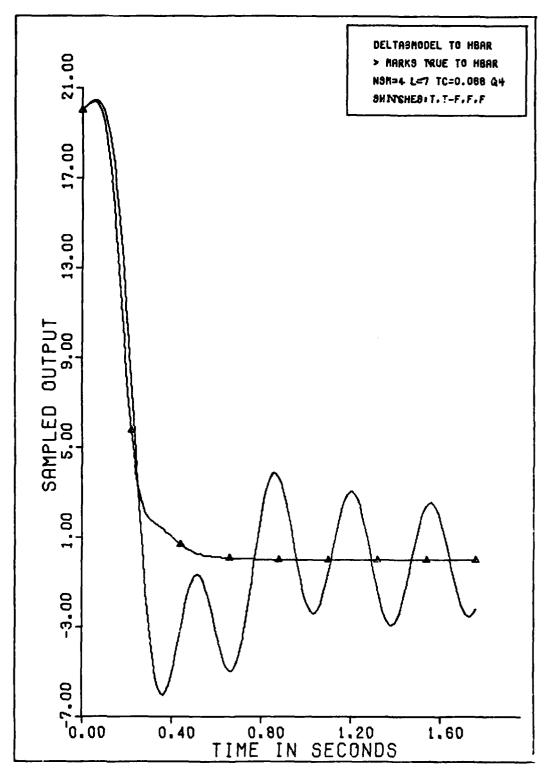


Fig C-46. System Output for Truth Model (Δ) and 30% Delta 3 Model to \widehat{H} Calculation, TC=0.088

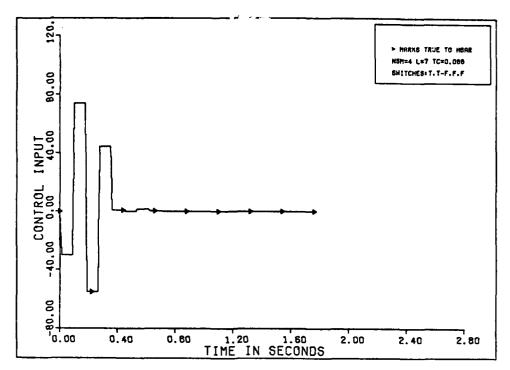


Fig C-47. Controls Applied for Truth Model to $\overline{\rm H}$ Calculation, TC=0.088

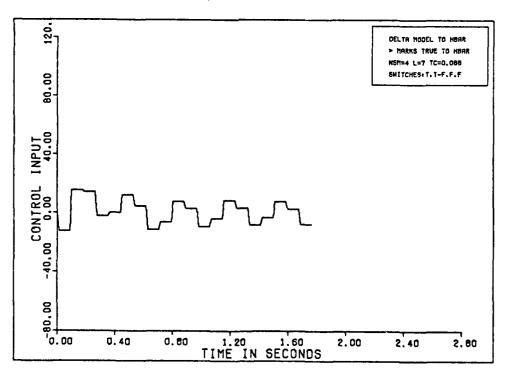


Fig C-48. Controls Applied for 30% Delta 3 Model to $\overline{\rm H}$ Calculation, TC=0.088

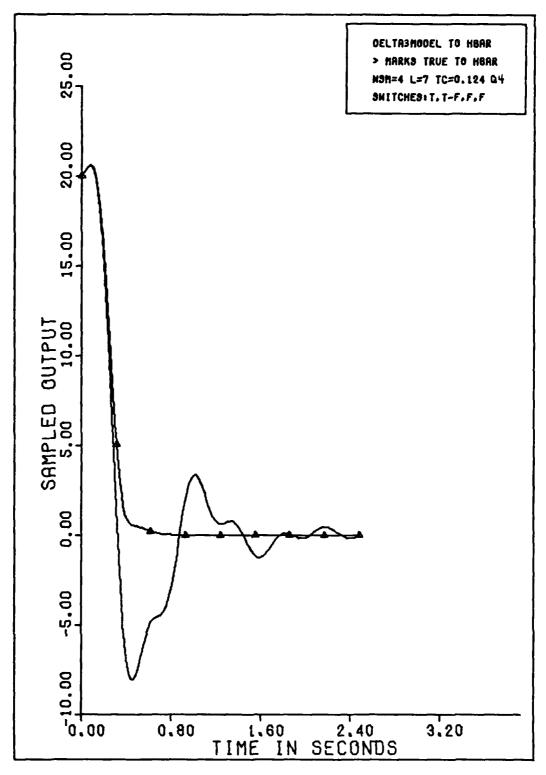


Fig C-49. System Output for Truth Model (Δ) and 30% Delta 3 Model to H Calculation, TC=0.124

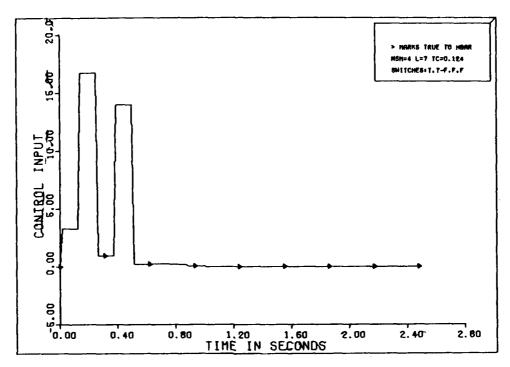


Fig C-50. Controls Applied for Truth Model to $\overline{\rm H}$ Calculation, TC=0.124

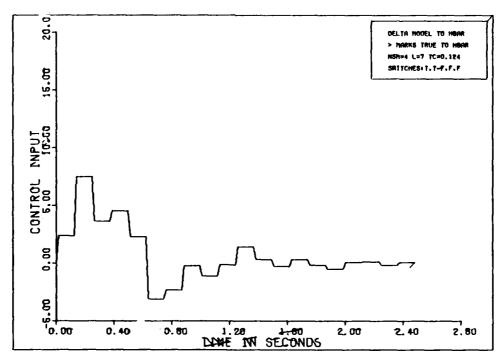


Fig C-51. Controls Applied for 30% Delta 3 Model to $\overline{\rm H}$ Calculation, TC=0.124

Appendix D

FORTRAN Code for Terrain Following Test Cases of Chapter V

This Appendix contains the code used in the terrain following

Test Case 1 of Chapter V. Two libraries must be attached prior to

compilation:

- 1. IMSL, ID = Library, SN = ASD for a sorting routine.
- 2. CONTROL, ID = L720033, SN = AFML for a matrix inversion routine.

Figures 50 through 53 are outputs from this program.

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NCISH3FIO		00C160
OI 4E N° TO4		921000
OIMENSION		001040
MCISM3FTO		006190
DIMENSION	4 TEET (23U),T4ET4(6J3),YST(J31),IDTS(17),ERROX(202)	0.1230
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		097530
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		136310
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	INYS(3)/2JHTC=.F 11J=.3 RSK=1 /	00 770
	INYS(F)/2JHL=7 A=153 W=.59.669.2/	074770
	3(7)/2uH1.6.=3T1LEVEL 0=03/	006450
	IDYS(0)/204 TIME IN SECONDS /	044350
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B1(2)= 3
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B1(4)= 10
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DATA IDUS(11)/2CHELEVATOR CMO (RADS) /
DATA INUS(17)/5CHFIG • CONTROL INPUTS(RADS) AIRCRAFT#1
                                                                                                                                                    CALL PLOT( .,0.03,-3)
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DATA INTS(17)/50MFG , PITCM ENGLE
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                                                                                                                                                                                                                                                                                                                                                                                                                      CALL SONTROL (YD,YZ,ZC,ZEZ,HEQ,DEQ,HTQHI,HTQZ,UCOHP,
                                                                                                                                                                                            CALL FISCRET(AT,BT,TDESIRE,TOBS,N,NT,NDR1,+EAIMT,FLT,GLT,FST,GST)
                                                                                                                                                                                                                                                                                                              CALL YNESIRE (Y, YSET (KYSET), ALPHA, ML, YD)
                                                                                                                                                                                                                                                                               DO 16 K2=1,KF
REHOVED 4FADERS FOR DESIRED OUTPUT POINTS
                                                                                                                                                                                                                                                                                                                                                                                                 CALL YTI(X, N, ML, YZ, BT, FLT, CFL, NOR1)
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US(1)='-1
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34L STATF(X,FST,FK,5ST,6SU,N,U,NOR1)
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CALL HGRAPHITSS, US, NT3, IDJS, 1,3,0)
CALL HGRAPHITSS, THETA, NT3, IDTS, 1,0,7)
                                                                                                                                                                                                                                                                                                              TSS(WIT+1)=TSET(229)
TSS(WIT+1)=YET(230)
YS(WIT+1)=YET(NIPT+1)
YS(WIT+2)=YST(WIPT+2)
GALL HG4APH(ISS,YS,WIP,IDYS,-1,0,0)
YSST(1)=YSET1 & ISET201=TSET(211)
YSST(2)=YSF12 & ISET202=TSET(202)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                        00 17' K=2,200,1
GRRF (K)=18S(YSET(K) -YS(3·K-2))
3U4=SU4+ETKOK(K)
+U.L.ML,NSM,NDR3)
THESE ARE THE CONTROL LIGITS
1F(U.L.....2F2) U=-0.752
IF(U.G.E.+.L.76) U=+G.43E
                                                                                                                                                                                                                                                                           CALL SCALE(VST95.9NTPf91)
VSET1=YSET(1)
                                                                                                                                                                                                                                                 CALL SCALE(TSET,7.,223,1)
                                                                                                                                                                                              YS (KS)=Y
T>S(KS)=TSS(KS-1)+T)AS
                                                                                                                                           CALL DUTPHT (X,CT,Y,4)
                                                                                           KYSET=KYSET+NSM
                                                                                                                                                                                   THETA(KS) = X(3)
                                                                                                                                                                                                                                                                                                   YSET2=YSET(2)
                                                                                                                                                                                                                                                               NIP; =4TP+228
                                                                                                                                                                                                                                                                                                                                                                                                                                               ER 202(1) = J.
SU4= n.
                                                                                                                                                                      1)S (YS) =1)
                                                                                                                                                           4S=KS+1
                                                                                                                                                                                                                         COAT INDE
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                                                                                                                                                                                                                                                                                                                                                                                                                          00200
AVE=SUH/200.
CALL US44MX(ERROK,200,19X4IN,XMAX)
PRINT',"FUP W=",44,",PEAK FRROR=",XMEX,"AVG ERROR=",3AVE, LOYS(1)="AL"ITUDE "
IDYS(2)="ER"OR "
                                                                                                                                                                                                                                                                                                                        EQUATIONS PROGRAHED YOL()=YSET(K)-(ALPHA**K) (YSET-Y), WHERE ALPHA=FXP(-TDESIRE/TAU), TAU IS THE TIME CONSTANT OF THE FIRST OF DECAYING EXPONENTIAL.
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         SUBROUTIVE VZIKK,N,ML,V7,C,FL,CFL,NNR1)
DIMENSION X(1),YZ(1),FL(NDK1,1),CFL(1),G(1)
                                                                   IDYS(11) = INYS(1)

IDYS(12) = "EFROK (FT)"

CALL HEAPH(TSET, EPPOR, 20f, IDYS, 1,0,0)

ICYS(2) = "T. PKOFILE"

IDYS(1) = "DESTRED AL"

IDYS(11) = "PFOFILE AL"

IDYS(12) = "T.T. 100f(FT)"

TSET(2'2) = TET20.

GALL HGRANDH(TSET, YSET, 228, IDYS, 1, 0,0)
                                                                                                                                                                                                                                                                                                                                                                                                        YD(K)=SET(K) - ((ALPH1**K) + (SETNOW-Y))
                                                                                                                                                                                                                                                                              SUBROUTINE YNESIKE(Y<sub>9</sub>SFT,ALPHA,ML,YD)
Dimemsion yn(1),Set(1)
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   EQUATION, PROGREMEDS Y7(K) = C+(FL++K)+X
                                                                                                                                                                                                          PLOTE (P.) "END OF MAIN"
                                                                                                                                                                                                                                                                                                                                                                             SETNOW=SET(1)
00 10 K=1,ML
                                                                                                                                                                                                                                                                                                                                                                                                                      CO IT INUE
                                                                                                                                                                                                                                                                                                                                                                                                                                 RETURN
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                                                                                                                                                                                          SURPOUTINE CONTROL (YD,YZ,ZC,ZEQ,HEO,QEQ,HIQHI,HTQZ,UCOMP,+U,L,ML,NSH,NDK3)
DIMENSION YP(1),YZ(1),ZC(1),ZEQ(NSH,1),HEO(NSH,1)
DIMENSION YP(1),YZ(1),4TO;I(L,1),HTQZ(1),UCOMP(1)
                                                                                                                                                                                                                                                                                                                                                10 12: J=1,L

HT77 (J) = 0.

DG 11L K=J,L

HT72 (J) = TOT7 (HEO(1,K-J+1), QEQ(1,K), ZEQ(1,K), NSH) +HTQZ(J)

CO IT IYUS

CO-1T IN UE
                                                                                                                                                                                                                                                          THE "40%AL FOURTION" IS PROGRAMED AS FOLLOMS: THE VECTOR OF INPUTS CALCULATED U=(HTGHI)*HT0Z*
                                                                                                                                                                                                                                                                                                                                                                                                                            FORM JUCORP, THE CONTROL JECTOR CALL MATY(HTGHL#HTGZ,JCOMP,LBL#T97)
PLCK JFF THE FTRST ELEMENT AS THE CONTROL TO
                        CALL RUMATIC, FL, N, N, OFL, NDR1)
                                    30 10 J=1,N
Y7(I)=Y7(I)+CFL(J)*X(J)
                                                                                                                                                                                                                                                                                                DO 13: I=1, ML
7C(I)=YD(I)-YZ(I)
CU4IINUE
                                                            20NT TNJE

DG 2E K=1,N

C(K) = GFL (K)

CONT TNJE

CONT TNJE

KETURI

END
 DO 33 I=1;ML
Y7(I)=9
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                (1) d+( )(.=n
                                                                                                                                                                                                                                                                                                                                                                                                                                                                    BE APPLIED
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END
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                                                                                                                            THIS SUB DISCRETIZES THE A AND B MATRICES USING FOUTLIES ON A FACKAGE CALED "CONFOL".

THE SAMPLE TIME OF TRESIZE IS HOW OFTEN THE CONTROL INPUT IS CALCULATED. TIME TOPS IS THE DELTA TOF THE OUTPUT
                                                SUBROUTINE DISCRET (AT, BT, I DESIRE, TOUS, N, NT, NDR1, +EAINT, FLT, GLT, FST, GST)
01-5EAINT, FLT, GLT, EST, GST)
01-5EAINTOU AT (NDR1, 1), 3T (1), GST (1)
01-5EAINTOUR FAINT (NDR1, 1), FLT (NDR1, 1), GLT (1), FST (NDR1, 1)
COHMON/MAINT/NDIM, NOTM1, CCM1/INOU/KIN, KOUT, KPUNCH
                                                                                                                                                                                          SUBMOUTINE WEIGHT (NSM)L, ML, GC, GEO)
DI ATYSION OC(1), DED(NSM)L)
THIS IS FOR MODAZ GEO WIENS
K=4L/C
                                                                                                                                                                                                                                                                                                                                                                                                                                                           00 24 )=KK,ML
1C(3)=1.0[+6
                                                                                                                                                                                                                                                                                                                                                                                                                     00 11 T=1,K
                                                                                                                                                                                                                                                                                                                                                                                                                                10(1)=1.
                                                                                                                                                                                                                                                                                                                                                                                                                                              20171100
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    CC 41 INDE
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                KETUZN
ENJ
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                                                      JC 2960
                                                                                                                                                                                                                                            003160
                                                                                                                                                                                                                                                                                                                                                                  0-3290
                                                                                                                                                                                                                        EQUATION CORED! Y=C+X, W4ERE X MAY OF MAY NOT MAVE NOISE ON IT
                                                     EQUATION CONFOR X(K+1)=FS*X(K)+GS*U, WHERE THE STATE MAY OR MAY NOT HAVE MAISE ON IT, DEPENDING ON THE SMITCH SETTINGS.
                 SUPROUTINE STATE(X,FS,FSX,GS,GSU,N,U,NDR)
DIMENSION X(1),FS(NDR,1),GS(1)
DIMENSION GPU(1),FSX(1)
                                                                                                                                                                                                                                                                                                                          DIMENSIN' DWAT (NDR,1)
DO 21 J=1,NF,1
WRITE(5,17) I, (DMAT(1,1), J=1,NC,1)
FORMAT(1HC,12,(T4,4(1PE13.4,1X)))
                                                                                                                                                                                                                                                                                                                   SUBROUTINE FRINTHING, NC, DHAT, NDR)
                                                                                                          SUBPOUTINE CUTPUTIX,C, Y, V)
DIMENSION X(1), C(1)
                                                                                 DU 17 T=1,N
3SU(I)=69(I)+U
CG4III.UE
                                                                                                                                                                                                                                          Y=1.0
00 13 I=1,N
Y=Y+f(I)*X(I)
CO4IINUE
KETURN
EN)
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	SE TISSA	
	END	003310
		0.3320
		003330
	SUBFOUTINE I VMAT(RV, AMAT, KR, NC, VMAT, NDR)	01340
	DIJENSTON PV(1), AMAI(488,1), VMAI(1)	0003380
	00 21 T=19NF	3366
	\dagger \dagge	403370
	30 1f 9=1,NC	0688 10
	V×7 f (1) = VMAT (1) +QJ (J) * AMAT (J, 1)	3393
	30개 가기트	007830
	00211200	3410
	KETUPI	07 34 50
	EN.)	30.34.30
		9031.,4
		0.3459
	SUBMOUTE IF PRINTR (NE, 2 V, 40R)	063460
	DI 4E:45 TO 4 RV (NDR)	0.3470
	J=1	003480
	WRITE 10, J, (RV(I), 1=1, NE)	103490
_	FURMAT (143, 12, (14,4 (12E13,4,1X)))	013500
	RETURN	013510
	EAU	0.3520
		0.3530
		0.33543
	SHREGUTINE MATUCAMAT, V. A 14TV, NR, NC, NDK, NDC)	363550
	CITEMSION AMAT (NDR, NDS), V(NDC), AMATV(NDR)	JE 3569
	00 21 I=1,NF	003570
	AMATV(T)=^.u	363580
	JO 17 J≖1,NC	063800
	AMATU(I)=AMATU(I)+AMAT(I,)) "V(J)	J: 3600
_	CONTINUE	003610
	CO ITINIE	363620
	RETUR	003630
	CHE	0.53640
		063650
		003e60
	SUBPOUTINE HERAPH(X, Y, N, ID, NO, NP, NS)	013670
	DIMENSION X(1), Y(1), 1)(1) \$ IF(NO.EO.2) GO TO 30	003680
	IF (40.LT.0) GO TO 10	3632

	SCAL F(X. 7N. 1)	0.370
ت	CALL FLOT(A.5, U.s, -3) & CALL PLOT(., 11., 3)	00371
		30372
	CALL PLOT(-7.15,1.3%;2) \$ CALL PLOT(-7.15,9.65,2)	00373
	23	0.374
	CALL FIOT (01375
	~	03376
02	83,	10377
		0.378
	CALL PLOT (+1.05,9.55,2) 8 CALL PLOT (-7.05,9.35,2)	01379
	Pl.OT (12,9.65,3)	U85 ∟0
ñ,		06.381
	CYM3 of (-6.6291.139.1910	96.382
		00 383
	CALL AXIS(-1.85,2.1,13(11),20,5.,18 .,7(N+1),7(N+2))	0.364
7	Y(4+2) =-Y(N+2)	60385
	X(4+1)=X(4+1)-2.1"X(H+2) { Y(H+1)=Y(N+1)+1.05*Y(N+2)	06.386
	CALL LING (Y, X,	0.387
	X(1+1)=x(11+1)+2.1+X(N+2) 1 Y(N+1)=Y(N+1)-1.85+Y(N+2)	0,368
	٠	90369
	RETUZU S END	06£ 00
	SURPOUTING VERAPH(X,Y,N,IT,NO,NP,NS)	165.0
	DIMENSION X(1), Y(1), I)(1) \$ IF(NO.E0.2) GO TO 30	01392
	IF (40.LT.A) 60 TO 19	262 0
		16200
≐		01395
	FLOT (-1.35,1.35,3)	00396
	PLOF(-[-15,1.35,2]	16800
	PLOT (-1.35,3.65,2) \$ 3	86500
	5,3.55,3)	31:399
	⊂`	02400
نت		30401
		30405
		80400
	CALL PLOT (-7.35,9.60,3)	19100
ŝ		53400
		91410
	CALL AXIS(-f.4,1.8F,12(3),-21,4.9,1.,x(N+1),X(N+2))	204.67
	CALL AXIS(-f.4,1.05,1)(11),20,7.0,91.,7(N+1),7(N+2))	90700
2 2	X(4+1)=X(N+1)+0.4-X(N+2)	60470

	CALL _IME(X, V,	004100
	RETURN S END	034120
>	FULCTION DOT3(X,D,Y,NSM)	904140
	D1-1FNSTOW X(1),0(1),Y(1)	0.415
	00F3≈F•	0n4 16
	DO 1 1=19NS"	00417
	0013=x(I) +0(I)+4(I)+2313	06418
₩.	CONTINUE	4.19
	RETURN	90420
	CNB	00421
، ن		00422
د		, o d . o d
	SUBMOUTINE HEARIG, FL, JFL, JFLK, 6L, HFG, HEO, GEO, HT QH, HT QHI,	000,240
	+N+L+ML+M2M+MDR1)	004250
	DI4E4SIO4 C(1), FL(NO41,1), GL(1), CFL(1), CFLK(1)	304266
	DIMENSION HEC(1), HEQ(NSM,1), DED(NSM,1), HTOH(L,1), HTOHI(L,1)	31,427
	CO 4HD4/ 4A I N4 / NDI M, NDI 41, COM1/INCU/KIM, KOUI, KPUNCH	0.428
Ç,		00453
ပ		166470
ပ		00431
ပ	NOW GET THE PIECES OF THE ""TORMAL FON", WHICH	36432
، ب	IS USED TO CALCULATE THE CONTROL USED TO DRIVE	E 470
, د	THE OUTPUT ALM'S THE DESIFED INADECTORY.	30300
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ى د	THE SECOND ONE OF THE SECOND OF THE SECOND S	20.400
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ں د	OFCORPACES	
ပ		014410
ပ		034450
	1=H10N	000 - 30
	NDIM1=L+1	77710
رى	CHANGE L TO NOTS WHEN GO TO SOTH DEDER	30445
	HD(1) HJ	94400
		2 - 500
•		84433
2	CONT. TRUTE	T + + 1 = 1

ပ	FURM OFL	004200
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		004500
	00 2 J=15 N	044400
	L+6FL(JJ) *GL(JJ)	364558
20		394560
		054573
	SALL RUMA" (OFL,FL,N, N, 2)FLK, NDP1)	064580
O (EQUATE THE TWO MATRICES SO CAN GO THRU INNER	064530
ပ	LOOP AGAZE	0014633
	No 31 11119 N	004010
2	CFL(II)=CFLK(II)	1004E20
3 4	٤	
ני		104650
ပ		0.4660
ပ	WILL YOW FORM THE REST OF THE PIEDES NEEDED FOR THE	0.4670
ပ	TO A USED IN CALBULATION OF THE SONTROL	069720
ပ	FORM 4T34	304690
ပ	THIS IS THE RETD METHOD	304790
	DC 7.3 I=1,L	00.4710
	00 60 J=1,L	004729
	HT2H(1, 1) = ₽.	0.4730
	0.6 5.1 k= 1,5L	034240
		034120
ž		004766
9		024770
2 0		094780
ပ	HAVE FOATED THE UPPER SECTION OF HEDGEN DIAGONAL TEXAS.	0.4793
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י נ	DEFINES THE DEFENDING REPARK OF THE COPIES THE DEFENDING TO THE COPIES ONES.	012400
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	161 - C C C C C C C C C C C C C C C C C C	0040400
	IF(I.En. J) GO TO 80	004850
		004860
6 0		07870
3 3		314880
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SU3KOUTINE WEIGHTI(NS4,L,ML,QC,OEO)
DIMENSION OF (1), DED(NS M.L)
C THIS IS FOR IDFNIITY WEISHTING
DO 11 I=1,ML
7C(1)=1,R
RCTUPN
RETURN
                                                                                                                         SUBACOUTIVE WEIGHTZ (MSW,L, ML, QC, QEQ)

DIMENS TO TO (11), QCO (MSP,L)

C THIS IS FOR ALCK WEIGHTING

DC 11, 1) = 1,

DC 12 T = 2, L

TFO (1, T) = 2** QEO (1, I = 1)

LQ CONTINUE

TO 3 T = 1, L

DO 2 D = 2, NSM

TFO (1, T) = QEO (1, I)

20 SONTINUE

RETURN

RETURN

END
                                                                                                                                                                                                                                                     SUBROUTIVE WEIGHT3(NSM,L,ML,OC,OEO)
DIMENETOW OF (1), QEO(N3M,L)
THIS IS FOR GEO WING
QC(1)=1.
DO 11 I=2,ML
QC(1)=2*QF(I=1)
                                                                                                                                                                                                                                                                                                   CO ITTINE
                                                                                                                                                                                                                                                                                                            Pe TURY
ENJ
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SUSPOUTINE WEIGHTS (NSW,L, ML, DC, DED)
DIMENSION OF (1), DED (NSW,L)
C IMIS IS FALY GEO WING
OF 15 TO FALY GEO WING
OF 15 TO FALY GEO WING
TO (ML) = 1,
TO (ML) 
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     SUBAROUTINE WEIGHIG (NSM<sub>9</sub>L<sub>9</sub>HL, QC, DEO)
DIMENSION OF (1), QEQ(NSM<sub>9</sub>L)
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OF (1,1) = 1,0

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                                                       DIMENSION COMICED, 2.), AT(1, 9.), BT(4), CT(4), X(4), EAINT(4,4)
DIMENSION FLT(4,4), GLT(7), FST(4,4), GST(4)

DIMENSION CFL(4), CFLK(1), HFG(28), HFD(4,7)

DIMENSION OF (28), GFD(1,7), HFG(1,7)

DIMENSION OF (28), GFD(1,7), HFG(1,7)

DIMENSION YC(28), YC(28), YCC(28), YCC(28)

DIMENSION YC(6,13), US(5,13), TSS(5,13), TOYS(1,7), ERROR(202)

DIMENSION YC(6,13), TMETA(6,13), YST(4,31), 1DTS(1,7), ERROR(202)

COMMON/MAINI/NDIM, NOTMI, COMI/INCUKYN, KOUI, KPUNCH
                                                                                                                                                                                                                                                                                  EDUIVALENCE (HEC(1), HEn(1,1)), (NC(1), GEG(1,1))
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EQUIVALENCE (ZG(1), 7ST(1)), (YSFT(1), YST(602))
THE SYSTEM FONT ARE IN PARSE VOL FORM, G(N) IS
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OUTPUT.
PROGRAM HOVIT (INPUT, OJIPUT, PLOT, TAPES INPUT, CTAPES=OUTPUT)
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(AT (1) 91=194) / 34.479.33193.96./

(CT (1) 91=194) / 3*19.91./

(X(I) 91=194) / 4*10./
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A TNYS(1) / 2 UHS ET(*) V3 ACHIEVED W/
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VITA

David E. Chaffin was born on 30 May 1948 in Pontotoc, MS. He graduated (Cum Laude) from Memphis State University in August 1971 with a BSEE degree and an ROTC Commission (Distinguished Graduate). He completed pilot training at Moody AFB, GA, in November 1973 and was assigned to Williams AFB, AZ, as an instructor pilot in the 96 FTS and subsequently as an 82 FTW flight examiner in the T-37. His assignment prior to entering AFIT was to the 41 MAS, Charleston AFB, SC, in the C-141.

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Terrain Following		}	
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This thesis is a study of a digital control technique known as Output Predictive Control (OPC) or Model Algorithmic Control (MAC). In OPC, the behavior of the system is predicted using its impulse response function and the desired response is characterized by a reference trajectory. Controls are computed			
iteratively to drive the system output along the desired trajectory. In an earlier study, the system was made to follow the reference trajectory exactly, but only at the control application time; there were large oscillations of the			

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SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered) output between control changes. In this study, the control calculation is reformulated as a least squares curve fit problem, allowing some deviation from the desired trajectory. This approach is applied as a regulator for a very lightly damped fourth-order single-input/single-output system and as a pitch axis autopilot in a simplified terrain following problem. A qualitative discussion of robustness properties is included. The design of the controller is difficult due to the interrelationships of the internal parameters; however, the results of the terrain following example indicate that this is a viable approach for this problem.

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