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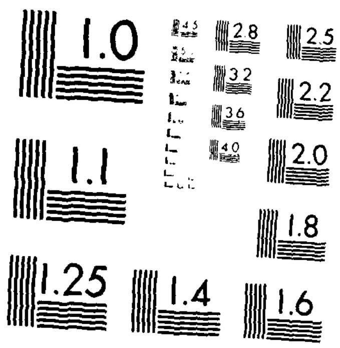

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A MODERN CONTROL DESIGN METHODOLOGY WITH APPLICATION TO THE CH-47 HELICOPTER

A DISSERTATION

SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS

AND THE COMMITTEE ON GRADUATE STUDIES

OF STANFORD UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

by

Richard D. Holdridge

January 1985

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

A. E. Bryson Jr.

(Principal Adviser)

I certify that I have read this thesis and that in my opinion it is fully adeauate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

R. Cannon

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

[illegible]

Approved for the University Committee
on Graduate Studies:

Dean of Graduate Studies & Research

A MODERN CONTROL DESIGN METHODOLOGY WITH APPLICATION TO THE CH-47 HELICOPTER

Richard D. Holdridge, Ph.D.

Stanford University, 1985

A control system design methodology is developed which produces robust, low-order optimal controllers for multiple-input multiple-output systems. The methodology attempts to focus the strengths of recent "Modern Control" design algorithms on the problems associated with real control system designs. The methodology is a set of procedures which aids the engineer in creating a realizable controller in either digital or analog form.

To demonstrate the usefulness of the methodology, two control augmentation systems (CAS) were designed and flight tested on a CH-47 helicopter at NASA Ames Research Center. The first design was a longitudinal cruise CAS giving the pilot decoupled control of forward velocity and climb rate. This design task demonstrated the low-order controller and robustness features of the methodology. It also demonstrated the use of modern control techniques in designing integral-error controllers. Flight test results are presented. The second controller is a translational velocity command/ precision hover hold system. This two mode controller demonstrates the methodology as applied to a more complicated design task which includes control law switching and inner loop/ outer loop considerations. Flight test results are also presented.

Acknowledgements

I am grateful to my adviser, Prof. A. E. Bryson, for suggesting this research topic and then providing the enthusiastic support needed to bring it to a successful conclusion. I am equally grateful to Mr. Bill Hindson who was tireless in his efforts to make the flight test such a success. I suspect I learned as much engineering from Bill while working on the flight control system as I did in the many courses I took.

Thanks also to the many people at Ames who made the flight research possible. It was really a team effort: Dr. Vic Lebacqz, Dr. Bob Chen, Ms. Katy Hilbert who helped in the engineering and the flight test; Lt. Col. Grady Wilson and Mr. George Tucker, the project test pilots; Mr. Jim Jeske and Mr. Dave Guevara who provided the computer support. At Stanford, Doug Bernard, Peter Chu, Bruce Gardner, and Dan Rosenthal were very helpful by providing software which I incorporated into the various programs.

I'm also grateful to Prof. R. Cannon and Prof. D. Debra for reviewing this thesis and making helpful comments.

Finally, I can never adequately express the gratitude I feel to my parents, Mr. and Mrs. Kenneth B. Holdridge, whose love and support have sustained me far more than they can know.

CONTENTS

FIGURES

State Equations

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -.045 & .036 & 0 & -32.2 \\ -.37 & -2.02 & 176.0 & 0 \\ .00191 & -.0396 & -2.98 & 0 \\ 0 & 0 & 1.0 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0 & 1 \\ -28.2 & 0 \\ -11.0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix} + \begin{bmatrix} .045 & -.036 \\ .37 & 2.02 \\ -.00191 & .0396 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_w \\ w_w \end{bmatrix} \quad (2.2)$$

Measurements

$$\begin{bmatrix} u \\ \dot{h} \\ \theta \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 176.0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_w \\ w_w \end{bmatrix} + \begin{bmatrix} v_u \\ v_{\dot{h}} \\ v_\theta \end{bmatrix} \quad (2.3)$$

$$Q = \begin{bmatrix} 24.6 & 0 \\ 0 & 9.98 \end{bmatrix} \quad (2.4)$$

$$R = \begin{bmatrix} .318 & 0 & 0 \\ 0 & .318 & 0 \\ 0 & 0 & .00039 \end{bmatrix} \quad (2.5)$$

where:

u- forward velocity, ft/sec

w- vertical velocity, ft/sec

q- pitch rate, $radians/sec$

θ- pitch angle, $radians$

δ_e- elevator, $radians$

δ_t- throttle, ft/sec^2

u_w- longitudinal gusts, ft/sec

w_w- vertical gusts, ft/sec

$v_u, v_{\dot{h}}, v_\theta$- measurement noise, $ft/sec, ft/sec, radians$

Q- disturbance spectral density [2]

R- measurement noise spectral density(assumes standard deviations of 1 ft/sec for u and $\dot{h}$ and 2 deg for θ with .16 second correlation times(T_c)). The spectral densities come from the approximation $S.D. \approx 2\sigma^2 T_c$.[9]

Figure 2.1: **Navion Linear Model Before Scaling.** Nominal airspeed is 100 knots (100 ft/sec). Note the large order of magnitude differences in the elements of the system matrices. This is caused by the different units of the states.

needed is a linear system in state variable form:

$$\begin{aligned} \dot{x} &= Fx + Gu + \Gamma w \\ y &= Hx + Lu + Nw + v \\ \dot{z} &= Az + By \\ u &= Cz + Dy \end{aligned} \tag{2.1}$$

where:

x– system states, $n \times 1$
z– compensator states, $r \times 1$
u– controls, $m \times 1$
w– plant disturbances, $m' \times 1$
y– sensor measurements, $p \times 1$
v– sensor noise, $p \times 1$
Q– plant disturbance spectral density matrix, $m' \times m'$
R– sensor noise spectral density matrix, $p \times p$

This model is needed for all plant conditions for which the controller is expected to operate. Typically, the conditions include the nominal operating point and several off-nominal conditions for which the control system must also be stable and perform adequately. Figure 2.1 shows the Navion model at the sea level, 104 knot flight condition. No off-nominal flight conditions are included in the example. With the dynamic model now available, the methodology can continue with the scaling of the model.

2.2. Model Scaling

Model scaling is the systematic process of changing the units of the variables in the plant model. This process is described and used by Bryson(BR,sect 7.2) and is a necessary first step in the process of compensator order reduction. Since

Chapter 2.

The Design Methodology

From the discussion of Chapter 1, the need for a structured approach to using modern control methods to design control systems is apparent. This chapter describes a design methodology developed to take advantage of the strengths of the modern control techniques while eliminating or reducing their weaknesses. The methodology is a refinement and an expansion of design procedures described by Bryson and taught in the advanced flight control course at Stanford University.[1] Figure 1.3 shows a flow chart describing the methodology. This chapter describes each step and explains why it is necessary. To facilitate the description of the methodolgy, a simple design task is traced through the process, namely the design of a longitudinal autopilot for commanding aircraft airspeed and climb rate. The plant model represents the Navion general aviation aircraft at sea level and about 100 knots(176 ft/sec) airspeed. The objective is a dynamic compensator which could be implemented on a digital compr ter in the aircraft.

2.1. Model Derivation

The development of dynamic models for use in control system synthesis is an entire engineering discipline in itself. For this design methodology, the model dures is the lack of experience in real world application, Chapters 3 and 4 present the results of applying these techniques to a real world problem. The "real world" problem is the design of a control system for a Boeing-Vertol CH-47 "Chinook" helicopter operated by the NASA Ames Research Center. Chapter 3 shows the application of the methodology to the design of a longitudinal cruise control augmentation system(CAS). Specifically, the CAS is designed to give the pilot a velocity/climb rate command capability for cruise flight. The controller is MIMO with 4 measurements and 2 controls. Chapter 4 applies the techniques to the more difficult task of designing a position hold/velocity command controller for the CH-47 during hover and low speed operations. For this task there are two modes of operation(velocity command and position hold), switching logic for going between the modes, 11 measurements, and 3 controls which must be considered in the design. For both these designs, simulation and flight test results are presented.

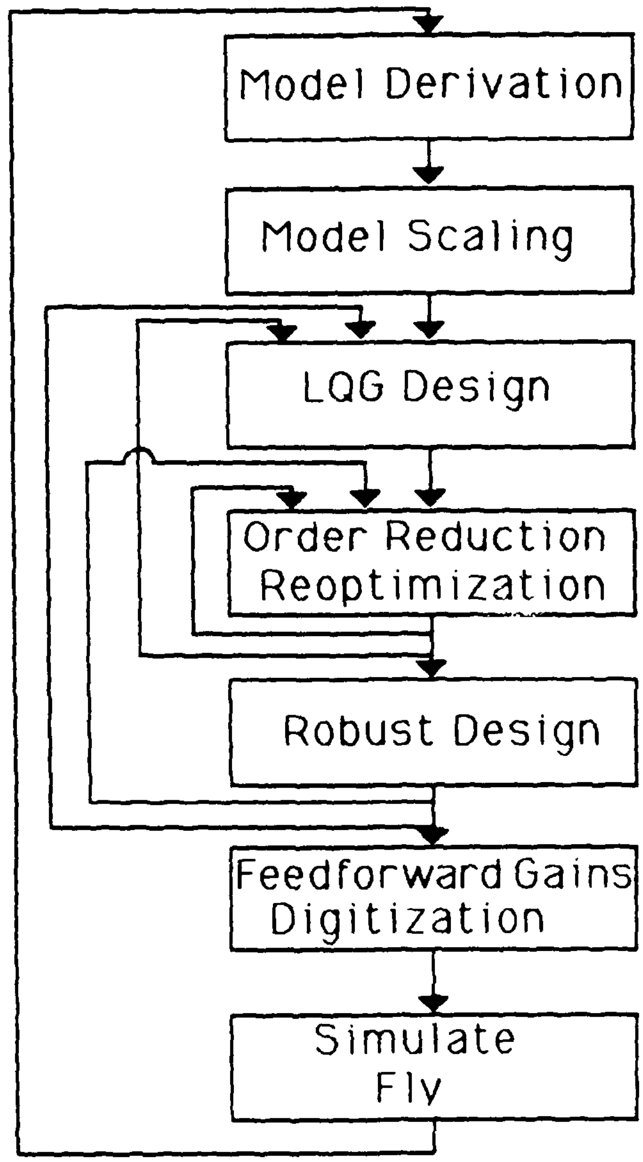


Figure 1.3: **The Design Methodology.** The many loops indicate the iterative nature of the process. The computer programs associated with each step are described in the appendices.

- The design and analysis tools for LQG techniques have only recently become easy to use in practical engineering applications.

These disadvantages provide a dilemma to the engineer faced with a difficult MIMO control design task. If he chooses to use LQG methods, he may be breaking new ground when he finally implements his system in actual operational hardware/software. On the other hand, if he uses classical techniques in his design procedure, he may end up with a design lacking in performance.

This report presents a control system design methodology which attempts to minimize the disadvantages of many modern control techniques, as described above, while taking advantage of the strengths of both modern and classical control techniques. Specifically, the methodology gives the engineer a structured approach to designing arbitrary order, robust, optimal controllers which can be implemented in digital or analog hardware. In this case, "arbitrary order" implies feedback compensation of any size, regardless of the plant model. This is an important consideration for high order plants. "Robust" is defined as insensitivity of the controller performance to changes in the plant. "Optimal" relates to the design methodology's attempt to minimize a quadratic performance index. This methodology is a refinement and expansion of techniques described by Bryson [2] and depends heavily on a robust-control design algorithm by Ly.[3] Figure 1.3 is a flow diagram showing the steps involved in the methodolgy. Chapter 2 of this report is a detailed description of this methodology. To clarify the description, a simple design is taken through all steps of the design procedures with explanations for design decisions made during the process.

Since one of the major disadvantages of using modern control design proce-

Modern (or LQG) design techniques are characterized by simultaneous closing of all loops from measurements to controls. Figure 1.2 shows the form of this type of controller. LQG design techniques offer several advantages to the designer of MIMO controllers:

- They ensure a stable design, if it exists, for the given measurements and controls.
- They result in coordinated, "graceful" controllers. In particular, the controls do not fight each other to satisfy the design requirements.
- For complicated systems, the design can be done fairly quickly.

Although these advantages make modern control design techniques very powerful, there are disadvantages which cannot be disregarded:

- The designs are often not robust to changes and uncertainties in the plant model, i.e. they are to "finely-tuned" to the plant model.
- For complex systems, the controller designs are complicated, making implementation difficult.
- Only a few designers have developed physical intuition for selecting performance indices.
- There is little physical intuition developed concerning the loops closed by the design process.
- There are relatively few examples of operational systems designed using these techniques. Practicing design engineers are therefore hesitant to use these techniques.

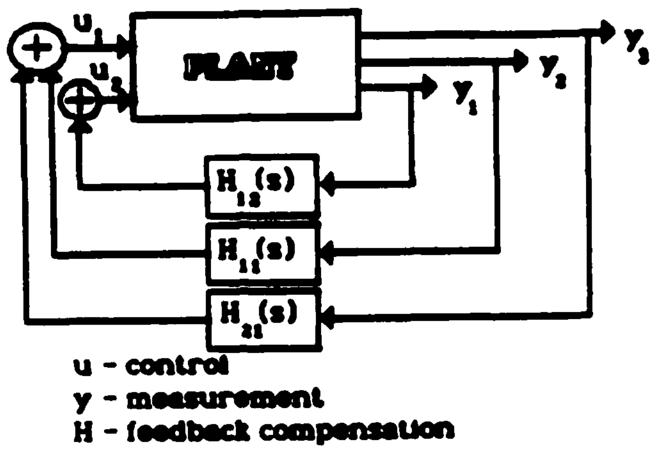


Figure 1.1: **Classical Control.** Characterized by incremental loop closures.

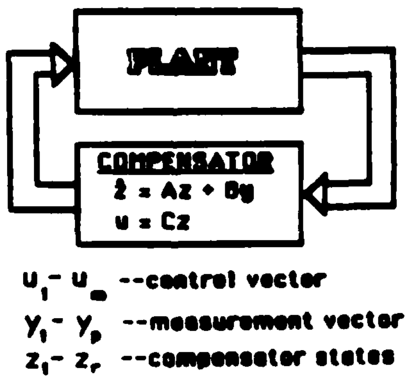


Figure 1.2: **Modern Control.** Characterized by simultaneous loop closures.

1.2. A Modern Control Design Methodology

Classical control techniques are routinely applied to the design of MIMO systems. The process is characterized by successive loop closing. (Figure 1.1) Some of the advantages of using this approach are:

- The designs are simple with clear physical intuition for each loop closed.
- For uncomplicated or open loop stable systems, the procedure is fairly fast.
- There is a large experience base for applying these methods.
- Numerous design and analysis tools exist.
- Operational hardware/software implementation is well understood and straightforward.

However, there are also some disadvantages to using classical design techniques for MIMO systems:

- For complicated or highly unstable systems, one loop may not stabilize the system.
- It may be difficult to decide what loops should be closed. This is especially true in complicated systems(large space structures for example), or in unfamiliar systems where little physical intuition has been developed.
- Different loops can "fight" each other resulting in using more control than is necessary or available.
- Many of the design techniques(Root locus, frequency response,etc.) are difficult to apply to MIMO systems.

- Better Numerical Methods(HQR, HQZ, SVD, etc.)- 1960-present

- Singular Value Techniques- Doyle and Stein and others,1970-present

- Gradient Design Methods- Ly and others,1980-present

These techniques are often labeled "modern control" where the previously mentioned methods(Root locus, Frequencly Response, etc.) are often called "classical control" techniques. Perhaps the major difference between the two is that classical techniques are best suited to single input single output(SISO) dynamic systems where the modern control techniques are equally applicable to multiple input multiple output(MIMO) systems.

Virtually all control systems in operational use today, in numerous diverse applications, have been designed using classical control techniques. These techniques have been preferred over the modern control methods because most of the applications are fairly simple SISO systems. Even if the systems being controlled aren't truly SISO, acceptable SISO approximations can often be made. For instance, aircraft motions can be separated into longitudinal and lateral motions which can be approximated by fast and slow linear SISO systems. Design methodologies based on classical control use these SISO approximations for autopilot designs. As we might expect, this approach results in less performance than might be possible had we not made the simplifying assumptions (necessary to use the design techniques). This procedure is completely inappropriate if the system to be controlled cannot be adequately approximated by several uncoupled SISO systems.

engineers had the opportunity to build greatly improved control systems. However, the existing analytical tools were difficult to apply. More systematic analysis and design tools were needed to aid in developing control systems. Such techniques were developed in the early part of this century. A few of these techniques(applicable to linear systems) are listed below:

- Nyquist Stability Analysis– Nyquist, 1930's
- Frequency Response– Bode, 1940's
- Root Locus– Evans, 1940's

McRuer's Chapter 1 contains an excellent summary of these early analytical techniques and their applications.[1] All these techniques(plus others) provided the theory, and the signal processing devices existed to design sophisticated control systems which were installed in operational systems such as aircraft, missiles, rockets, ships, etc. The requirements of the military during World War II pushed the development and refinement of these techniques and of hardware capable of implementing the designs.

During the 1950's, the tools and hardware available to control engineers continued to expand. It was during this decade that the digital computer became a practical tool for designing and implementing control systems. With the digital computer, the control design engineer had much more signal processing capability. Analysis and design techniques soon developed which took advantage of the digital computer. A few of these techniques are:

- Kalman Filter– Kalman,1960
- Linear Quadratic Gaussian(LQG) techniques– Bryson and others,1960-present

Chapter 1.

Introduction

1.1. Historical Background on Control System Design

Control system design, as an engineering discipline, is relatively new. It has been coupled closely with the development of measurement devices(sensors), electronic signal processing capability(analog and digital hardware), and the development of mathematical techniques for the design and analysis of dynamic systems. Before electronic signal processing, ingenious mechanical devices were designed which incorporated simple feedback mechanisms. "Simple" here implies their analytical complexity; sometimes these devices could be quite compicated mechanically. Some simple examples of these mechanical feedback devices are:

- Water level control in a tank using float valves
- James Watts' centrifugal governor for steam engines

Conventional techniques for analyzing dynamic systems (Newtonian dynamics, Lagrangian dynamics, etc.) were adequate to study and design these mechanical devices.

With the development of electronic signal processing and electronic sensors,

many dynamic systems, including the example here, have parameters with different units, it is often difficult to compare control gains or estimator gains for states or measurements with differing units. In the Navion example, to determine the relative importance of velocity to elevator and pitch angle to elevator gains would be difficult since velocity has units of *ft/sec* and pitch angle has units of radians. Model scaling allows the engineer to select a new set of units which result in the plant model having variables with units having a sort of "equivalent" importance to the designer. Of course, selection of such a set of units requires an understanding of the dynamics of the process being controlled. For the Navion, the angle variables are changed from *radians* to .01 *radians* while the linear variables remain in units of *ft/sec*. Such a selection is reasonable since .01 *radians* and 1 *ft/sec* are similar in importance to a pilot flying the aircraft. For a supersonic aircraft, a suitable selection might be .01 *radians* and 10 *ft/sec*.

Figure 2.2 shows the scaled dynamic model. This change of scaling is accomplished analytically using similarity transformations based on the changes in units. Appendix A presents the derivation of the transformations and the equations used to transform all matrices of the dynamic model into the new units. The computer program ROPTSYS, described in Appendix J, implements these equations as the first step in calculating an optimal full order compensator. The next step in the design methodology uses this scaled dynamic system as a starting point.

2.3. LQG Design

During this step in the design procedure, the optimal regulator and estimator gains are calculated for the scaled dynamic system. Appendix B shows the deriva-

State Equations

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix}_{scaled} = \begin{bmatrix} -.045 & .036 & 0 & -.322 \\ -.37 & -2.02 & 1.76 & 0 \\ .191 & -3.96 & -2.98 & 0 \\ 0 & 0 & 1.0 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix}_{scaled} + \begin{bmatrix} 0 & 1 \\ -.282 & 0 \\ -11.0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix}_{scaled} + \begin{bmatrix} .045 & -.036 \\ .37 & 2.02 \\ -.191 & 3.96 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_w \\ w_w \end{bmatrix}_{scaled} \tag{2.6}$$

Measurements

$$\begin{bmatrix} u \\ \dot{h} \\ \theta \end{bmatrix}_{scaled} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1.76 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix}_{scaled} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix}_{scaled} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_w \\ w_w \end{bmatrix}_{scaled} + \begin{bmatrix} v_u \\ v_{\dot{h}} \\ v_\theta \end{bmatrix}_{scaled} \tag{2.7}$$

$$\begin{aligned} Q_{scaled} &= \begin{bmatrix} 24.6 & 0 \\ 0 & 9.98 \end{bmatrix} \\ R_{scaled} &= \begin{bmatrix} .318 & 0 & 0 \\ 0 & .318 & 0 \\ 0 & 0 & 3.9 \end{bmatrix} \end{aligned} \tag{2.8}$$

where:

$u-$	forward velocity, ft/sec
$w-$	vertical velocity, ft/sec
$q-$	pitch rate, .01 $radians/sec$
$\theta-$	pitch angle, .01 $radians$
δ_e-	elevator, .01 $radians$
δ_t-	throttle, ft/sec^2
u_w-	longitudinal gusts, ft/sec
w_w-	vertical gusts, ft/sec
$v_u, v_{\dot{h}}, v_\theta-$	measurement noise, $ft/sec, ft/sec$, .01 $radians$
$Q-$	disturbance spectral density, (From Bryson [2] sect 9.4)
$R-$	measurement noise spectral density(assumes standard deviations of 1 ft/sec for u and $\dot{h}$ and 2 deg for θ with .16 second correlation times(T_c). The spectral densities come from the approximation, $S.D. \approx 2\sigma^2 T_c$.[9]

Figure 2.2: **Navion Linear Model After Scaling.** The results of the scaling are most noticeable in the F, G, and R matrices.

tion of the technique used to calculate these gains. The optimal gain calculation of this appendix is based on the eigenvector decomposition of the Hamiltonian matrix as described in Hall and Bryson.[17] A modification to the technique is the capability to weight the linear combination of states and controls, $y_o = H_o x + Du$, in determining regulator gains, and, by duality, to include plant noise in the measurement, $y_m = H_m x + Lu + Nw + v$, in determining estimator gains.[1] This modification is essential for aerospace applications since it allows acceleration to be used as a measurement for estimator design, and weighted in regulator design. The ROPTSYS computer program, described in Appendix J, calculates these regulator and estimator gains. It also calculates the compensator dynamic system based on these gains. One item of note is that the A and B matrices, used in the quadratic performance index($P.I. = \int_0^\infty (y_o^T A y_o + u^T B u)\, dt$), can start as the identity matrices since the system has been scaled in "equivalent" engineering units.

The compensator dynamic system is displayed in three formats:

Conventional Form

$$\begin{aligned} \dot{z} &= (F - GC - KH)z + Ky \\ u &= Cz \end{aligned} \tag{2.9}$$

where:

z- compensator states, $n \times 1$

y- sensor measurements, $p \times 1$

u- controls, $m \times 1$

K- steady state Kalman filter gains, $n \times p$

C- optimal regualtor gains, $m \times n$

[1] Franklin and Powell show this derivation for the direct digital design case.[6]

Modal Form

$$\begin{aligned}\dot{z} &= F_{mod}\, z + K_{mod}\, y \\ u &= C_{mod}\, z\end{aligned} \tag{2.10}$$

where:

F_{mod}– modal form of $(F - GC - KH)$

K_{mod}– modal form of K

C_{mod}– modal form of C

$$F_{mod} = \begin{bmatrix} \begin{matrix}\sigma_1 & \omega_1 \\ -\omega_1 & \sigma_1\end{matrix} & 0 & \cdots \\ 0 & \begin{matrix}\sigma_2 & \omega_2 \\ -\omega_2 & \sigma_2\end{matrix} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}, n \times n$$

$$K_{mod} = \begin{bmatrix} \star & \star & \cdots \\ \star & \star & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}, n \times p \tag{2.11}$$

$$C_{mod} = \begin{bmatrix} \star & \star & \cdots \\ \star & \star & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}, m \times n$$

Block Minimal Form

$$\begin{aligned}\dot{z} &= F_{min}\, z + K_{min}\, y \\ u &= C_{min}\, z\end{aligned} \tag{2.12}$$

where:

F_{min}– minimal form of $(F - GC - KH)$

K_{min}– minimal form of K

C_{min}– minimal form of C

$$F_{min} = \begin{bmatrix} 0 & 1 & & 0 & & \cdots \\ a_1 & a_2 & & & & \\ & 0 & & 0 & 1 & \cdots \\ & & & a_1 & a_2 & \\ & \vdots & & \vdots & & \ddots \end{bmatrix}, n \times n$$

$$K_{min} = \begin{bmatrix} \star & \star & \cdots \\ \star & \star & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}, n \times p \tag{2.13}$$

$$C_{min} = \begin{bmatrix} \star & \star & 0 & 1 & \cdots \\ 0 & 1 & \star & \star & \cdots \\ \star & \star & \star & \star & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}, m \times n$$

The modal form is calculated using the eigenvector matrix as a similarity transformation. Appendix C shows the equations needed to do this. The transformation to minimal form is derived in Appendix C. The modal and minimal realizations are important since they are unique realizations of the dynamic system. From the *block minimal realization of the compensator*, the designer can assess the relative importance of the different modes. To aid in this determination of modal importance, the ROPTSYS program also calculates two input/output measures, both based on work done by Bernard.[7] One measure is the singular value of the residue matrix associated with that mode. It is defined as:

$$M_1 = \bar{\sigma}(R_i) = \sqrt{g_1 g_1^T + g_2 g_2^T}\sqrt{h_1^T h_1 + h_2^T h_2} \tag{2.14}$$

where:

g_1, g_2- the two rows of K_{min} associated with the mode being analyzed
h_1, h_2- the two columns of C_{min} associated with the mode being analyzed
$\bar{\sigma}(R_i)$- the singular value of the residue matrix for the i^{th} mode

The second measure of merit, M_2, is just the first weighted by the real part of the mode being evaluated:

$$M_2 = \frac{\bar{\sigma}(R_i)}{|\sigma_i|} \tag{2.15}$$

The larger these measures are, the more important that mode is to the overall input/output characteristics of the compensator. In the case of unstable compensator modes, these should not be eliminated since they are usually required for stabilization of unstable plant modes. Figure 2.3 shows the results for the Navion control, which came from ROPTSYS. The input data required to get these results are shown in Appendix J.

From these results, we note that the open loop Navion has a well damped short period (the fast open loop mode) but the phugoid (the slow open loop mode) is only lightly damped. The regulator design improves these dynamics by forcing the two phugoid roots onto the real axis and speeding them up. The resulting compensator is fairly fast (as fast as the aircraft response itself) and well damped. This design was also analyzed using the RSANDY program, described in Appendix K, to evaluate the compensator performance in the presence of plant disturbances (vertical and longitudinal wind gusts) and measurement noise. The wind gust data come from a turbulence model described by Bryson.[1] The performance is tabulated in Figure 2.4.

Using these data, Figures 2.3 and 2.4, we can proceed to the next step of the design, simplification of the full-order compensator.

2.4. Compensator Order Reduction and Reoptimization

As with each step in this methodology, the subject of compensator order reduction and simplification is an engineering discipline in itself. For this methodology, the compensator mode measures, M_1 and M_2, are the criteria for deciding which

System	Eigenvalues	Damping
Open Loop(F)	$-2.51 \pm j2.59, -.017 \pm j.21$	.7, .08
Regulator(F-GC)	$-2.43 \pm j3.05, -1.03, -2.43$	.62, 1, 1
Estimator(F-KH)	$-11.3, -2.98, -.84 \pm j.43$	1, 1, .89
Compensator(F-GC-KH)	$-11.3, -3.04 \pm j2.34, -1.82$	1, .8, 1

Mode	Real	Imag	M_1	M_2
1	-11.34	0	2.62	.23
2	-3.04	2.34	1.86	.61
3	-3.04	-2.34	-	-
4	-1.82	0	.83	.46

Compensator Dynamic System Matrices

$$F_{min} = \begin{bmatrix} -11.342 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -14.686 & -6.0721 & 0 \\ 0 & 0 & 0 & -1.8155 \end{bmatrix}$$

$$K_{min}(scaled) = \begin{bmatrix} -.0133 & -2.6218 & .0244 \\ -.278 & -.0886 & .0652 \\ 1.49 & .872 & -.337 \\ .771 & -.0464 & -.101 \end{bmatrix}$$

$$K_{min}(unscaled) = \begin{bmatrix} -.0133 & -2.6218 & 2.44 \\ -.278 & -.0886 & 6.52 \\ 1.49 & .872 & -33.7 \\ .771 & -.0464 & -10.1 \end{bmatrix} \qquad (2.16)$$

$$C_{min}(scaled) = \begin{bmatrix} 1.0 & 0 & 1.0 & -.36 \\ -.0344 & .198 & .0216 & 1.0 \end{bmatrix}$$

$$C_{min}(unscaled) = \begin{bmatrix} -.01 & 0 & -.01 & .0036 \\ .0344 & -.198 & -.0216 & -1.0 \end{bmatrix}$$

Figure 2.3: **Navion Full Order Compensator.** The unscaled matrices are in units of the physical system.

Standard Deviations						
Controls		States				
δ_e (deg)	δ_t (deg/sec^2)	u (ft/sec)	w (ft/sec)	q (deg/sec)	θ (deg)	h (ft/sec)
.153	.284	.5	2.25	.66	.47	1.32

Figure 2.4: **Navion Full Order Compensator Performance.** This statistical performance is based on the noise characteristics described in Figure 2.1.

modes of a compensator can be eliminated. The M_2 term seems to be most useful in the work here on flight vehicles. A mode can probably be eliminated with little performance impact if its value of $M_2/M_{2_{largest}}$ is .1 or less. When this ratio is greater than .1, that mode may still be neglectable but the decision must rest on reduced order analysis results. In addition to eliminating modes, a compensator can also be simplified by eliminating unimportant measurements. This is desirable since it would lower the cost of the control system. The scaled K_{min} matrix provides the data which are used to decide if a specific measurement is necessary. If the magnitudes of the elements of a specific column of K_{min} are smaller than the other column elements, the measurement associated with that column may be neglectable. Of course, the final decision must be based on the simplified compensator analysis results.

Applying these design guidelines to the Navion example, Figure 2.3, we note the two real modes have an M_2 smaller than the single complex mode so we eliminate these modes and the associated rows of K_{min} and columns of C_{min}. Examining the values of scaled K_{min}, we note the column associated with the θ (pitch angle) measurement is smaller than the other so we try eliminating this measurement. The importance of the scaling process is evident here since the θ column elements in the unscaled K_{min} matrix have large magnitudes due to the radian units. Thus, without scaling, the θ measurement would have seemed more important than it was. The compensator is now second order, 2 input, and 2 output, a significant simplification from the fourth order, 3 input, and 2 output full order compensator.

The next step is to analyze and reoptimize the reduced order compensator

Simplified Compensator before Reoptimisation

$$\begin{aligned}\begin{bmatrix}\dot{z}_1\\ \dot{z}_2\end{bmatrix} &= \begin{bmatrix}0 & 1\\ -14.69 & -6.072\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix} + \begin{bmatrix}-.278 & -.0886\\ 1.485 & .873\end{bmatrix}\begin{bmatrix}u\\ \dot{h}\end{bmatrix}\\ \begin{bmatrix}\delta_e\\ \delta_t\end{bmatrix} &= \begin{bmatrix}0 & -.01\\ -.1978 & -.0216\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix}\end{aligned} \tag{2.17}$$

Simplified Compensator after Reoptimisation

$$\begin{aligned}\begin{bmatrix}\dot{z}_1\\ \dot{z}_2\end{bmatrix} &= \begin{bmatrix}0 & 1\\ -13.59 & -16.93\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix} + \begin{bmatrix}-.1366 & .2124\\ 2.676 & -3.241\end{bmatrix}\begin{bmatrix}u\\ \dot{h}\end{bmatrix}\\ \begin{bmatrix}\delta_e\\ \delta_t\end{bmatrix} &= \begin{bmatrix}0 & -.01\\ -13.14 & -1.228\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix}\end{aligned} \tag{2.18}$$

Full Order vs Reduced Order Performance

System	Standard Deviation						
	δ_e (deg)	δ_t (deg/sec^2)	u (ft/sec)	w (ft/sec)	q (deg/sec)	θ (deg)	$\dot{h}$ (ft/sec)
Full Order	.153	.284	.5	2.25	.66	.47	1.32
Reduced Order	.2	.31	.57	2.39	.77	.58	1.23

Figure 2.5: **Navion Reduced Order Compensator Design Results.** The reduced order compensator was unstable before the reoptimization. The performance is based on the disturbance and noise properties of Figure 2.1

using the RSANDY computer program. The RSANDY program, described in Appendix K, is a modified version of a design and analysis code written by Ly.[8] The program designs robust, low order compensators using a gradient search technique based on a quadratic performance index. The results of using this code on the Navion simplified compensator are shown in Figure 2.5.

The reduced order compensator resulted in an unstable closed loop system. This points to the necessity of the reoptimization step after compensator simplification. The utility of Ly's code is also evident here since it allows unstable initial guesses when reoptimizing the compensator. Another important feature, not used in this example, is the capability of including several plant conditions in the optimization to ensure compensator stability robustness to changes in plant parameters. The selection of weighting matrices in the quadratic performance index, used by the RSANDY program, was based on "Bryson's Rule" as applied to the scaling parameters. Briefly, "Bryson's Rule" suggests that the outputs and controls be weighted by the inverse square of their scale factors. For this example, the outputs were u(velocity) and $\dot{h}$(climb rate), and the controls were δ_e(elevator) and δ_t(throttle), with units of ft/sec, ft/sec, $radians$, and ft/sec^2, respectively. The scaled units were ft/sec, ft/sec, .01 $radians$, and ft/sec^2. The performance index is then:

$$P.I. = \int_0^{t_f} (y^T Q y + u^T R u) dt \tag{2.19}$$

where:

$$\begin{aligned} y &= \begin{bmatrix} u \\ \dot{h} \end{bmatrix} \\ u &= \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix} \\ Q &= \begin{bmatrix} \frac{1}{1^2} & 0 \\ 0 & \frac{1}{1^2} \end{bmatrix} or \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ R &= \begin{bmatrix} \frac{1}{(.01)^2} & 0 \\ 0 & \frac{1}{1^2} \end{bmatrix} or \begin{bmatrix} 10000 & 0 \\ 0 & 1 \end{bmatrix} \end{aligned} \tag{2.20}$$

For more complicated problems, these weighting terms may need to be adjusted to get the desired performance. The input file for RSANDY used to get the results of Figure 2.5 is listed in Appendix K.

The results of Figure 2.5 show what might be expected. The simplified compensator has slightly degraded performance in that both the aircraft motion and control activity is slightly larger than the full order compensator. These statistical performance parameters are important since they indicate the disturbance rejection properties of the design but we recall the design objective was a velocity and climb rate *command* system for the Navion. Since the designs thus far are only regulators, we still need to design the command capability for the controller.

2.5. Command Inputs

Generally, control systems are expected to do more than regulate the outputs of a process to some nominal value. We need the ability to change the output of the compensated system to any selected realizable value. To accomplish this end, the desired outputs are used to determine actuator commands which are the steady state controls for the desired outputs. Figure 2.6 shows this concept. The maximum number of outputs which can be commanded is the same as the number of independent controls in the system. This means that the feedforward matrix is square. An additional constraint is that the desired outputs must be physically realizable. For instance, velocity and position cannot be decoupled, i.e. you cannot command a steady velocity while holding position. Appendix D derives the algorithm which calculates this decoupling feedforward matrix for the case of equal numbers of controls and desired outputs. This algorithm is implemented in the SETPNT computer program described in Appendix L.

To complete the Navion autopilot design, we need to include the climb rate and forward velocity command capabilities required by the specifications. For this aircraft, these two outputs can be decoupled (controlled independently) with the two controls, elevator and throttle. Using the SETPNT program with the Navion data(shown in Appendix L), the feedforward matrix for the full order compensator

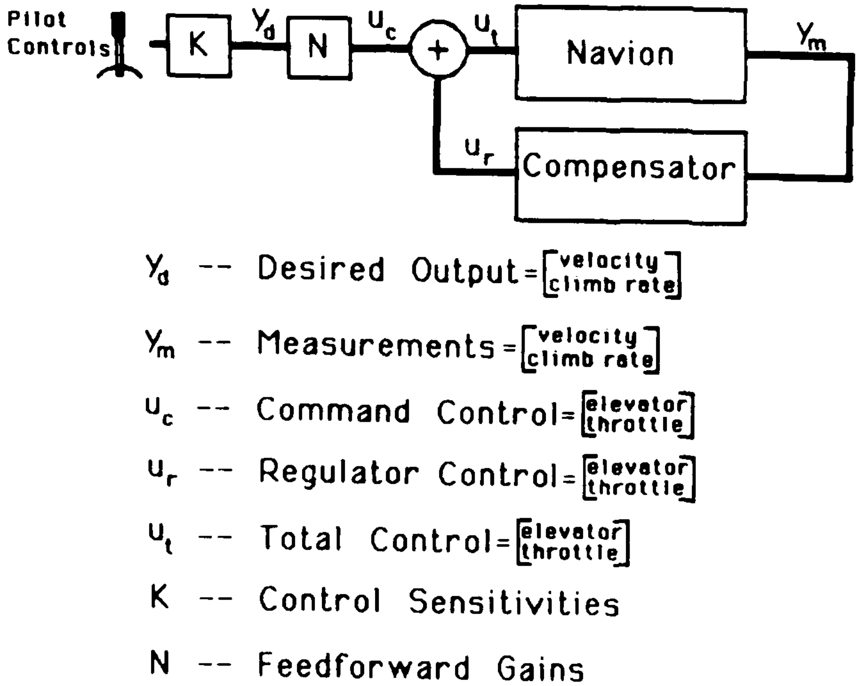


Figure 2.6: **Commanding a Desired Output.** The K matrix is diagonal and based on human factor considerations. The N matrix comes from an analysis of the system in steady state; the derivation is described in Appendix D.

is:

$$N = \begin{bmatrix} .002165 & -.001578 \\ .4505 & .1398 \end{bmatrix} \tag{2.21}$$

For the reduced order controller, the result is:

$$N = \begin{bmatrix} .002243 & -.002124 \\ .5354 & .2653 \end{bmatrix} \tag{2.22}$$

where:

$$\begin{bmatrix} \delta_e(radians) \\ \delta_t(ft/sec^2) \end{bmatrix} = N \begin{bmatrix} u_{desired}(ft/sec) \\ \dot{h}_{desired}(ft/sec) \end{bmatrix} \tag{2.23}$$

One item to note here is the fact that the feedforward matrices are dependent on both the plant and the controller. The correctness of these decoupling feedforward matrices becomes clear when the Navion designs are evaluated in simulation.

2.6. Simulation and Test

The final step of any design methodology is the demonstration of performance. The first step in such a demonstration is the use of a simple linear simulation. Once the design is validated in linear simulation, the simulation might be expanded to model some of the important nonlinearities in the physical system. In this methodology, the RSANDY program, described in Appendix K, includes the option of creating a linear simulation model. This model is then used by the SIMPLOT program (described in Appendix M) to simulate the closed or open loop system with or without the random disturbances. Using these RSANDY and SIMPLOT programs the Navion full and reduced order compensators can be compared.

The results of step commands in velocity and climb rate are shown in the following figures. Comparing Figures 2.7 and 2.8 we note the performance is

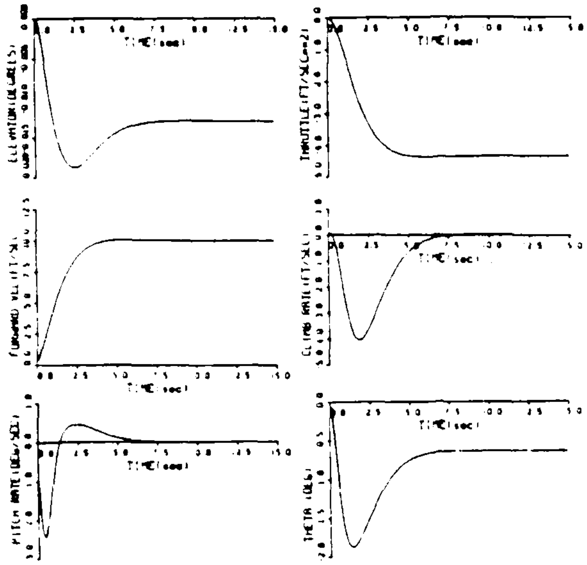


Figure 2.7: **Velocity Response for Full Order Compensator.** The system has a rise time of about 2.5 seconds and near critical damping.

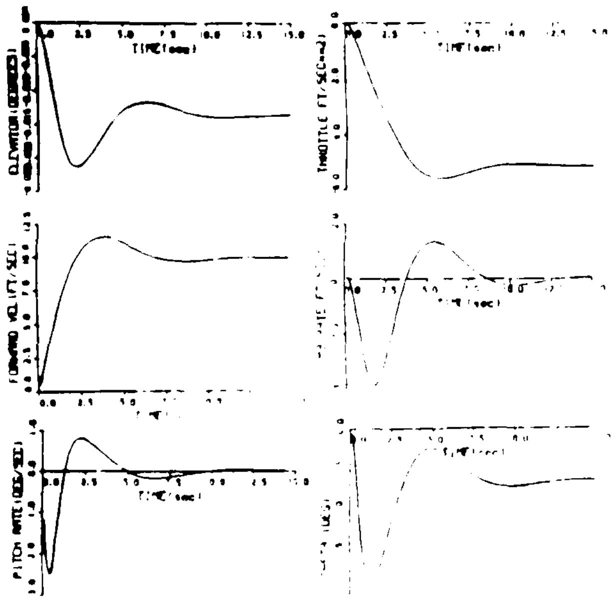


Figure 2.8: **Velocity Response for Reduced Order Compensator.** The rise time is about 2.5 seconds but the damping is only about .5.

unscaled model q and θ appear much less noisy than the u and $\dot{h}$ measurements indicating the possibility that u and $\dot{h}$ may not even be necessary. After scaling, the spectral densities are closer in magnitude but θ is still more accurate. With the scaling accomplished, the methodology continued with the design of the full order compensator using the ROPTSYS program.

3.4. LQG Design of the Full Order Compensator

The design of the full order compensator is straightforward since we have all the data necessary to run the design program ROPTSYS. Since we have the system scaled, the first choices for output and control weighting matrices in the regulator design are identity matrices. With this selection, the compensator is calculated and shown in Figure 3.6. Examining the closed loop roots (the estimator and regulator roots) we note the very slow estimator pole at -.0088. The slow estimator pole results from having a very accurate measurement of θ (low noise spectral density) but relatively noisy measurements of u and $\dot{h}$. The fast filter roots estimate mostly θ and q while the slow mode estimates mainly u. If we had introduced $\dot{h}$ and u commands into the compensator(Equation 3.9), the slow estimator mode would not have affected the response to commands, since the estimator would have been "tracking" closely before the commands. For perfect tracking, the estimator modes are not excited at all. This need to include the command in the compensator was not recognized until later so the responses of Figure 3.7 show the poor performance when commands are *not* properly fed forward to the compensator. Figure 3.8 shows

State Equations

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{\delta}_e \\ \dot{\delta}_c \end{bmatrix} = \begin{bmatrix} -.0204 & .0377 & .0236 & -.3217 & .0127 & .0426 \\ -.0663 & -.551 & .9902 & -.0186 & .0467 & -.936 \\ -.42 & 1.76 & -1.682 & 0 & 3.91 & 1.53 \\ 0 & 0 & 1.0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -40.0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -40.0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \\ \delta_e \\ \delta_c \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 40.0 & 0 \\ 0 & 40.0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_c \end{bmatrix} + \begin{bmatrix} .0205 & -.037 \\ .0663 & .5512 \\ .42 & -1.76 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_w \\ w_w \end{bmatrix} \tag{3.6}$$

Measurements

$$\begin{bmatrix} q \\ \theta \\ \dot{h} \\ u \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 100.0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_c \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_w \\ w_w \end{bmatrix} + \begin{bmatrix} v_q \\ v_\theta \\ v_{\dot{h}} \\ v_u \end{bmatrix} \tag{3.7}$$

$$Q = \begin{bmatrix} 24.6 & 0 \\ 0 & 9.98 \end{bmatrix}$$
$$R = \begin{bmatrix} .323 & 0 & 0 & 0 \\ 0 & 8.1 \times 10^{-4} & 0 & 0 \\ 0 & 0 & 16.0 & 0 \\ 0 & 0 & 0 & 1.1 \end{bmatrix} \tag{3.8}$$

where:

u	forward velocity, ft/sec
w	vertical velocity, ft/sec
q	pitch rate, .01 $radians/sec$
θ	pitch angle, .01 $radians$
δ_e	pitch control, .1 $inches$
δ_c	collective lever, .1 $inches$
u_w	longitudinal gusts, ft/sec
w_w	vertical gusts, ft/sec
$v_q, v_\theta, v_{\dot{h}}, v_u$	measurement noise, .01 $radians/sec$, .01 $radians$, ft/sec, ft/sec
Q	disturbance spectral density, [1]
R	measurement noise spectral density(assumes standard devations shown in Figure 3.1 with 3 Hz bandwidth) The spectral densities come from the approximation $S.D. \approx 2\sigma^2 T_c$. [9]

Figure 3.5: **CH-47 Scaled Longitudinal Linear Model at 60 knots.** Even after scaling, the θ measurement is much more accurate than the others.

State Equations

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{\delta}_e \\ \dot{\delta}_c \end{bmatrix} = \begin{bmatrix} -.0204 & .0377 & 2.36 & -32.17 & .127 & .426 \\ -.0663 & -.551 & 99.02 & -1.86 & .467 & -9.36 \\ -.0042 & .0176 & -1.682 & 0 & .391 & .153 \\ 0 & 0 & 1.0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -40.0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -40.0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \\ \delta_e \\ \delta_c \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 40.0 & 0 \\ 0 & 40.0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_c \end{bmatrix} + \begin{bmatrix} .0205 & -.037 \\ .0663 & .5512 \\ .42 & -1.76 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_w \\ w_w \end{bmatrix} \tag{3.3}$$

Measurements

$$\begin{bmatrix} q \\ \theta \\ \dot{h} \\ u \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 100.0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \\ \delta_e \\ \delta_c \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_c \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_w \\ w_w \end{bmatrix} + \begin{bmatrix} v_q \\ v_\theta \\ v_{\dot{h}} \\ v_u \end{bmatrix} \tag{3.4}$$

$$\begin{aligned} Q &= \begin{bmatrix} 24.6 & 0 \\ 0 & 9.98 \end{bmatrix} \\ R &= \begin{bmatrix} 3.23 \times 10^{-5} & 0 & 0 & 0 \\ 0 & 8.1 \times 10^{-8} & 0 & 0 \\ 0 & 0 & 16.0 & 0 \\ 0 & 0 & 0 & 1.1 \end{bmatrix} \end{aligned} \tag{3.5}$$

where:

u	forward velocity, ft/sec
w	vertical velocity, ft/sec
q	pitch rate, $radians/sec$
θ	pitch angle, $radians$
δ_e	pitch control, $inches$
δ_c	collective lever, $inches$
u_w	longitudinal gusts, ft/sec
w_w	vertical gusts, ft/sec
$v_q, v_\theta, v_{\dot{h}}, v_u$	measurement noise, $radians/sec, radians, ft/sec, ft/sec$
Q	disturbance spectral density, [1]
R	measurement noise spectral density(assumes standard devations shown in Figure 3.1 with 3 Hz bandwidth) The spectral densities come from the approximation $S.D. \approx 2\sigma^2 T_c$. [9]

Figure 3.4: **CH-47 Longitudinal Linear Model at 60 knots.** The highly accurate θ measurement comes from the inertial navigation system(INS), the pitch rate from a body mounted rate gyro, the velocity from the pitot-static system, and the climb rate from an instantaneous vertical speed indicator (IVSI).

other consideration in the development of a linear model for this design is the need to avoid "nuisance disengages" of the experimental control system in the CH-47. These automatic disengages are a safety feature of the modified control system which cause the experimental control system to be tripped off when the control rates exceed a known rate. The approach used to eliminate the possibly of these problems was to include simple first order actuator models:

$$\dot{u}_{actual} = -40\, u_{actual} + 40\, u_{desired} \tag{3.2}$$

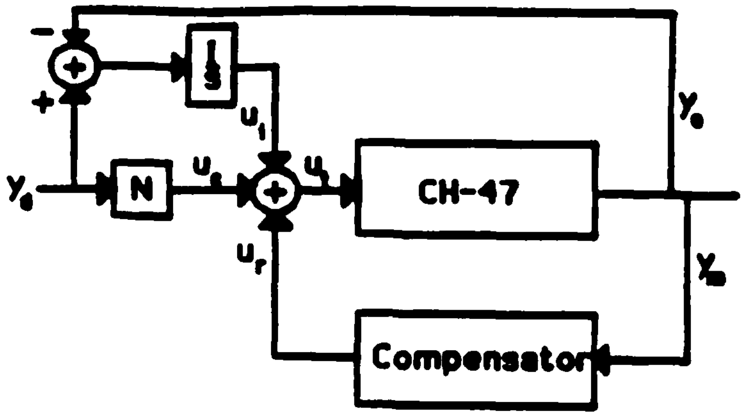
By weighting $\dot{u}_{actual}$ in the performance index, the control rates should not get large, hence eliminating the nuisance disengages.[1] Before starting the control design, the linear model was scaled to help in compensator order reduction.

3.3. Model Scaling

The selection of units for the CH-47 at a 60 knot flight condition is dependent on our understanding of the aircraft dynamics. In this case, 1 ft/sec of velocity or climb rate is about as important to the pilot as .01 *radian* of pitch angle or .01 $radian/sec$ of pitch rate. Similarly, the pilot would feel comfortable using .1 *inch* of either control to command the 1 ft/sec of velocity. Another way of looking at this scaling is to note that a .01 *radian* pitch angle would result in a 1 ft/sec climb rate at the nominal airspeed of 60 knots($\approx 100 ft/sec$). Figures 3.4 and 3.5 show the linear model at 60 knots both before and after scaling the system into the units above.

The usefulness of the scaling step is again evident if we look at the measurement noise spectral density matrix for the scaled and unscaled models. In the

[1] Flight test later confirmed that the experimental system seldom had these type disengages.



Y_a -- Actual Outputs (Subset of Measurements)

Y_d -- Desired Outputs

Y_m -- Measurements

u_c -- Command Control

u_i -- Integral Control

u_r -- Regulator Control

u_t -- Total Control

Figure 3.3: **Controller Structure for The Longitudinal Cruise Autopilot.** Flexibility comes from making the controls, outputs, and measurements vectors rather than scalars.

The form of the controller to be used for the design depends on its function. For this design, the controller must give the pilot a command capability. From Section 2.4, we recall that the command capability comes from the feedforward matrix which decouples the desired outputs. Appendix D shows that this matrix results from inverting the steady-state dynamic system. In flight, this matrix would exactly decouple the two desired outputs only if the helicopter were actually linear and had the same parameters as the model. Of course, this can never happen for several reasons:

- The helicopter dynamics are not linear.
- The helicopter has dynamics which were not modeled.
- The atmosphere is never "standard".
- The helicopter burns off fuel during flight, changing its inertia properties.
- The sensors have biases and scale factor errors.

The list could go on but it is clear we need to correct for differences between the model and the actual aircraft. One obvious solution is to use integral-error control. Figure 3.3 shows a form of the controller which includes this capability.

An interesting difference between this type of controller and more conventional flight control systems is the presence of off-diagonal terms in the integral-error feedback. Normally, the integral feedback is from desired output to the primary actuator for that output. For instance, a classically designed integral controller would use integral of velocity error for pitch control and integral of $\dot{h}$ error for collective. These off diagonal gains would be difficult to find using classical techniques since four transfer functions would be used to calculate the four integral gains. Finding these gains is straightforward using the RSANDY program. An-

$$
\begin{aligned}
\begin{bmatrix} \dot{u}(ft/sec) \\ \dot{w}(ft/sec) \\ \dot{q}(radians/sec) \\ \dot{\theta}(radians) \end{bmatrix} &= F \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + G \begin{bmatrix} \delta_e(inches\ of\ longitudinal\ stick) \\ \delta_c(inches\ of\ collective\ lever) \end{bmatrix} \\
y_m(measurements) = \begin{bmatrix} q \\ \theta \\ \dot{h} \\ u \end{bmatrix} &= \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -1.0 & 0 & 100.0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix}
\end{aligned}
\tag{3.1}
$$

Figure 3.2: **CH-47 Longitudinal Model.** This is a conventional longitudinal model found in most textbooks. The climb rate measurement is based on the approximation, $\dot{h} = -w + u_{nominal}\theta$.

the need for a fairly rigid control structure. This was necessary since the controller was to be programmed in fixed point assembly language on the aircraft's Sperry 1819A flight control computer. Since major controller structural changes would be difficult and time consuming, the baseline controller had to have a broad control structure which would allow design flexibility to come from changes in the compensator order or in the matrices themselves. With these goals and constraints in mind, the application of the methodology began.

3.2. Linear Models and Basic Control Structure

The models used for these designs come from Reference 11. This reference gives the aerodynamic coefficients at several different flight conditions and a general form of the "F" and "G" matrices based on these coefficients, the inertia properties of the aircraft, and the nominal airspeed. Appendix G shows this general form as well as the resulting linear models used for this research. Figure 3.2 shows the parameters of the longitudinal model.

Measurement	Units	Approx. Noise Standard Deviation	Approx. Correlation Time in Seconds	Spectral Density $S.D. \approx 2(\sigma^2)T_c$
$\theta_{vertical\ gyro}$	*degrees*	.1	.053	1.061×10^{-3}
$\phi_{vertical\ gyro}$	*degrees*	.1	.053	1.061×10^{-3}
$\psi_{directional\ gyro}$	*degrees*	1.0	.053	.1061
θ_{INS}	*degrees*	.05	.053	2.653×10^{-4}
ϕ_{INS}	*degrees*	.05	.053	2.653×10^{-4}
ψ_{INS}	*degrees*	.1	.053	1.061×10^{-3}
p	*degrees/sec*	2.0	.053	.424
q	*degrees/sec*	1.0	.053	.106
r	*degrees/sec*	.5	.053	2.653×10^{-2}
a_x	ft/sec^2	3.22	.053	1.1
a_y	ft/sec^2	3.22	.053	1.1
a_z	ft/sec^2	3.22	.053	1.1
$h_{barometric}$	ft	2.0	.318	2.546
h_{radar}	ft	.5	.053	2.653×10^{-2}
$vel_{pitot\ static}$	ft/sec	3.0	.318	5.73
$\alpha_{boom\ vane}$	*degrees*	2.0	.053	.424
$\beta_{boom\ vane}$	*degrees*	2.0	.053	.424

Figure 3.1: **Sensors Available on the NASA CH-47.** The standard deviations are estimates based on flight test data from the CH-47 instrumentation system. The .053 second correlation times corresponds to a 3 hz bandwidth.

Similarly, to establish a constant speed climb, the pilot must add collective thrust to begin climbing but simultaneously adjust pitch attitude to hold airspeed. In a sense, the pilot (through his extensive training) becomes an inner-loop decoupling controller, needed to give good speed and climb rate performance, the ultimate goal in cruising flight. The design goal, in terms of human factors, can be restated as reducing the pilot's workload in cruise flight by taking him out of the aircraft inner loops and giving him a direct velocity command system.

With the design goal stated, the physical hardware and flight software constraints must also be considered. Appendix F briefly describes the highly modified CH-47B flight research helicopter flown and maintained at the NASA Ames Research Center. The Langley Report gives a more detailed description of this particular helicopter, which has been modified to include a full authority fly-by-wire flight control system and extensive instrumentation.[10] Figure 3.1 shows the list of sensors available on the aircraft. Unfortunately, many of these sensors were quite noisy in the sense that they contained frequencies associated with the rotor motion. Rather than attempt to use the noisy measurements directly in the digital compensator, the TR-48 analog computer on the aircraft was programmed to filter several of the important aircraft motion sensor outputs. Specifically, fourth order Bessel filters were used on the longitudinal, lateral, and vertical accelerometers; a third order Bessel filter was used on the roll rate gyro; and second order Bessel filters on pitch rate, yaw rate, altitude, and pitot-static airspeed measurements. The filters were designed with 5 Hertz breakpoints to eliminate the "3 per rev" and "6 per rev" main rotor harmonics at 11 and 22 Hz. A brief description of these filters is included in Appendix H. A further constraint on the design process was

Chapter 3.

Longtidinal CAS for the CH-47

3.1. Design Goals and Constraints

The first example of an application of the methodology in Chapter 2 is the design of a longitudinal cruise autopilot for the CH-47. The goal was to synthesize a controller which gave the pilot independent control of airspeed and climb rate using separate pilot controls. For this design, the pilot longitudinal stick was used for the airspeed control and his collective lever was used for climb rate control. This implementation is unconventional since most helicopter control systems, even the highly augmented ones, give the pilot either pitch rate or pitch angle command from longitudinal stick and direct collective thrust command from the collective lever. Some of the more modern helicopters (CH-47D, HH60, CH-53) do close outer loops such as altitude or speed-hold around the collective thrust and pitch rate inner loops, but these are usually implemented as additional pilot-selectable autopilot modes. One trouble with pitch-angle, collective-thrust controllers is the coupling between the two. To increase speed in level flight, the pilot must pitch down, add collective thrust to maintain altitude and accelerate, then pitch up and reduce to a thrust slightly higher than the original to hold the new airspeed.

the compensator and then further simplifies the discrete compensator by putting it back into block minimal form. The SETPNT program uses an algorithm which finds the exact digital representation of a 2×2 compensator subsystem. One advantage of having the digital compensator in block minimal form is the reduction of arithmetic operations required by the computer. Specifically, the minimal form reduces the number of multiplies and adds, required by the compensator, by $r(r-1)$ where r is the order of the compensator. For large order compensators, such as required by systems controlling structural modes, the reduction can be important. The SETPNT program calculates this digital compensator in a form immediately usable in a floating point digital controller.

2.7. Summary

This chapter has shown an approach to designing control systems based on "modern control" methodologies. The approach is especially useful for MIMO systems of large order where compensator order reduction is essential. The Navion autopilot design was a simple example chosen to illustrate the design methodology. In applying this methodology to real control systems, problems will surface requiring the designer to modify and iterate the design to achieve the desired performance specifications. The next two chapters show this methodology applied to a real design problem. They illustrate the usefulness of the approach applied to a fairly complicated design task. They also show the type of problems which surface in real design applications.

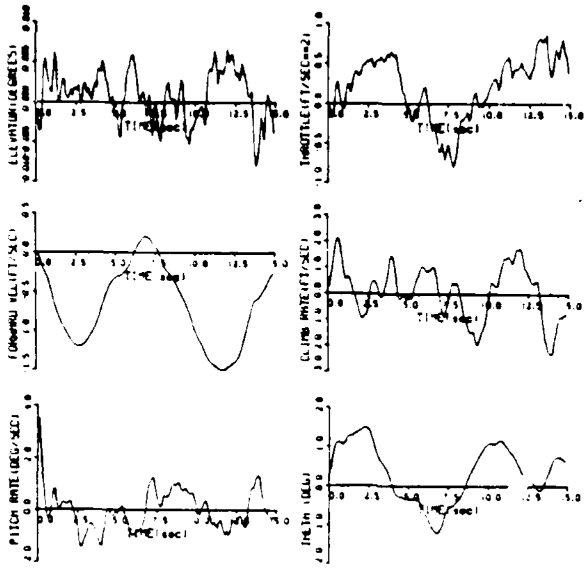


Figure 2.12: **Navion Reduced Order Compensator Performance in Turbulence.** The performance is nearly identical to the full order compensator (Figure 2.11) and is shown numerically in Figure 2.5

could be "tuned" by changing the weighting matrices and disturbance properties in the RSANDY program.

Eventually, the control system may be put into the physical system and tested. Since these compensator designs can be computationally intensive, it is unlikely to see any analog or continuous implementations for anything other than the simplest designs. Since the entire design process has been in the continuous domain, the final compensator must therefore be discretized to be useful in a digital computer based control system. The process of discretization is simple since the compensator is in a block minimal form. If the control is assumed to be a zero order hold (ZOH), i.e. step commands over the cycle time, then the discrete form can be solved exactly for the 2×2 and 1×1 blocks which make up the compensator dynamic system. The SETPNT program does this exact ZOH discretization for

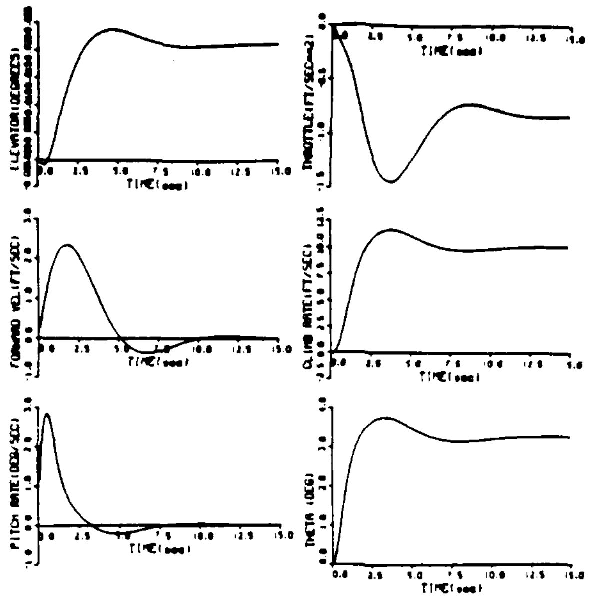


Figure 2.10: **Climb Rate Response for Reduced Order Compensator.** As with the velocity responses of Figures 2.7 and 2.8, the reduced order compensator has slightly reduced stability with a damping of about .6.

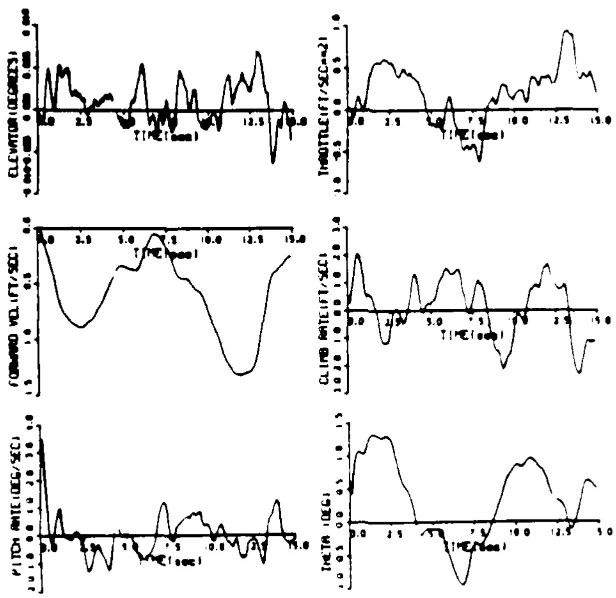


Figure 2.11: **Navion Full Order Compensator Performance in Turbulence.** The primary difference between the full order performance and reduced order performance (this figure and Figure 2.12) is in the control response which is smoother here.

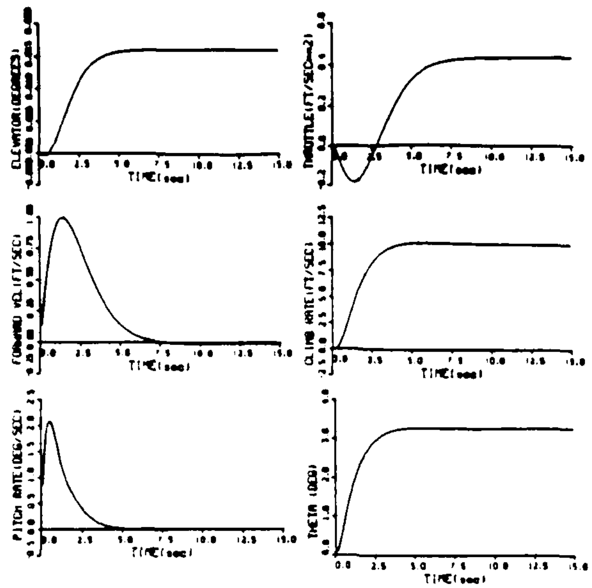


Figure 2.9: **Climb Rate Response for Full Order Compensator.** The rise time is 2 seconds with critical damping.

as we might expect. The velocity is better damped and faster using the full order compensator. Also, with the elimination of the θ measurement, we note the reduced order compensator has greater pitch angle excursions due to the velocity command. Comparing the climb rate responses of Figures 2.9 and 2.10, we note similar performance between the full and reduced order compensators. To compare the disturbance rejection characteristics of the two designs, we use the SIMPLOT program with plant disturbances and measurement noise. Figures 2.11 and 2.12 show the system performance in response to an initial pitch rate of 5 degrees in the presence of identical disturbances. As expected the full order compensator does a better job, as seen earlier in Figure 2.5. At this point, the design could be iterated by eliminating more modes or measurements, or by adding modes or measurements to improve performance. Alternately, the reduced order design the responses when the commands *are* correctly accounted for in the compensator.

$$
\begin{aligned}
\dot{z} &= A\,z + B\,y_m + T_{min}^{-1}\,T_{mod}^{-1}\,G\,u_{command} \\
u_{regulator} &= C\,z
\end{aligned}
\tag{3.9}
$$

where:

- A: the block minimal form of the compensator dynamics matrix$(F-GC-KH)$ which already includes the regulator control effects (the GC term)
- B : The minimal form of the Kalman gain matrix from ROPTSYS
- C : The minimal form of the optimal regulator gain matrix from ROPTSYS
- G: the control distribution matrix for the physical system
- T_{min}^{-1}: the similarity transformation from the modal form to the block minimal form described in Appendix C
- T_{mod}^{-1}: the similarity transformation from the nominal form to the modal form, composed of the eigenvectors of $F-GC-KH$

At this point in the process, alternative approaches to the design were used.(Still before we realized how to implement Equation 3.9 above.) Two such alternatives are shown below:

- Pick noise spectral density matrices independent of the actual noise but which give good time responses.
- Use an inverse optimal solution as described by Bernard to establish the performance index weighting matrices and noise spectral density matrices.[7]

3.4.1. Redesign Using Arbitrary Measurement Spectral Densities

The first intermediate approach to improving the poor time response in the velocity channel required selecting noise spectral densities which give an adequate time response. This approach violates the assumptions of the LQG estimator design procedure where the Kalman filter gains are calculated to minimize the estimate errors in the presence of the given noise. However, the noise properties are

$$F_{min} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -260.43 & -20.31 & 0 & 0 & 0 & 0 \\ 0 & 0 & -14.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -27.3 & -6.8 & 0 \\ 0 & 0 & 0 & 0 & 0 & -4.86 \end{bmatrix} \tag{3.10}$$

$$K_{min}(scaled) = \begin{bmatrix} -.58 & -12.1 & -.011 & .0078 \\ 6.98 & 226.5 & .0411 & .058 \\ -.72 & -100.7 & -.154 & .233 \\ -1.99 & -8.5 & .355 & -.75 \\ 9.12 & -3.78 & -2.36 & 4.35 \\ -11.34 & -49.3 & 2.44 & -4.44 \end{bmatrix} \tag{3.11}$$

$$K_{min}(unscaled) = \begin{bmatrix} -58 & -121 & -.011 & .0078 \\ 69.8 & 22649 & .0411 & .058 \\ -72 & -10070 & -.154 & .233 \\ -199 & -850 & .355 & -.75 \\ 912 & -378 & -2.36 & 4.35 \\ -1134 & -4930 & 2.44 & -4.44 \end{bmatrix} \tag{3.12}$$

$$C_{min}(scaled) = \begin{bmatrix} 4.05 & .74 & .75 & -.506 & -.46 & -.25 \\ 0 & 1 & 1 & 0 & 1 & 1 \end{bmatrix} \tag{3.13}$$

$$C_{min}(unscaled) = \begin{bmatrix} .405 & .074 & .075 & -.0506 & -.046 & -.025 \\ 0 & -.1 & -.1 & 0 & -.1 & -.1 \end{bmatrix} \tag{3.14}$$

System	Eigenvalues	Damping
Open Loop(F)	$-40.0, -40.0, -2.54, .503, -.105 \pm j.276$	1, 1, 1, *unstable*, .35
Regulator(F-GC)	$-4.64 \pm 5.82, -5.04 \pm 1.2, -2.94 \pm 4.01$	.62, .98, .59
Estimator(F-KH)	$-40.0, -40.0, -11.55 \pm 8.69, -3.74, -.0088$	1, 1, .79, 1, 1
Compensator(F-GC-KH)	$-10.15 \pm 12.54, -14.5, -3.39 \pm 3.97, -4.86$	.63, 1, .65, 1

Mode	Real	Imag	M_1	M_2
1	-10.15	12.54	277.9	27.4
2	-10.15	-12.54	–	–
3	-14.54	0	126	8.66
4	-3.4	3.97	68	20
5	-3.4	-3.97	–	–
6	-4.87	0	52	10.8

Figure 3.6: **CH-47 Longitudinal Full Order Compensator.** Notice the highly unstable open loop mode at $s = .503$. According to the test pilots, the 60 knot flight condition is the most unstable in the envelope.

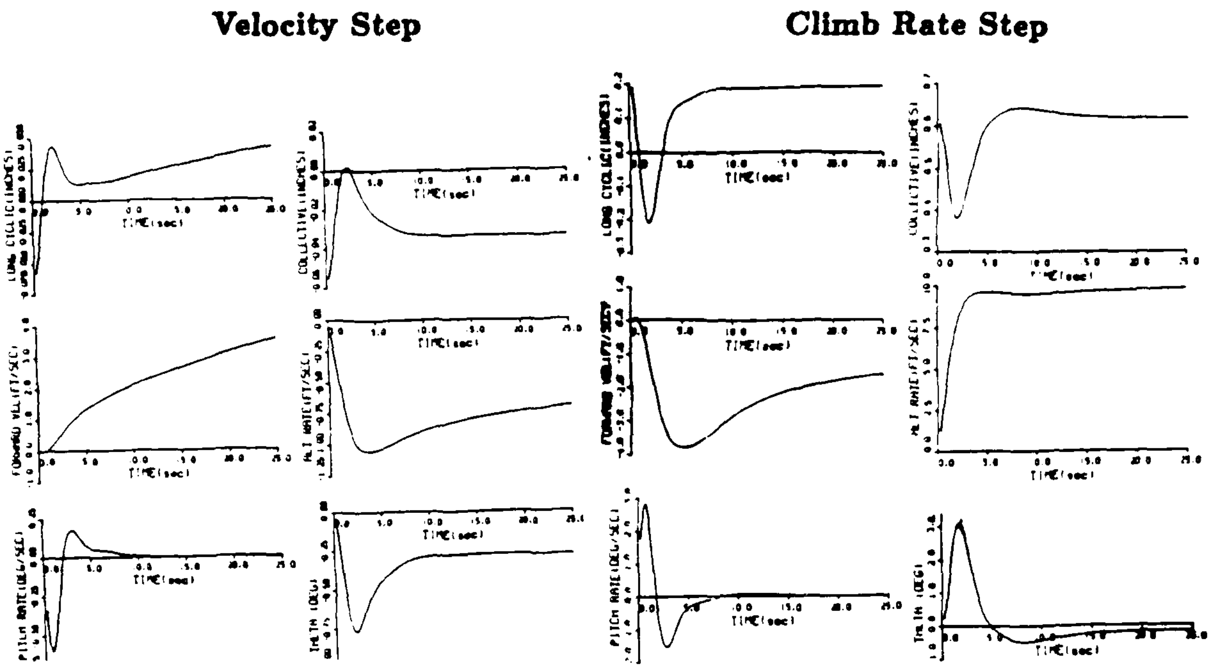


Figure 3.7: **Longitudinal CAS Time Responses using Nomimal Noise.** The poor velocity command response is dominated by the slow estimator mode ($s = -.0088$).

fairly uncertain and furthermore, the goal of this design was not a good estimator, but a good compensator. The selection of Q and R matrices which give "good" performance is an iterative process. Figure 3.9 shows the compensator when the spectral densities of all the measurements are set to .2. The very slow estimator pole is eliminated. Figure 3.10 shows the improved velocity response and the unchanged climb rate response.

3.4.2. Redesign Using an Inverse Optimal Controller

The second intermediate approach uses Bernard's "inverse optimal controller" technique.[7] This technique computes A, B, Q and R matrices which, if used in an LQG design, give a closed loop system with desired poles. Figure 3.11 shows this compensator including the A, B, Q and R provided by Bernard. The time

Velocity Step **Climb Rate Step**

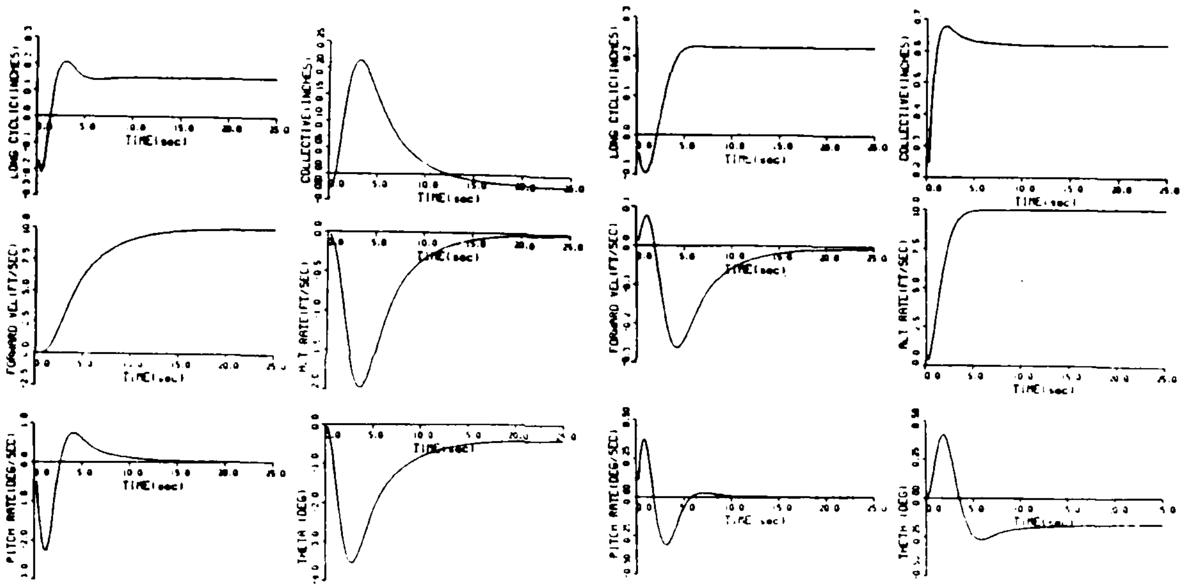


Figure 3.8: **Longitudinal CAS Time Responses with Commands to the Compensator.** With the command correctly fed to the compensator, the response is identical to a full-state feedback controller. The climb rate response is unchanged from Figure 3.7.

$$F_{min} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -14.715 & -7.43 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -4.27 & -1.61 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -2.7 & -3.16 \end{bmatrix} \tag{3.15}$$

$$K_{min}(scaled) = \begin{bmatrix} .00014 & .00048 & -.009 & -1.12 \\ -.001 & -.0018 & -2.40 & 3.99 \\ -.0076 & -.00093 & -.18 & .99 \\ .0012 & .0018 & 3.11 & -3.66 \\ -.000093 & 1.1 \times 10^{-4} & -.15 & -.24 \\ .00015 & .0018 & -.026 & -.20 \end{bmatrix} \tag{3.16}$$

$$K_{min}(unscaled) = \begin{bmatrix} .014 & .048 & -.009 & -1.12 \\ -.10 & -.18 & -2.40 & 3.99 \\ -.076 & -.093 & -.18 & .99 \\ .12 & .18 & 3.11 & -3.66 \\ -.0093 & .00011 & -.15 & -.24 \\ .015 & .018 & -.026 & -.20 \end{bmatrix} \tag{3.17}$$

$$C_{min}(scaled) = \begin{bmatrix} 0.0 & 1.0 & 0.0 & 1.0 & 1.65 & 1.17 \\ .26 & .40 & .23 & .38 & 0.0 & 1.0 \end{bmatrix} \tag{3.18}$$

$$C_{min}(unscaled) = \begin{bmatrix} 0.0 & -.1 & 0.0 & -.1 & -.165 & -.117 \\ -.026 & -.040 & -.023 & -.038 & 0.0 & -.1 \end{bmatrix} \tag{3.19}$$

System	Eigenvalues	Damping
Open Loop(F)	$-40.0, -40.0, -2.54, .503, -.105 \pm j.276$	1, 1, 1, *unstable*, .35
Regulator(F-GC)	$-2.62, -.866 \pm j.913, -1.035 \pm .384, -.281$	1, .69, .94, 1
Estimator(F-KH)	$-40.0, -40.0, -4.45, -1.0 \pm j.721, -1.31$	1, 1, 1, .81, 1
Compensator(F-GC-KH)	$-3.72 \pm j.947, -.803 \pm j1.90, -1.58 \pm j.445$	.97, .39, .96

Mode	Real	Imag	M_1	M_2
1	-3.72	.947	11.33	3.05
2	-3.72	-.947	–	–
3	-.803	1.90	5.24	6.53
4	-.803	-1.90	–	–
5	-1.58	.45	.254	1.61
6	-1.58	-.45	–	–

Figure 3.9: **Longitudinal CAS using Arbitrary Measurement Spectral Density.** The slow estimator mode of Figure 3.6 is eliminated.

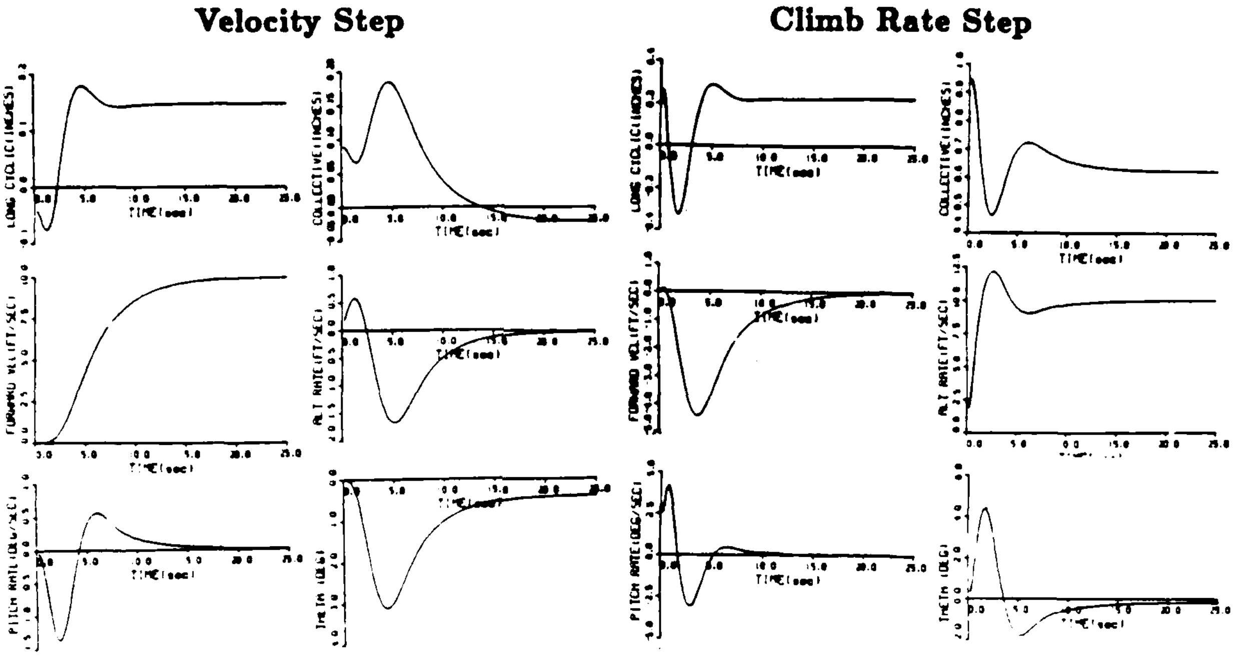


Figure 3.10: **Longitudinal CAS Time Responses using Arbitrary Noise.** The poor velocity response of Figure 3.7 is eliminated.

responses of Figure 3.12 confirm the improved performance.

Figure 3.13 shows the statistical performance of the original design and the two alternate designs. As expected, the nominal design has the lowest errors. The inverse optimal controller is nearly as good but the other is clearly the worst. Based on the combination of statistical performance and the time responses, the inverse optimal design was the best of the full order compensators. With the full order compensator in hand, the process of order reduction began.

3.5. Compensator Order Reduction

Using the M_2 criterion of section 2.3, both the nominal and the inverse optimal compensators indicate reduction to third order is feasible. From a more practical

$$F_{min} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -205.73 & -22.68 & 0 & 0 & 0 & 0 \\ 0 & 0 & -3.73 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1.55 & -2.33 & 0 \\ 0 & 0 & 0 & 0 & 0 & -.68 \end{bmatrix} \tag{3.20}$$

$$K_{min}(scaled) = \begin{bmatrix} -.013 & -.87 & -.34 & -.0015 \\ -.17 & 4.95 & .17 & -1.03 \\ .37 & -.84 & .01 & 1.84 \\ -.011 & -.43 & -.12 & .88 \\ .022 & .34 & .069 & -.57 \\ .014 & .63 & .16 & -1.40 \end{bmatrix} \tag{3.21}$$

$$K_{min}(unscaled) = \begin{bmatrix} -1.29 & -86.68 & -.033 & -.0015 \\ -16.62 & 494.75 & .17 & -1.03 \\ 37.28 & -84.30 & .01 & 1.84 \\ -1.132 & -42.52 & -.12 & .88 \\ 2.16 & 33.85 & .069 & -.57 \\ 1.44 & 63.12 & .16 & -1.40 \end{bmatrix} \tag{3.22}$$

$$C_{min}(scaled) = \begin{bmatrix} 0.0 & 1.0 & 1.0 & 1.61 & .33 & 1.0 \\ .10 & .25 & .21 & 0.0 & 1.0 & -.42 \end{bmatrix} \tag{3.23}$$

$$C_{min}(unscaled) = \begin{bmatrix} 0.0 & -0.1 & -.1 & -.16 & -.033 & -.1 \\ -.01 & -.025 & -.021 & 0.0 & -.1 & .042 \end{bmatrix} \tag{3.24}$$

System	Eigenvalues	Damping
Open Loop(F)	$-40.0, -40.0, -2.54, .503, -.105 \pm j.276$	1, 1, 1, *unstable*, .35
Regulator(F-GC)	$-2.13 \pm j.78, -.56 \pm j.23, -.82 \pm j.33$	.94, .93, .93
Estimator(F-KH)	$-40.0, -40.0, -11.54 \pm j8.70, -1.01, -.52$	1, 1, .80, 1, 1
Compensator(F-GC-KH)	$-11.34 \pm j8.78, -3.73, -1.17 \pm j.44, -.68$	.79, 1, .94, 1

Mode	Real	Imag	M_1	M_2
1	-11.34	8.78	15.33	1.35
2	-11.34	-8.78	–	–
3	-3.73	0.0	2.11	.56
4	-1.17	.44	2.59	2.22
5	-1.17	-.44	–	–
6	-.68	0.0	1.67	2.46

Figure 3.11: **Longitudinal Compensator based on Inverse Optimal Solution.** The slow estimator mode of the nominal design, Figure 3.6, is gone.

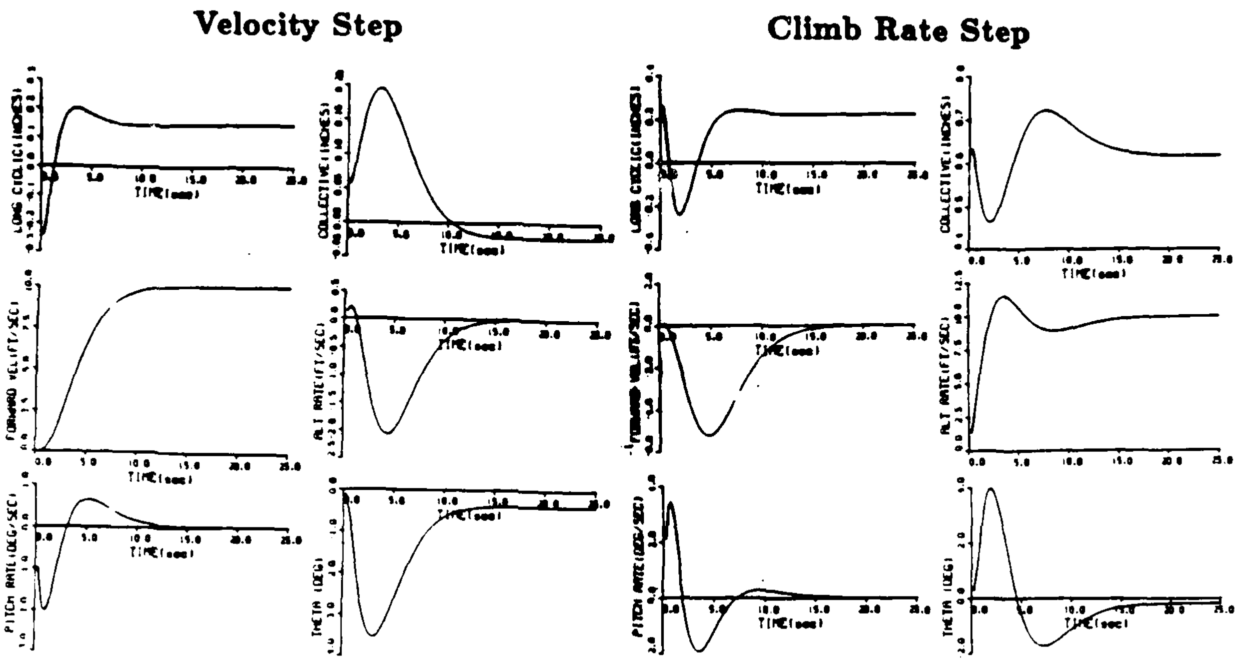


Figure 3.12: **Longitudinal CAS Time Responses using Inverse Optimal Controller.** The velocity reponse is much improved from Figure 3.7.

Standard Deviation							
System	δ_e (inches)	δ_c (inches)	u (ft/sec)	w (ft/sec)	q (deg/sec)	θ (deg)	$\dot{h}$ (ft/sec)
Nominal	.12	.06	1.01	1.51	0.84	0.78	1.49
Arbitrary Noise	.39	.21	4.24	3.96	3.46	3.34	2.65
Inverse Optimal	.16	.07	1.43	2.90	1.24	1.29	1.72

Figure 3.13: **Performance Comparison of Full Order Compensators.** These data are based on the measurement noise shown in Figure 3.1 and disturbance noise of Figure 3.4.

standpoint, using output feedback of the measurements is also a possibility. This is appropriate if we recall from section 3.1 that all the measurements were being analog filtered before entering the flight control computer. The next two sections show these two designs.

3.5.1. Robust Longitudinal Third Order Compensator

Using the nominal compensator reduced to third order as a starting guess, the RSANDY program was used to optimize the low order compensator using its robust design feature. The following flight conditions were used with the weightings shown.

Condition	Airspeed(knots)	Climb Rate(ft/min)	Weighting
Nominal	60	0	.8
Off Nominal 1	60	500	.05
Off Nominal 2	60	-500	.05
Off Nominal 3	40	0	.05
Off Nominal 4	80	0	.05

Stability is ensured by the RSANDY program for each of these flight conditions. Figure 3.14 shows the results including the closed loop roots at the nominal flight condition. There is still a slow mode ($s = -.059$) which is shown in the time responses of Figure 3.15 indicating the need for integral control.

When the integral control loop is added to the third order controller, the RSANDY program was again used to set the four gains in the K_I matrix of Figure 3.3. The program did not converge with only the four gains of K_I allowed to vary in the optimization. By releasing both the K_I *and* the compensator gains, the compensator of Figure 3.16 emerged. Figure 3.17 shows the associated time responses. The same approach was used to set the integral gains for the full-order compensator when the integral control loop was added. Figures 3.18 and 3.19

$$F_{min} = \begin{bmatrix} 0.0 & 1.0 & 0.0 \\ -226.3 & -78.49 & 0.0 \\ 0.0 & 0.0 & -1.397 \end{bmatrix} \tag{3.25}$$

$$K_{min} = \begin{bmatrix} -22.17 & -121.7 & -.35 & -.11 \\ 53.14 & 3527. & .87 & .24 \\ -31.38 & -84.46 & -.90 & -.38 \end{bmatrix} \tag{3.26}$$

$$C_{min} = \begin{bmatrix} 0.0 & -.10 & -.10 \\ -.11 & -.056 & .012 \end{bmatrix} \tag{3.27}$$

Real Part	Imag Part	Damping	Freq(rad/sec)	Freq(Hz)
-75.45	0.0	1.0	75.45	12.01
-40.00	0.0	1.0	40.00	6.37
-40.18	0.0	1.0	40.18	6.40
-3.12	0.0	1.0	3.12	.50
-.96	1.36	.58	1.67	.27
-.96	-1.36	.58	1.67	.27
-.059	0.0	1.0	.059	.0094
-.42	0.0	1.0	.42	.068
-.96	0.0	1.0	.96	.15

Figure 3.14: **Longitudinal Reduced Order Compensator.** Reducing from 6^{th} to 3^{rd} order decreases the number of independent gains in the compensator from 36 to 18.

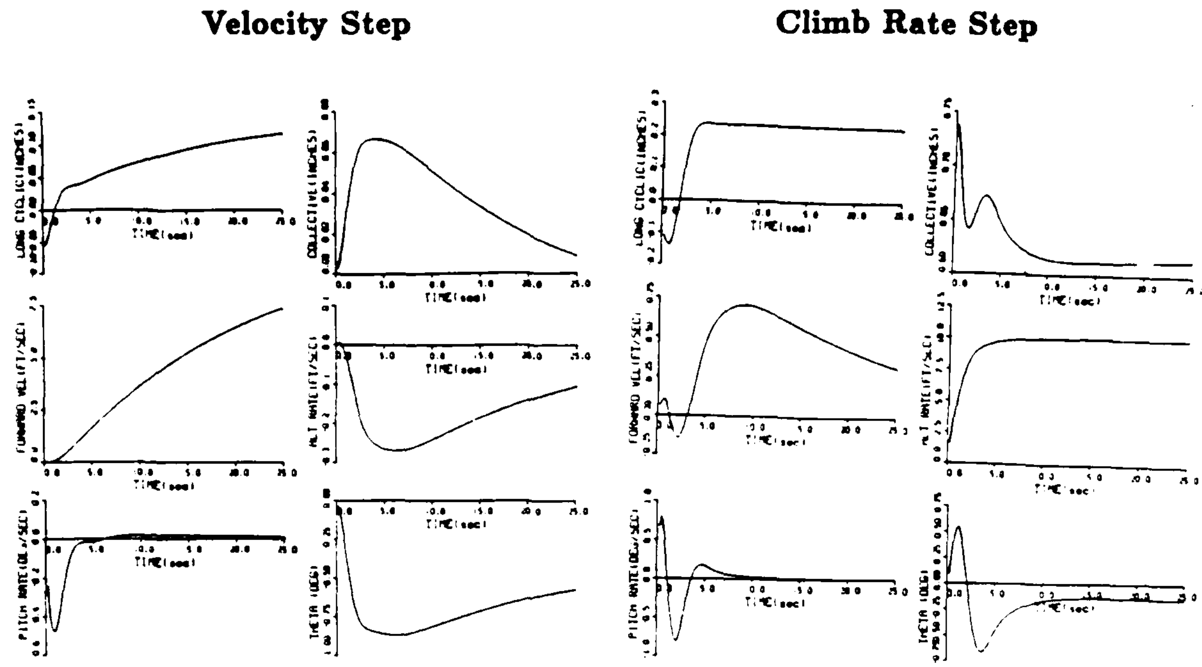


Figure 3.15: **Longitudinal Reduced Order Compensator Time Responses.** The velocity response is still quite slow but climb rate is adequate.

show the resulting compensator and time responses.

3.5.2. Longitudinal Output Feedback Controller

Since the measurements available $(q\theta u\dot{h})$ are nearly the same [2] as the states of a fourth order model, the gains of a regulator design are a good starting point in using RSANDY to compute output feedback gains. In fact, using these gains with no further optimization gave quite impressive performance as shown in Figures 3.20 and 3.21.

As with the reduced order compensator, an integral control loop is necessary to ensure that the actual commands are achieved in flight. Using the K_I gains from the reduced order design(Figure 3.16) and the output feedback controller of

[2] The fourth order model has states $(uwq\theta)$ and $\dot{h} \approx u_{nominal}\theta - w$.

$$A_{min} = \begin{bmatrix} 0.0 & 1.0 & 0.0 \\ -229.5 & -16.82 & 0.0 \\ 0.0 & 0.0 & -2.48 \end{bmatrix} \tag{3.28}$$

$$K_{min} = \begin{bmatrix} -22.83 & -190.9 & -.07 & .059 \\ 57.00 & 3528. & .044 & -.33 \\ -18.57 & -59.93 & -1.37 & -.67 \end{bmatrix} \tag{3.29}$$

$$C_{min} = \begin{bmatrix} 0.0 & -.1 & -.1 \\ .45 & -.071 & .041 \end{bmatrix} \tag{3.30}$$

$$I = \begin{bmatrix} -.0054 & .0098 \\ -.00823 & .047 \end{bmatrix} \tag{3.31}$$

Closed Loop Eigenvalues

Real Part	Imag Part	Damping	Freq(rad/sec)	Freq(Hz)
-39.75	0.0	1.0	39.75	6.32
-40.03	0.0	1.0	40.03	6.37
-7.61	11.46	.55	13.75	2.19
-7.61	-11.46	.55	13.75	2.19
-1.81	2.17	.64	2.83	.45
-1.81	-2.17	.64	2.83	.45
-1.77	0.0	1.0	1.77	.28
-.044	.092	.44	.10	.016
-.044	-.092	.44	.10	.016
-.53	.37	.82	.65	.10
-.53	-.37	.82	.65	.10

Figure 3.16: **Longitudinal Reduced Order Compensator with Integral Control.** The A_{min}, K_{min}, and C_{min} matrices are not the same as in Figure 3.14.

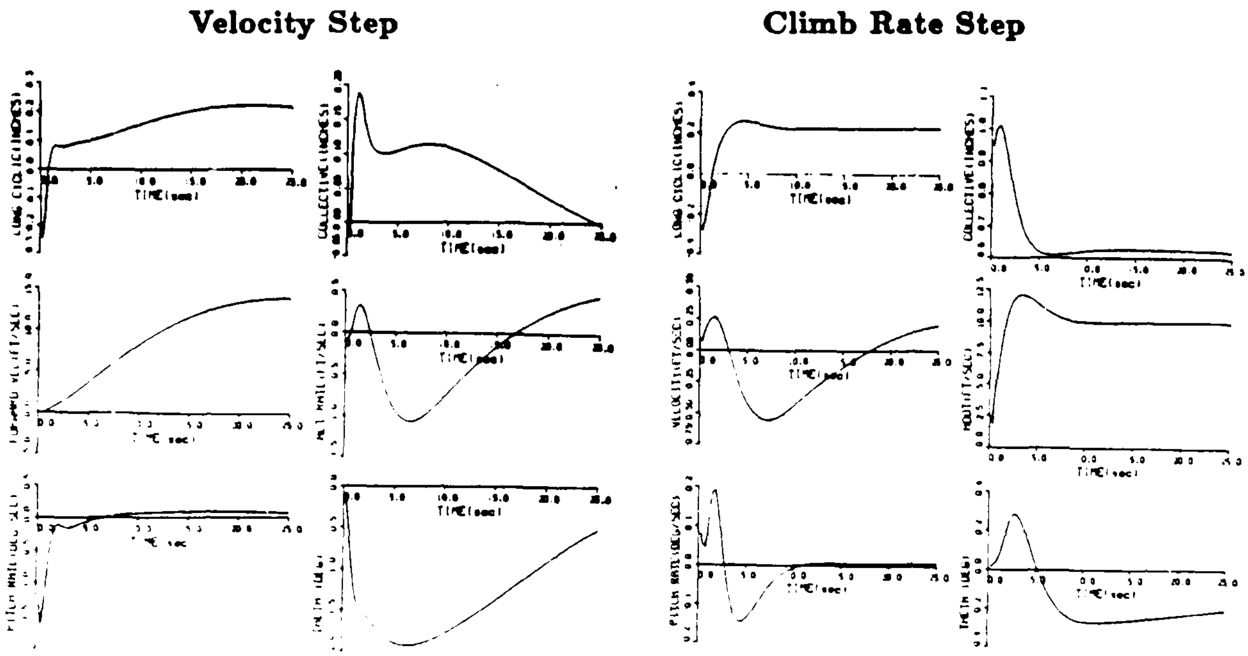


Figure 3.17: **Longitudinal Reduced Order Integral Controller Time Responses.** Although the velocity response is still fairly slow, this design was selected for evaluation in flight.

$$F_{min} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -205.7 & -22.67 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1.781 & -2.661 & 0 & 0 \\ 0 & 0 & 0 & 0 & -4.279 & 0 \\ 0 & 0 & 0 & 0 & 0 & -.263 \end{bmatrix} \tag{3.32}$$

$$K = \begin{bmatrix} -1.96 & -86.7 & -.148 & -.0213 \\ -16.62 & 494.8 & .166 & -.81 \\ -1.11 & -42.6 & -.437 & .475 \\ 2.171 & 33.8 & .727 & -.174 \\ 37.3 & -84.3 & .148 & 1.09 \\ 1.33 & 63.1 & .0823 & -.395 \end{bmatrix} \tag{3.33}$$

$$C = \begin{bmatrix} 4.932 & .122 & .477 & 1.01 & -.068 & -.44 \\ -.0105 & -.025 & 0 & -.1 & -.021 & .042 \end{bmatrix} \tag{3.34}$$

$$I = \begin{bmatrix} -.00003 & -.01 \\ .000157 & .053 \end{bmatrix} \tag{3.35}$$

Closed Loop Eigenvalues

Real Part	Imag Part	Damping	Freq(rad/sec)	Freq(Hz)
-40.01	.0022	1.0	40.01	6.37
-40.01	-.0022	1.0	40.01	6.37
-11.43	8.21	.81	14.07	2.239
-11.43	-8.21	.81	14.07	2.239
-.543	2.87	.185	2.93	.466
-.543	-2.87	.185	2.93	.466
-3.38	0.0	1.0	3.38	.537
-2.86	0.0	1.0	2.86	.455
-.299	.90	.315	.947	.151
-.299	-.90	.315	.947	.151
-.561	.334	.86	.65	.104
-.561	-.334	.86	.65	.104
-.206	0.0	1.0	.206	.0329
-4.24×10^{-5}	0.0	1.0	4.24×10^{-5}	6.75×10^{-6}

Figure 3.18: **Longitudinal Full Order Compensator with Integral Control.** As with the third order design, the A, K, and C matrices are different from the full order design without integral control (Figure 3.11).

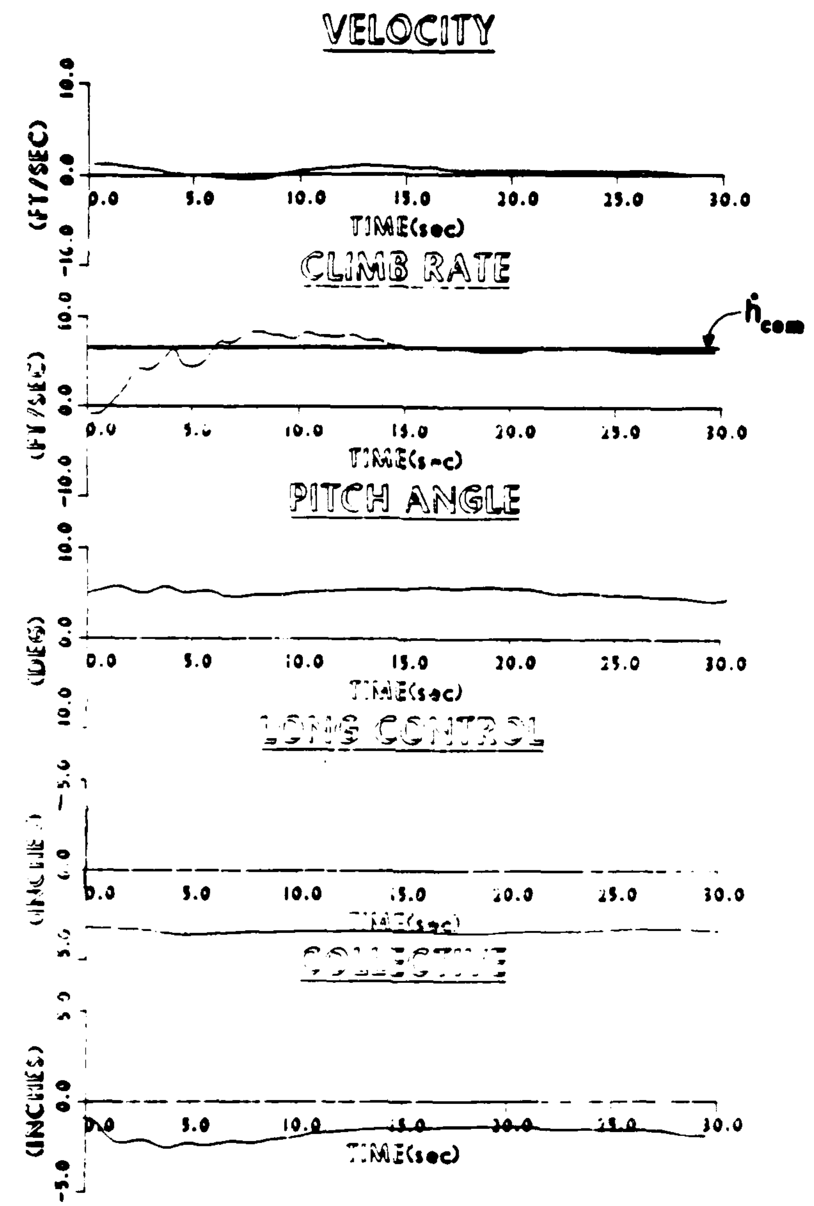


Figure 3.31: **Third Order Compensator Flight Response to Climb Rate Command.** Atmospheric turbulence masked the transient portion of the response but steady state was achieved in about 10 seconds, similar to the simulation of Figure 3.17.

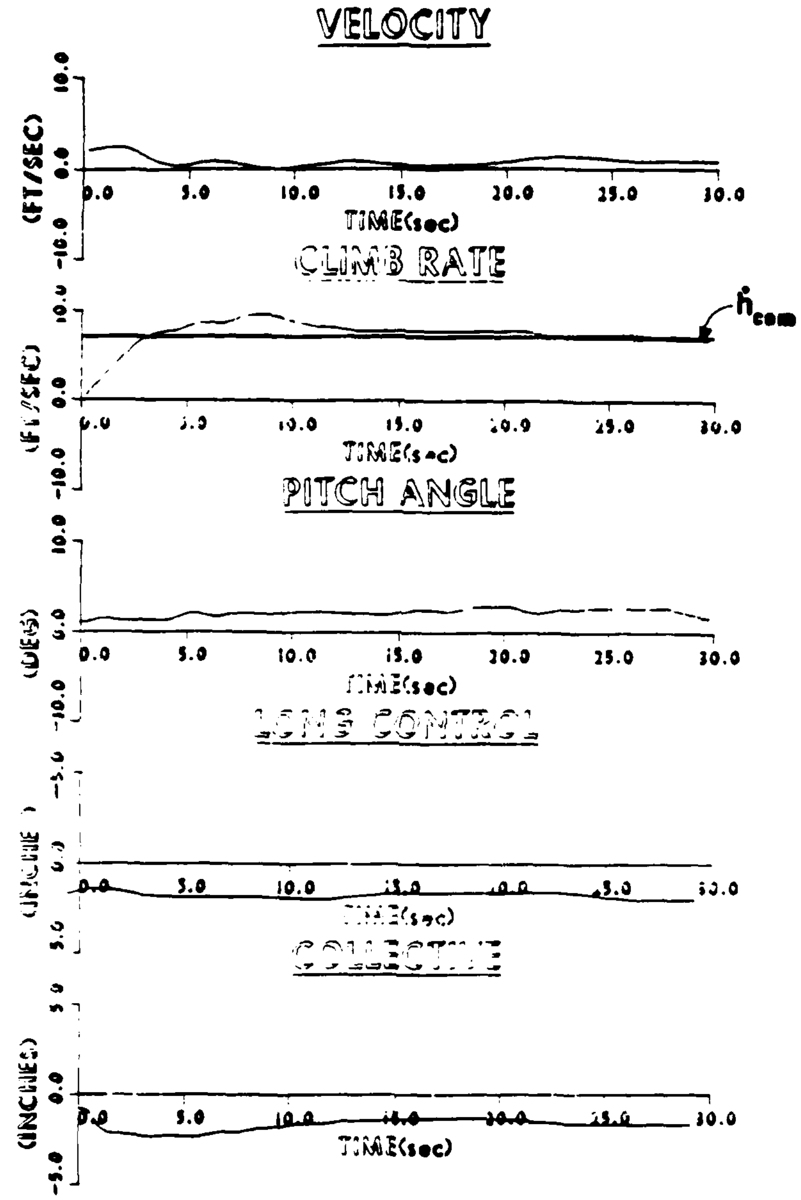


Figure 3.30: **Full Order Compensator Flight Response to Climb Rate Command.** As in the velocity response of Figure 3.27, the $\dot{h}$ command response was well predicted by the simulation results of Figure 3.19. This response also shows the decoupling between velocity and climb rate.

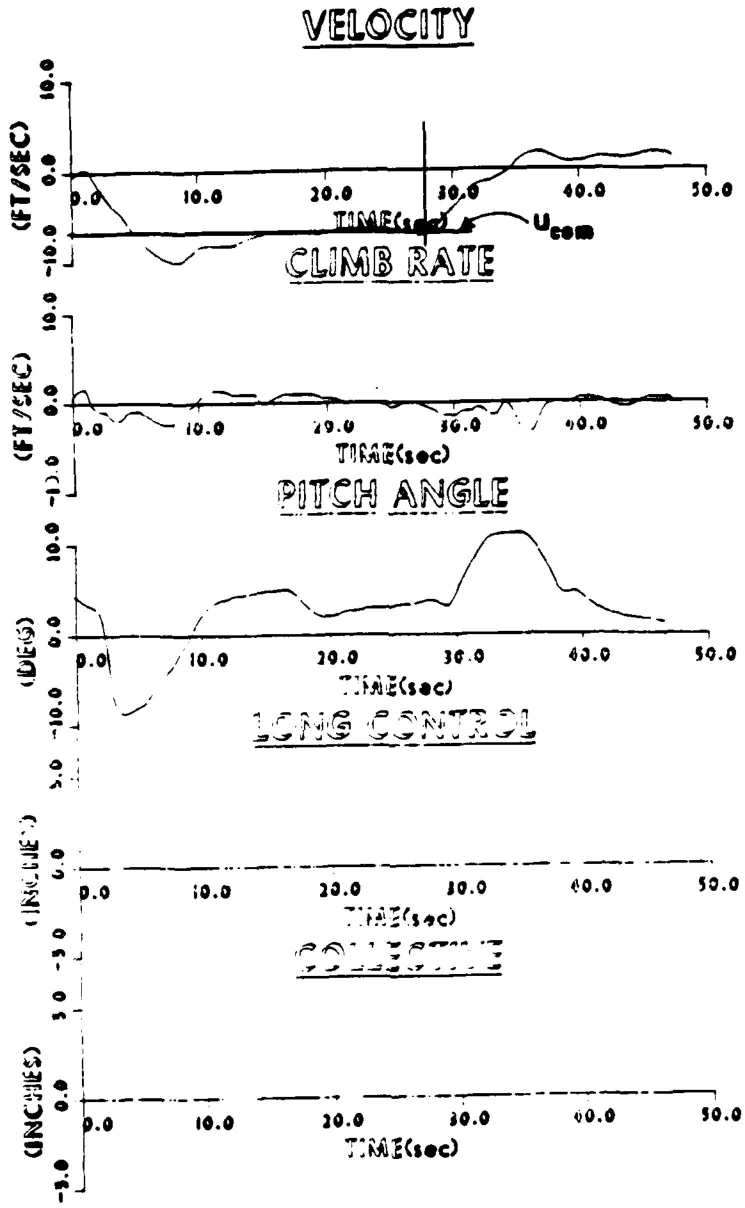


Figure 3.29: **Output Feedback Compensator Flight Response to Velocity Command.** As in the responses of Figures 3.27 and 3.28, this flight response agrees with the simulation predictions. In this case, however, the overall loop gain (final gain to the actuator) was reduced by half.

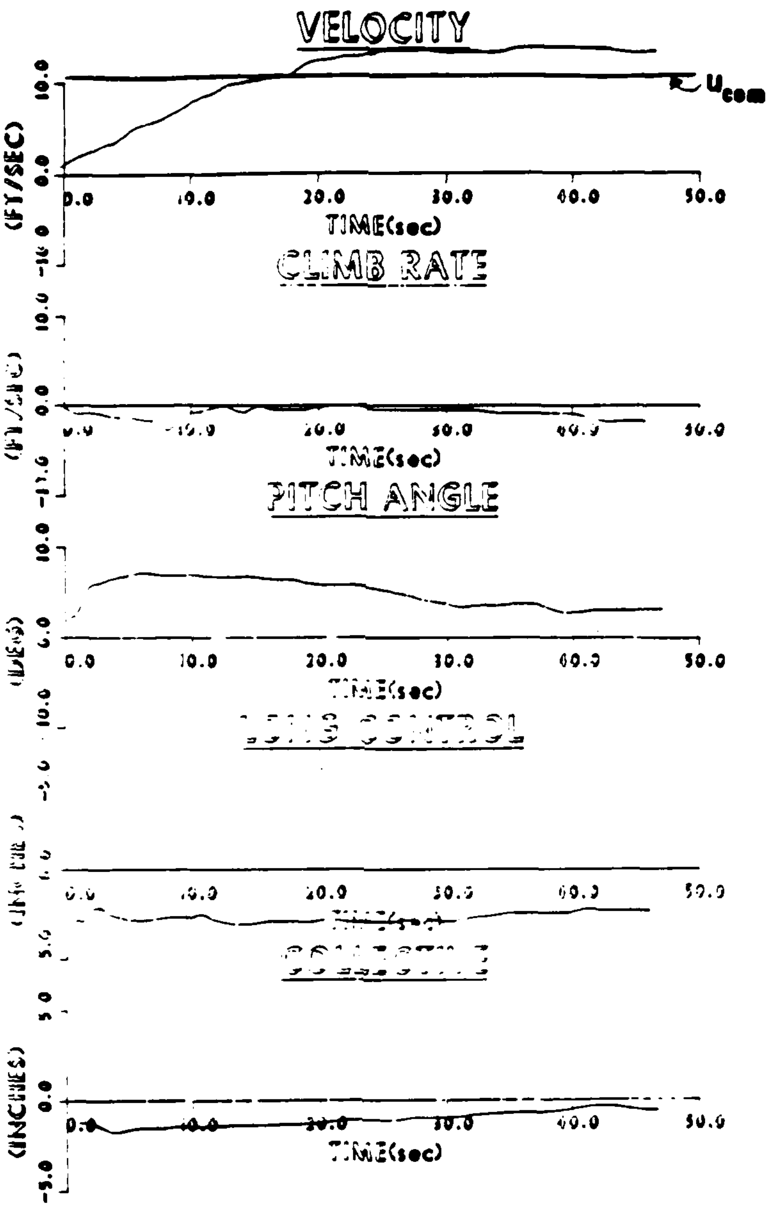


Figure 3.28: **Third Order Flight Response to Velocity Command.** This reponse to a command of approximately 10 ft/sec follows closely the simulation results of Figure 3.17.

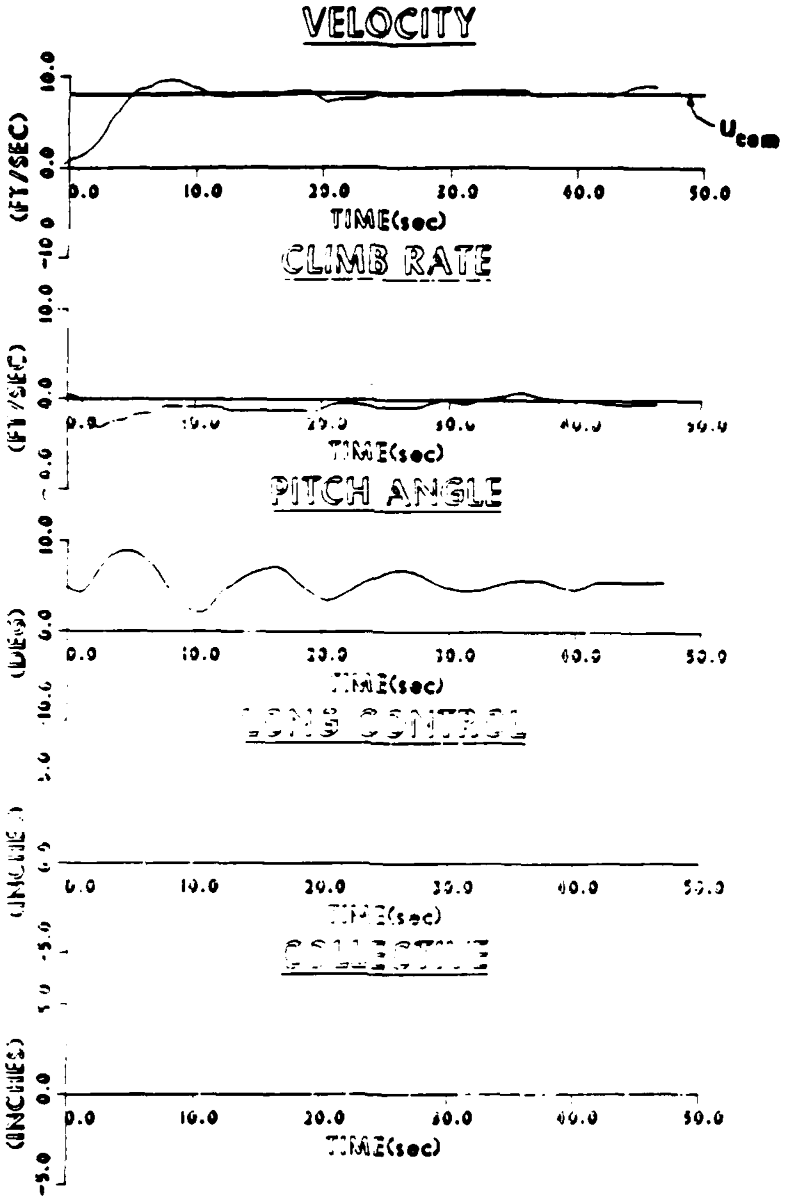


Figure 3.27: **Full Order Compensator Flight Response to Velocity Command.** The rapid velocity response and poorly damped pitch angle were also evident in the simulation response of Figure 3.19.

in a realistic task such as flying a precision approach.

3.8. Summary of Results for the Longitudinal CAS Design

The results of this section can be separated into two categories:

- the design task
- the flight test results

The design task was important because it established an experience base for use of the design methodology. This task showed that use of integral-error feedback in a state variable based controller eliminates the effects of an inaccurate plant model in achieving commanded outputs. It also showed the difficulty encountered when using LQG design techniques with specified time domain properties. In this example, three methods of setting weighting matrices and spectral density matrices were compared. From a practical standpoint, this first design task was very important since an accurate way of scaling the analytical design for use in the fixed point flight computer was developed. An equally important result of this task was the coding and testing of a general form of a modern controller for the Sperry 1819 flight computer.

The flight test results showed the technical feasibility of decoupled control using a "modern" controller. The test system had adequate handling qualities but, due to time constraints, no attempt was made to iterate the designs for "good" handling qualities. Also, the disturbance rejection capabilities were not thoroughly investigated.

took place at the Crows Landing test facility(in the San Joaquin valley) to avoid the heavy traffic of the South San Francisco Bay Area near Ames Research Center. The purpose of the flight test was to validate the performance of the different controllers rather than "tune" the system for maximum pilot acceptance. Step commands from the computer or the pilot were used to evaluate the different systems. The nominal airspeed was 60 knots but stability and performance were checked from 40 to 80 knots. Figures 3.27, 3.28 and 3.29 show the responses of the full-order, third-order, and direct feedback compensators to velocity step commands of about 10 ft/sec. All three of these systems show good decoupling between velocity and climb rate. Their velocity responses are similar to the simulation results of figures 3.12, 3.17, and 3.23 but the pitch angle behavior is less damped than the simulation results. Chen has shown that unmodeled dynamics, especially rotor dynamics, are the probable cause for the lower achievable control bandwidth in flight.[12] In fact, the output feedback flight implementation had the overall pitch and collective loop gains reduced by half to achieve an acceptable response. Figures 3.30, 3.31 and 3.32 show similar results for climb rate commands. The importance of integral control is demonstrated in figure 3.33 which shows the response to a climb rate command for the third order controller without integral control. Although a steady climb rate is achieved, an unwanted velocity change of similar magnitude is also present.

Pilot opinion was mixed concerning the system. They were impressed at how well it held airspeed and climb rate but the transient behavior was not totally acceptable and the system was "sloppy" in response to gusts. This is valid criticism based on the pitch angle responses. Unfortunately the system was not evaluated

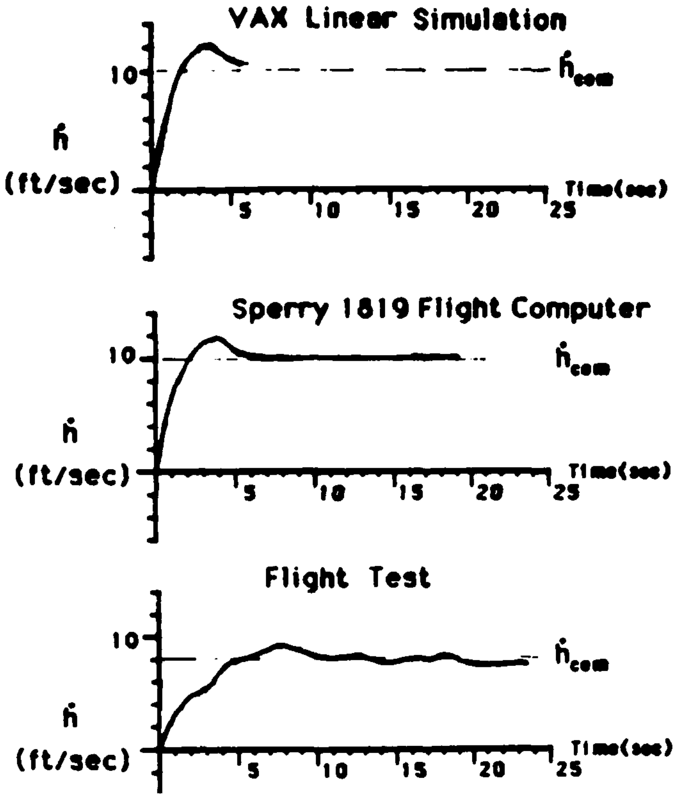


Figure 3.26: **Comparison of Analytical Design and Flight Test Implementation of the Controller.** This figure confirms the correctness of the steps needed to go from the analytical design to flight. These responses are for the 3^{rd} order compensator with integral control.

tinuous designs were digitized and scaled correctly. The OBS was also useful in preliminary pilot evaluation of the control laws and in initial setting of the stick sensitivities and other pilot-related items. Figure 3.26 shows a comparison of the time responses for a climb rate command for the third order system. This confirmed the accurate digitization and scaling of the analytical design. All flight controllers were similarly checked prior to each flight.

3.7. Flight Test Results

Once the designs had been implemented and checked out in the flight hardware, the flight testing began. Since the controller was designed for cruise, the testing

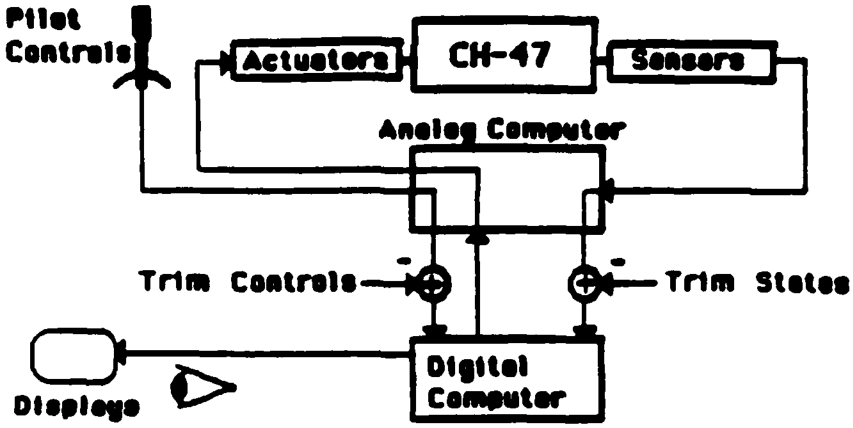


Figure 3.25: **Flight Test Implementation.** Sensor outputs and actuator commands were filtered in the analog computer while the control laws were executed in the digitial computer.

pose matrix multiply routine was programmed to take advantage of the minimal form of the compensator dynamics matrix.

- The existing instrumentation output subroutines were modified to send internal compensator data to the ground support station.

- Since the Sperry 1819A flight computer is an 18 bit fixed point machine, the matrices from the previous section were scaled to avoid numerical overflow during program execution. Appendix E describes this "fixed point scaling" technique and lists the SCALEM computer programs which accomplish this.

The actual assembly code implementing the controller is shown in Appendix I.

One important capability of the research system was onboard simulation(OBS). The OBS allowed the real-time flight software to be checked in the closed-loop system prior to actual flight. It was especially useful in confirming that the concould work without integral assistance. This would determine how well the design models compared with the real aircraft. Using the SETPNT program, the digital block minimal forms of each of these compensators were computed for flight implementation.

3.6. Flight Test Implementation

Once the analytical designs were complete, the tedious task of actual flight implementation began. Figure 3.25 shows a block diagram of the control structure on the research vehicle. The TR-48 analog computer was used to filter the sensor outputs and the digital actuator commands from the Sperry computer. The digital commands from the computer were filtered to avoid possible actuator wear caused by the 20 Hz chatter. The control laws were implemented in the Sperry 1819A digital flight control computer. Before the designs of the previous sections could be tested, the flight control computer software had to be modified to use them. In order to implement design changes more quickly, the flight software was set up to use the compensator matrices directly. Some of the considerations involved in programming the general form of the compensator in assembly language (shown in Figure 3.3) are listed below:

- Since the design was based on a linear perturbation model, the measurement and control trim values were approximated as the values at engage time; these were subtracted from their sensed values for use by the controller. This had the added advantage of eliminating engage transients.
- The compensator states were initialized to zero before system engage.
- To minimize time required for the compensator calculations, a special pur-

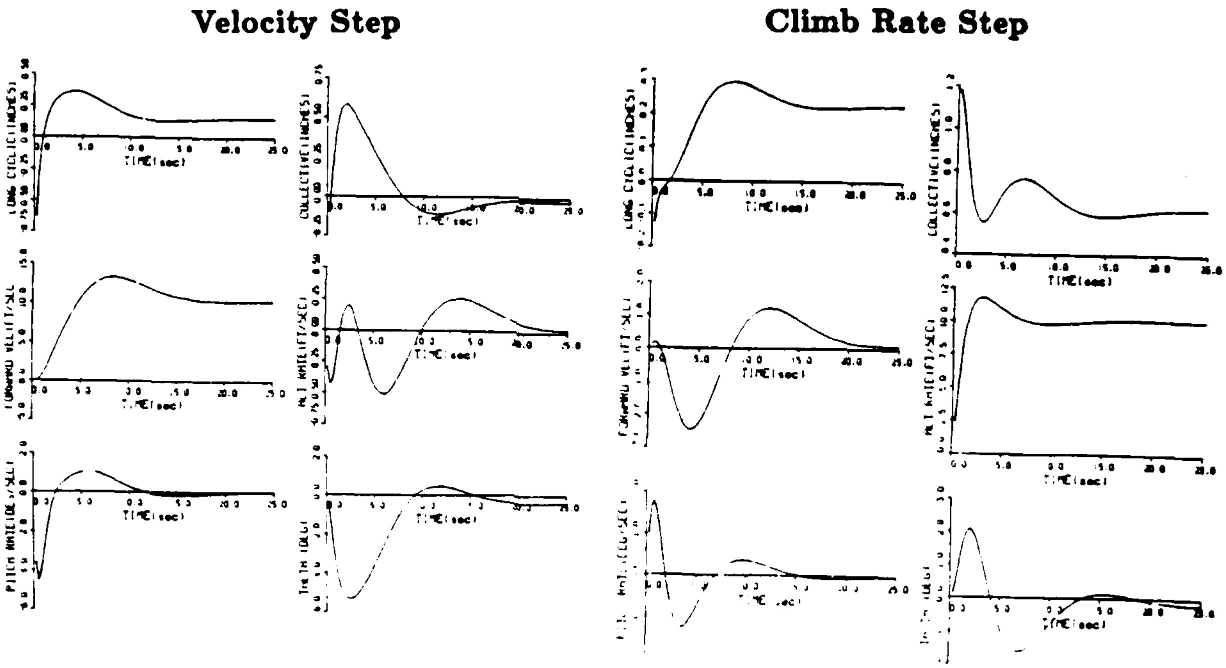


Figure 3.23: **Longitudinal Output and Integral Feedback Controller Time Responses.** This design was selected for flight evalualtion.

Standard Deviation							
System	δ_e (inches)	δ_c (inches)	u (ft/sec)	w (ft/sec)	q (deg/sec)	θ (deg)	$\dot{h}$ (ft/sec)
Nominal	.12	.06	1.01	1.51	0.84	0.78	1.49
Arbitrary Noise	.39	.21	4.24	3.96	3.46	3.34	2.65
Inverse Optimal	.16	.07	1.43	2.90	1.24	1.29	1.72
Inv Opt w/Int Cntrl	.34	.18	.82	1.53	2.0	1.1	1.64
3^{rd} Order	.08	.08	2.83	0.83	0.67	0.78	1.39
3^{rd} Order w/ Int Cntrl	.10	.14	0.72	0.83	0.55	0.38	0.86
Output Feedback	.32	.19	.82	1.58	1.29	0.80	0.80
Output Feedback w/Int Cntrl	.32	.21	.93	1.54	1.30	0.84	0.81

Figure 3.24: **Performance Comparison of All Compensators.** The boldbaced systems were selected for flight evaluation.

$$D = \begin{bmatrix} -5.74 & -12.51 & .041 & .103 \\ -1.23 & -10.44 & -.057 & .013 \end{bmatrix} \tag{3.37}$$

$$I = \begin{bmatrix} -.017 & .054 \\ -.013 & .084 \end{bmatrix} \tag{3.38}$$

Closed Loop Eigenvalues

Real Part	Imag Part	Damping	Freq(rad/sec)	Freq(Hz)
-37.52	0.0	1.0	37.52	5.97
-39.42	0.0	1.0	39.42	6.27
-2.39	0.0	1.0	2.39	.38
-1.17	.58	.89	1.30	.21
-1.17	-.58	.89	1.30	.21
-.13	0.0	1.0	.13	.021
-.23	.36	.54	.43	.068
-.23	-.36	.54	.42	.068

Figure 3.22: **Longitudinal Output and Integral Feedback Controller.** As with the full order and 3^{rd} order designs, the use of integral control reduces damping slightly.

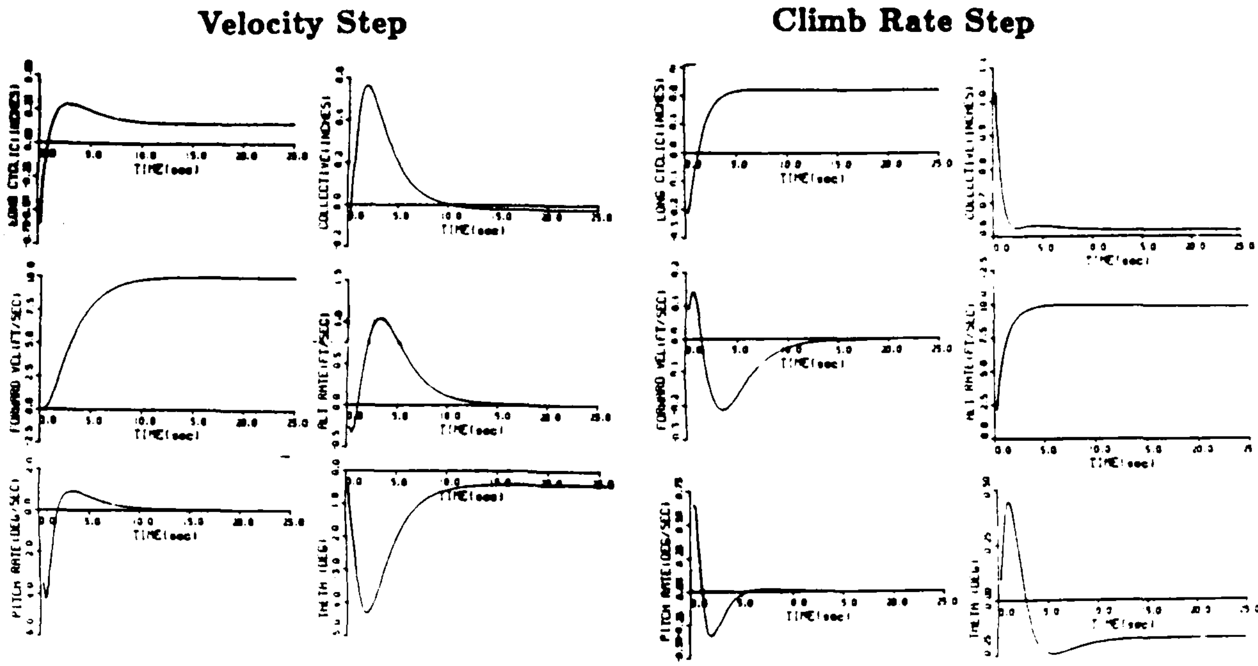


Figure 3.21: **Longitudinal Output Feedback Controller Time Responses.** These responses are critically damped and typical of full-state feedback designs.

Figure 3.20, good results were achieved with no further optimization. Figures 3.22 and 3.23 show these results.

3.5.3. Summary of Design Results

A number of controllers have been presented to show the iterative nature of the design methodology and to show an application of several methods to meeting the requirements. Selecting designs for flight test implementation required a review of these results. Figure 3.24 shows a comparison of all the designs. The controllers shown in boldface in Figure 3.24 were selected as candidates for flight. The three designs with integral-error control show a comparison of three sizes of compensators (full-order, reduced order and output feedback). The 3^{rd} order controller without integral control was included to see if the decoupling matrix

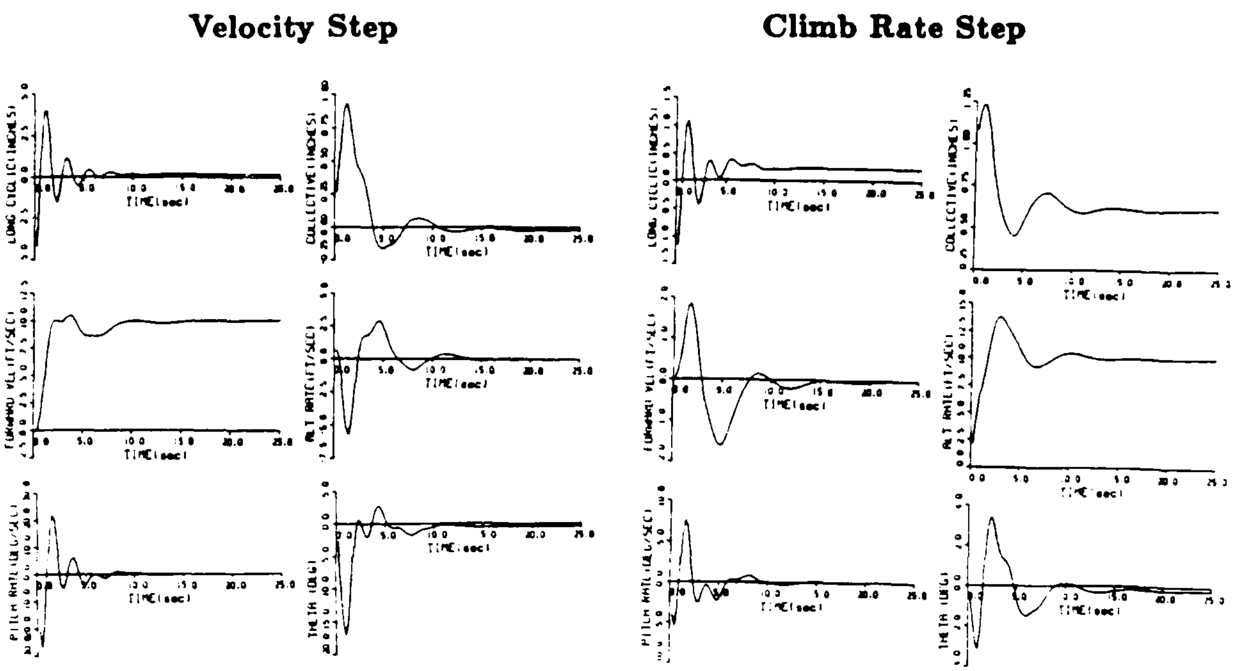


Figure 3.19: **Longitudinal Full Order Integral Controller Time Responses.** This design was also selected for flight evaluation.

$$D = \begin{bmatrix} -5.74 & -12.51 & .041 & .103 \\ -1.23 & -10.44 & -.057 & .013 \end{bmatrix} \tag{3.36}$$

System	Eigenvalues	Damping
Open Loop(F)	$-40.0, -40.0, -2.54, .503, -.105 \pm j.276$	1, 1, 1, *unstable*, .35
Closed Loop($F - G\,D\,H_m$)	$-39.4, -37.52, -2.07 \pm j.213, -.72, -.47$	1, 1, .99, 1, 1

Figure 3.20: **Longitudinal Output Feedback Controller.** Since the measurements (q, θ, $\dot{h}$, and u) are almost the same as the states of a 4^{th} order aircraft model (u, w, q, and *theta*), the output gains were set to the full-state feedback gains from a 4^{th} order regulator design.

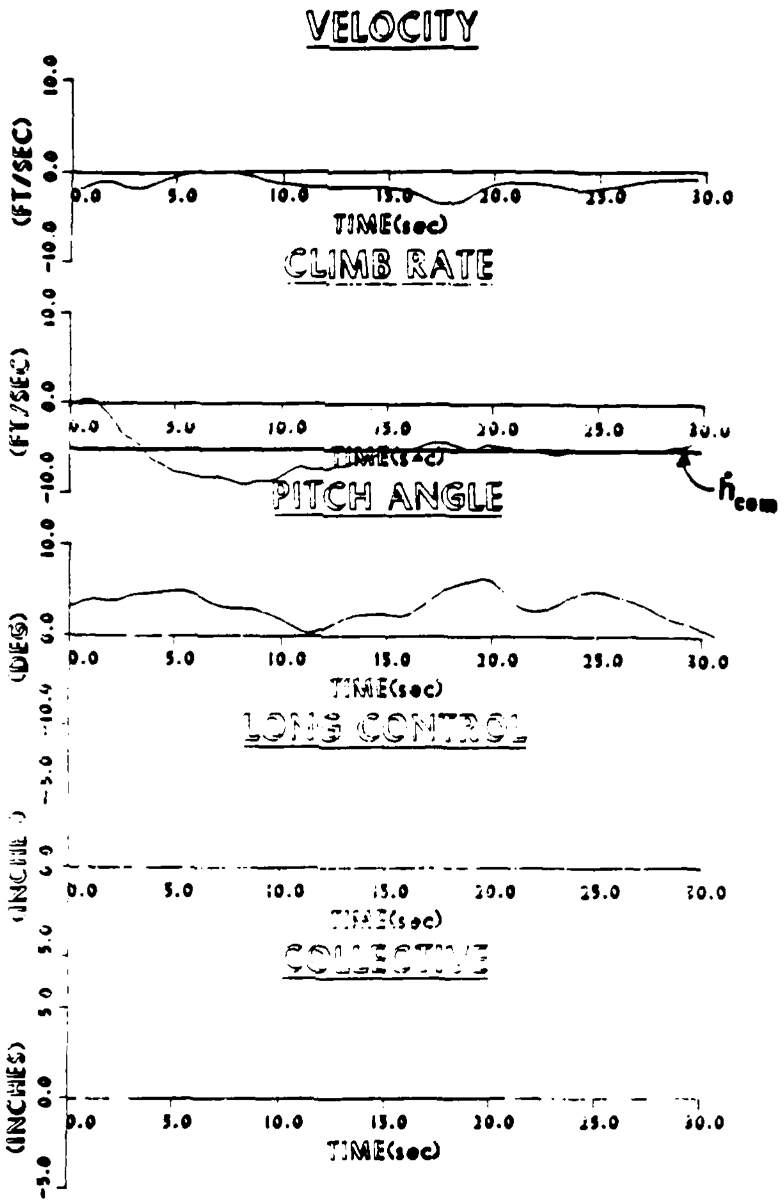


Figure 3.32: **Output Feedback Compensator Flight Response to Climb Rate Command.** As in Figure 3.29, the overall loop gains to the actuators were decreased by half from the analytical design.

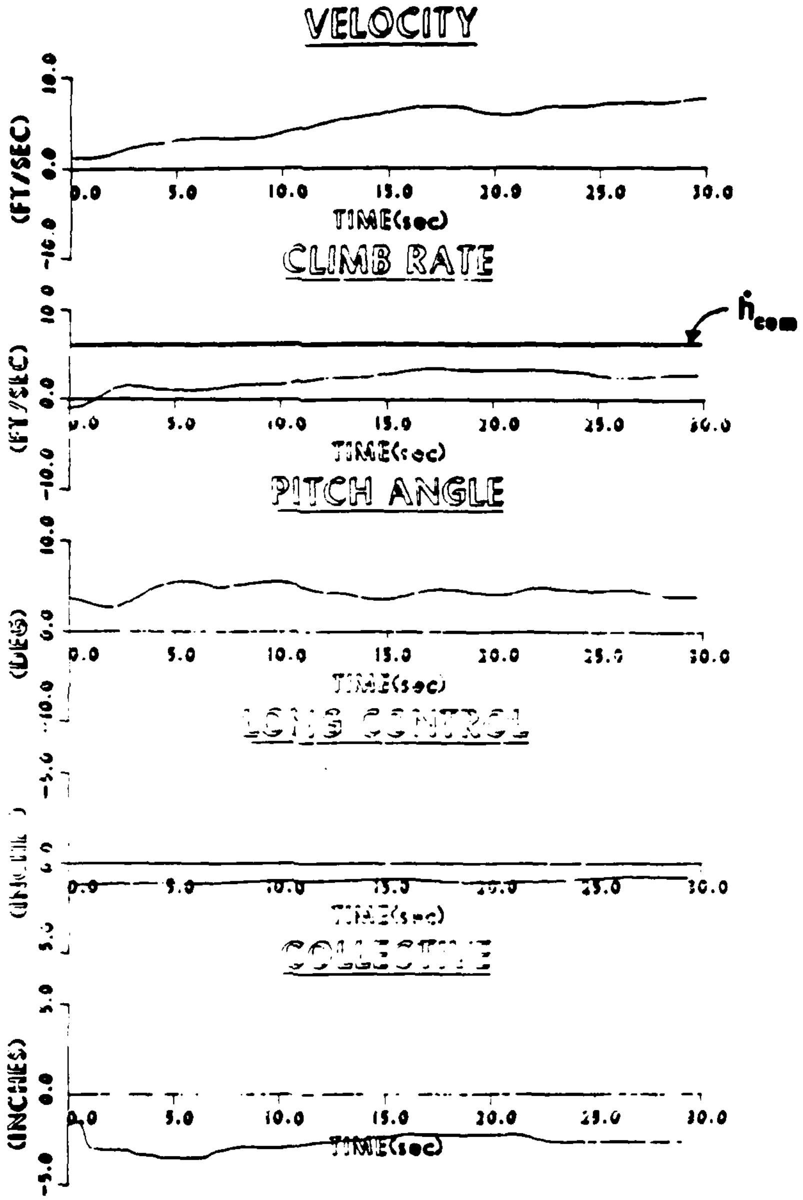


Figure 3.33: **Third Order Flight Response to Climb Rate Command without Integral Control.** This figure documents the effectiveness of the integral control loops. It also emphasizes the need for better models of the CH-47.

Chapter 4.

Hover Controller for the CH-47

4.1. Design Goals and Constraints

With the experience gained in the design of the longitudinal CAS, a more difficult task was selected for the next flight experiment. The second application of the methodology was the design of a translational velocity command, precision hover hold control system for the CH-47. This system was to provide the pilot with "split-axis" control of translational velocity in an heading-oriented inertial coordinate frame. "Split-axis" here means the pilot could select either a velocity command or position-hold control mode in each of the three translational degrees of freedom of the aircraft. As in Chapter 3, this design required decoupling of the three axes of interest. Figure 4.1 shows the coordinate system used for the design. As in Chapter 3, this control law is somewhat unconventional since the pilot's workload is reduced by removing him from inner loop attitude control tasks. For this system, forward velocity is controlled by longitudinal stick displacement, side velocity by lateral stick, and vertical velocity by the collective lever. If a particular pilot control is within a small distance of the neutral position (the detent), then the system enters a position-hold mode for that axis. Yaw rate control, using the

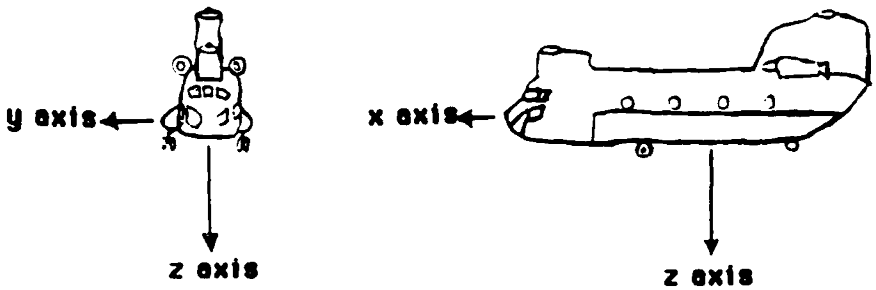


Figure 4.1: **Hover Control System Coordinate System.** The x, y, and z coordinates are in a heading-oriented inertial system.

standard CH-47 SAS, comes from the pedals. No operational helicopter control systems have this type of capability although the concept was tried on a modified CH-47 helicopter during early work on the Army's Heavy Lift Helicopter(HLH) concept.[13] This type of control law has numerous advantages with potential applications such as:

- Search and rescue
- Shipboard operations
- Slung load operations

Before proceeding with the description of how the design methodology was applied, the design constraints must be mentioned. As in the longitudinal CAS design, the TR-48 was used to filter the aircraft motion sensor data. The inertial velocity and position measurements came from either a laser or radar tracker on the ground. This was necessary since the onboard inertial navigation system(INS) had a drift of several knots ($\approx 5 ft/sec$) and provided only position data (no velocities). To avoid major changes in the flight software, a general form of the controller was programmed in the flight computer which provided for a flexible control structure.

$$\begin{bmatrix} \dot{u}\ (ft/sec) \\ \dot{v}\ (ft/sec) \\ \dot{w}\ (ft/sec) \\ \dot{p}\ (radians/sec) \\ \dot{q}\ (radians/sec) \\ \dot{r}\ (radians/sec) \\ \dot{\theta}\ (radians) \\ \dot{\phi}\ (radians) \\ \dot{\delta}_{e_{actual}}\ (inches) \\ \dot{\delta}_{c_{actual}}\ (inches) \\ \dot{\delta}_{a_{actual}}\ (inches) \end{bmatrix} = F \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \\ \theta \\ \phi \\ \delta_{e_{actual}} \\ \delta_{c_{actual}} \\ \delta_{a_{actual}} \end{bmatrix} + G \begin{bmatrix} \delta_{e_{desired}}\ (inches\ of\ longitudinal\ stick) \\ \delta_{c_{desired}}\ (inches\ of\ collective\ lever) \\ \delta_{a_{desired}}\ (inches\ of\ lateral\ stick) \end{bmatrix}$$

$$y_m(measurements) = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ p \\ q \\ r \\ \theta \\ \phi \end{bmatrix} \tag{4.1}$$

Figure 4.2: **CH-47 Hover Model.** This is the conventional 8^{th} order model described in Appendix G.

4.2. Linear Model and Basic Control Structure

The 8^{th} order basic airframe model is described in Appendix G. This model was augmented with three actuator states as shown in Equation 3.2. These actuator states allow the the designer to penalize control rate, a necessary step to avoid nuisance disengages of the research control system during flight. Figure 4.2 shows this model as it was used for the control law synthesis. One item to note is that there is no yaw control in the model. The yaw SAS was approximated by adding -1 to the $N_{\delta r}$ element of the "F" matrix of Figure 4.2 and Appendix G.

Since the longitudinal CAS showed the necessity of integral-error control, the hover control structure had to accommodate this capability. Figure 4.3 shows the hover controller. Unlike the longitudinal CAS, integral control decoupling is not done in the inner loop. Instead, *PID* (Proportional Integral Derivative) outer loops are closed separately to $\dot{x}_{command}$, $\dot{y}_{command}$, and $\dot{z}_{command}$, which act as controls for these outer loops. The velocity command system is the inner loop. Setting up the control structure in this way had several advantages:

- The inner loop and outer loop designs, both fairly complicated, could be separated.

- By using the desired outputs as controls, the magnitude of the outer loop gains became physically meaningful. This proved to be important later when these gains were adjusted during flight to achieve good performance.

- Keeping the inner loop separate made the mode switching between pilot velocity command and *PID* control easier.

Before the full-order design began, the system was scaled in equivalent units.

4.3. Model Scaling

The hover model was scaled into the same units as used in the longitudinal CAS design. *Ft/sec* remained *ft/sec*; *radians* and *radian/sec* became .01 *radians* and .01 *radians/sec*; and *inches* of control became .1 *inches* of control. Figures 4.4 and 4.5 show the model before and after scaling. The ROPTSYS computer program did this scaling.

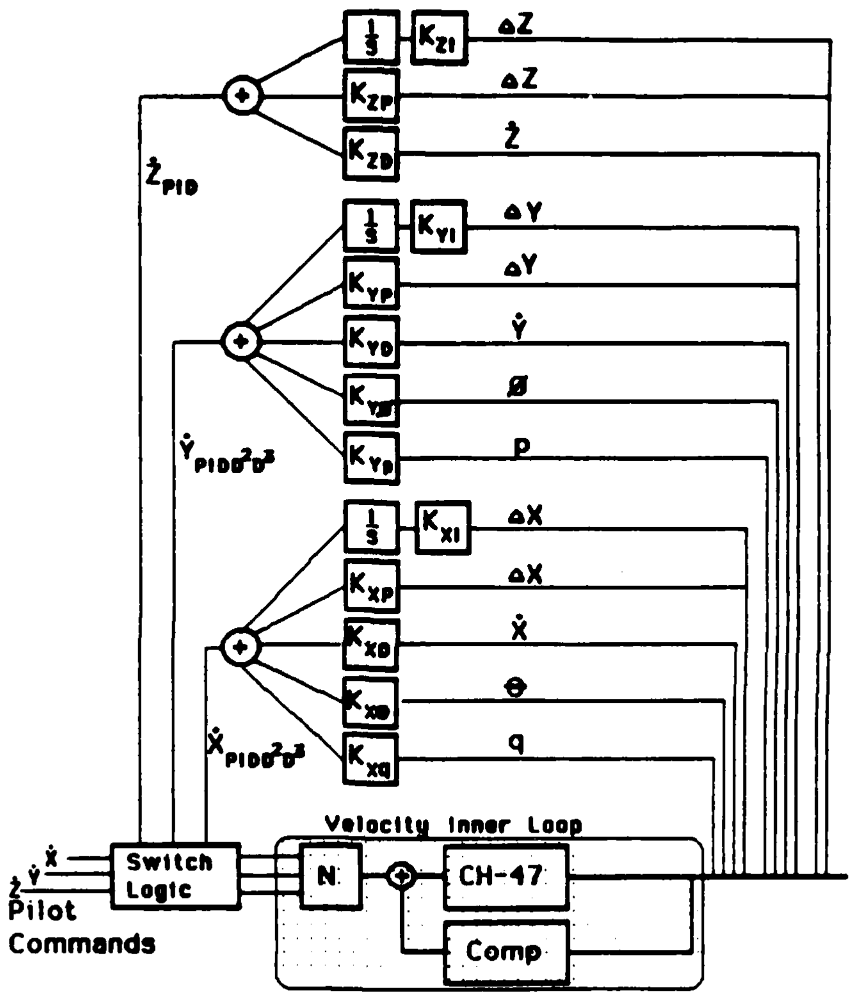


Figure 4.3: **Hover Control System.** The control system is divided into a distinct inner loop (velocity command) and outer loops which provide position hold using *PID* control.

State Equations

$$\dot{x} = F\,x + G\,u$$

$$F = \begin{bmatrix} -0.021 & -0.00085 & 0.0326 & 0.0205 & 2.585 & -0.106 & -31.986 & 0.0 & 0.114 & 0.939 & 0.0 \\ -0.00019 & -0.137 & 0.00265 & -1.494 & 0.00414 & -0.165 & 0.0292 & 31.99 & 0.0118 & 0.0635 & 1.159 \\ 0.0248 & 0.00374 & -0.296 & 0.0419 & 0.435 & 0.362 & -3.71 & 0.0 & 0.303 & -8.062 & .00002 \\ -0.00013 & -0.00652 & 0.00058 & -0.716 & 0.0382 & -0.0708 & 0.0 & 0.0 & -0.00596 & -0.0142 & .432 \\ 0.00925 & 0.00017 & 0.00234 & 0.0427 & -1.23 & -0.00433 & 0.0 & 0.0 & 0.329 & 0.019 & 0.0 \\ 0.00039 & -0.00112 & 0.00027 & -0.0544 & -0.158 & -1.0 & 0.0 & 0.0 & 0.0461 & -0.00037 & .0425 \\ 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.00788 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 1.0 & 0.00091 & 0.116 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & -40.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & -40.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & -40.0 \end{bmatrix}$$

$$G = \begin{bmatrix} 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 40.0 & 0.0 & 0.0 \\ 0.0 & 40.0 & 0.0 \\ 0.0 & 0.0 & 40.0 \end{bmatrix}$$

$$Q = \begin{bmatrix} 24.6 & 0 & 0 \\ 0 & 24.6 & 0 \\ 0 & 0 & 9.98 \end{bmatrix}$$

$$R = \begin{bmatrix} 2.6\times10^{-2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2.6\times10^{-2} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2.6\times10^{-2} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.293\times10^{-4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3.232\times10^{-5} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 8.079\times10^{-6} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 3.232\times10^{-7} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3.232\times10^{-7} \end{bmatrix}$$

Figure 4.4: **CH-47 Hover Linear Model.** The last 3 states are 40 radian actuator models.

State Equations

$$\dot{x}_{scaled} = F_{scaled}x_{scaled} + G_{scaled}u_{scaled}$$

$$F_{scaled} = \begin{bmatrix} -0.021 & -0.00085 & 0.0326 & 0.000205 & .02585 & -0.00106 & -.31986 & 0.0 & 0.0114 & 0.0939 & 0.0 \\ -0.00019 & -0.137 & 0.00265 & -.1494 & 0.0000414 & -0.00165 & 0.000292 & .3199 & 0.00118 & 0.00635 & .1159 \\ 0.0248 & 0.00374 & -0.296 & 0.000419 & 0.00435 & 0.00362 & -.0371 & 0.0 & 0.0303 & -.8062 & .000002 \\ -0.013 & -0.652 & 0.058 & -0.716 & 0.0382 & -0.0708 & 0.0 & 0.0 & -0.0596 & -0.142 & 4.32 \\ 0.925 & 0.017 & 0.234 & 0.0427 & -1.23 & -0.00433 & 0.0 & 0.0 & 3.29 & 0.19 & 0.0 \\ 0.039 & -0.112 & 0.027 & -0.0544 & -0.158 & -1.0 & 0.0 & 0.0 & 0.461 & -0.0037 & .425 \\ 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.00788 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 1.0 & 0.00091 & 0.116 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & -40.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & -40.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & -40.0 \end{bmatrix}$$

$$G_{scaled} = \begin{bmatrix} 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 40.0 & 0.0 & 0.0 \\ 0.0 & 40.0 & 0.0 \\ 0.0 & 0.0 & 40.0 \end{bmatrix}$$

$$Q_{scaled} = \begin{bmatrix} 24.6 & 0 & 0 \\ 0 & 24.6 & 0 \\ 0 & 0 & 9.98 \end{bmatrix}$$

$$R_{scaled} = \begin{bmatrix} 2.6\times10^{-2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2.6\times10^{-2} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2.6\times10^{-2} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.293 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3.232\times10^{-1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 8.079\times10^{-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 3.232\times10^{-3} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3.232\times10^{-3} \end{bmatrix}$$

Figure 4.5: **CH-47 Scaled Hover Linear Model.** After scaling, the weak coupling terms in the F matrix become very obvious.

4.4. LQG Design and Compensator Order Reduction

The scaled 11^{th} order model shown in Figure 4.5 was used by the ROPTSYS program to calculate the full-order compensator. At this point, an important simplification should be emphasized. The system was to control $\dot{x}$, $\dot{y}$, and $\dot{z}$ which are inertial velocities. The model as used included u, v, and w which are body axis airmass velocities. The implicit assumption, needed to facilitate the design, was that the two sets of velocities were equal:

$$\begin{aligned} \dot{x} &= u \\ \dot{y} &= v \\ \dot{z} &= w \end{aligned} \tag{4.2}$$

This assumption is reasonable only if θ and ϕ remain small, which they must for safe hover in a large helicopter such as the CH-47. The outputs, y_o, weighted in the performance index:

$$P.I. = \int_0^\infty (y_o^T A y_o + u^T B u)\, dt \tag{4.3}$$

were the three velocities (u, v, and w) and the three control rates. Since the system had been scaled, the weighting matrices, A and B, were just 6×6 and 3×3 identity matrices. Using these assumptions and criterion, the resulting full-order compensator is shown in Figure 4.6.

Based on these data, especially the modal cost M_2, the 11^{th} order compensator was reduced to 5^{th} order. This represents a significant reduction of complexity in the resulting compensator. The 11^{th} order design had 121 independent gains while the 5^{th} order compensator had only 55. After the order reduction, the compensator

$$F_{min} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -80.615 & -15.033 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -55.126 & -11.587 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -5.78 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -2.74 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -2.33 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.48 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.01 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -.203 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -.104 \end{bmatrix}$$

$$K_{min}(unscaled) = \begin{bmatrix} .0032 & -.00096 & .0024 & -.0112 & -.63 & .023 & -32.4 & .097 \\ .0294 & .0183 & -.00274 & .21 & -17.3 & -2.76 & 59.8 & 4.3 \\ -.002 & -.06 & .0127 & -.442 & .166 & -.99 & .587 & -61.4 \\ .0072 & -.32 & -.023 & -3.6 & -1.64 & -10.62 & -17.3 & 170.1 \\ -.077 & .0115 & .616 & -.074 & -.079 & -.56 & -1.45 & -6.74 \\ -.028 & .56 & .17 & 5.56 & 4.24 & 16.2 & 1.34 & -100.8 \\ -.054 & -.0134 & .136 & -.233 & 25.4 & 3.68 & 3.78 & .33 \\ .087 & -.0084 & -.69 & .146 & .00055 & .81 & .50 & .053 \\ -.0003 & -.02 & .0033 & -.18 & .83 & -.34 & -.48 & -2.19 \\ .000054 & -.034 & -.0022 & -.21 & -.023 & -.56 & .018 & 5.16 \\ -.014 & -.00012 & -.00117 & -.00145 & .125 & .0133 & 4.37 & -.028 \end{bmatrix}$$

$$C_{min}(unscaled) = \begin{bmatrix} 0.0 & -.1 & -.0128 & -.00328 & .0226 & -.00356 & -.1 & .00119 & -.024 & .00067 & -.1 \\ .0011 & -.0036 & .0089 & .00294 & -.1 & .0044 & -.0041 & -.1 & -.012 & .012 & -.0108 \\ .065 & .0056 & 0.0 & -.1 & .0145 & -.1 & .0166 & -.0058 & -.1 & -.1 & -.00247 \end{bmatrix}$$

System Eigenvalues										
	Open Loop(F)		Regulator(F-GC)		Estimator(F-KH)		Compensator(F-GC-KH)		Compensator Measures	
Mode	Real	Imag	Real	Imag	Real	Imag	Real	Imag	M_1	M_2
1	-1.41	0	-.406	.085	-7.63	4.85	-7.52	4.91	4.47	.59
2	-1.07	0	-.406	-.085	-7.63	-4.85	-7.52	-4.91	-	-
3	-.902	0	-.382	.072	-6.04	4.6	-5.79	4.64	5.58	.96
4	-.297	0	-.382	-.072	-6.04	-4.6	-5.79	4.64	-	-
5	.079	.46	-.839	.4	-5.88	0	-5.78	0	.65	.11
6	.079	-.46	-.839	-.4	-.975	0	-2.73	0	1.18	.43
7	.062	.46	-1.2	.33	-.11	0	-2.32	0	.3	.13
8	.062	-.46	-1.2	-.33	-.12	0	-1.48	0	.69	.47
9	-40.0	0	-1.3	.11	-40.0	0	-1.01	0	.032	.032
10	-40.0	0	-1.3	-.11	-40.0	0	-.20	0	.063	.31
11	-40.0	0	-.98	0	-40.0	0	-.10	0	.046	.45

Figure 4.6: **Hover Full Order Compensator Design Results.** The open loop has two unstable modes which are divergent pitch and roll oscillations. Figure 4.7 is the reduced and reoptimized compensator based on this full order design. Order reduction was based on the M_2 terms shown here.

was optimized using the RSANDY program. Figure 4.7 shows the optimal reduced order compensator including the closed loop roots. This optimization step was difficult since the initial guess (the original 11^{th} order compensator reduced to 5^{th}) was quite unstable. This caused numerical overflows on the VAX computer used to run the RSANDY program. Convergence to a stable 5^{th} order compensator was finally achieved after numerous iterations of the outputs and the output weightings of Equation 4.3. Figure 4.7 shows these outputs, y_o, and the elements of the diagonal A and B matrices. This figure also shows another aspect of the difficulty of this optimization. The entire C matrix was allowed to vary which meant that there were 60 gains being adjusted by the RSANDY program, 5 more than the 55 independent gains of a minimal realizaton.

The simulation step responses are shown in Figures 4.9, 4.10, and 4.11. All three velocity responses look good but the pitch angle damping has several overshoots. A modal analysis later confirmed this by showing the mode at $-.50 \pm j2.03$ of Figure 4.7 to be strongest in θ. With the velocity inner loop regulator designed, the feedforward matrix was calculated for direct command of $\dot{x}$, $\dot{y}$, and $\dot{z}$. The PID outer loop gains could now be designed.

4.5. Outer Loop Design

As discussed in Section 4.2, the velocity command inner loop and the PID outer loop were separate. With the inner loop velocity controller set, the outer loop design began. This approach (inner loop first then outer loop) is common in the development of operational aircraft autopilots except that the inner loops are normally designed classically using incremental loop closure. Initially, these PID

$$F_{min} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -17.93 & -4.90 & 0 & 0 & 0 \\ 0 & 0 & -1.98 & 0 & 0 \\ 0 & 0 & 0 & -.815 & 0 \\ 0 & 0 & 0 & 0 & -6.31 \end{bmatrix}$$

$$K_{min} = \begin{bmatrix} -.035 & -.050 & -.040 & -.56 & 1.96 & .216 & 3.22 & -74.7 \\ -.037 & -.74 & .071 & -.28 & -1.6 & -7.63 & -19.7 & 169.0 \\ -.58 & .140 & -.23 & .19 & 28.9 & 16.05 & 1.35 & -100.3 \\ -.45 & .0079 & 1.45 & .068 & 6.5 & 1.20 & 2.64 & 7.16 \\ .018 & -.0058 & -.003 & -.029 & -.36 & -.66 & 13.7 & 8.32 \end{bmatrix}$$

$$C_{min} = \begin{bmatrix} -.092 & .0080 & -.13 & -.020 & -5.14 \\ .026 & -.0045 & -.029 & .022 & -.52 \\ .44 & -.021 & -.062 & .00078 & -.42 \end{bmatrix}$$

$$N = \begin{bmatrix} -.071 & -.0061 & .013 \\ .0070 & .0021 & -.079 \\ -.012 & .059 & -.0034 \end{bmatrix}$$

Closed Loop Eigenvalues				
Real Part	Imag Part	Damping	Freq(rad/sec)	Freq(Hz)
-39.99	.0085	1.0	39.99	6.37
-39.99	-.0085	1.0	39.99	6.37
-40.01	0.0	1.0	40.01	6.37
-7.14	0.0	1.0	7.14	1.14
-2.37	2.77	.65	3.65	.58
-2.37	-2.77	.65	3.65	.58
-.50	2.03	.24	2.09	.33
-.50	-2.03	.24	2.09	.33
-.54	1.59	.32	1.68	.27
-.54	-1.59	.32	1.68	.27
-.55	.50	.74	.74	.12
-.55	-.50	.74	.74	.12
-.61	.43	.82	.75	.12
-.61	-.43	.82	.75	.12
-.90	0.0	1.0	.90	.14
-.22	0.0	1.0	.22	.0035

Performance Index Data		
Outputs or Controls	Units	Weighting
u	ft/sec	5×10^3
v	ft/sec	5×10^3
w	ft/sec	5×10^2
p	rad/sec	1×10^5
q	rad/sec	1×10^5
r	rad/sec	1×10^5
$\dot{\delta}_e$	$inches/sec$	1×10^5
$\dot{\delta}_c$	$inches/sec$	1×10^5
$\dot{\delta}_a$	$inches/sec$	1×10^5
$\dot{u}$	ft/sec^2	5×10^3
$\dot{v}$	ft/sec^2	5×10^3
$\dot{w}$	ft/sec^2	5×10^3
δ_e	$inches$	1×10^2
δ_c	$inches$	1×10^2
δ_a	$inches$	1×10^3

Figure 4.7: **Reduced Order Hover Compensator.** The poorly damped modes ($s = -.5 \pm j2.03$) dominate the pitch angle response as Figure 4.9 shows.

outer loop gains were set using the RSANDY program. This approach did not work well as the convergence was very slow. The alternative was to set the gains intuitively. This approach was actually quite reasonable if one recalls the control structure of Figure 4.3. The gains were set by determining how much velocity would be reasonable to use to correct a given position error. For instance, if the aircraft were 10 feet from the desired hover point and a pilot would be willing to use 5 ft/sec of $\dot{y}$ then $K_{\dot{y}\delta_y}$ would be .5 $\frac{ft/sec}{ft\ error}$. This approach worked well for the y and z axes but failed for the x axis. For this axis, a conventional transfer function analysis was used to set the 5 outer loop gains which were then adjusted in simulation.

4.5.1. Transfer Function Analysis for X Axis Outer Loop

The first step in the process required a transfer function from $u_{command}$ to u_{actual} for the helicopter with velocity inner controller. This came from use of Bernard's code for calculating the matrix of transfer functions for any MIMO linear dynamic system.[7] These transfer functions were 11^{th} order so to make the process tractable, the NAVFIT program at NASA Ames simplified them to 3^{rd} order. The following transfer function resulted:

$$\frac{u_{actual}}{u_{command}} = \frac{.94}{(s+.24)\ \left[(s+.5)^2 + 1.87^2\right]} \tag{4.4}$$

To justify the use of θ and q as second and third derivatives of x, consider the longitudinal equation of motion from Etkin: [14]

$$F_x - mg\ sin\theta = m\left[\dot{u} + (q_B^E + q)\ w - (r_B^E + r)\ v\right] \tag{4.5}$$

where if the following assumptions are made:

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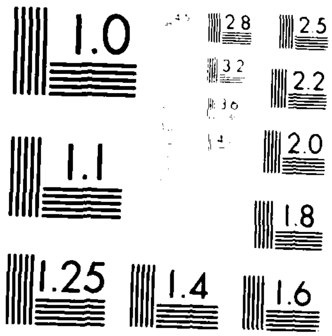
1.0
2.8
2.5
3.2
2.2
2.0
1.1
1.8
1.25
1.4
1.6

$q_B^E \approx 0$ Earth rotation negligible

$r_B^E \approx 0$ Earth rotation negligible

$qw \approx 0$ Second order effect

$rv \approx 0$ Second order effect

$sin\ \theta \approx \theta$ Small angle assumption

$F_x \approx 0$ Reasonable for a helicopter in hover

$\dot{u} \approx \ddot{x}$ Small angle assumption(θ)

then these simplications result:

$$
\begin{aligned}
\ddot{x} &\approx -g\theta \\
\ddot{u} &\approx -g\dot{\theta} \approx -gq
\end{aligned}
\tag{4.6}
$$

The actual gain setting is done by including the following for the $PIDD^2D^3$ controller in Figure 4.8.

$$
PIDD^2D^3 = K_P x + K_I \frac{x}{s} + K_D xs + K_{D^2} xs^2 + K_{D^3} xs^3 \tag{4.7}
$$

where

$$
\begin{aligned}
K_P &= K_{\dot{x}\delta_x} \\
K_I &= K_{\dot{x}\int x} \\
K_D &= K_{\dot{x}\dot{x}} \\
K_{D^2} &= K_{\dot{x}\theta} \\
K_{D^3} &= K_{\dot{x}q}
\end{aligned}
\tag{4.8}
$$

Rewriting Equation 4.7 as:

$$
PIDD^2D^3 = K_{D^3}\left(s^4 + \frac{K_{D^2}}{K_{D^3}}s^3 + \frac{K_D}{K_{D^3}}s^2 + \frac{K_P}{K_{D^3}}s + \frac{K_I}{K_{D^3}}\right)\frac{1}{s} \tag{4.9}
$$

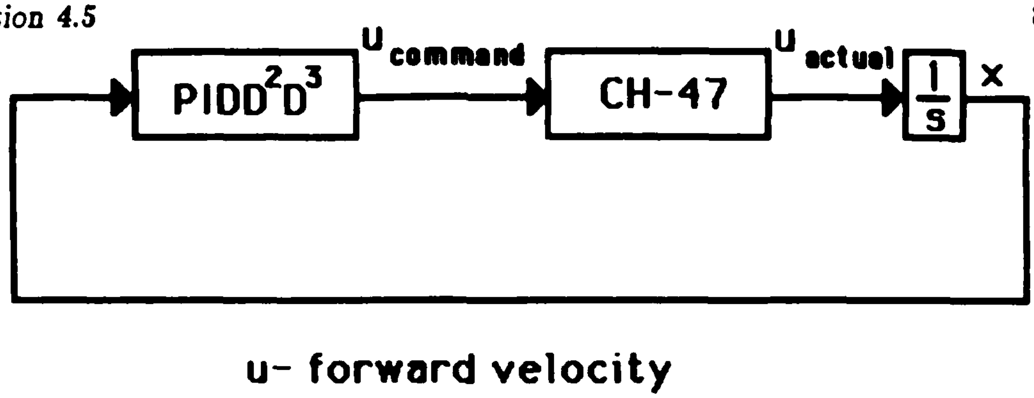

Figure 4.8: **Transfer Function Analysis.** The $PIDD^2D^3$ compensation was calculated to cancel the two lightly damped poles of Equation 4.4 and move the two poles at the origin to the left.

then the four numerator zeros of the $PIDD^2D^3$ controller were selected to cancel the lightly damped poles of Equation 4.4 and to draw the two poles at the origin to the left. The gain K_{D^3} was selected for good speed of response. Following are the gains calculated:

$$
\begin{aligned}
K_P = K_{XP} &= -1.085 \frac{fps}{(ft\ error)} \\
K_I = K_{XI} &= -.131 \frac{fps}{(ft\ sec\ error)} \\
K_D = K_{XD} &= -2.94 \frac{fps}{fps} \\
K_{D^2} = K_{X\theta} &= .551 \frac{fps}{deg} \\
K_{D^3} = K_{XQ} &= .393 \frac{fps}{(deg/sec)}
\end{aligned}
\tag{4.10}
$$

4.5.2. Outer Loop Simulation

With these gains as a starting point, the time responses were improved using the onboard simulation in the flight computer. Although this approach ("tweeking" the gains) may seem somewhat unscientific, it was appropriate for several reasons:

- Extensive use of the onboard simulation had the added advantage of helping discover many errors in the flight software before actual flight.
- Pilot comments concerning the performance and response characteristics could be better incorporated into the design.
- Working directly with the fixed point digital computer avoided the additional time and effort required to digitize and scale the continuous design.
- The transient-free switching between the velocity command and position hold modes could be developed. This is discussed in the next section.

The *PID* gains coming from this simulation are shown below:

$$
\begin{array}{ccc}
K_{XP} = -.75 \frac{fps}{(ft\ error)} & K_{YP} = -1.0 \frac{fps}{(ft\ error)} & K_{ZP} = -2.0 \frac{fps}{(ft\ error)} \\
K_{XI} = -3.8 \times 10^{-4} \frac{fps}{(ft\ sec\ error)} & K_{YI} = -7.6 \times 10^{-4} \frac{fps}{(ft\ sec\ error)} & K_{ZI} = -1.9 \times 10^{-3} \frac{fps}{(ft\ sec\ error)} \\
K_{XD} = -3.0 \frac{fps}{fps} & K_{YD} = -.18 \frac{fps}{fps} & K_{ZD} = -4.5 \frac{fps}{fps} \\
K_{X\theta} = .2 \frac{fps}{deg} & K_{Y\phi} = 0.0 \frac{fps}{deg} & \\
K_{XQ} = 2.0 \frac{fps}{(deg/sec)} & K_{YP} = 0.0 \frac{fps}{(deg/sec)} &
\end{array}
\tag{4.11}
$$

Time responses from simulation are shown in Figures 4.9 to 4.13. These figures show the results of both the inner and outer loop designs.

4.6. Flight Test Implementation

The flight implementation of the hover control system was based on the software and flight procedures developed for the longitudinal CAS flight test. As before, the sensor data were filtered by the TR-48 analog computer before being digitized and sent to the Sperry digital computer. There were two areas where the hover controller was quite different from the longitudinal system and required new flight capabilities. The first was the inertial position and velocity data and the second was the transient-free switching required to make the transition from

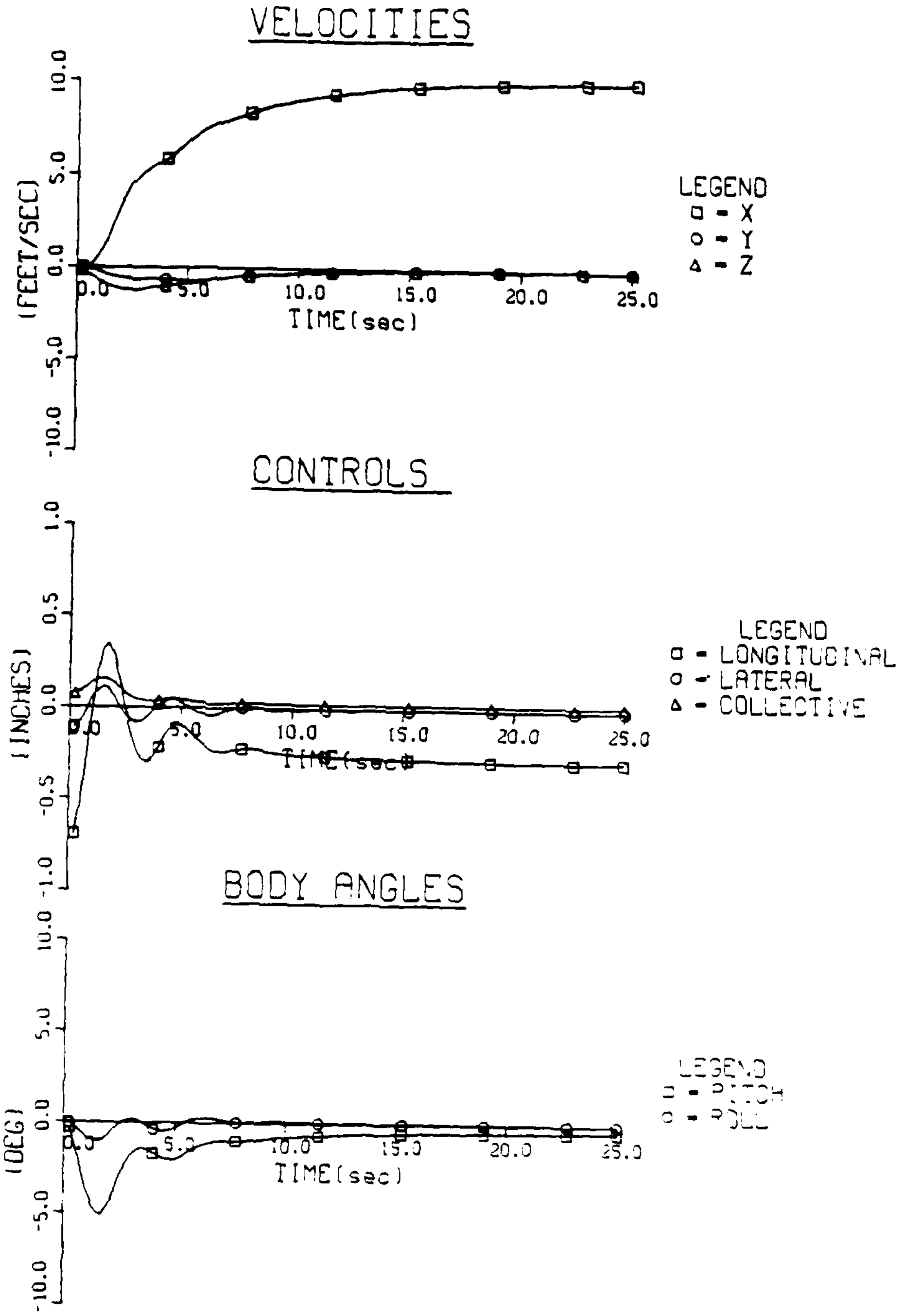

Figure 4.9: **Hover Forward Velocity Step Command in Simulation.** The poor damping is evident in the pitch angle response.

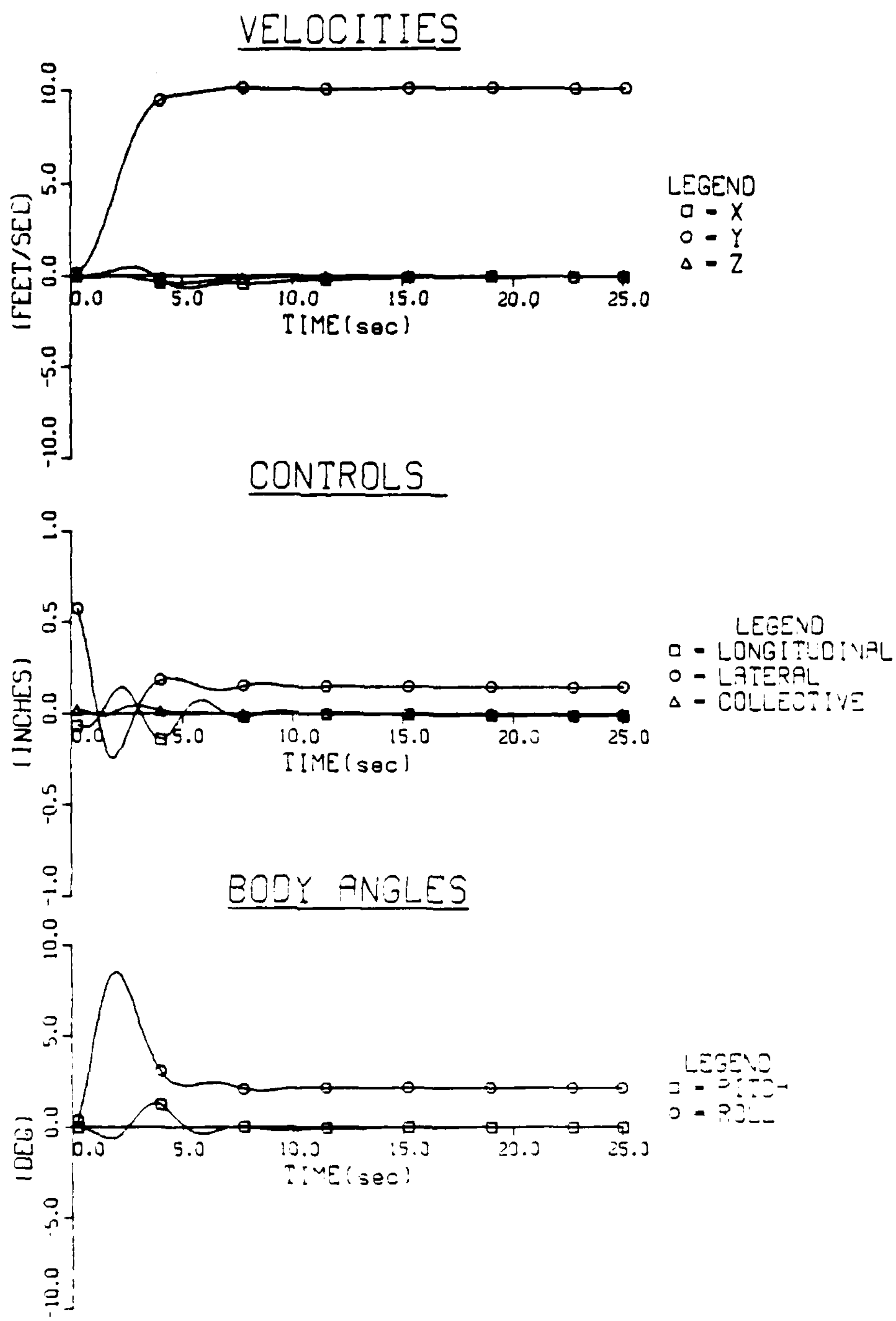

Figure 4.10: **Hover Side Velocity Step Command in Simulation.** Side velocity performance is adequate but the poorly damped pitch mode is also excited.

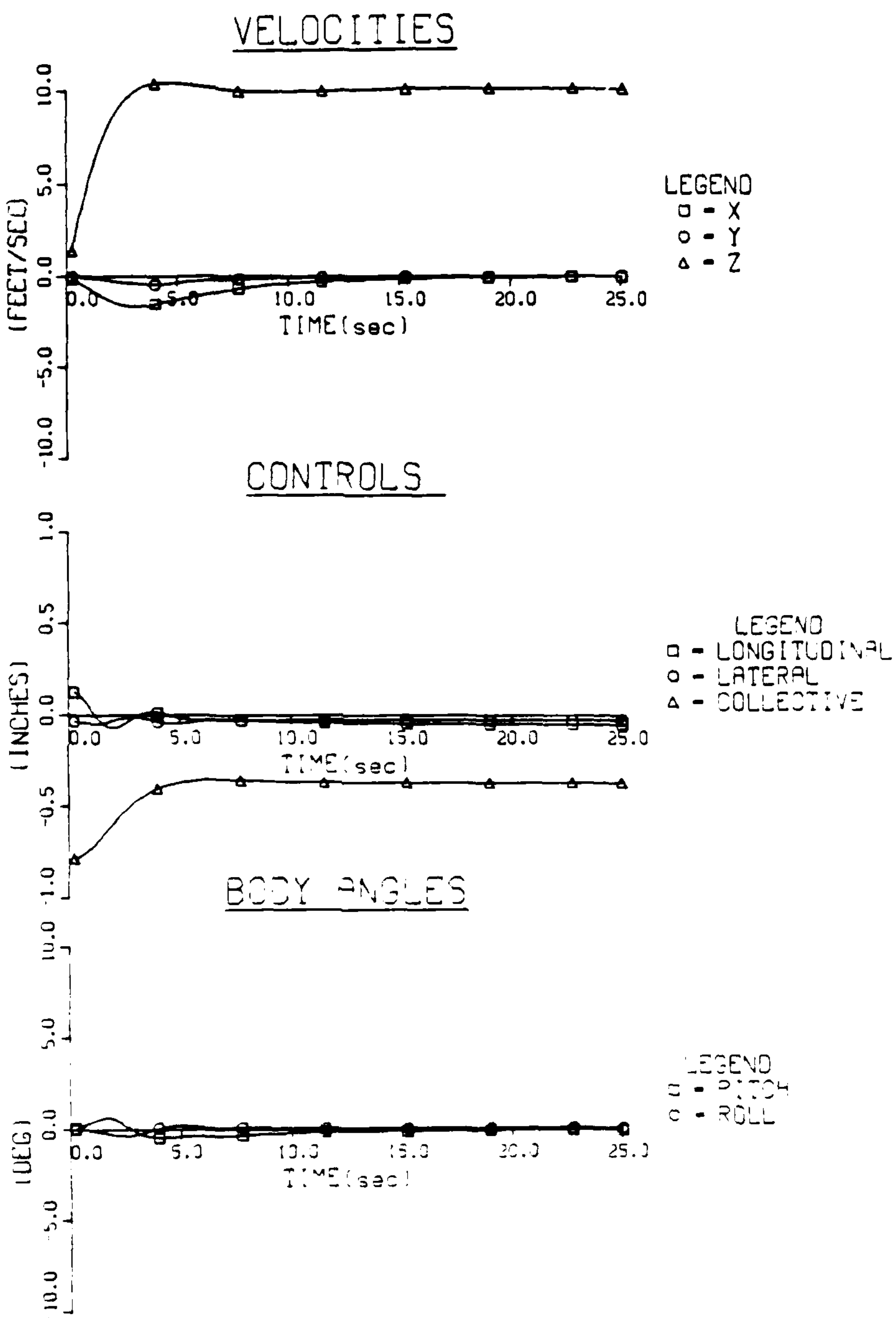

Figure 4.11: **Hover Vertical Velocity Step Command in Simulation.** The heave response is adequate and does not excite the pitch modes as strongly as the lateral velocity response of Figure 4.10

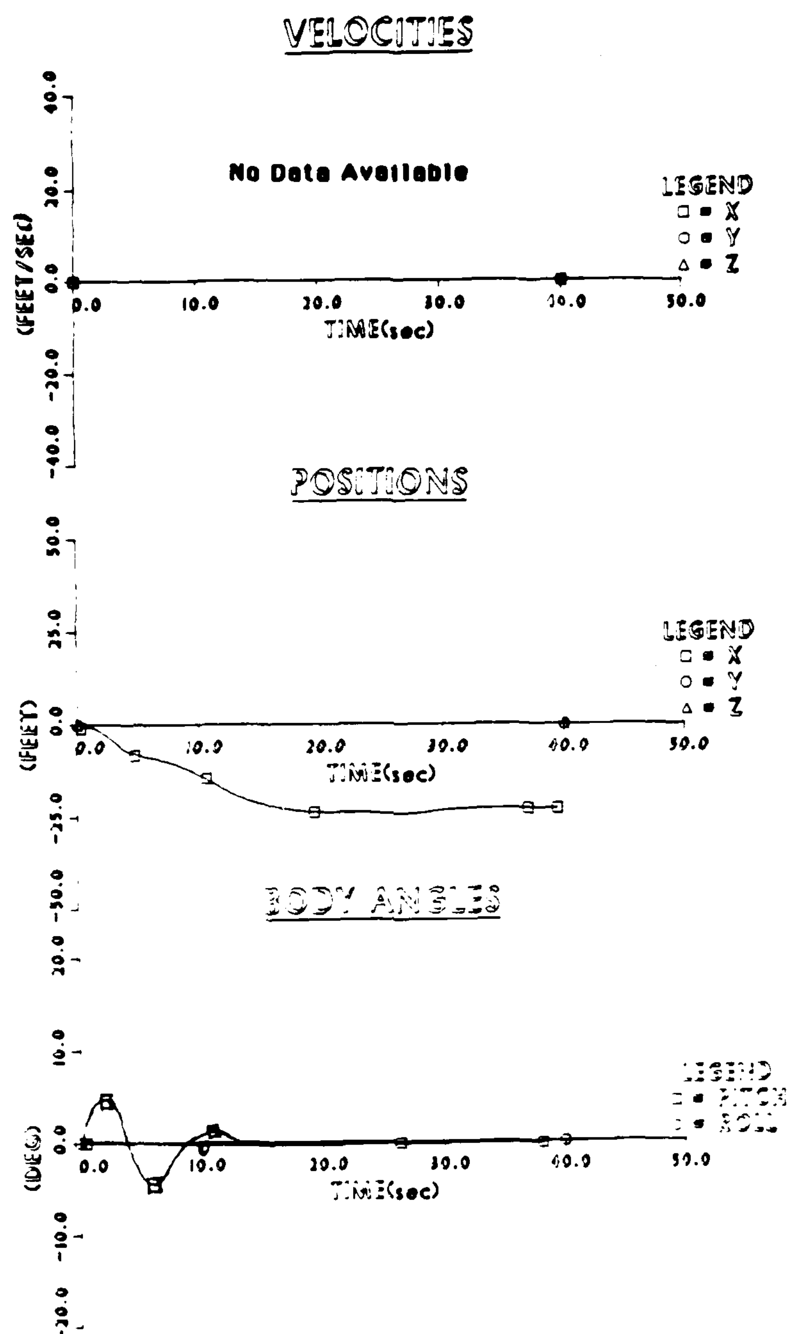

Figure 4.12: **Hover Forward Position Step Command in Simulation.** This response came from the onboard simulation and shows the the outer loop performance using the flight software.

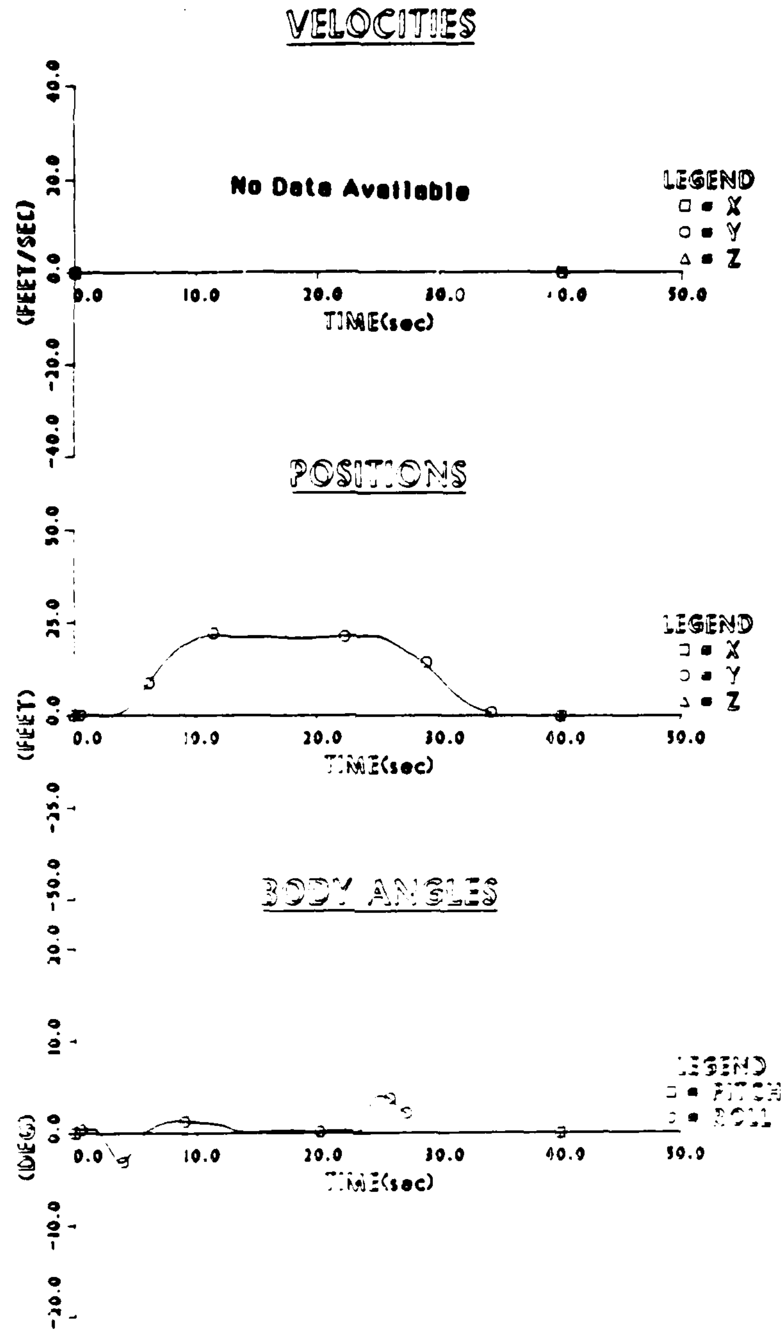

Figure 4.13: **Hover Lateral Position Step Command in Simulation.** Again, the flight software shows good outer loop performance.

pilot velocity command to automatic position hold.

4.6.1. Inertial Velocity and Position Data

Although the hover controller uses the inertial data (x, $\dot{x}$, y, $\dot{y}$, z, and $\dot{z}$) as it does the other measurements, a considerable effort was required to get these data.[1] Since the INS positions drifted so quickly and there were no inertial velocities available from the INS, an alternative source for these data was needed. The ground based tracker at Crows Landing was able to provide these data using a ground-to-air telemetry link that was specially developed for this program. The steps required to make these ground based position measurements usable by the control laws are described below:

- The laser or radar tracker measured position of the aircraft in a runway based polar coordinate system.
- These measurements of azimuth angle (Az), elevation angle (El), and range (r) were telemetered from the ground tracking station to the helicopter.
- These data, as well as tracker status information, were decoded and scaled into units common to the rest of the flight software.
- The Az, El, and range data were converted to a runway based rectangular coordinate system with a new origin located over the runway.
- These data were used with aircraft accelerometer data (rotated into the runway coordinate frame) in a second order complementary filter to estimate x, $\dot{x}$, y, $\dot{y}$, z, and $\dot{z}$. Figure 4.14 shows the block diagram of this complementary filter.

[1] This work was done primarily by Bill Hindson of NASA Ames

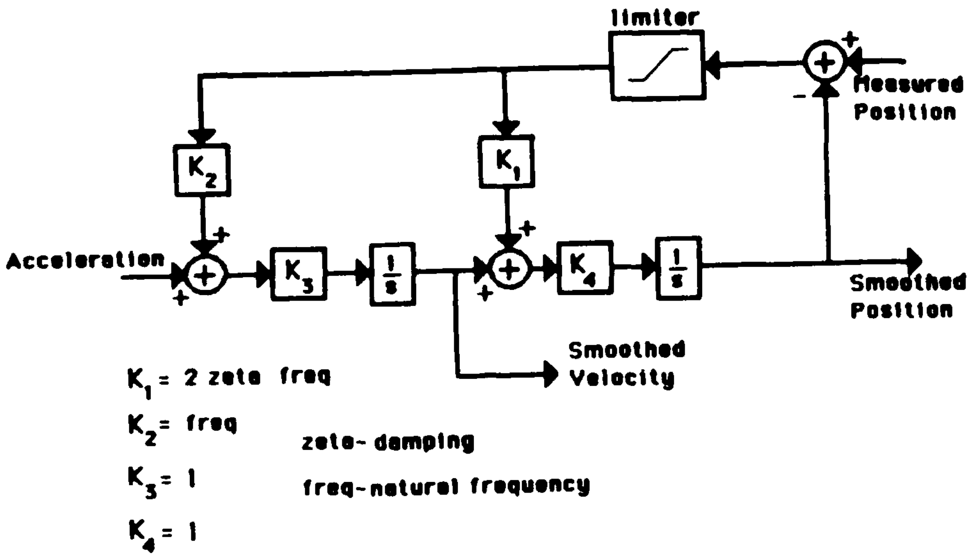

Figure 4.14: **Second Order Complementary Filter.** The filter uses acceleration and position to determine the smoothed position and velocity needed by the control law.

- These smoothed values of x, $\dot{x}$, y, $\dot{y}$, z, and $\dot{z}$ were then rotated through the aircraft heading angle to the heading-oriented inertial frame required by the control system.

- Based on the tracker status information coming from the ground and based on data reasonableness checks, an algorithm kept the inertial data consistent during short term tracker breaklocks. For longer term breaklocks, the experimental control system was disengaged to avoid the large control motions caused by trying to follow bad data. Initially, the laser tacker was used since it provided more precise range information (1 - 2 foot acurracy). Unfortunately, the laser had frequent and unpredictable breaklocks which made the data essentially unusable in the control loop. Because of this inability to hold lock, the radar tracker was used for the flight test although its accuracy was only 5 - 10 feet.

4.6.2. Transient-Free Switching

Since this control system had both manual and automatic capability in the three body axes, a way was needed to transition smoothly among these different control modes. This task was complicated by the following characteristics of the control system:

- The pilot had the freedom to change heading at any time.
- The x coordinate of the desired hover point had to follow the x coordinate of the actual position when the pilot was commanding $\dot{x}$ velocity. At the same time, the helicopter had to hold both y and z position in the heading inertial frame.
- Same as above in the y and z directions.
- A detent on the pilot controls was needed. If the pilot's control was less than the detent value, that axis was in position hold mode; else, the pilot was commanding a velocity.

Figures 4.15, 4.16, and 4.17 show the switching logic for the three axes. The assembly code, shown in Appendix I, implements this logic.

4.7. Flight Test Results

The hover flight testing was done at the Crows Landing test facility. The testing was limited to this location since the system required the use of the radar tracker at Crows. Unlike the longitudinal CAS control system, the hover controller was very difficult to debug and make operational. The flight testing was divided into three phases to accommodate these difficulties. The first phase developed the

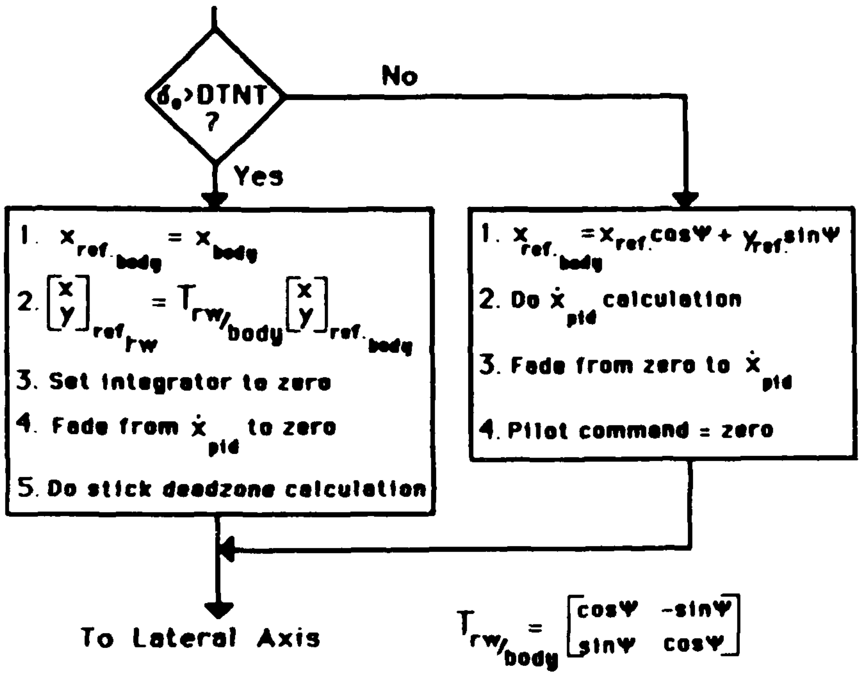

Figure 4.15: **X Axis Transient-Free Switching Logic.** The transformation from body to runway uses heading angle from the INS. The best deadzone or detent value was about .25 inches.

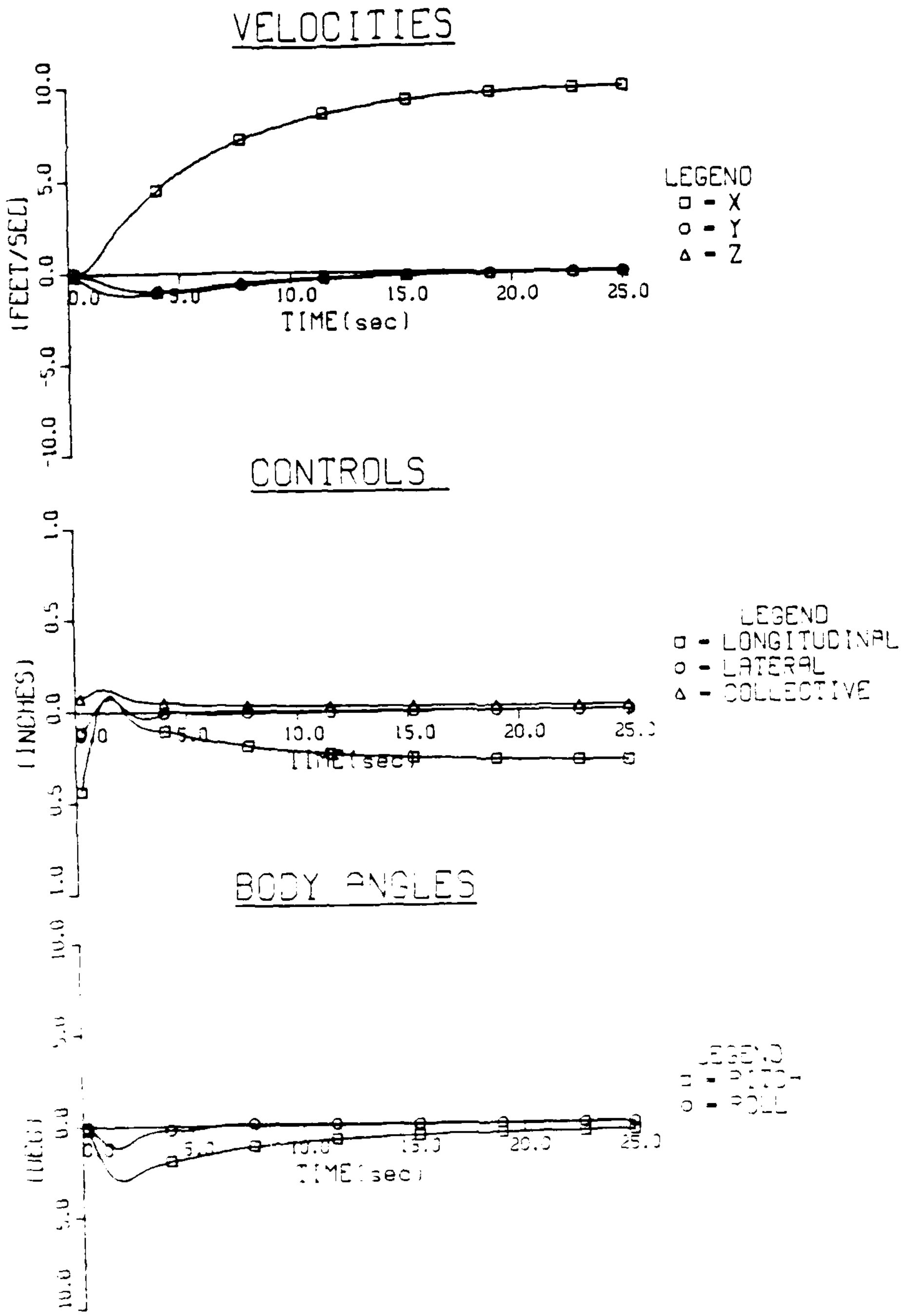

Figure 4.25: **Hover Forward Velocity Step Command in Simulation.** The pitch angle response is improved from the original design of Figure 4.9.

quicken the lateral response while in hold mode hence reducing any coupling due to action in the longitudinal axis. With these two changes to reduce the coupling, and the redesigned inner loop velocity system, the final flight testing began.

4.7.4. Final Closed Loop Flight Test in Hover

With the redesigned controller, the velocity performance was significantly improved. Figure 4.28 shows the response to a command in $\dot{x}$. The poor pitch damping has been eliminated and the coupling to bank angle is gone. The y axis velocity performance remains good as shown in Figure 4.29. The z velocity response remained almost identical to the original design shown in Figure 4.21. The position hold performance is also evident in these figures when the velocity commands are removed and the system reenters the postion hold mode. Figures 4.30 and 4.31 confirm the good hold performance in the y and z axes but the poor damping in position hold in x. The x axis position hold dynamics are dominated by a slow, poorly damped mode ($\varsigma \approx .4$ and $\omega \approx 50\ sec$). A significant amount of flight time was spent adjusting gains in the PID outer loops to improve this x hold performance. Shown below are the final set of outer loop gains which resulted from these efforts. Later flight tests used the integrator in the x axis $PIDD^2D^3$ controller only when the error was less than 40 feet. This improved the damping slightly to about .5.

$$
\begin{array}{ccc}
K_{XP} = -.20\ \frac{fps}{(ft\ error)} & K_{YP} = -1.0\ \frac{fps}{(ft\ error)} & K_{ZP} = -2.0\ \frac{fps}{(ft\ error)} \\
K_{XI} = -7.6\times10^{-4}\ \frac{fps}{(ft\ sec\ error)} & K_{YI} = -7.6\times10^{-3}\ \frac{fps}{(ft\ sec\ error)} & K_{ZI} = -1.9\times10^{-3}\ \frac{fps}{(ft\ sec\ error)} \\
K_{XD} = -2.0\ \frac{fps}{fps} & K_{YD} = -1.0\ \frac{fps}{fps} & K_{ZD} = -4.5\ \frac{fps}{fps} \\
K_{X\theta} = 1.0\ \frac{fps}{deg} & K_{Y\phi} = -.5\ \frac{fps}{deg} & \\
K_{XQ} = 3.0\ \frac{fps}{(deg/sec)} & K_{YP} = -.5\ \frac{fps}{(deg/sec)} &
\end{array}
\tag{4.12}
$$

$$F_{min} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -17.93 & -4.90 & 0 & 0 & 0 \\ 0 & 0 & -1.98 & 0 & 0 \\ 0 & 0 & 0 & -.815 & 0 \\ 0 & 0 & 0 & 0 & -6.31 \end{bmatrix}$$

$$K_{min} = \begin{bmatrix} -.035 & -.050 & -.040 & -.56 & 2.18 & .216 & 3.23 & -74.7 \\ -.037 & -.74 & .071 & -.28 & -1.57 & -7.63 & -19.7 & 169.0 \\ -.58 & .140 & -.23 & .19 & 29.2 & 16.05 & 1.30 & -100.3 \\ -.45 & .0079 & 1.45 & .068 & 6.52 & 1.20 & 2.57 & 7.16 \\ .018 & -.0058 & -.003 & -.029 & 3.4 & -.66 & 14.03 & 8.32 \end{bmatrix}$$

$$C_{min} = \begin{bmatrix} .07 & .054 & -.0776 & -.0036 & -4.61 \\ .026 & -.0045 & -.029 & .022 & -.52 \\ .44 & -.021 & -.062 & .00078 & -.42 \end{bmatrix}$$

$$N = \begin{bmatrix} -.048 & -.0098 & -.0024 \\ .007 & -.0079 & .0021 \\ 0.0 & -.0034 & .0059 \end{bmatrix}$$

Closed Loop Eigenvalues				
Real Part	Imag Part	Damping	Freq(rad/sec)	Freq(Hz)
-40.2	0.0	1.0	40.2	6.39
-40.01	0.0	1.0	40.01	6.367
-39.99	0.0	1.0	39.99	6.365
-6.007	0.0	1.0	6.007	.956
-2.37	2.70	.66	3.59	.57
-2.37	-2.70	.66	3.59	.57
-.94	2.13	.40	2.33	.37
-.94	-2.13	.40	2.33	.37
-.60	1.51	.37	1.62	.26
-.60	-1.51	.37	1.62	.26
-.55	.48	.75	.73	.116
-.55	-.48	.75	.73	.116
-.62	.402	.84	.74	.117
-.62	-.402	.84	.74	.117
-.90	0.0	1.0	.90	.14
-.17	0.0	1.0	.17	.027

Performance Index Data		
Outputs or Controls	Units	Weighting
u	ft/sec	5×10^3
v	ft/sec	5×10^3
w	ft/sec	5×10^8
p	rad/sec	1×10^5
q	rad/sec	1×10^8
r	rad/sec	1×10^5
$\dot{\delta}_e$	$inches/sec$	1×10^5
$\dot{\delta}_c$	$inches/sec$	1×10^5
$\dot{\delta}_a$	$inches/sec$	1×10^5
$\dot{u}$	ft/sec^2	5×10^8
$\dot{v}$	ft/sec^2	5×10^3
$\dot{w}$	ft/sec^2	5×10^8
δ_e	$inches$	1×10^2
δ_c	$inches$	1×10^2
δ_a	$inches$	1×10^2

Figure 4.24: **Redesigned Hover Compensator.** Only the columns of K associated q and θ and the row of C corresponding to longitudinal control (δ_e) are changed from the initial design of Figure 4.7.

good time responses. In this case, the measurement noise characteristics were left unchanged and an unrealistically high value of the vertical velocity disturbance was used. Specifically, the vertical gust root mean square (rms) was increased from 2.3 ft/sec to 10 ft/sec. Vertical gust was selected since it affects the pitch angle more strongly than the other disturbances. With this one change, the RSANDY program was used to find a new compensator. To speed up the convergence in the RSANDY program, only the columns of the K_{min} matrix associated with measurements of q and θ, and the row of C_{min} associated with the longitudinal control were allowed to vary. This approach was also logical since we wished to keep the vertical and lateral axes unchanged from the first design. The redesigned compensator in shown in Figure 4.24 and can be compared to the initial design in Figure 4.7. Figure 4.25 shows the simulation response of the redesigned velocity command inner loop with the improvement in pitch damping compared to the initial design shown in Figure 4.9. Figures 4.26 and 4.27 show that the y and z responses were essentially unchanged by the redesign.

Since there was nothing in the simulation to suggest that there would be coupling from $\dot{x}$ command to ϕ, the approach to solving this problem was based on the experience gained thus far. Two changes were made to the controller which would have to wait for flight to be evaluated. The first change was the zeroing of the feedforward gain from $\dot{x}$ command to δ_a in the N matrix of Figure 4.3. This was a logical approach to solving the problem since the N matrix was highly dependent on accurate modeling and the longitudinal flight test had already shown the model to be lacking. The other change made to solve this coupling was to include nonzero values for K_{Y_ϕ} and K_{Y_P} in the lateral PID outer loop. This change was made to

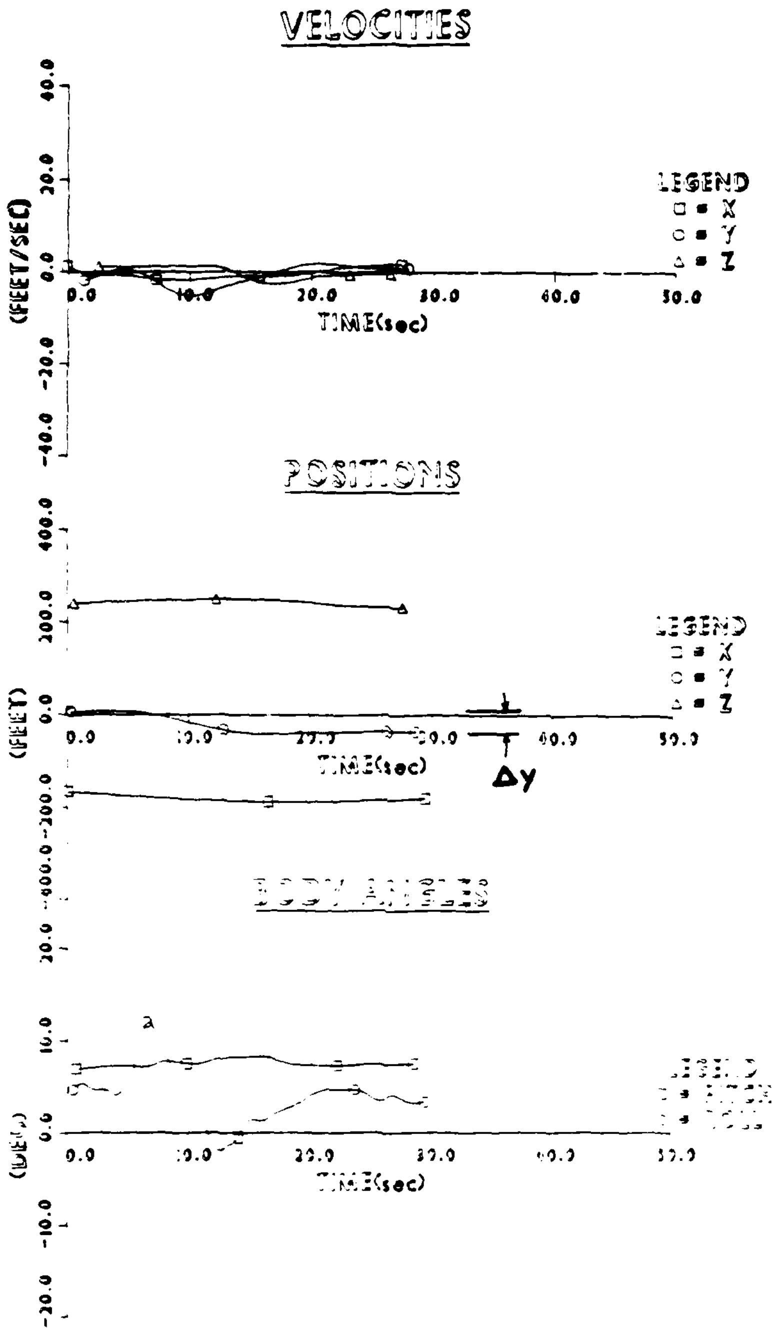

Figure 4.23: **Preliminary Lateral Position Step Command in Flight.** The y position hold performance is well damped and similar to the simulation of Figure 4.13.

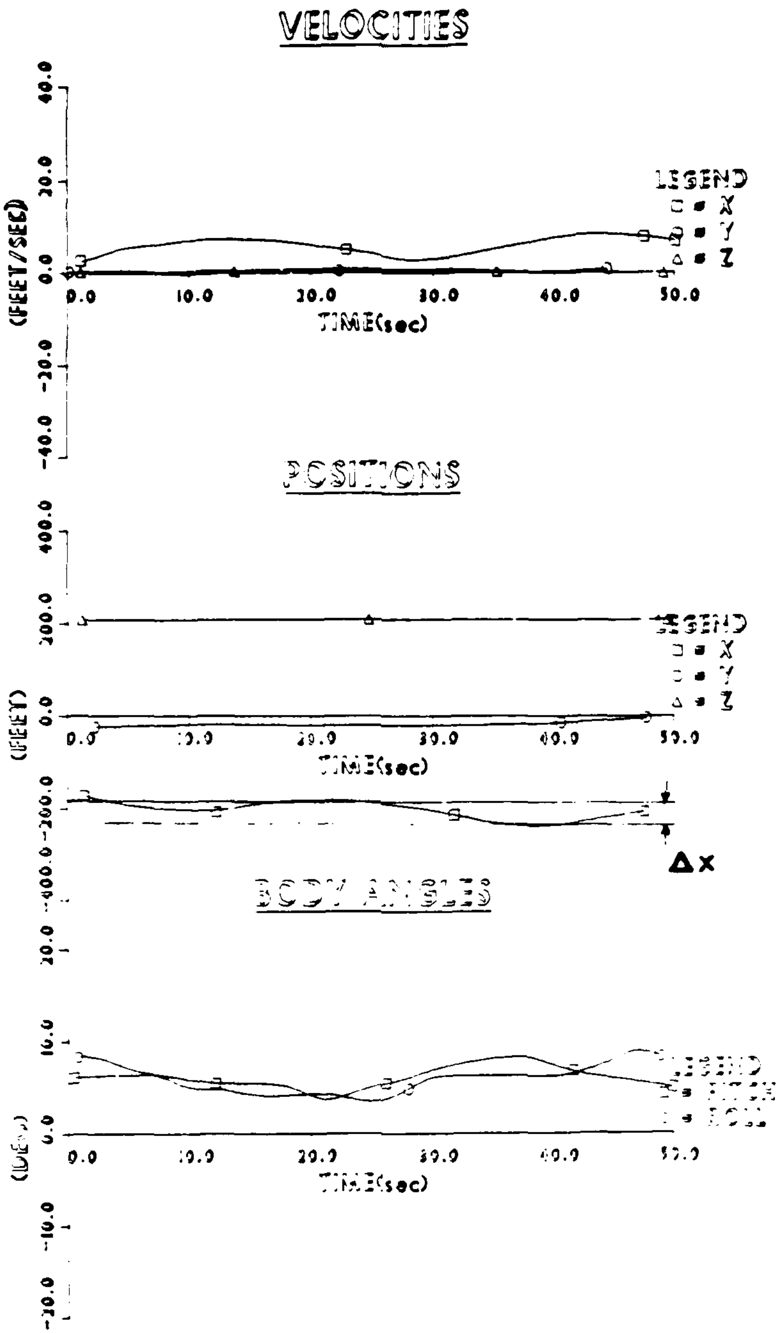

Figure 4.22: **Preliminary Forward Position Step Command in Flight.** The x position damping is very poor ($\varsigma \approx .1$), unlike the near critical damping of the simulation shown in Figure 4.12.

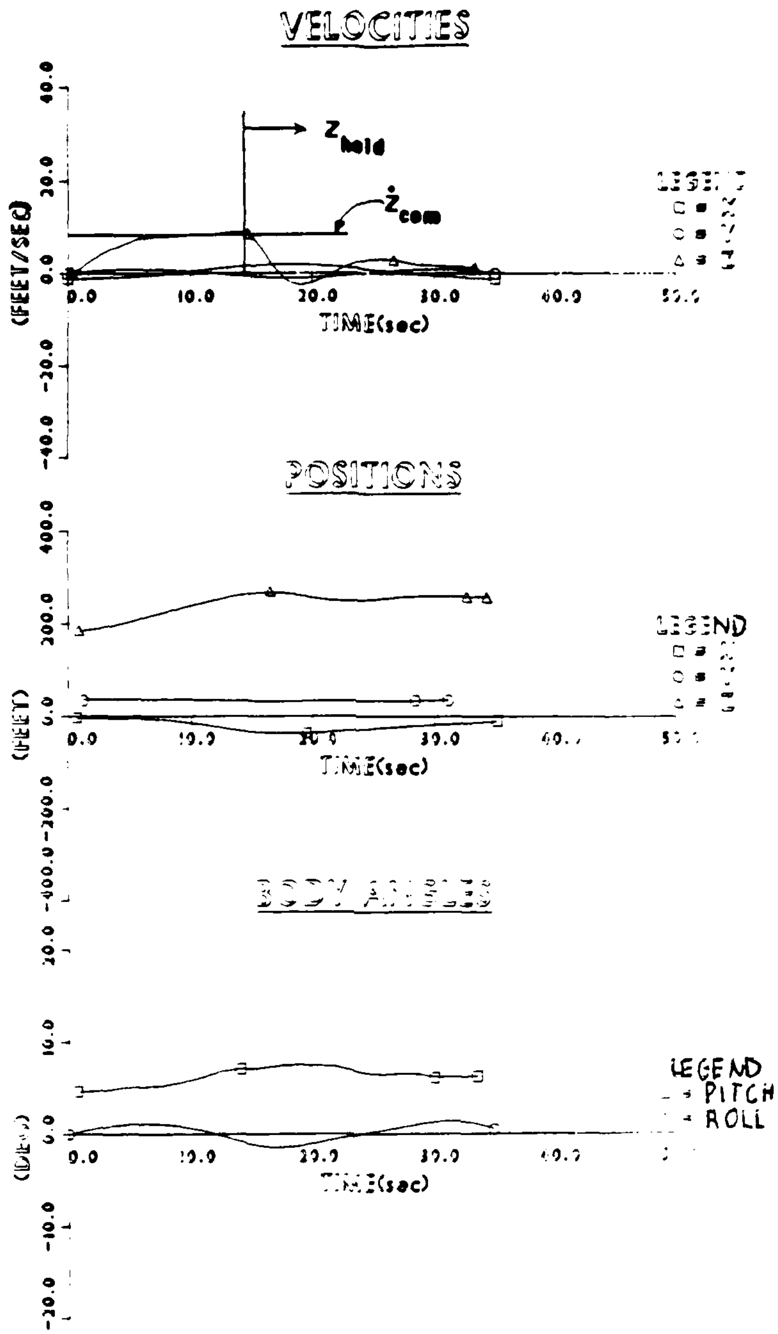

Figure 4.21: **Preliminary $\dot{z}$ Flight Response.** The 5 second time to steady state matches the simulation shown in Figure 4.11.

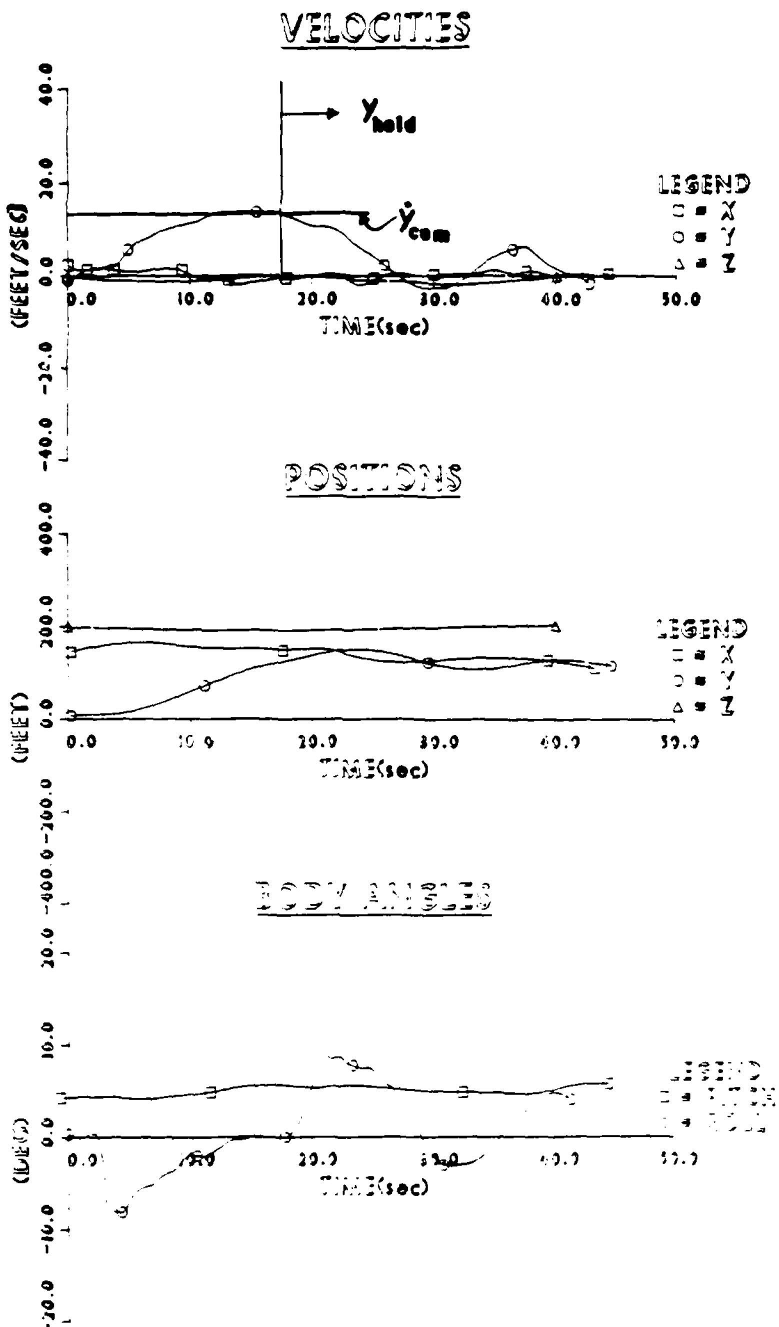

Figure 4.20: **Preliminary $\dot{y}$ Flight Response.** The $\dot{y}$ response is well behaved and similar to the simulation results of Figure 4.10. The peak roll angle is about 8 degrees for both responses to a command of about 10 ft/sec.

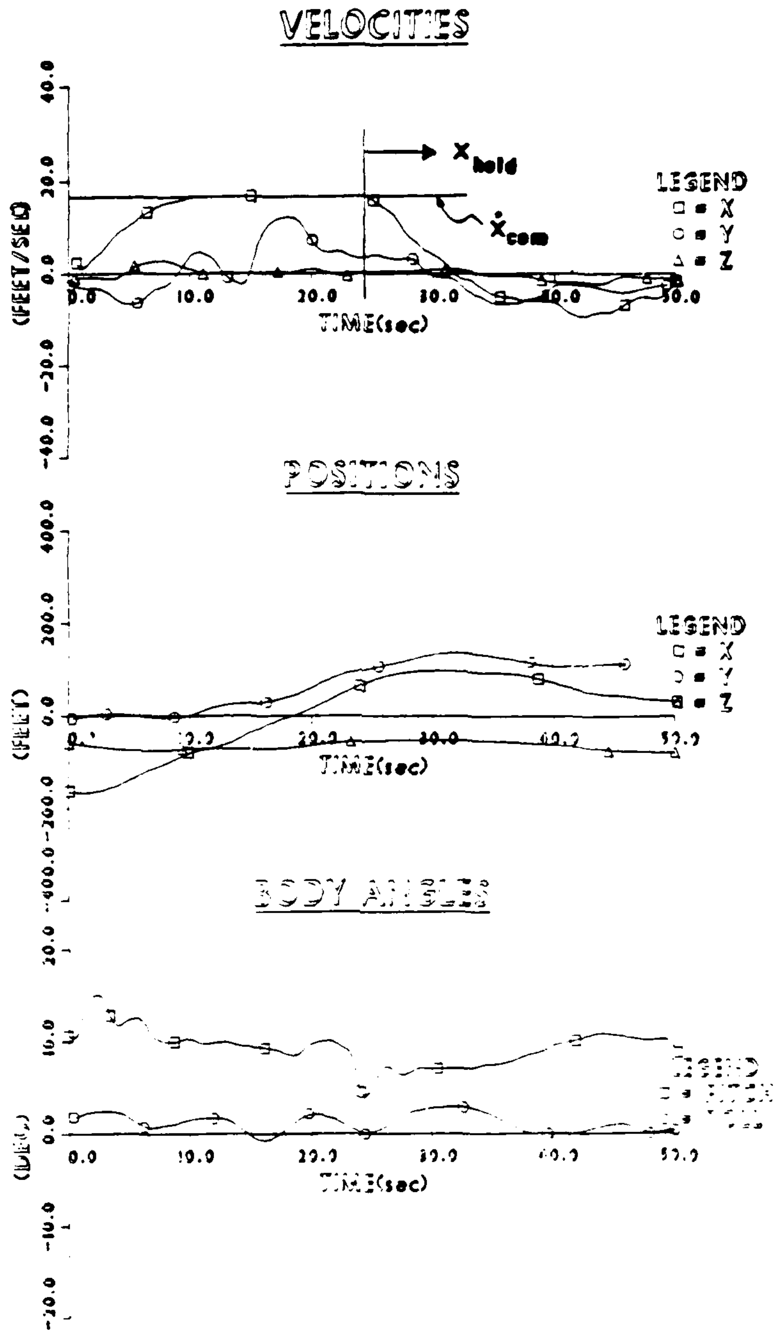

Figure 4.19: **Preliminary $\dot{x}$ Flight Response with Pitch Roll Coupling.** With the instability of Figure 4.18 corrected, the roll coupling, shown here, was discovered.

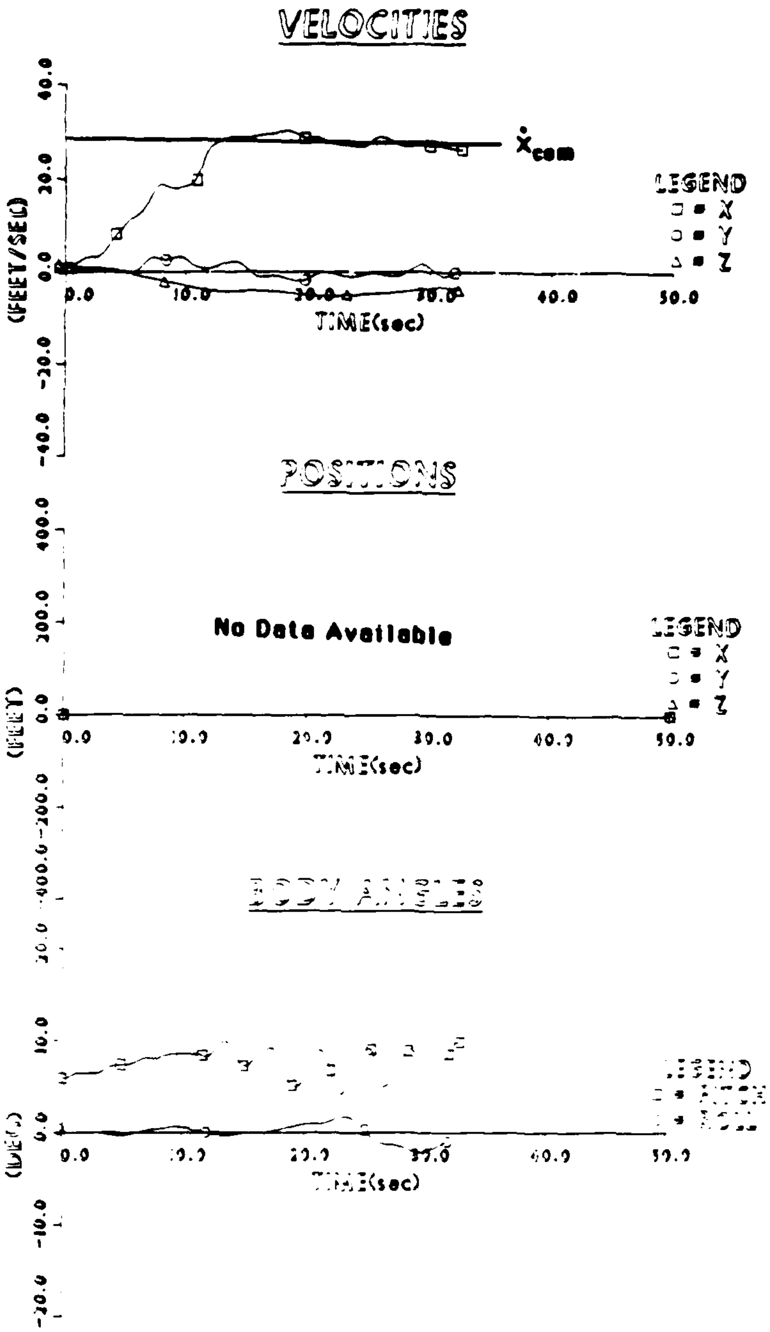

Figure 4.18: **Preliminary $\dot{x}$ Flight Response with Pitch Oscillation.** The poorly damped simulation response of Figure 4.9 became unstable in flight as the pitch angle shows. The decoupling using the outer loops worked well.

system in flight. Figure 4.18 shows the flight results with the extremely poor x axis performance. After a redesign of the velocity inner loop system, described in the next section, another problem was found. There was unacceptable coupling between the x and y axes. The coupling, evident in Figure 4.19, was manifested as roll osscillations resulting from the $\dot{x}$ command. The next section also describes the approach taken to solve this pitch to roll coupling problem. The coupling was one way, however, as seen in Figure 4.20 where the response to a step in $\dot{y}$ is quite acceptable and similar to the simulation results of Figure 4.10. The $\dot{z}$ command capability is also quite good as Figure 4.21 shows. The x position hold performance of Figure 4.22 was very poor due to the low damping ($\approx$ .1). Y position (Figure 4.22) was much better damped and faster than x. The z position hold performance was very good with vertical position changes of less than 10 feet during the velocity commands of Figures 4.19, 4.20, and 4.21. Use of the radar tracker data in the inner loops, which was considered risky due to its complexity, worked well throughout the flight test.

4.7.3. Hover Controller Redesign

The redesign of the system was necessitated by bad performance in two modes. First, the x velocity response was slightly unstable in flight. The other problem was the coupling from x velocity command to roll angle. The first problem was handled by redesigning the inner loop velocity control system in order to slow the longitudinal response. This redesign was first attempted by changing the weighting matrices in the RSANDY program to get a better damped longitudinal response. This approach did not work so the technique of Section 3.4.1 was used. Section 3.4.1 described using an arbitrary set of measurement spectral densities to achieve new capabilities needed by the hover controller including data uplink capability and complementary filtering to get smooth inertial data. The second phase included preliminary flight test which discovered poor velocity performance which necessitated a redesign of the velocity inner loop. The final phase of the flying evaluated the redesigned control system.

4.7.1. Support Systems Development Flying

The complexity of the hover controller required that essentially all the aircraft systems and all the ground support equipment be working in order to exercise the system. A number of flights was required just to ensure that the uplink system and the associated complementary filters were producing good inertial data. Once these systems were operating correctly, the flight testing continued with checks of the *mode switching* and *transient suppression logic* while using the real data coming from the complementary filters. It was while doing this work that the laser tracker's poor ability to hold lock was discovered and the decision was make to go with the less accurate radar tracker.

4.7.2. Preliminary Closed Loop Flight Test in Hover

Preliminary closed loop testing included velocity step commands in the three axes and changes in desired position while remaining in the hover hold mode. These closed loop tests confirmed what the longitudinal CAS tests had already shown. The flight responses were less damped than the simulations had predicted. In other words, we couldn't achieve as high a bandwidth in flight as in simulation. This was most evident in the x axis where the well damped velocity response in the simulation (Figure 4.9) turned into a neutrally stable or slightly unstable

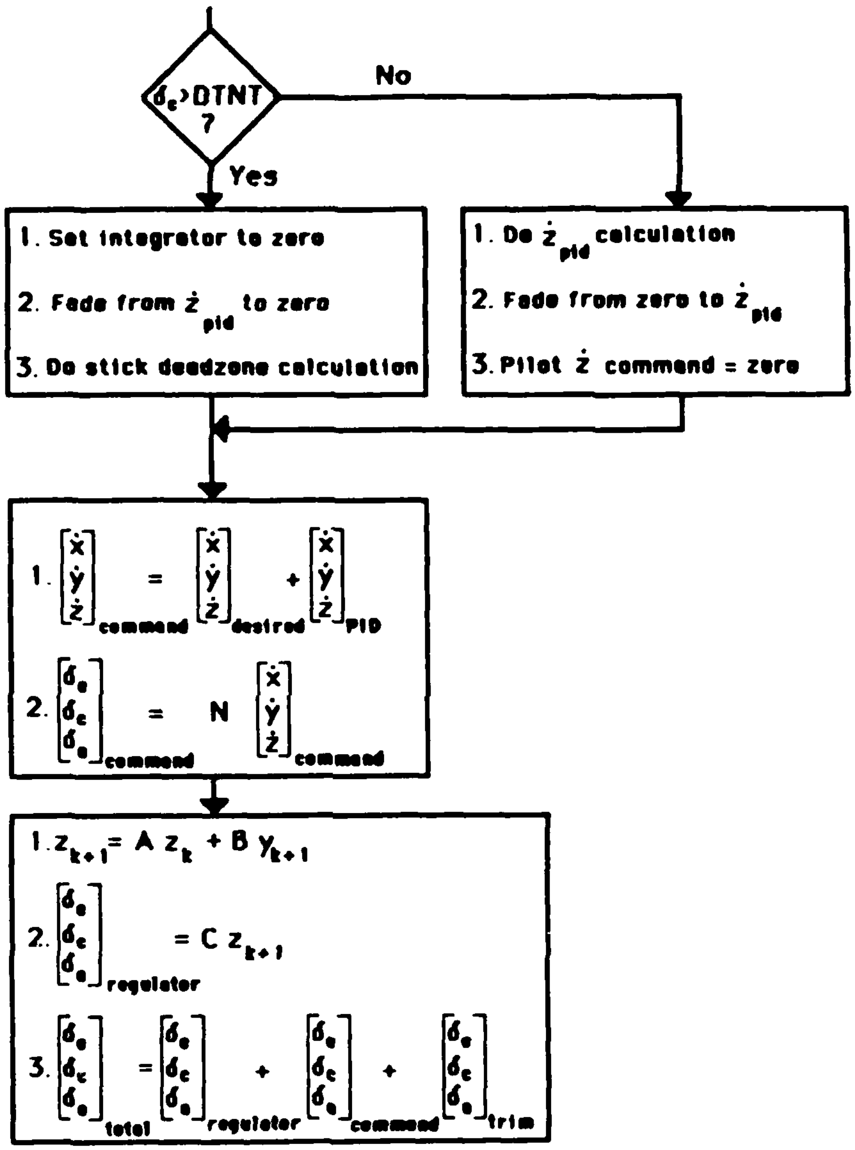

Figure 4.17: **Z Axis Transient-Free Switching Logic.** This figure also shows the rest of the hover controller which was shown in Figure 4.3.

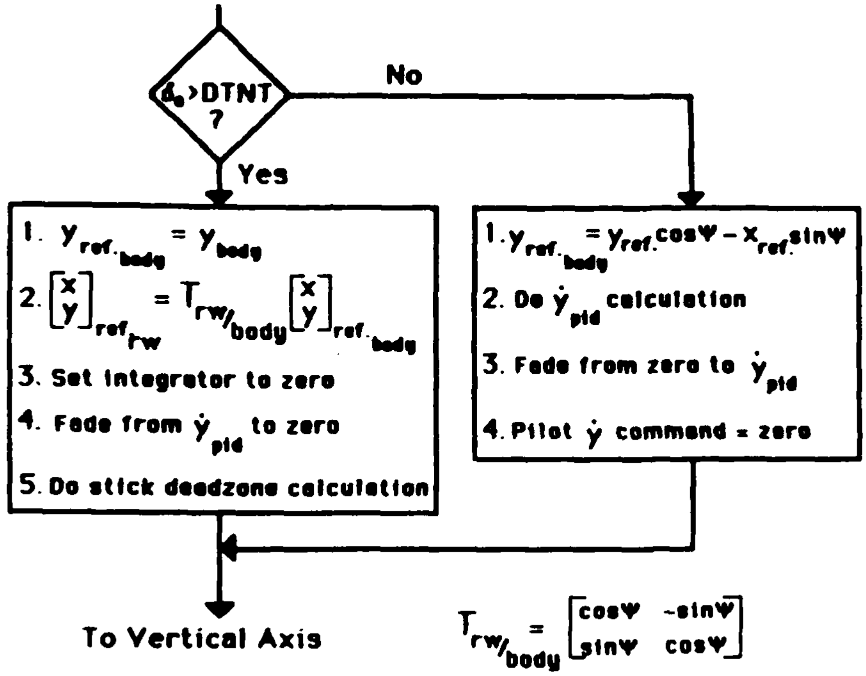

Figure 4.16: **Y Axis Transient-Free Switching Logic.** The switching logic for the x and y axes was identical. The best detent was .25 inches.

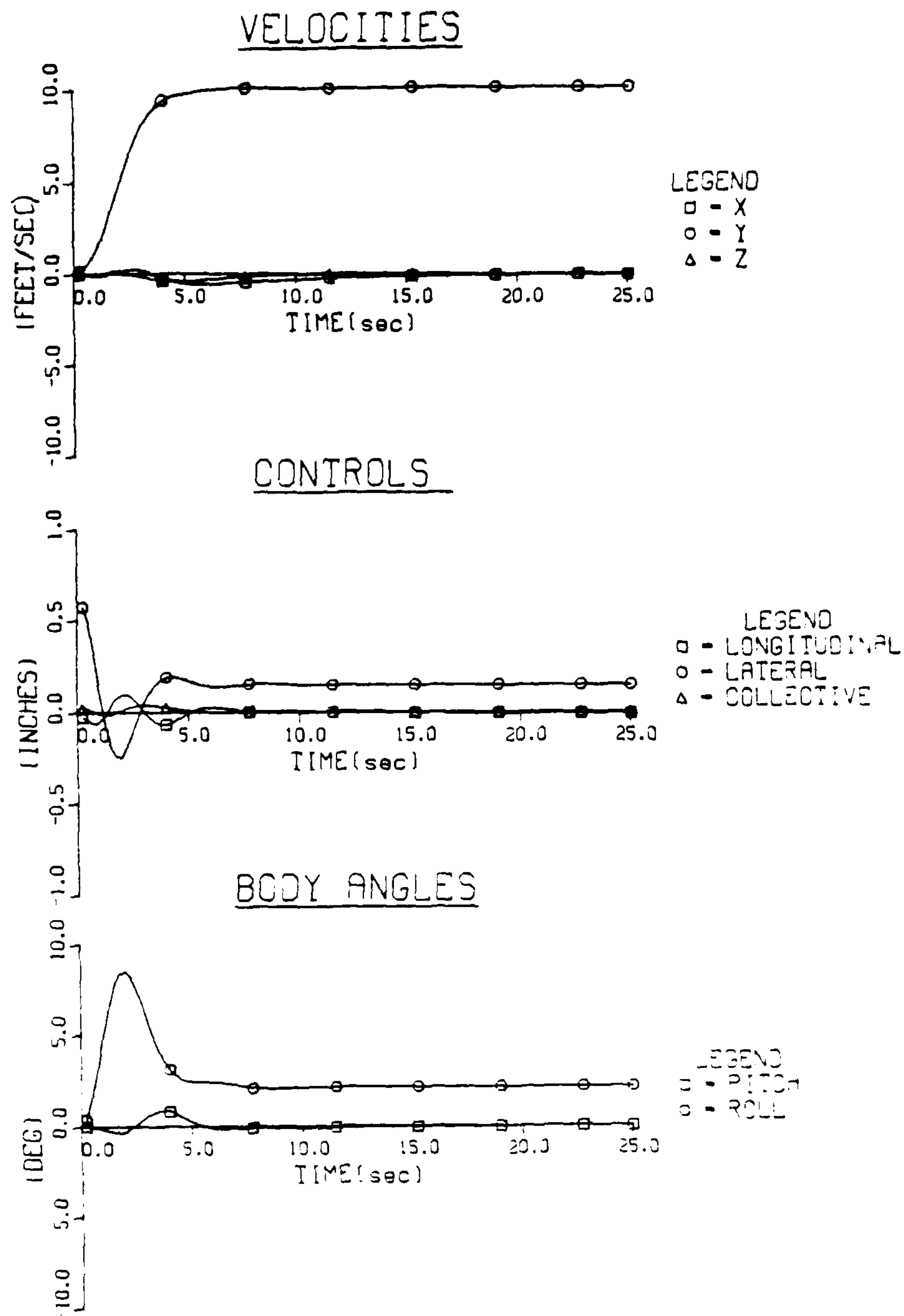

Figure 4.26: **Hover Side Velocity Step Command in Simulation.** The response is nearly identical to the original design of Figure 4.10.

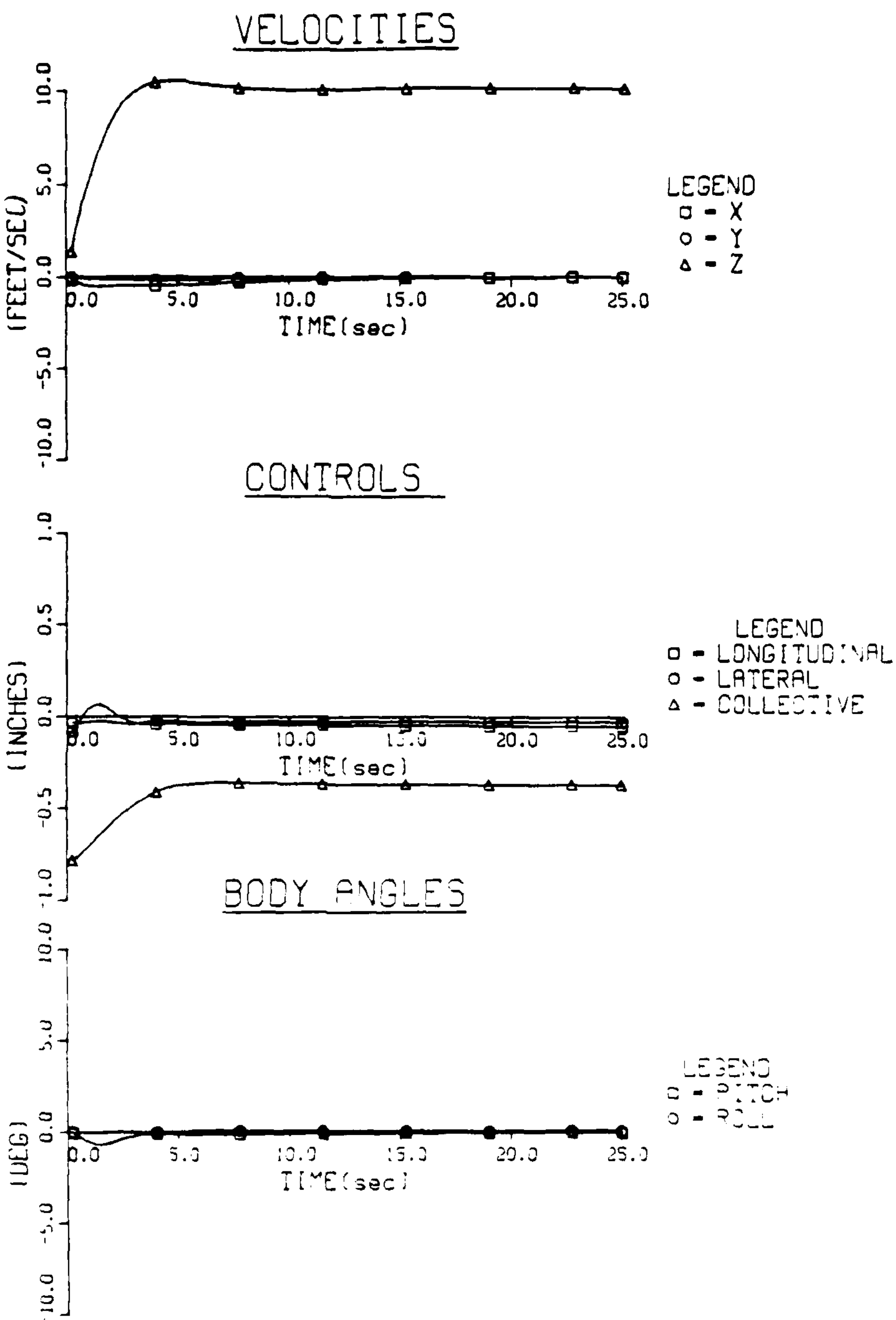

Figure 4.27: **Hover Vertical Velocity Step Command in Simulation.** The response is nearly identical to the original design of Figure 4.11.

4.8. Summary of Results of the Hover Controller Design

As with the longitudinal CAS, the discussion of results is separated into two groups:

- the effectiveness of the methodology
- the flight test results

The hover controller emphasized the usefulness of the design methodology for a more complicated control system. To have used classical incremental loop closures to do this design would probably have taken longer or would have required more specific experience in helicopter control systems than I had. This task also showed the advantage of using a modern control inner loop to modify the open loop plant in such a way as to increase the physical intuition for the design engineer. The increased physical intuition made classically designed outer loops simpler. In this case, the plant was changed from control motion in, measurement out to desired output in, actual output out. This change simplified the selection of the outer loop control structure and made the outer loop gains more intuitive. Figure 4.3 showed these advantages. This task also emphasized the relative speed and ease with which design iterations can be made on MIMO systems. When the first design of the hover controller was found unacceptable in flight, the redesign described in Section 4.7.3 was done in only 2 - 3 days which avoided delays in the flight testing. As with the longitudinal CAS design, the analysis tools developed to use the methodology (described in the various appendices) were sufficient but their

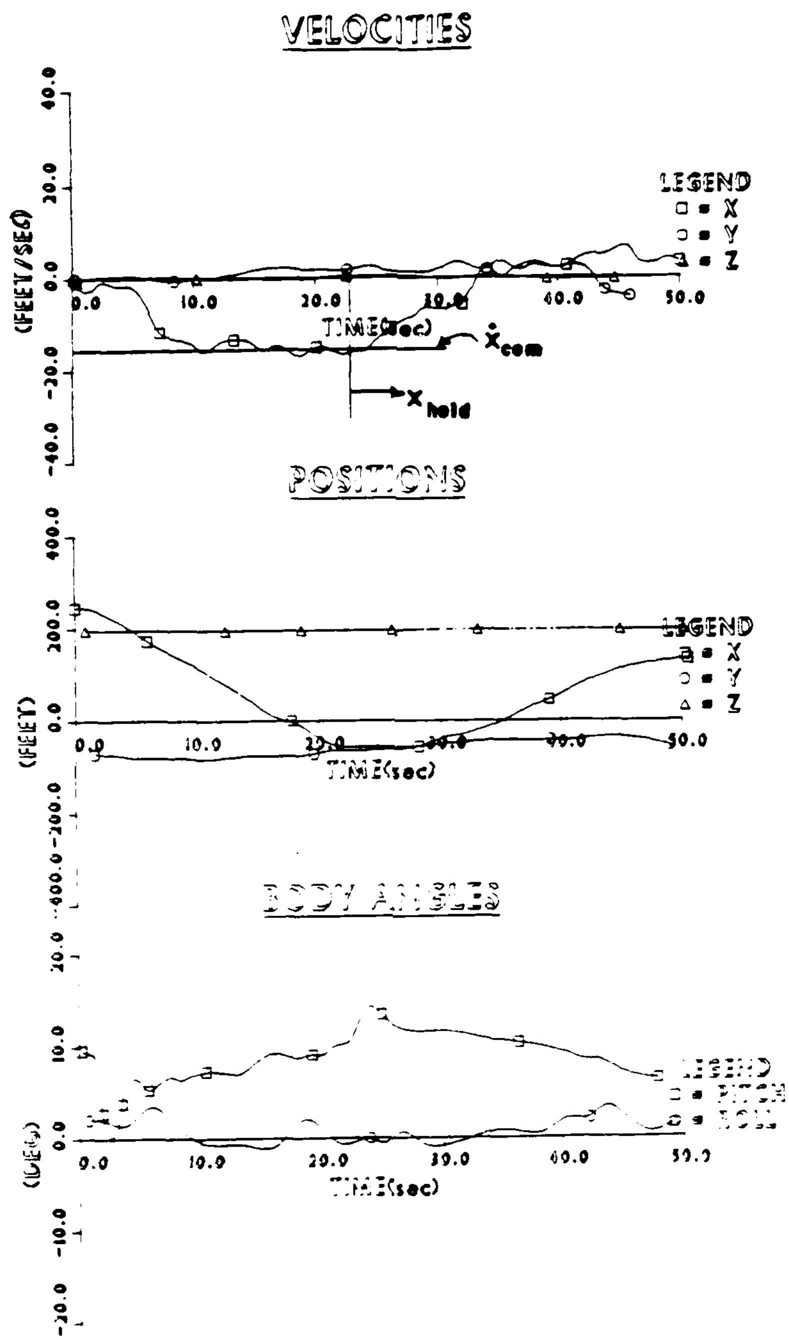

Figure 4.28: **Final $\dot{x}$ Flight Response.** The instability in pitch (Figure 4.18) and the pitch roll coupling (Figure 4.19) are gone but the pitch angle damping is still less than the simulation response of Figure 4.25.

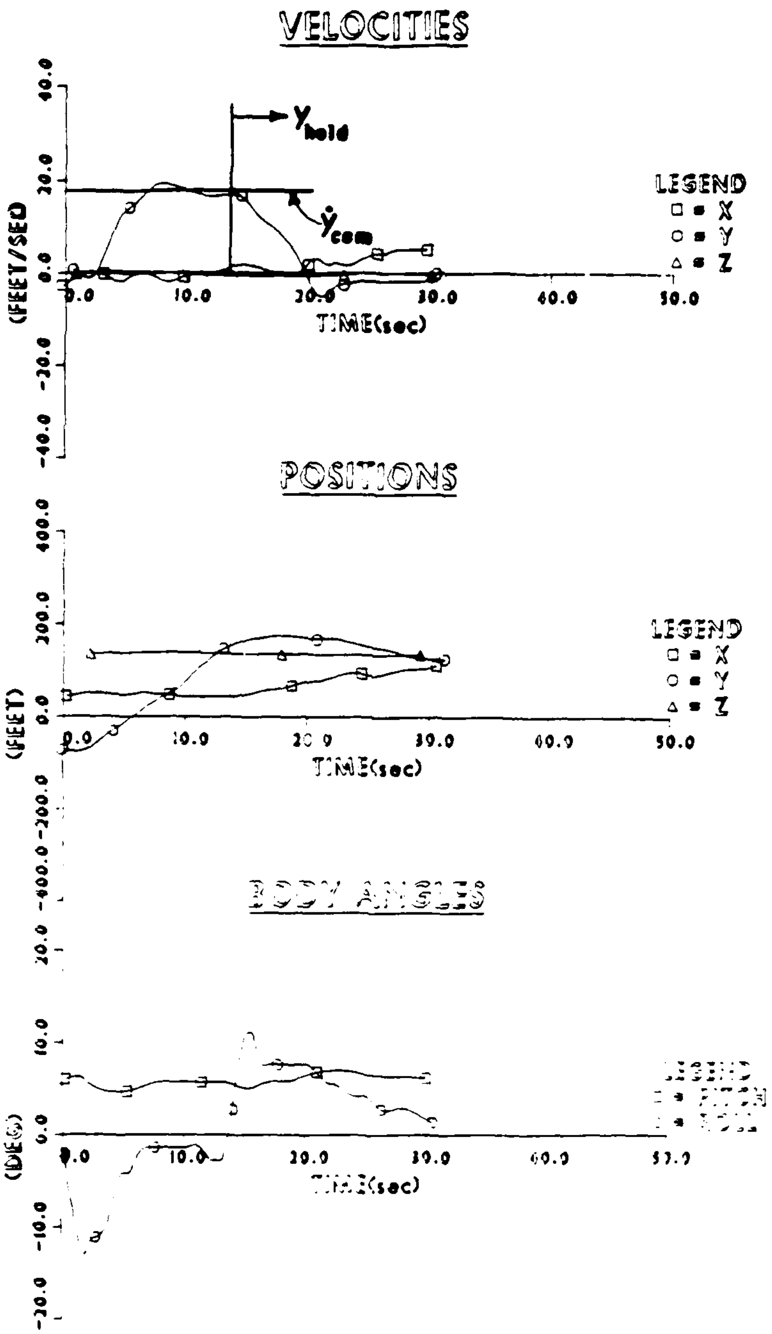

Figure 4.29: **Final $\dot{y}$ Flight Response.** The $\dot{y}$ response is little changed from the first flight test results of Figure 4.20.

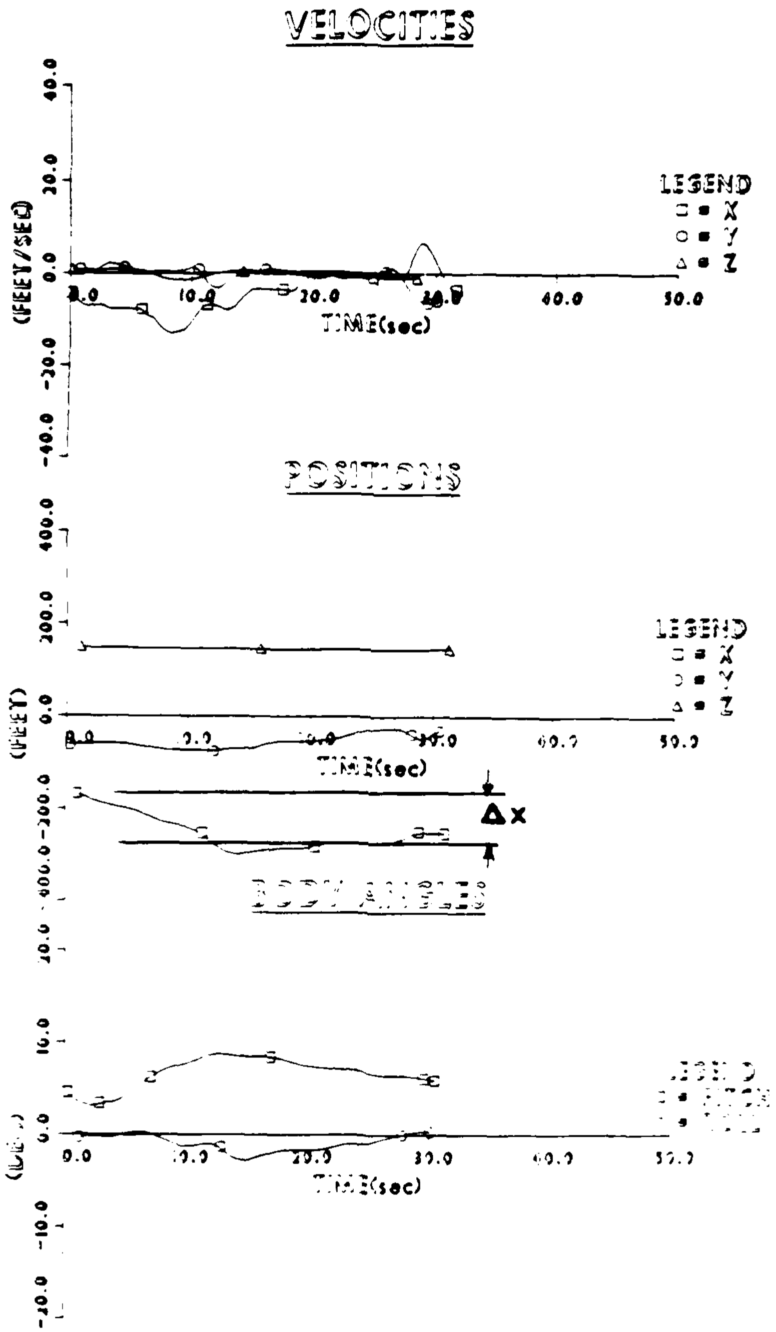

Figure 4.30: **Final Hover Forward Position Step Command in Flight.** The performance is much improved from Figure 4.22 but the damping of ≈ .4 is still not good enough for operational use.

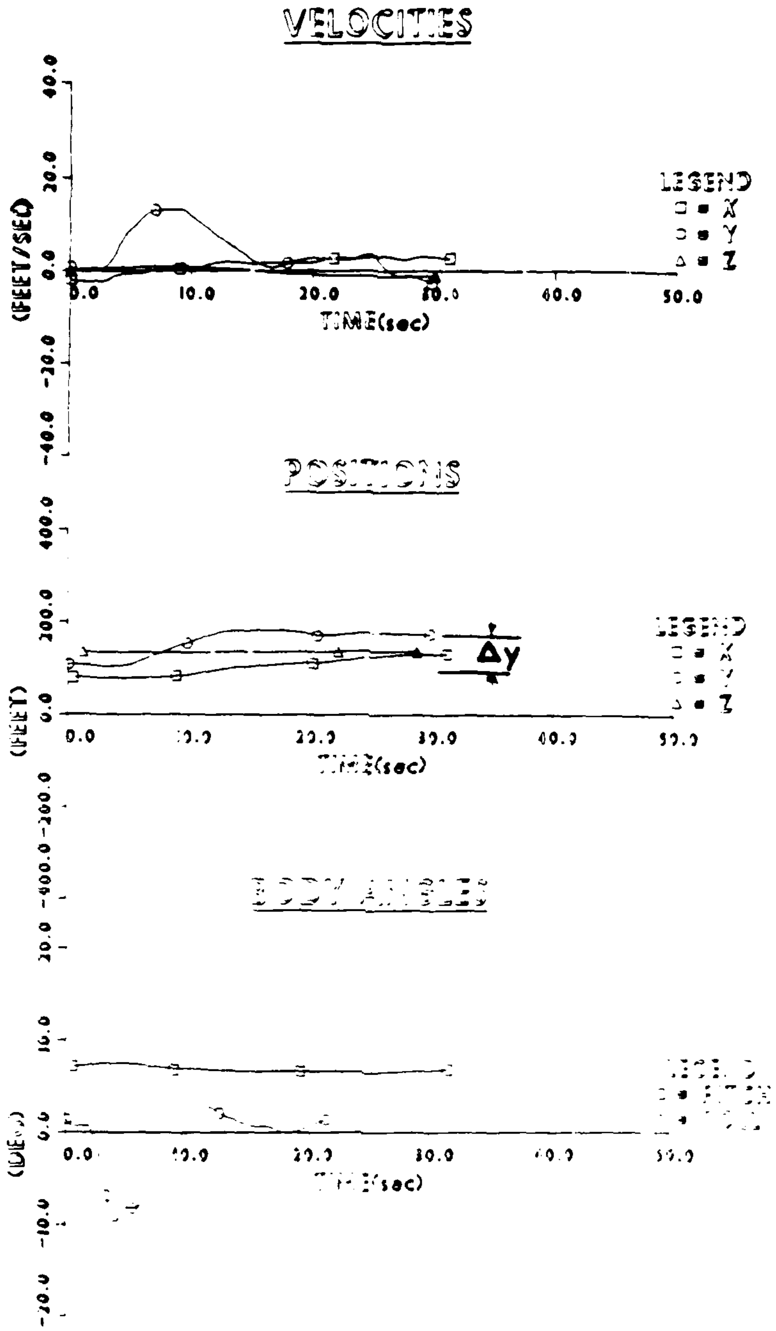

Figure 4.31: **Hover Lateral Position Step Command in Flight.** The lateral position response is adequate and little changed from the first tests of Figure 4.23.

"user friendliness" needed improvement.

In flight test, the hover controller was fairly successful. Many advanced helicopter or VTOL airplane designs call for a translational velocity control(TVC) system such as was tested here. Normally the evaluations of these concepts seldom leave the simulators to address the hardware and software difficulties of flight implementation. This test reemphasized two of the important difficulties of TVC systems, the inertial position/velocity sensor and the human factors involved. The primary contribution of this work was the development of a flexible TVC system where these type issues can be studied. Specifically, this system showed good velocity command performance in all three axes, excellent hold performance in the lateral and vertical axes, and marginally acceptable hold performance longitudinally. The switching logic worked well from a control viewpoint but the pilots who flew the system commented on the need for a better indication of switching from hold mode to velocity command mode in each axis.

Chapter 5.

Conclusions

The conclusions are separated into those applicable to the design methodology and those associated with the flight tests.

5.1. Methodology

- The process of scaling and using the modal input/output measures is an effective way to reduce the order of the compensator.
- The scaled block minimal realization of the compensator is useful in identifying unimportant measurements and controls.
- The decoupling feedforward matrix depends heavily on an accurate model so practical designs will usually require some sort of integral control. For very poor models, integral control alone should be used for implementing output commands.
- The software tools were adequate for application of the methodology.
- Both "modern" and "classical" control techniques are important for MIMO control system design. The specific application determines the appropriate techniques to use. In this research, the use of a modern control inner loop

with classically designed outer loops was a useful approach for the hover controller.

5.2. Flight Tests

- Although requiring some change of pilot technique (retraining), the decoupled velocity and climb rate controller was well received by the pilots who flew it.
- The hover controller performed adequately as a translational velocity command system, had good position hold capability in the vertical and lateral axes, but its hold performance in the longitudinal direction was marginal.
- Integral control was crucial to achieve decoupled control for both the cruise and hover control systems.

5.3. Lessons Learned

Finally, two "lessons learned" (or relearned) during this research should be emphasized, even though they may seem obvious. First, there is no substitute for experience. For this methodology, experience was important in:

- selecting the correct units for scaling the dynamic system
- determining which gains are "small" for compensator simplification
- selecting outputs and their weightings in the optimization using the ROPTSYS and RSANDY computer programs
- selecting scale factors for fixed-point scaling, Appendix E

- selecting stick and collective lever gains for the pilot
- determining the structure of the integral control loops

Also, experience in use of the methodology itself, especially the design tools, was critical. The hover controller, though much more complicated, took about as much time to design as the longitudinal CAS. The other lesson is that the design of the control logic is often the easiest and fastest step in building an operational control system. Most of the work is spent on:

- software design, coding, and testing
- hardware modifications and testing
- ground based closed loop testing

Chapter 6.

Recommendations for Further Research

The CH-47 research helicopter at Ames is a very flexible test vehicle and is being improved by the addition of a floating point digital computer programmable in a higher order language. With this improvement, a number of potential research projects should be considered:

- Parameter identification to improve the existing models used for design and simulation
- Refinement of the two designs presented here and pilot evaluation in a more realistic setting such as instrument landing
- Outer loop guidance work (Microwave Landing System, 4-dimensional navigation, etc.) using these inner loops
- Application of singular value LQG-LTR (Linear Quadratic Gaussian - Loop Transfer Recovery) to account for unmodeled rotor dynamics

One difficulty in applying the methodology was the poor convergence characteristics of the first order gradient algorithm in the RSANDY program. A second order technique to speed convergence would be an important improvement to the program. Another possibility for research is finding a way of commanding a system without exciting all the closed-loop modes similar to the method described in

Chapter 3 for the case of the full-order compensator.

Saberi has shown a technique for calculating helicopter stability derivatives during low speed flight near the ground.[18] This research vehicle is an excellent testbed for validating these derivatives.

References

1. McRuer,D., Ashkenas, I., and Graham, D., *Aircraft Dynamics and Automatic Control*, Princeton University Press, Princeton, New Jersey, 1973.

2. Bryson,A.E., Notes from the "Advanced Stability and Control of Flight Vehicles" course at Stanford(AA271b), 1983.

3. Ly,U.L., "A Design Algorithm for Robust Low-Order Controllers", Stanford University, SUDAAR 536, November 1982.

4. Bryson,A.E. and Ho,Y., *Applied Optimal Control*, Hemishpere Publishing Corporation, New York, 1975.

5. Kailath,T., *Linear Systems*, Prentice-Hall,Inc., Englewood Cliffs, New Jersey, 1980.

6. Franklin,G.F. and Powell,J.D., *Digital Control of Dynamic Systems*, Addison-Wesley Publishing Company, Menlo Park, California, 1981.

7. Bernard,D., "Control System Design for Lightly Coupled Space Structures", PhD Dissertation, Stanford University, September 1984.

8. Ly,U.L., "Optimal Robust Low-Order Controller Design, User Guide for the Program SANDY", Stanford University, 1982.

Appendix D.

Set Point Design

This appendix derives the feedforward matrix which commands a dynamic system, including compensator, to a new equilibrium. This matrix turns desired outputs into the steady-state controls needed to achieve the outputs. The restrictions are that these outputs (or new operating point) be physically realizable and that the number of controls be equal to the number of outputs.

Consider the following dynamic system:

$$
\begin{aligned}
\dot{x} &= Fx + Gu \\
y_s &= H_s x + D_{su} u \\
\dot{z} &= Az + By_s + G_z u_c \\
u &= Cz + Dy_s + u_c
\end{aligned}
\qquad (D.1)
$$

where:

x– plant states

y_s– measurements

z– compensator states

u– controls

The general form of the transformation is:

$$
\begin{aligned}
T &= \begin{bmatrix} T_1 & 0 & \dots & 0 \\ 0 & T_2 & 0 & 0 \\ \vdots & 0 & \ddots & 0 \\ 0 & 0 & 0 & \frac{1}{c_l} \end{bmatrix} \\
T^{-1} &= \begin{bmatrix} T_1^{-1} & 0 & \dots & 0 \\ 0 & T_2^{-1} & 0 & 0 \\ \vdots & 0 & \ddots & 0 \\ 0 & 0 & 0 & c_l \end{bmatrix}
\end{aligned}
\tag{C.11}
$$

where:

$$
T_i = \frac{\begin{bmatrix} c_{l,2i}(f_i g_i - e_i h_i) & e_i c_{l,2i} - b_i c_{l,2i-1} \\ -c_{l,2i-1}(f_i g_i - e_i h_i) & g_i c_{l,2i-1} - h_i c_{l,2i-1} \end{bmatrix}}{-f_i {c_{l,2i-1}}^2 + (e_i - h_i) c_{l,2i-1} c_{l,2i} + g_i {c_{l,2i}}^2} \tag{C.12}
$$

i– the i^{th} complex mode

l– row index corresponding to the largest value of $c_1^2 + c_2^2$ for that mode's double column, or the largest value of c_1^2 for the a real mode

A listing of a FORTRAN subroutine, MINCOM, which does this transformation is shown in Appendix L.

The "*0 1*" in the C_{min} matrix results from scaling the system by the largest values in the C double columns.

Consider a second order system in general form:

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} e & f \\ g & h \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} y$$
$$u = \begin{bmatrix} c_1 & c_2 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \tag{C.6}$$

The desired transformation will put this system into the following form:

$$\begin{bmatrix} \dot{z}'_1 \\ \dot{z}'_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ a_1 & a_2 \end{bmatrix} \begin{bmatrix} z'_1 \\ z'_2 \end{bmatrix} + \begin{bmatrix} b'_1 \\ b'_2 \end{bmatrix} y$$
$$u = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} z'_1 \\ z'_2 \end{bmatrix} \tag{C.7}$$

The similarity transformation requires the two systems to have identical eigenvalues, that is:

$$|sI - A| = |sI - A_{min}|$$
$$\Downarrow$$
$$a_1 = fg - eh \tag{C.8}$$
$$a_2 = e + h$$

Introducing the transformation matrix and expanding:

$$TA_{min} = AT$$
$$C_{min} = CT$$
$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} 0 & 1 \\ fg - eh & e + h \end{bmatrix} = \begin{bmatrix} e & f \\ g & h \end{bmatrix} \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \tag{C.9}$$
$$\begin{bmatrix} 0 & 1 \end{bmatrix} = \begin{bmatrix} c_1 & c_2 \end{bmatrix} \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}$$

where $c_1^2 + c_2^2$ has the largest magnitude of any row pair in double column associated with the mode being made minimal. Solving the equations above we have the desired transformation:

$$T = \frac{\begin{bmatrix} c_2(fg - eh) & ec_2 - bc_1 \\ -c_1(fg - eh) & gc_2 - hc_1 \end{bmatrix}}{-fc_1^2 + (e - h)c_1c_2 + gc_2^2} \tag{C.10}$$

where:

$$A = \begin{bmatrix} \star & \star & 0 & 0 & \cdots \\ \star & \star & & & \\ 0 & \begin{matrix} \star & \star \\ \star & \star \end{matrix} & & 0 & 0 \\ 0 & 0 & & \ddots & 0 \\ \vdots & 0 & & 0 & \star \end{bmatrix}, r \times r \tag{C.2}$$

$$B = [Full], r \times p$$

$$C = [Full], m \times r$$

We want a transformation to a new form:

$$\begin{aligned} \dot{z}' &= A_{min}\, z' + B_{min}\, y \\ u &= C_{min}\, z' \end{aligned} \tag{C.3}$$

where:

A_{min}- minimal form of A

B_{min}- minimal form of B

C_{min}- minimal form of C

$$A_{min} = \begin{bmatrix} \begin{matrix} 0 & 1 \\ a_1 & a_2 \end{matrix} & 0 & \cdots \\ 0 & \begin{matrix} 0 & 1 \\ a_1 & a_2 \end{matrix} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}, n \times n$$

$$B_{min} = \begin{bmatrix} \star & \star & \cdots \\ \star & \star & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}, n \times p \tag{C.4}$$

$$C_{min} = \begin{bmatrix} \star & \star & 0 & 1 & \cdots \\ 0 & 1 & \star & \star & \cdots \\ \star & \star & \star & \star & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}, m \times n$$

$$\begin{aligned} z &= Tz' \\ A_{min} &= T^{-1}AT \\ B_{min} &= T^{-1}B \\ C_{min} &= CT \end{aligned} \tag{C.5}$$

Appendix C.

Minimal Realizations

The design methodology described in Chapter 2 used minimal realizations in two places. The first was when the ROPTSYS computer program displayed the compensator in minimal form to be better suited for the optimization in the RSANDY program. This eliminated redundant parameters which could cause trouble in the RSANDY gradient search procedures. The second use of a minimal realization came when the discrete compensator was transformed to minimal form for computational efficiency. In the first case, the transformation was from arbitrary form to block modal form then to block minimal form. The second was from an arbitrary 2×2 block form to the block minimal form. The derivation is shown for an arbitrary 2×2 system then expanded for any order.

Given the following form of the dynamic system:

$$\begin{aligned} \dot{z} &= Az + By \\ u &= Cz \end{aligned} \tag{C.1}$$

By the duality property of regulators and estimators (Figure B.1), these gains, $K^T = (R + NQN^T)^{-1}(NQ\Gamma^T + H_m P)$, are determined using the randomly disturbed equations of motion:

$$\begin{aligned} \dot{x} &= Fx + \Gamma w \\ y_m &= H_m + Nw + v \end{aligned} \qquad (B.12)$$

where

Q– noise spectral density matrix of plant distrubances, w

R– noise spectral density matrix of measurement noise, v

Regulator	F	G	H	L	A	B	S	C
Estimator	F^T	${H_m}^T$	Γ^T	N^T	Q	R	P	K^T

Figure B.1: **Duality Between Regulators and Estimators.** This shows the property of duality which allows the use of the regulator results for design of an optimal estimator (a steady-state Kalman filter).

Adjoining the constraints (the equations of motion) to form the Hamiltonian:

$$H = \mathcal{L} + \lambda^T(Fx + Gu) \tag{B.5}$$

Recalling the optimality conditions:

$$\dot{\lambda}^T = \frac{\partial H}{\partial x} \tag{B.6}$$

$$0 = \frac{\partial H}{\partial u} \tag{B.7}$$

Introducing the system equations, $\dot{x} = Fx + Gu$, and expanding the optimality equations, we have the Euler-Lagrange equations (here in matrix form):

$$\begin{bmatrix} \dot{x} \\ \dot{\lambda} \end{bmatrix} = \begin{bmatrix} F - G(B + L^TAL)^{-1}L^TAM & -G(B + L^TAL)^{-1}G^T \\ -M^TAM - M^TAL(B + L^TAL)^{-1}L^TAM & -F - M^TAL(B + L^TAL)^{-1}G^T \end{bmatrix} \begin{bmatrix} x \\ \lambda \end{bmatrix} \tag{B.8}$$

As shown in *Bryson and Ho* [4] or *Franklin and Powell* [6], the solution to these equations is $\lambda = Sx$ where $S = \Lambda_- \mathcal{X}_-^{-1}$. Λ_- and $\mathcal{X}_-$ are the submatrices of the eigenvector matrix of the Hamiltonian matrix associated with eigenvalues having negative real values, i.e.

$$\begin{bmatrix} x \\ \lambda \end{bmatrix} = \begin{bmatrix} \mathcal{X}_- & \mathcal{X}_+ \\ \Lambda_- & \Lambda_+ \end{bmatrix} \begin{bmatrix} \xi_- \\ \xi_+ \end{bmatrix} \tag{B.9}$$

With this solution for λ, the optimal steady state control, u, can be expressed as a linear combination of the state variables, x:

$$\begin{aligned} u &= Cx \\ C &= (B + L^TAL)^{-1}(L^TAM + G^TS) \end{aligned} \tag{B.10}$$

The same approach applies to finding the estimator gains, K, of the equation:

$$\dot{\hat{x}} = F\hat{x} + Gu + K(y_m - H_m\hat{x}) \tag{B.11}$$

Appendix B.

Optimal Compensator Design

The design methodology described in Chapter 2 uses an optimal full order compensator as the starting point. This appendix summarizes the derivation of the optimal compensator. From Hall and Bryson, we see that to design a set of regulator gains which minimize a quadratic performance index, we minimize the Hamiltonian with respect to the control.[17] In this case, the performance index includes the control in the output, thus enabling the weighting of state rates(accelerations). This is essential in aerospace applications where vehicle acceleration is an important parameter in the design and analysis of the control system. Starting with the modified performance index:

$$J = \int_0^\infty \mathcal{L} dt = \int_0^\infty \frac{1}{2}(y^T A y + u^T B u) dt \tag{B.1}$$

where:

$$y = Mx + Lu \tag{B.2}$$

$$y^T = x^T M^T + u^T L^T \tag{B.3}$$

Expanding the integrand of J:

$$\mathcal{L} = \frac{1}{2}\left[x^T M^T A M x + x^T M^T A L u + u^T L^T A M x + u^T (L^T A L + B) u\right] \tag{B.4}$$

σ– standard deviation of the noise variable
T_c– correlation time of the noise

With these transformations, the resulting compensator will use scaled measurements to calculate a scaled control signal. If we want to use the compensator in the physical system, we need only unscale the gain matrices. The compensator based on the scaled variables is:

$$\begin{aligned} \dot{z} &= \bar{A}z + \bar{B}\bar{y}_s \\ \bar{u} &= \bar{C}z + \bar{D}\bar{y}_s \end{aligned} \tag{A.8}$$

We unscale the system by replacing scaled vectors $\bar{u}$ and $\bar{y}_s$ with their unscaled equivalents $\bar{u} = T_c{}^{-1}u$ and $\bar{y}_s = T_m{}^{-1}y_s$:

$$\begin{aligned} \dot{z} &= \bar{A}z + \bar{B}\,T_m{}^{-1}\,y_s \\ \bar{u} &= T_c\bar{C}z + \bar{D}\,T_m{}^{-1}\,y_s \end{aligned} \tag{A.9}$$

Now the compensator uses actual (unscaled) measurements and gives unscaled control signals as outputs.

To make the scaling process consistent, I've listed some rules of thumb below:

- Scale the matrices consistently; for example, if a measurement is also a state, use the same units.
- Scale intermediate state variables in an actuator model the same as the control itself. For example, if we have a first order actuator model, $\dot{u}_a = -au_a + au_c$, then scale the actuator position state(u_a), its rate($\dot{u}_a$), and the command(u_c) identically.
- Similarly, if sensor noise filters are included in the plant model, then these noise filter states should be scaled the same as the measurements they filter.

turbances:

$$
\begin{aligned}
y_s &= T_m \bar{y}_s \\
y_c &= T_p \bar{y}_c \\
w &= T_d \bar{w} \\
v &= T_m \bar{v}
\end{aligned} \qquad (A.4)
$$

With these transformations, the scaled dynamic system is:

$$
\begin{aligned}
\dot{\bar{x}} &= \bar{F}\bar{x} + \bar{G}\bar{u} + \bar{\Gamma}\bar{w} \\
\bar{y}_s &= \bar{H}_s\bar{x} + \bar{D}_{su}\bar{u} + \bar{N}\bar{w} + \bar{v} \\
\bar{y}_c &= \bar{H}_c\bar{x} + \bar{D}_{cu}\bar{u}
\end{aligned} \qquad (A.5)
$$

where:

$$
\begin{aligned}
\bar{F} &= T_s^{-1} F T_s \\
\bar{G} &= T_s^{-1} G T_c \\
\bar{\Gamma} &= T_s^{-1} \Gamma T_d \\
\bar{H}_s &= T_m^{-1} H_s T_s \\
\bar{D}_{su} &= T_m^{-1} D_{su} T_c \\
\bar{N} &= T_m^{-1} N T_d \\
\bar{H}_c &= T_p^{-1} H_c T_s \\
\bar{D}_{cu} &= T_p^{-1} D_{cu} T_c \\
\bar{Q} &= T_d^{-1} Q T_d^{-1} \\
\bar{R} &= T_m^{-1} R T_m^{-1}
\end{aligned} \qquad (A.6)
$$

The scaled power spectral density matrices were derived using the approximation:

$$PSD \approx 2\sigma^2 T_c \qquad (A.7)$$

where:

F- plant dynamics matrix, $n \times n$

G- control distribution matrix, $n \times m$

Γ- plant disturbance distribution matrix, $n \times m'$

H_s- state to measurement distribution matrix, $p \times n$

D_{su}- control to measurement distribution matrix, $p \times m$

N- plant disturbance to measurement distribution matrix, $p \times m'$

H_c- state to output distribution matrix, $p' \times n$

D_{cu}- control to output distribution matrix, $p' \times m$

Q- plant disturbance spectral density matrix, $m' \times m'$

R- sensor noise spectral density matrix, $p \times p$

The scaling process continues by describing the changes of units on the states, controls, etc. as simple transformations. For instance, if we want new states, $\bar{x}$, and new controls, $\bar{u}$, to be $s_{x_1}x_1, s_{x_2}x_2, \ldots s_{x_n}x_n$ and $s_{u_1}u_1, s_{u_2}u_2, \ldots s_{u_n}u_n$, then we can define scaling (also similarity) transformations:

$$\begin{aligned} x &= T_s\bar{x} \\ u &= T_c\bar{u} \end{aligned} \qquad (A.2)$$

where:

$$T_s = \begin{bmatrix} \frac{1}{s_{x_1}} & & & \\ & \frac{1}{s_{x_2}} & & \\ & & \ddots & \\ & & & \frac{1}{s_{x_n}} \end{bmatrix}$$
$$T_c = \begin{bmatrix} \frac{1}{s_{u_1}} & & & \\ & \frac{1}{s_{u_2}} & & \\ & & \ddots & \\ & & & \frac{1}{s_{u_n}} \end{bmatrix} \qquad (A.3)$$

Using an identical procedure, we scale the outputs, measurements, and plant dis-

Appendix A.

Engineering Scaling

This appendix derives engineering scaling equations used in the ROPTSYS computer program. This process transforms the model of the physical system into a "similar" model where the units of the variables have changed. Similar means the eigenvalues of the system are not changed by the transformation to the new coordinates. As described in section 2.2, the new units are chosen to make the new variables of the dynamic system of equal importance to the design engineer. The process begins with the linear model shown below:

$$
\begin{aligned}
\dot{x} &= Fx + Gu + \Gamma w \\
y_s &= H_s x + D_{su} u + Nw + v \\
y_c &= H_c x + D_{cu} u \\
J &= \int_0^\infty (y_c^T A y_c + u^T B u)\, dt
\end{aligned}
\tag{A.1}
$$

where:

x-	system states, $n \times 1$
z-	compensator states, $r \times 1$
u-	controls, $m \times 1$
w-	plant disturbances, $m' \times 1$
y_s-	sensor measurements, $p \times 1$
y_c-	weighted outputs, $p' \times 1$
v-	sensor noise, $p \times 1$

ber, 1971.

18. Saberi,H.A.,"Ground Effect on Helicopter Aerodynamics and Stability",PhD Dissertation, Stanford University, October 1984.

9. Bryson,A.E., Notes from the "Optimal Estimation and Control Logic in the Presence of Noise" course at Stanford(AA278b), 1984.

10. Kelly,J.R., Niessen,F.R.,Garren,J.F., and Abbott,T.S., "Description of the VTOL Approach and Landing Technology(VALT) CH-47 Research System", NASA TP 1436, August 1979.

11. Ostroff,A.J., Downing,D.R., and Rood,W.J., "A Technique Using a Nonlinear Helicopter Model for Determining Trims and Derivatives", NASA TN D-8159, May 1976.

12. Chen,R.T.N. and Hindson,W.S., "Influence of Rotor and Other High-Order Dynamics on Helicopter Flight Control System Bandwidth", a paper to be presented at the International Conference on Rotorcraft Basic Research, Research Triangle Park, NC, February 1985.

13. Hutto,A.J., "Flight Test Report on the Heavy-Lift Helicopter Flight Control System", 31st Annual National Forum of the American Helicopter Society, May 1975.

14. Etkin,B., *Dynamics of Atmospheric Flight*, John Wiley and Sons,Inc., Toronto, 1972.

15. Valkenburg,M.E., *Introduction to Modern Network Synthesis*, John Wiley and Sons,Inc., New York, 1964.

16. Gardner,B.E.,"Feedforward/Feedback Control Logic for Robust Target Tracking", PhD Dissertation, Stanford University, December 1984.

17. Hall,W.E. and Bryson,A.E., "Optimal Control and Filter Synthesis by Eigenvector Decomposition", SUDAAR No. 436, Stanford University, Novem-

If $DD_{su} = 0$, then these equations can be rewritten as:

$$\begin{bmatrix} \dot{x} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} F + GDH_s & GC \\ B(I + D_{su}D)H_s & A + BD_{su}C \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix} + \begin{bmatrix} G \\ BD_{su} + G_z \end{bmatrix} u_c \qquad (D.2)$$

Defining $x_T = \begin{bmatrix} x \\ z \end{bmatrix}$, we can rewrite the equations above as:

$$\dot{x_T} = F_T x_T + G_T u_c \qquad (D.3)$$

Expressing the desired outputs, y_D, as a linear combination of x_T and u_c we have:

$$y_D = H_D x_T + L_D u_c \qquad (D.4)$$

At steady state, $\dot{x_T} = 0$, and the two previous equations become:

$$\begin{bmatrix} F_T & G_T \\ H_D & L_D \end{bmatrix} \begin{bmatrix} x_T \\ u_c \end{bmatrix}_{ss} = \begin{bmatrix} 0 \\ y_D \end{bmatrix} \qquad (D.5)$$

inverting:

$$\begin{aligned} \begin{bmatrix} x_T \\ u_c \end{bmatrix}_{ss} &= \begin{bmatrix} F_T & G_T \\ H_D & L_D \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ y_D \end{bmatrix} \\ &= \begin{bmatrix} \star & M \\ \star & N \end{bmatrix} \begin{bmatrix} 0 \\ y_D \end{bmatrix} \end{aligned} \qquad (D.6)$$

The steady-state controls are $u_c = N y_D$ and new equilibrium state vector is $x_T = M y_D$ where:

$$\begin{bmatrix} \star & M \\ \star & N \end{bmatrix} = \begin{bmatrix} F + GDH_s & GC & G \\ B(I + D_{su}D)H_s & A + BD_{su}C & BD_{su} + G_z \\ H_D & & L_D \end{bmatrix}^{-1} \qquad (D.7)$$

This last equation is used by the SETPNT program, Appendix L, to calculate the N matrix.

Appendix E.

Fixed Point Scaling

This appendix describes the technique of scaling the analytical designs to run on the Sperry 1819A flight computer. The process is similar in principle to scaling engineering problems for an analog computer. This computer is an 18 bit fixed-point digital computer. There are two problems which must be considered when doing this scaling. The first is avoiding overflows (exceeding $2^{17} - 1$ during calculations) and the second is maintaining precision in the results. The procedure which follows handles both these potential problems.

Consider the compensator dynamic system:

$$\begin{aligned} \dot{z} &= Az + By \\ u &= Cz \end{aligned} \tag{E.1}$$

where y and u are in engineering units (not yet computer scaled). In the computer, these variable have computer scaling factors, K, such that $\dot{z}K_{\dot{z}}$, zK_z, yK_y, and uK_u have units of bits. For example, if $K_\theta = 500\frac{bits}{deg}$, then then 5 deg of θ is 2500 bits in the computer. In these computer scaled variables, the compensator appears:

$$\begin{aligned} [\dot{z}]\, K_{\dot{z}} &= K_A\, [A]\, \frac{K_{\dot{z}}}{K_z K_A}\, [z]\, K_z + K_B\, [B]\, \frac{K_{\dot{z}}}{K_y K_B}\, [y]\, K_y \\ [u]\, K_u &= K_C\, [C]\, \frac{K_u}{K_z K_C}\, [z]\, K_z \end{aligned} \tag{E.2}$$

where A, B, and C are in engineering units. The scale factors, K, for y and u are part of the computer environment (set up by the programmers of the original flight program) but we need to calculate $K_{\dot{z}}$ and K_z. This is simplified by the digital implemention; we have z_{k+1} and z_k rather than $\dot{z}$ and z. This means only one scale facter, K_z, is needed. To find this factor, first estimate the largest value that any z_{k+1} or z_k can achieve by finding the maximum single product in the matrix multiply, $[B]\,[y]_{max}$. For controls, measurements, and desired outputs, the maximum values can be set using engineering judgement and intuition. Since we also want precision in the z term, we select K_z so that z_{max} uses all of the 18 bits available:

$$K_z = \frac{2^{17}}{z_{max}} \qquad (E.3)$$

where z_{max} is rounded up to the next power of 2. 2^{17} is used since the largest negative number expressed in 18 bits is -2^{17}.

With the K_z term, the problem of overflow is solved. Now we need only ensure that precision is maintained in the calculations by choosing the additional scale factors, K_A, K_B, and K_C that scale the elements of the A, B, and C matrices. Making use of all 18 bits, we can find these scale factors in the same way as the K_z term above was calculated:

$$\begin{aligned} K_A &= \frac{2^{17}}{a_{max}\frac{K_z}{K_z}} \\ K_B &= \frac{2^{17}}{b_{max}\frac{K_z}{K_y}} \\ K_C &= \frac{2^{17}}{c_{max}\frac{K_z}{K_u}} \end{aligned} \qquad (E.4)$$

where a_{max}, b_{max}, and c_{max} are the maximum elements of the A, B, and C matrices which have been rounded up to the nearest power of 2.

One product from the matrix multiplies is:

$$(b_{ij}\frac{K_z}{K_y})K_B(y_jK_y) \tag{E.5}$$

This number is included in the double precesion(36 bits) A register in the 1819A and is always less than $2^{35}-1$. We want to accumulate these double precision elements to get one element of By. Finally, we divide by K_A (or equivalently shift the A register) to regain the single precision inner product. This is done for each of the matrix multiplies.

The same approach is used to scale the feedforward matrix and the integral gain matrix used in the longitudinal CAS. The two BASIC computer programs, which do this scaling for the longitudinal CAS and for the hover controller, are listed in Appendix N along with example data files.

Appendix F.

CH-47 Research Helicopter

The helicopter used for this research is a highly modified version of the Boeing-Vertol CH-47 "Chinook" used by the U.S Army for cargo and troop transport. Figure F.1 shows the tandem rotor helicopter, which is operated by the NASA Ames Research Center. Reference 10 is a more complete description of this particular helicopter including the many modifications made to the basic CH-47. Below are listed some of the modifications and improved capabilities:

- Full authority, variable stability, fly-by-wire flight control system in all four axes.
- Programmable analog and digital computers capable of executing the control laws.
- Programmable force-feel system on the experimental pilot's stick.
- Flight instrumentation system capable of recording over 100 variables at 100 times per second.
- Operator's console for control of the experimental systems.
- Additional sensors: INS, radar altimeter, body-mounted accelerometers, improved air data sensors, numerous control position sensors, boom-mounted angle of attack and sideslip vanes, rate gyros
- Digital ground to air uplink capability

Figures F.2 and F.3, from reference 10, show the cabin layout in this experimental vehicle and a block diagram of the experimental control system.

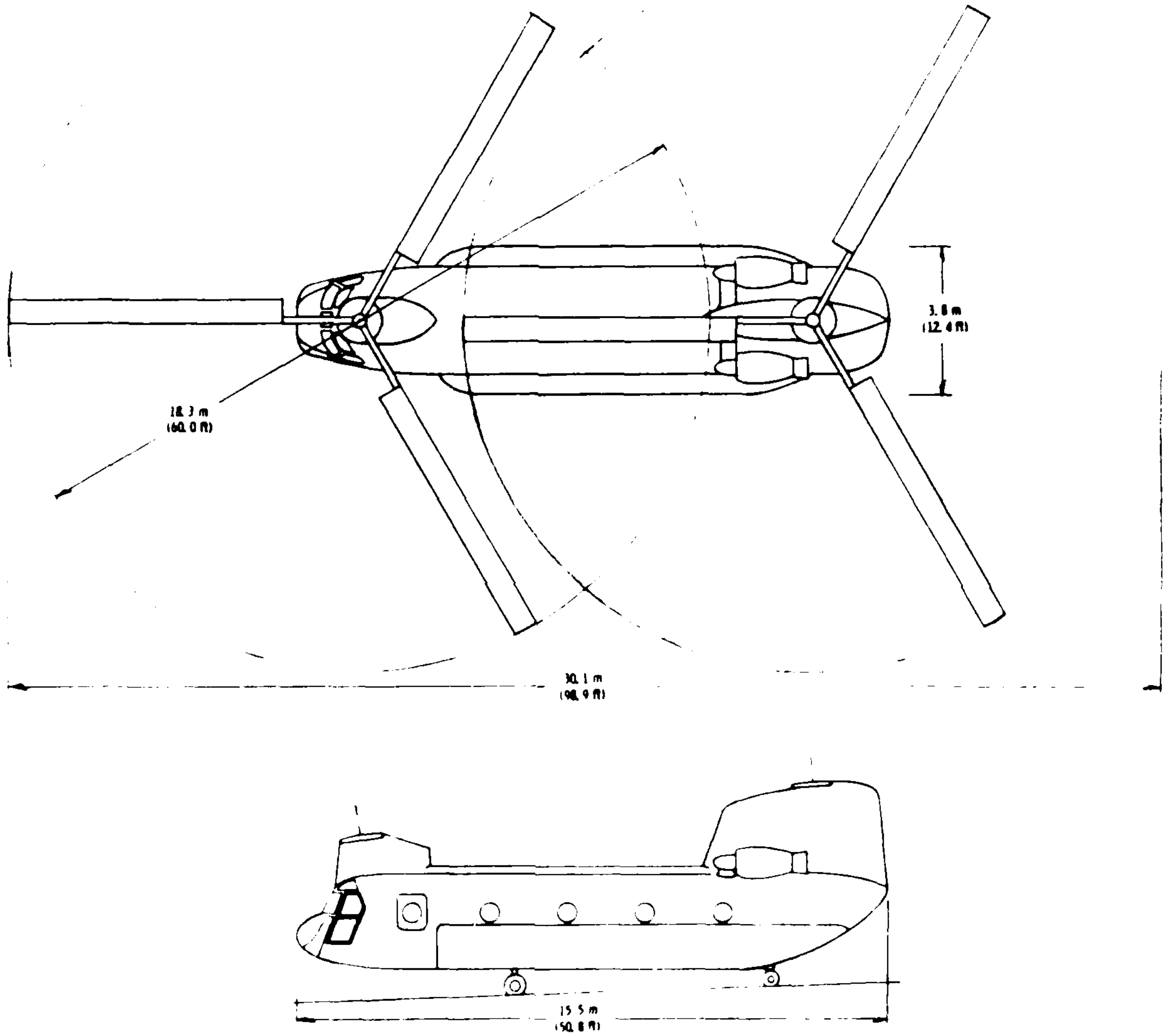

Figure F.1: **Boeing-Vertol CH-47 Chinook Helicopter.** The large tandem rotor helicopter is used operationally by the U.S. Army for cargo and troop transport. Maximum gross weight is 38000 pounds with typical operating wieght of 30000 pounds.

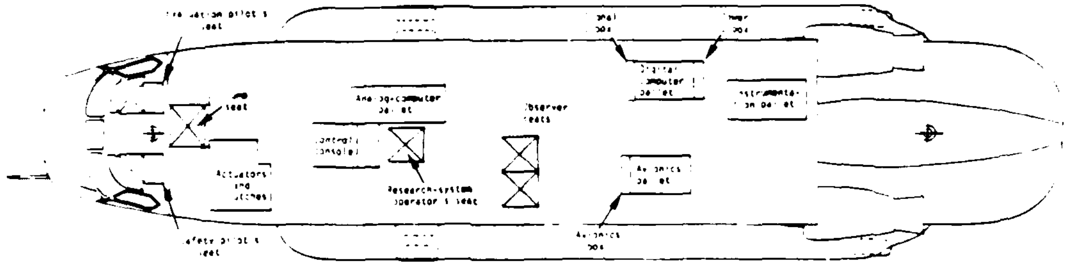

Figure F.2: **Cabin Layout.** The research helicopter requires a crew of 4; safety pilot, experimental pilot, research system operator, and crew chief.

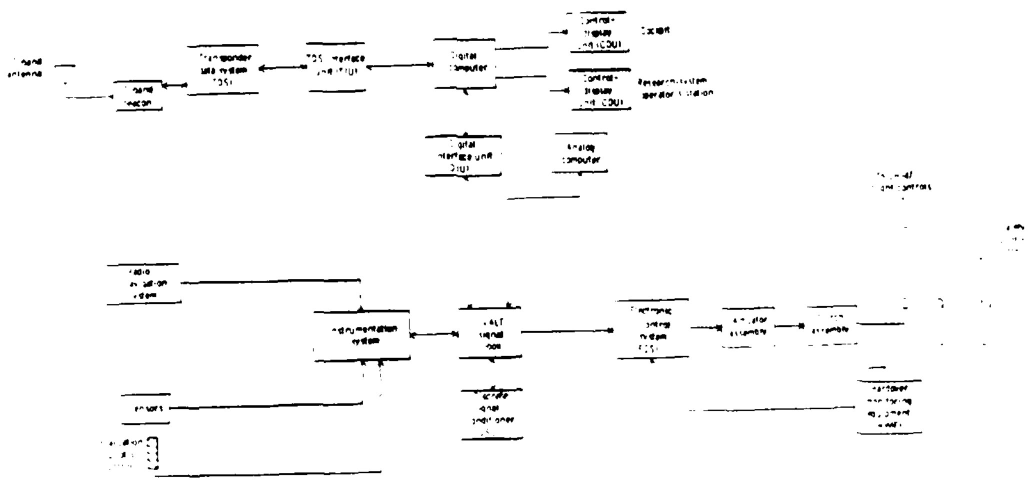

Figure F.3: **Experimental Flight Systems.** The flexibility of the experimental system is emphasized here where we note the many interfaces between the various components.

Appendix G.

CH-47 Linear Models

The models described in this appendix were calculated using the information from reference 11. The general forms for the decoupled 4^{th} order models and for the coupled 8^{th} order are shown in Figures G.1 and G.2. The linear models for the flight conditions related to this research are shown in Figures G.3 to G.16.

$$\begin{bmatrix}\dot{U}_P\\ \dot{W}_P\\ \dot{Q}_P\\ \dot{\theta}_P\end{bmatrix} = \begin{bmatrix} \frac{X_U}{m} & \frac{X_W}{m} & \left(\frac{X_Q}{m} - W_N\right) & -g\cos\theta_N \\ \frac{Z_U}{m} & \frac{Z_W}{m} & \left(U_N + \frac{Z_Q}{m}\right) & -g\sin\theta_N \\ \frac{M_U}{I_{YY}} & \frac{M_W}{I_{YY}} & \frac{M_Q}{I_{YY}} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} U_P \\ W_P \\ Q_P \\ \theta_P \end{bmatrix} + \begin{bmatrix} \frac{X_{\delta_B}}{m} & \frac{X_{\delta_C}}{m} \\ \frac{Z_{\delta_B}}{m} & \frac{Z_{\delta_C}}{m} \\ \frac{M_{\delta_B}}{I_{YY}} & \frac{M_{\delta_C}}{I_{YY}} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_{B,P} \\ \delta_{C,P} \end{bmatrix}$$

$$\begin{bmatrix}\dot{P}_P\\ \dot{\phi}_P\\ \dot{R}_P\\ \dot{V}_P\end{bmatrix} = \begin{bmatrix} \left(\frac{I_1 L_P}{I_{XX}} + \frac{I_3 N_P}{I_{ZZ}}\right) & 0 & \left(\frac{I_1 L_R}{I_{XX}} + \frac{I_3 N_R}{I_{ZZ}}\right) & \left(\frac{I_1 L_V}{I_{XX}} + \frac{I_3 N_V}{I_{ZZ}}\right) \\ 1 & 0 & \tan\theta_N & 0 \\ \left(\frac{I_2 L_P}{I_{XX}} + \frac{I_1 N_P}{I_{ZZ}}\right) & 0 & \left(\frac{I_2 L_R}{I_{XX}} + \frac{I_1 N_R}{I_{ZZ}}\right) & \left(\frac{I_2 L_V}{I_{XX}} + \frac{I_1 N_V}{I_{ZZ}}\right) \\ \left(W_N + \frac{Y_P}{m}\right) & g\cos\theta_N & \left(\frac{Y_R}{m} - U_N\right) & \frac{Y_V}{m} \end{bmatrix} \begin{bmatrix} P_P \\ \phi_P \\ R_P \\ V_P \end{bmatrix}$$

$$+ \begin{bmatrix} \left(\frac{I_1 L_{\delta_S}}{I_{XX}} + \frac{I_3 N_{\delta_S}}{I_{ZZ}}\right) & \left(\frac{I_1 L_{\delta_R}}{I_{XX}} + \frac{I_3 N_{\delta_R}}{I_{ZZ}}\right) \\ 0 & 0 \\ \left(\frac{I_2 L_{\delta_S}}{I_{XX}} + \frac{I_1 N_{\delta_S}}{I_{ZZ}}\right) & \left(\frac{I_2 L_{\delta_R}}{I_{XX}} + \frac{I_1 N_{\delta_R}}{I_{ZZ}}\right) \\ \frac{Y_{\delta_S}}{m} & \frac{Y_{\delta_R}}{m} \end{bmatrix} \begin{bmatrix} \delta_{S,P} \\ \delta_{R,P} \end{bmatrix}$$

Figure G.1: **Longitudinal and Lateral 4^{th} Order Models.** The longitudinal model above was used in the design of the longitudinal CAS (Chapter 3).

$$
\begin{bmatrix} \dot U_P \\ \dot V_P \\ \dot W_P \\ \dot P_P \\ \dot Q_P \\ \dot R_P \\ \dot\theta_P \\ \dot\phi_P \end{bmatrix}
=
\begin{bmatrix}
\frac{X_U}{m} & \frac{X_V}{m} & \frac{X_W}{m} & \frac{X_P}{m} & \left(\frac{X_Q}{m} - W_N\right) & \left(\frac{X_R}{m} + V_N\right) & -g\cos\theta_N & 0 \\
\frac{Y_U}{m} & \frac{Y_V}{m} & \frac{Y_W}{m} & \left(\frac{Y_P}{m} + W_N\right) & \frac{Y_Q}{m} & \left(\frac{Y_R}{m} - U_N\right) & -g\sin\theta_N\sin\phi_N & g\cos\theta_N\cos\phi_N \\
\frac{Z_U}{m} & \frac{Z_V}{m} & \frac{Z_W}{m} & \frac{Z_P}{m} & \left(\frac{Z_Q}{m} + U_N\right) & \frac{Z_R}{m} & -g\overset{\sin}{\cos}\theta_N & 0 \\
\left(\frac{I_1 L_U}{I_{XX}} + \frac{I_3 N_U}{I_{ZZ}}\right) & \left(\frac{I_1 L_V}{I_{XX}} + \frac{I_3 N_V}{I_{ZZ}}\right) & \left(\frac{I_1 L_W}{I_{XX}} + \frac{I_3 N_W}{I_{ZZ}}\right) & \left(\frac{I_1 L_P}{I_{XX}} + \frac{I_3 N_P}{I_{ZZ}}\right) & \left(\frac{I_1 L_Q}{I_{XX}} + \frac{I_3 N_Q}{I_{ZZ}}\right) & \left(\frac{I_1 L_R}{I_{XX}} + \frac{I_3 N_R}{I_{ZZ}}\right) & 0 & 0 \\
\frac{M_U}{I_{YY}} & \frac{M_V}{I_{YY}} & \frac{M_W}{I_{YY}} & \frac{M_P}{I_{YY}} & \frac{M_Q}{I_{YY}} & \frac{M_R}{I_{YY}} & 0 & 0 \\
\left(\frac{I_2 L_U}{I_{XX}} + \frac{I_1 N_U}{I_{ZZ}}\right) & \left(\frac{I_2 L_V}{I_{XX}} + \frac{I_1 N_V}{I_{ZZ}}\right) & \left(\frac{I_2 L_W}{I_{XX}} + \frac{I_1 N_W}{I_{ZZ}}\right) & \left(\frac{I_2 L_P}{I_{XX}} + \frac{I_1 N_P}{I_{ZZ}}\right) & \left(\frac{I_2 L_Q}{I_{XX}} + \frac{I_1 N_Q}{I_{ZZ}}\right) & \left(\frac{I_2 L_R}{I_{XX}} + \frac{I_1 N_R}{I_{ZZ}}\right) & 0 & 0 \\
0 & 0 & 0 & 0 & \cos\phi_N & -\sin\phi_N & 0 & 0 \\
0 & 0 & 0 & 1 & -\sin\phi_N\tan\theta_N & \cos\phi_N\tan\theta_N & 0 & 0
\end{bmatrix}
\begin{bmatrix} U_P \\ V_P \\ W_P \\ P_P \\ Q_P \\ R_P \\ \theta_P \\ \phi_P \end{bmatrix}
$$

$$
+
\begin{bmatrix}
\frac{X_{\delta_B}}{m} & \frac{X_{\delta_C}}{m} & \frac{X_{\delta_S}}{m} & \frac{X_{\delta_R}}{m} \\
\frac{Y_{\delta_B}}{m} & \frac{Y_{\delta_C}}{m} & \frac{Y_{\delta_S}}{m} & \frac{Y_{\delta_R}}{m} \\
\frac{Z_{\delta_B}}{m} & \frac{Z_{\delta_C}}{m} & \frac{Z_{\delta_S}}{m} & \frac{Z_{\delta_R}}{m} \\
\left(\frac{I_1 L_{\delta_B}}{I_{XX}} + \frac{I_3 N_{\delta_B}}{I_{ZZ}}\right) & \left(\frac{I_1 L_{\delta_C}}{I_{XX}} + \frac{I_3 N_{\delta_C}}{I_{ZZ}}\right) & \left(\frac{I_1 L_{\delta_S}}{I_{XX}} + \frac{I_3 N_{\delta_S}}{I_{ZZ}}\right) & \left(\frac{I_1 L_{\delta_R}}{I_{XX}} + \frac{I_3 N_{\delta_R}}{I_{ZZ}}\right) \\
\frac{M_{\delta_B}}{I_{YY}} & \frac{M_{\delta_C}}{I_{YY}} & \frac{M_{\delta_S}}{I_{YY}} & \frac{M_{\delta_R}}{I_{YY}} \\
\left(\frac{I_2 L_{\delta_B}}{I_{XX}} + \frac{I_1 N_{\delta_B}}{I_{ZZ}}\right) & \left(\frac{I_2 L_{\delta_C}}{I_{XX}} + \frac{I_1 N_{\delta_C}}{I_{ZZ}}\right) & \left(\frac{I_2 L_{\delta_S}}{I_{XX}} + \frac{I_1 N_{\delta_S}}{I_{ZZ}}\right) & \left(\frac{I_2 L_{\delta_R}}{I_{XX}} + \frac{I_1 N_{\delta_R}}{I_{ZZ}}\right) \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} \delta_{B,P} \\ \delta_{C,P} \\ \delta_{S,P} \\ \delta_{R,P} \end{bmatrix}
$$

$I_{XX} = 50\ 386.3$ kg-m^2 (37 163 slug-ft^2)

$I_{YY} = 273\ 536$ kg-m^2 (201 750 slug-ft^2)

$I_{ZZ} = 257\ 685$ kg-m^2 (190 059 slug-ft^2)

$I_{XZ} = 19\ 338.3$ kg-m^2 (14 632 slug-ft^2)

$m = 14\ 968.6$ kg (1 025.67 slug)

where

$$
I_1 = \frac{I_{XX} I_{ZZ}}{I_{XX} I_{ZZ} - I_{XZ}^2} \qquad I_2 = \frac{I_{XX} I_{XZ}}{I_{XX} I_{ZZ} - I_{XZ}^2} \qquad I_3 = \frac{I_{ZZ} I_{XZ}}{I_{XX} I_{ZZ} - I_{XZ}^2}
$$

Figure G.2: **Coupled 8^{th} Order Model.** This model was used in the design of the hover controller, described in Chapter 4.

THIS IS DATA FOR ZDOT= 0 FT/MIN AND XDOT OR AIRSFEED=
60 KNOTS

	X	Y	Z	L	M	N
U	-0.02046	-0.00017	-0.06631	-0.00024	-0.00420	0.00030
V	0.00014	-0.07404	0.00487	-0.00548	-0.00006	-0.00009
W	0.03764	0.00330	-0.55118	0.00166	0.01764	-0.00036
DB	0.12688	0.51850	0.46734	0.00376	0.39113	0.02811
DC	0.42640	0.04854	-9.35989	-0.00864	0.15286	0.00552
DS	0.00003	1.11989	-0.00044	0.40554	0.00000	0.00887
DR	0.00004	-0.05298	0.00008	-0.13452	0.00011	0.19699
P	0.00380	-2.03591	0.21481	-0.81835	0.02270	-0.01663
Q	2.35790	0.00340	-1.17918	0.00117	-1.68183	-0.07923
R	-0.04676	-0.22199	0.28535	-0.06732	0.00267	-0.03912

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	-0.02046	0.03764	2.35790	-32.14647
2	-0.06631	-0.55118	99.02081	-1.85603
3	-0.00420	0.01764	-1.68183	0.00000
4	0.00000	0.00000	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

	1	2
	0.12688	0.42640
	0.46734	-9.35989
	0.39113	0.15286
	0.00000	0.00000

LATERAL F-MATRIX IS:

	1	2	3	4
1	-0.85072	0.00000	-0.08531	-0.00569
2	1.00000	0.00000	0.05774	0.00000
3	-0.08221	0.00000	-0.04570	-0.00053
4	-2.03591	32.14647	%-100.42200	-0.07404

LATERAL G-MATRIX IS:

	1	2
	0.42183	-0.05875
	0.00000	0.00000
	0.04139	0.19246
	1.11989	-0.05298

THE 8TH ORDER F-MATRIX IS:

	1	2	3	4	5	6	7	8
1	-0.02046	0.00014	0.03764	0.00380	2.35790	-0.04676	-32.14647	[illegible]
2	-0.00017	-0.07404	0.00330	-2.03591	0.00340	%-100.42200	0.00902	32.14[illegible]
3	-0.06631	0.00487	-0.55118	0.21481	99.02081	0.28535	-1.85603	[illegible]
4	-0.00017	0.00569	0.00157	-0.85072	-0.03096	-0.08531	0.00000	[illegible]
5	-0.00420	-0.00006	0.01764	0.02270	-1.68183	0.00267	0.00000	[illegible]
6	[illegible]	-0.00053	-0.00024	-0.08221	-0.08152	-0.04570	0.00000	[illegible]
7	0.00000	0.00000	0.00000	0.00000	0.99999	0.00436	[illegible]	[illegible]
8	[illegible]	0.00000	0.00000	1.00000	0.00023	0.05774	0.00000	[illegible]

THE 8TH ORDER G-MATRIX IS:

	1	2	3	4
1	0.12688	0.42640	0.00003	0.00004
2	0.51850	0.04854	1.11989	-0.05298
3	0.46734	-9.35989	-0.00044	0.00008
4	[illegible]	-0.00667	0.42183	-0.05375
5	[illegible]	0.15286	0.00000	0.00011
6	[illegible]	-0.00501	0.04139	-0.01069
7	[illegible]	0.00000	0.00000	0.00000
8	[illegible]	0.00000	0.00000	0.00000

Figure G.3: **Linear Model for Airspeed of 60 knots, Climb Rate 0 ft/min.**

THIS IS DATA FOR ZDOT= [illegible] [illegible]
40 [illegible]NOTS

	X	Y	Z	L	M	N
[illegible]	[illegible]	-0.00006	[illegible]	[illegible]014	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]555	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]4433	[illegible]0151	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]75760	[illegible]	[illegible]5534	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]55870	[illegible]01174	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]40660	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]17136	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]1748	[illegible]475	[illegible]	[illegible]1442
[illegible]	[illegible]	[illegible]	[illegible]14124	[illegible]	[illegible]	[illegible]11142
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]8241	[illegible]	[illegible]

[illegible]

Figure G.4: **Linear Model for Airspeed of 40 knots, Climb Rate 0 ft/min.**

THIS IS DATA FOR ZDOT= [illegible] FT/MIN AND [illegible]

80 KNOTS

	[illegible]	Y	Z	L	[illegible]	[illegible]
U	-0.[illegible]	0.00026	-0.0[illegible]44	[illegible]14	[illegible]	[illegible]
V	[illegible]24	-0.08899	[illegible]425	[illegible]564	[illegible]	[illegible]
W	[illegible]	[illegible]	[illegible]3408	0.00166	[illegible]4	[illegible]
DB	[illegible]	[illegible]	[illegible].47[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]4	[illegible]	10.23[illegible]	[illegible]4	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]2	0.4[illegible]	[illegible]	[illegible]
[illegible]	[illegible]2	[illegible]42	[illegible]4	[illegible]1334	[illegible]	[illegible]
[illegible]	[illegible]515	[illegible]4	[illegible]457	[illegible]2356	[illegible]	[illegible]
[illegible]	[illegible]59	[illegible]	[illegible]	[illegible]	[illegible]561	[illegible]
[illegible]	[illegible]	[illegible]425	[illegible]	[illegible]615	[illegible]	[illegible]

[illegible] HAL [illegible] MATRIX IS:

[illegible] .1+517 [illegible]

.14[illegible]7 [illegible]

[illegible] LATERAL [illegible] IS:

Figure G.5: **Linear Model for Airspeed of 80 knots, Climb Rate 0 ft/min.**

THIS IS DATA FOR ZDOT= [illegible] FT/MIN AND [illegible] OF AIRSPEED=
60 KNOTS

	X	Y	Z	L	M	N
U	-0.01924	-0.[illegible]039	-0.07755	-0.[illegible]035	-0.00518	[illegible]
V	[illegible]	-0.[illegible]41	0.[illegible]30	-0.[illegible]511	-0.[illegible]	-0.[illegible]14
W	0.[illegible]	[illegible]	0.22448	-0.00199	0.01[illegible]	-0.[illegible]
DB	0.12495	[illegible]	0.52490	0.00959	0.39146	[illegible]
DC	0.45862	[illegible]4051	-9.13301	-0.00432	0.16807	0.00181
DS	[illegible]	1.1[illegible]	[illegible]	0.40[illegible]	0.[illegible]	[illegible]
DR	[illegible]7	-0.05031	0.00740	-0.17521	0.[illegible]	.17502
P	[illegible]43	-2.2[illegible]	0.25493	-0.87[illegible]	0.[illegible]459	-0.11495
Q	1.22194	[illegible]	-1.44592	-0.02289	-1.70716	-0.04605
R	-0.[illegible]	-[illegible]	0.51518	0.77781	0.01524	-0.03829

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	-0.01924	-0.03901	-5.[illegible]139	-32.14122
2	-0.07755	0.22448	93.751[illegible]8	-1.94458
3	-0.00518	0.01[illegible]	-1.70716	0.00000
4	[illegible]	[illegible]	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

	1	2
1	0.12495	0.45862
2	0.52490	-9.13301
3	0.39146	[illegible]
4	0.00000	[illegible]

LATERAL F-MATRIX IS:

	1	2	3	4
1	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]	[illegible]

LATERAL G-MATRIX IS:

	1	2
1	[illegible]	[illegible]
2	[illegible]	[illegible]
3	[illegible]	[illegible]
4	[illegible]	[illegible]

Figure G.6: **Linear Model for Airspeed of 60 knots, Climb Rate 500 ft/min.**

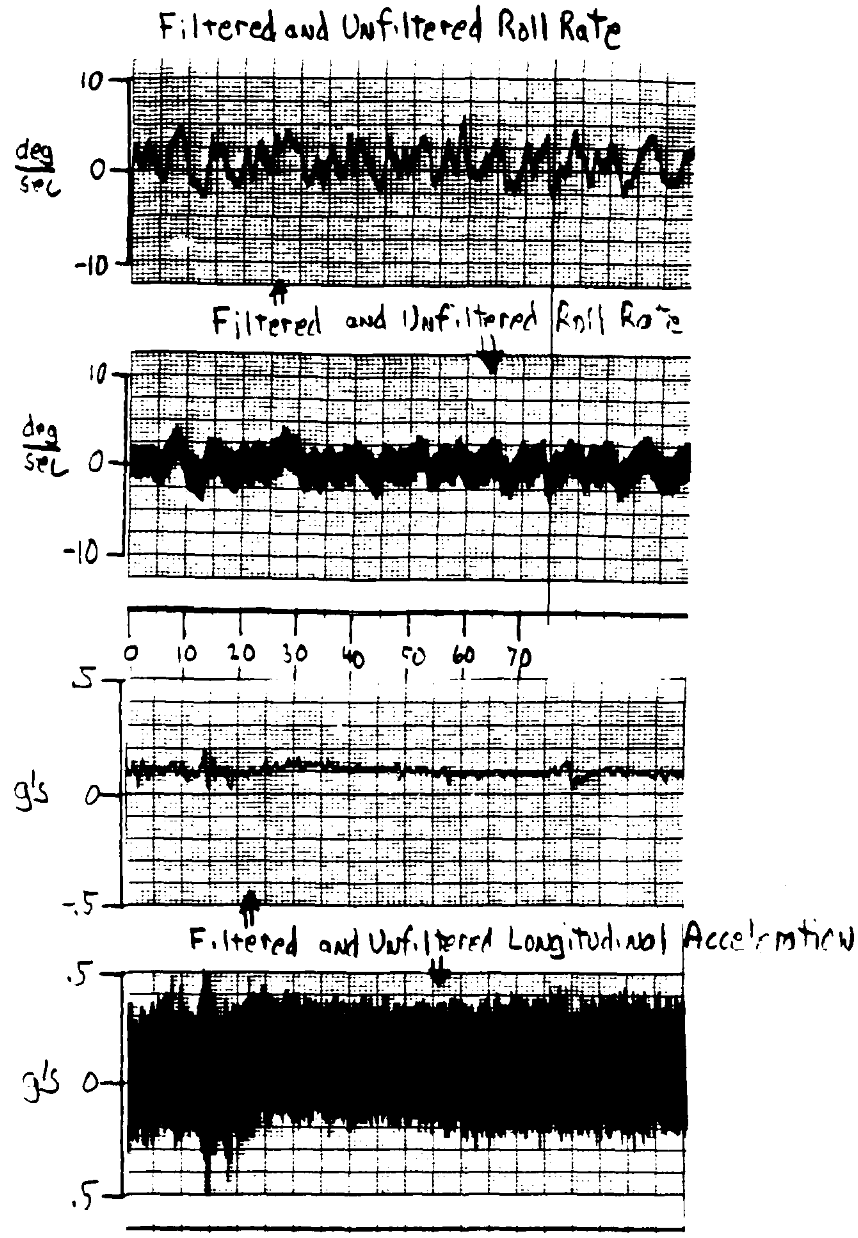

Figure H.2: **Comparison of Filtered and Unfiltered Data in Flight.** The importance of the filters is evident here where -data- is shown before and after the filter.

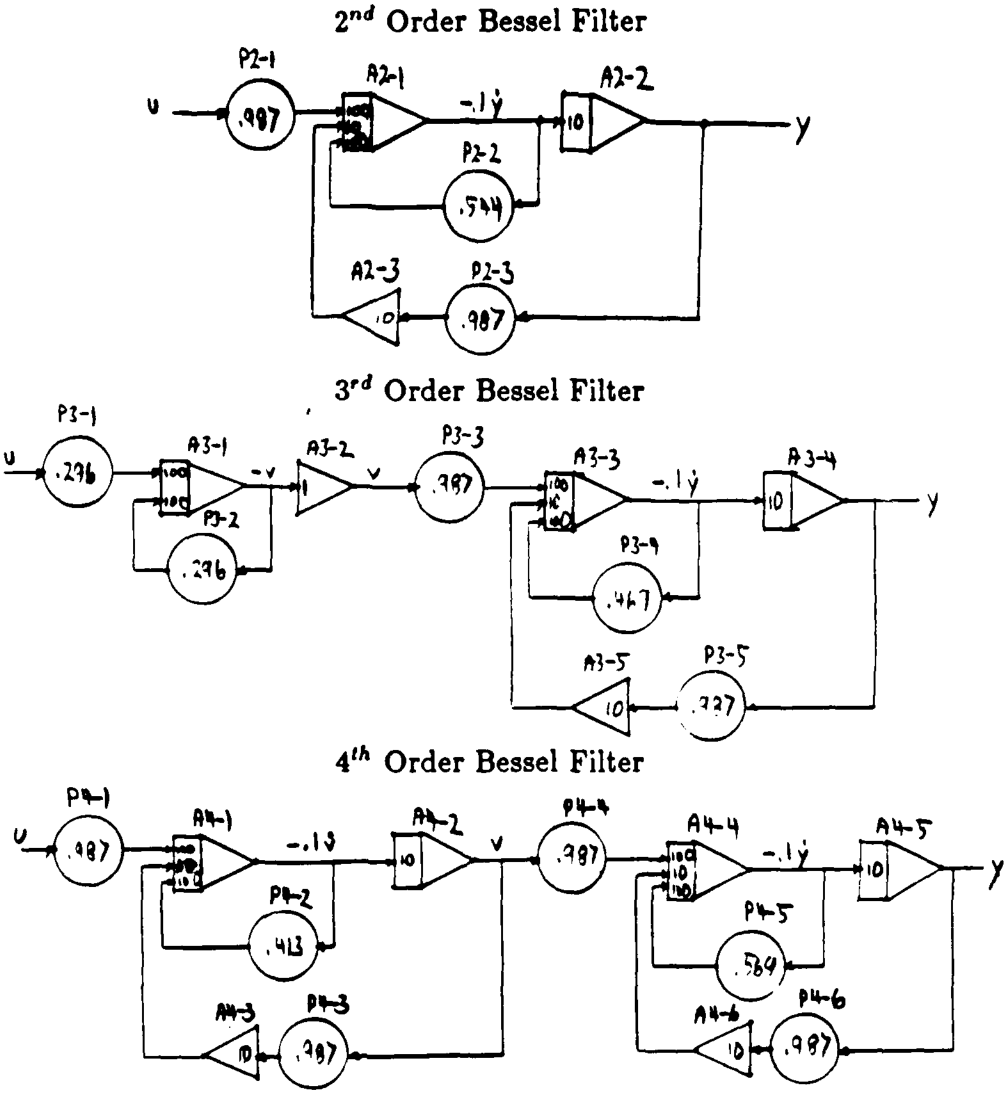

Figure H.1: **Bessel Filter Analog Flow Diagrams.** These filters were programmed on the airborne TR-48 analog computer.

shown in Figure H.2 where the unfiltered and filtered measurements are compared. By the end of flight test, all these filters were replaced by hardwired 3^{rd} order Bessel filters located in a signal conditioning box.

Appendix H.

Bessel Filters

The Bessel filters described here were designed to eliminate the "3 per rev" and "6 per rev" harmonics at 11 Hz and 22 Hz due to the 225 rpm rotor. The break frequency was chosen at 5 Hz as a compromise between noise attenuation and measurement bandwidth. The actual filter designs came from reference 15. Nine filters were patched on the airborne TR-48 analog computer:

4^{th} order– Body axis accelerations (A_x, A_y, A_z)

3^{rd} order– Roll rate (p)

2^{nd} order– Pitch rate (q), Yaw rate (r), Velocity (u), Altitude (h)

The transfer functions for these filters are shown below:

$$\frac{974603}{s^4 + 98s^3 + 4323s^2 + 96906s + 974603}$$

$$\frac{29220}{s^3 + 76s^2 + 2374s + 29220} \tag{H.1}$$

$$\frac{987}{s^2 + 54s + 987}$$

Figure H.1 shows the analog patch diagrams for these filters. Their effectiveness is

THIS IS DATA FOR ZDOT= -500 FT/MIN AND XDOT OR AIRSPEED= 20 KNOTS

	X	Y	Z	L	M	N
U	-0.00641	0.00087	-0.11816	-0.00012	0.00468	0.00050
V	0.00053	-0.11666	0.00208	-0.00619	-0.00088	0.00135
W	0.03589	0.00354	-0.37819	0.00067	0.00836	0.00028
DB	0.11223	0.03487	0.15524	-0.01678	0.34191	0.04829
DC	0.70594	0.06762	-8.31674	-0.01528	0.03169	0.00386
DS	-0.00007	1.15112	0.00073	0.41279	0.00000	0.01026
DR	-0.00005	-0.03522	-0.00002	-0.13336	-0.00015	0.20260
P	-0.00190	-1.40184	-0.09404	-0.66455	-0.05462	-0.01072
Q	2.52291	-0.02457	0.38001	0.07991	-1.31713	-0.16680
R	-0.02995	-0.15189	-0.44359	-0.04845	-0.00624	-0.04239

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	-0.00641	0.03589	10.85624	-32.05505
2	-0.11816	-0.37819	33.78001	-3.05181
3	0.00468	0.00836	-1.31713	0.00000
4	0.00000	0.00000	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

	1	2
1	0.11223	0.70594
2	0.15524	-8.31674
3	0.34191	0.03169
4	0.00000	0.00000

LATERAL F-MATRIX IS:

	1	2	3	4
1	-0.68970	0.00000	-0.06718	-0.00584
2	1.00000	0.00000	0.09521	0.00000
3	-0.06389	0.00000	-0.04757	0.00090
4	-9.73517	32.05505	-33.55189	-0.11666

LATERAL G-MATRIX IS:

	1	2
1	0.42988	-0.05528
2	0.00000	0.00000
3	0.04340	0.19834
4	1.15112	-0.03522

THE 8TH ORDER F-MATRIX IS:

	1	2	3	4	5	6	7	8
1	-0.00641	0.00053	0.03589	-0.00190	10.85624	-0.02995	-32.05505	0.00000
2	0.00087	-0.11666	0.00354	-9.73517	-0.02437	-33.55189	0.02449	32.05402
3	-0.11816	0.00208	-0.37819	-0.09404	33.78001	-0.44359	-3.05181	0.00000
4	0.00008	-0.00584	0.00080	-0.68970	0.01469	-0.06718	0.00000	0.00000
5	0.00468	-0.00088	0.00836	-0.05462	-1.31713	-0.00624	0.00000	0.00000
6	0.00051	0.00090	0.00034	-0.06389	-0.16567	-0.04757	0.00000	0.00000
7	0.00000	0.00000	0.00000	0.00000	0.99997	0.00802	0.00000	0.00000
8	0.00000	0.00000	0.00000	1.00000	0.00076	0.09520	0.00000	0.00000

THE 8TH ORDER G-MATRIX IS:

	1	2	3	4
1	0.11223	0.70594	-0.00007	-0.00005
2	0.03487	0.06762	1.15112	-0.03522
3	0.15524	-8.31674	0.00073	-0.00002
4	0.00330	-0.01419	0.42988	-0.05528
5	0.34191	0.03169	0.00000	-0.00015
6	0.04847	0.00277	0.04340	-0.01060
7	0.00000	0.00000	0.00000	0.00000
8	0.00000	0.00000	0.00000	0.00000

Figure G.16: **Linear Model for Airspeed of 20 knots, Climb Rate -500 ft/min.**

THIS IS DATA FOR ZDOT= 500 FT/MIN AND XDOT OR AIRSPEED= 20 KNOTS

	X	Y	Z	L	M	N
U	0.00129	0.00122	-0.16248	0.00027	0.00965	0.00031
V	-0.00143	-0.10831	0.01176	-0.00563	0.00097	0.00131
W	0.03219	0.00341	-0.31546	0.00096	0.01226	0.00010
DB	0.10490	0.04843	0.16602	-0.00798	0.32750	0.03966
DC	0.69235	0.05507	-8.15329	-0.01434	0.00333	0.00324
DS	0.00013	1.14249	-0.00136	0.41067	0.00000	0.01006
DR	0.00008	-0.03710	0.00018	-0.13291	0.00027	0.20108
P	0.01602	-1.73729	0.31697	-0.74894	0.08761	-0.00977
Q	2.52136	-0.06817	-0.09012	0.04674	-1.34224	-0.13206
R	-0.17655	-0.19694	1.42350	-0.06014	0.01388	-0.04086

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	0.00129	0.03219	-5.81197	-32.05065
2	-0.16248	-0.31546	33.30988	-3.09780
3	0.00965	0.01226	-1.34224	0.00000
4	0.00000	0.00000	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

1	2
0.10490	0.69235
0.16602	-8.15329
0.32750	0.00333
0.00000	0.00000

LATERAL F-MATRIX IS:

	1	2	3	4
1	-0.77635	0.00000	-0.07861	-0.00527
2	1.00000	0.00000	0.09665	0.00000
3	-0.06962	0.00000	-0.04692	0.00090
	6.59604	32.05065	-33.59694	-0.10831

LATERAL G-MATRIX IS:

1	2
0.42761	-0.05543
0.00000	0.00000
0.04302	0.19681
1.14249	-0.03710

THE 8TH ORDER F-MATRIX IS:

	1	2	3	4	5	6	7	8
1	0.00129	-0.00143	0.03219	0.01602	-5.81197	-0.17655	-32.05065	[illegible]
2	0.00122	-0.10831	0.00341	6.59604	-0.06817	-33.59694	0.02086	32.04992
3	-0.16248	0.01176	-0.31546	0.31697	33.30988	1.42350	-3.09780	[illegible]
4	0.00040	-0.00527	0.00103	-0.77635	-0.00541	-0.07361	0.00000	[illegible]
5	0.00965	0.00097	0.01226	0.08761	-1.34224	0.01388	0.00000	[illegible]
6	0.00034	0.00090	0.00018	-0.06962	-0.13249	-0.04692	0.00000	[illegible]
7	0.00000	0.00000	0.00000	0.00000	0.99998	0.00577	0.00000	[illegible]
8	0.00000	0.00000	0.00000	1.00000	0.00065	[illegible]	0.00000	[illegible]

THE 8TH ORDER G-MATRIX IS:

	1	2	3	4
1	0.10490	0.69235	0.00013	0.00008
2	0.04843	0.05507	1.14249	-0.03710
3	0.16602	-8.15329	-0.00136	0.00018
4	0.00787	-0.01347	0.42761	-0.05543
5	0.32750	0.00333	0.00000	0.00027
6	0.04027	0.00220	0.04302	-0.01057
7	0.00000	0.00000	0.00000	0.00000
8	0.00000	0.00000	0.00000	0.00000

Figure G.15: **Linear Model for Airspeed of 20 knots, Climb Rate 500 ft/min.**

THIS IS DATA FOR ZDOT= 0 FT/MIN AND XDOT OR AIRSPEED= 20 KNOTS

	X	Y	Z	L	M	N
U	-0.00259	0.00095	-0.14099	0.00004	0.00679	0.00042
V	-0.00046	-0.11155	0.00524	-0.00591	-0.00006	0.00132
W	0.03412	0.00334	-0.34885	0.00077	0.00992	0.00021
DB	0.10849	0.04076	0.16269	-0.01247	0.33528	0.04371
DC	0.69883	0.06166	-8.21477	-0.01453	0.02107	0.00344
DS	0.00004	1.14599	-0.00040	0.41153	0.00000	0.01014
DR	0.00002	-0.03632	0.00012	-0.13309	0.00009	0.20170
P	0.00784	-1.57519	0.18709	-0.70862	0.03618	-0.00921
Q	2.51853	-0.04279	0.21293	0.06396	-1.31598	-0.14872
R	-0.09582	-0.17614	0.39539	-0.05466	-0.00294	-0.04145

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	-0.00259	0.03412	2.51853	-32.05281
2	-0.14099	-0.34885	33.61293	-3.07534
3	0.00679	0.00992	-1.31598	0.00000
4	0.00000	0.00000	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

	1	2
	0.10849	0.69883
	0.16269	-8.21477
	0.33528	0.02107
	0.00000	0.00000

LATERAL F-MATRIX IS:

	1	2	3	4
1	-0.73454	0.00000	-0.07320	-0.00556
2	1.00000	0.00000	0.09595	0.00000
3	-0.06583	0.00000	-0.04709	0.00089
	-1.57519	32.05281	-33.57614	-0.11155

LATERAL G-MATRIX IS:

	1	2
	0.42853	-0.05537
	0.00000	0.00000
	0.04317	0.19743
	1.14599	-0.03632

THE 8TH ORDER F-MATRIX IS:

	1	2	3	4	5	6	7	8
1	-0.00259	-0.00046	0.03412	0.00784	2.51853	-0.09582	-32.05281	0.00000
2	0.00095	-0.11155	0.00334	-1.57519	-0.04279	-33.57614	0.02265	32.05194
3	-0.14099	0.00524	-0.34885	0.18709	33.61293	0.39539	-3.07534	0.00000
4	0.00021	-0.00556	0.00088	-0.73454	0.00558	-0.07320	0.00000	0.00000
5	0.00679	-0.00006	0.00992	0.03618	-1.31598	-0.00294	0.00000	0.00000
6	0.00044	0.00089	0.00028	-0.06583	-0.14829	-0.04709	0.00000	0.00000
7	0.00000	0.00000	0.00000	0.00000	0.99997	0.00336	0.00000	0.00000
8	0.00000	0.00000	0.00000	1.00000	0.00071	0.09594	0.00000	0.00000

THE 8TH ORDER G-MATRIX IS:

	1	2	3	4
1	0.10849	0.69883	0.00004	0.00002
2	0.04076	0.06166	1.14599	-0.03632
3	0.16269	-8.21477	-0.00040	0.00012
4	0.00489	-0.01359	0.42853	-0.05537
5	0.33528	0.02107	0.00000	0.00009
6	0.04409	0.00239	0.04317	-0.01058
7	0.00000	0.00000	0.00000	0.00000
8	0.00000	0.00000	0.00000	0.00000

Figure G.14: **Linear Model for Airspeed of 20 knots, Climb Rate 0 ft/min.**

THIS IS DATA FOR ZDOT= -500 FT/MIN AND XDOT OR AIRSPEED=
0 KNOTS

	X	Y	Z	L	M	N
U	-0.02325	-0.00038	0.02826	-0.00037	0.00623	0.00050
V	-0.00097	-0.14525	0.00135	-0.00635	0.00008	-0.00070
W	0.03589	0.00301	-0.32741	0.00047	0.00203	0.00026
DB	0.11831	0.01249	0.02908	-0.02638	0.33695	0.05075
DC	0.94701	0.06887	-8.13578	-0.01448	0.02009	0.00098
DS	-0.00015	1.16274	0.00125	0.41643	0.00000	0.00924
DR	-0.00008	-0.05288	-0.00009	-0.13909	-0.00026	0.20448
P	0.03242	-1.32917	-0.17822	-0.65429	0.00108	0.00184
Q	2.59202	0.00144	0.46157	0.10871	-1.24188	-0.17600
R	-0.12040	-0.14595	0.31169	-0.04691	-0.00288	-0.04263

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	-0.02325	0.03589	10.92535	-31.98588
2	0.02826	-0.32741	0.46157	-3.70723
3	0.00623	0.00203	-1.24188	0.00000
4	0.00000	0.00000	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

	1	2
1	0.11831	0.94701
2	0.02908	-8.13578
3	0.33695	0.02009
4	0.00000	0.00000

LATERAL F-MATRIX IS:

	1	2	3	4
1	-0.67402	0.00000	-0.06569	-0.00683
2	1.00000	0.00000	0.11590	0.00000
3	-0.05012	0.00000	-0.04769	-0.00123
4	-9.66250	31.98588	-0.14595	-0.14525

LATERAL G-MATRIX IS:

	1	2
1	0.43322	-0.06042
2	0.00000	0.00000
3	0.04264	0.19982
4	1.16274	-0.05288

THE 8TH ORDER F-MATRIX IS:

	1	2	3	4	5	6	7	8
1	-0.02325	-0.00097	0.03589	0.03242	10.92535	-0.12040	-31.98588	0.00000
2	-0.00038	-0.14525	0.00301	-9.66250	0.00144	-0.14595	0.03116	31.98475
3	0.02826	0.00135	-0.32741	-0.17822	0.46157	0.31169	-3.70723	0.00000
4	-0.00018	-0.00683	0.00059	-0.67402	0.04066	-0.06569	0.00000	0.00000
5	0.00623	0.00008	0.00203	0.00108	-1.24188	-0.00288	0.00000	0.00000
6	0.00049	-0.00123	0.00031	-0.05012	-0.17287	-0.04769	0.00000	0.00000
7	0.00000	0.00000	0.00000	0.00000	0.99996	0.00840	0.00000	0.00000
8	0.00000	0.00000	0.00000	1.00000	0.00097	0.11590	0.00000	0.00000

THE 8TH ORDER G-MATRIX IS:

	1	2	3	4
1	0.11831	0.94701	-0.00015	-0.00008
2	0.01249	0.06887	1.16274	-0.05288
3	0.02908	-8.13578	0.00125	-0.00009
4	-0.00660	-0.01454	0.43322	-0.06042
5	0.33695	0.02009	0.00000	-0.00026
6	0.05024	-0.00014	0.04264	-0.01106
7	0.00000	0.00000	0.00000	0.00000
8	0.00000	0.00000	0.00000	0.00000

Figure G.13: **Linear Model for Airspeed of 0 knots, Climb Rate -500 ft/min.**

THIS IS DATA FOR ZDOT= 500 FT/MIN AND XDOT OR AIRSPEED= 0 KNOTS

	X	Y	Z	L	M	N
U	-0.01857	-0.00001	0.02097	-0.00014	0.01356	0.00023
V	-0.00127	-0.13179	0.00975	-0.00583	0.00027	-0.00055
W	0.02894	0.00244	-0.25982	0.00052	0.00285	0.00018
DB	0.10910	0.01113	0.03148	-0.02213	0.31958	0.04294
DC	0.93710	0.05696	-8.05096	-0.01419	0.01764	0.00052
DS	0.00012	1.15717	-0.00110	0.41509	0.00000	0.00906
DR	0.00007	-0.05506	0.00005	-0.13905	0.00021	0.20349
P	-0.02869	-1.64496	0.35800	-0.73128	0.01003	-0.00148
Q	2.57072	0.00500	0.40010	0.09244	-1.24855	-0.14708
R	-0.08620	-0.18117	0.43277	-0.05704	0.01044	-0.04078

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	-0.01857	0.02894	-5.76261	-31.98550
2	0.02097	-0.25982	0.40010	-3.71050
3	0.01356	0.00285	-1.24855	0.00000
4	0.00000	0.00000	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

	1	2
1	0.10910	0.93710
2	0.03148	-8.05096
3	0.31958	0.01764
4	0.00000	0.00000

LATERAL F-MATRIX IS:

	1	2	3	4
1	-0.75477	0.00000	-0.07538	-0.00624
2	1.00000	0.00000	0.11601	0.00000
3	-0.05966	0.00000	-0.04659	-0.00103
	6.68837	31.98550	-0.18117	-0.13179

LATERAL G-MATRIX IS:

	1	2
1	0.43176	-0.06079
2	0.00000	0.00000
3	0.04234	0.19880
	1.15717	-0.05506

THE 8TH ORDER F-MATRIX IS:

	1	2	3	4	5	6	7	8
1	-0.01857	-0.00127	0.02894	-0.02869	-5.76261	-0.08620	-31.98550	0.00000
2	-0.00001	-0.13179	0.00244	6.68837	0.00500	-0.18117	0.02737	31.98464
3	0.02097	0.00975	-0.25982	0.35800	0.40010	0.43277	-3.71050	0.00000
4	-0.00005	-0.00624	0.00061	-0.75477	0.03562	-0.07538	0.00000	0.00000
5	0.01356	0.00027	0.00285	0.01003	-1.24855	0.01044	0.00000	0.00000
6	0.00023	-0.00103	0.00023	-0.05966	-0.14433	-0.04659	0.00000	0.00000
7	0.00000	0.00000	0.00000	0.00000	0.99997	0.00738	0.00000	0.00000
8	0.00000	0.00000	0.00000	1.00000	0.00086	0.11600	0.00000	0.00000

THE 8TH ORDER G-MATRIX IS:

	1	2	3	4
1	0.10910	0.93710	0.00012	0.00007
2	0.01113	0.05696	1.15717	-0.05506
3	0.03148	-8.05096	-0.00110	0.00005
4	-0.00539	-0.01442	0.43176	-0.06079
5	0.31958	0.01764	0.00000	0.00021
6	0.04252	-0.00059	0.04234	-0.01105
7	0.00000	0.00000	0.00000	0.00000
8	0.00000	0.00000	0.00000	0.00000

Figure G.12: **Linear Model for Airspeed of 0 knots, Climb Rate 500 ft/min.**

THIS IS DATA FOR ZDOT= 0 FT/MIN AND XDOT OR AIRSPEED= 0 KNOTS

	X	Y	Z	L	M	N
U	-0.02114	-0.00019	0.02484	-0.00028	0.00925	0.00040
V	-0.00085	-0.13712	0.00374	-0.00608	0.00017	-0.00062
W	0.03259	0.00265	-0.29557	0.00048	0.00234	0.00022
DB	0.11408	0.01175	0.30310	-0.02410	0.32921	0.04655
DC	0.93867	0.06353	-8.06188	-0.01403	0.01905	0.00072
DS	0.00000	1.15902	-0.00002	0.41552	0.00000	0.00914
DR	-0.00001	-0.05395	0.00011	-0.13896	0.00000	0.20382
P	0.02051	1.49383	0.04190	-0.69495	0.04267	0.00080
Q	2.58521	0.00414	0.43507	0.10020	-1.22925	-0.16052
R	-0.10552	-0.16450	0.36222	-0.05220	-0.00433	-0.04172

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	-0.02114	0.03259	2.58521	-31.98577
2	0.02484	-0.29557	0.43507	-3.70815
3	0.00925	0.00234	-1.22925	0.00000
4	0.00000	0.00000	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

	1	2
	0.11408	0.93867
	0.30310	-8.06188
	0.32921	0.01905
	0.00000	0.00000

LATERAL F-MATRIX IS:

	1	2	3	4
1	-0.71638	0.00000	-0.07077	-0.00652
2	1.00000	0.00000	0.11593	0.00000
3	-0.05442	0.00000	-0.04718	-0.00112
4	-1.49383	31.98577	-0.16450	-0.13712

LATERAL G-MATRIX IS:

	1	2
	0.43224	-0.06056
	0.00000	0.00000
	0.04246	0.19915
	1.15902	-0.05395

THE 8TH ORDER F-MATRIX IS:

	1	2	3	4	5	6	7	8
1	-0.02114	-0.00085	0.03259	0.02051	2.58521	-0.10552	-31.98577	0.00000
2	-0.00019	-0.13712	0.00265	-1.49383	0.00414	-0.16450	0.02922	31.98478
3	0.02484	0.00374	-0.29557	0.04190	0.43507	0.36222	-3.70815	0.00000
4	-0.00013	-0.00652	0.00058	-0.71638	0.03817	-0.07077	0.00000	0.00000
5	0.00925	0.00017	0.00234	0.04267	-1.22925	-0.00433	0.00000	0.00000
6	0.00039	-0.00112	0.00027	-0.05442	-0.15758	-0.04718	0.00000	0.00000
7	0.00000	0.00000	0.00000	0.00000	0.99997	0.00788	0.00000	0.00000
8	0.00000	0.00000	0.00000	1.00000	0.00091	0.11593	0.00000	0.00000

THE 8TH ORDER G-MATRIX IS:

	1	2	3	4
1	0.11408	0.93867	0.00000	-0.00001
2	0.01175	0.06353	1.15902	-0.05395
3	0.30310	-8.06188	-0.00002	0.00011
4	-0.00596	-0.01418	0.43224	-0.06056
5	0.32921	0.01905	0.00000	0.00000
6	0.04609	-0.00037	0.04246	-0.01105
7	0.00000	0.00000	0.00000	0.00000
8	0.00000	0.00000	0.00000	0.00000

Figure G.11: Linear Model for Airspeed of 0 knots, Climb Rate 0 ft/min.

'IS IS DATA FOR ZDOT= -500 FT/MIN AND XDOT OR AIRSPEED=
-20 KNOTS

	X	Y	Z	L	M	N
U	-0.04431	-0.00170	0.18208	-0.00058	0.00498	0.00033
V	-0.00184	-0.14266	-0.00104	-0.00631	0.00121	-0.00271
W	0.04284	0.00272	-0.34017	0.00049	-0.00447	0.00025
DB	0.13510	-0.01042	-0.09822	-0.03337	0.34340	0.04849
DC	1.22694	0.06576	-8.22802	-0.01187	0.01087	-0.00194
DS	-0.00025	1.16691	0.00182	0.41832	0.00000	0.00791
DR	-0.00013	-0.07451	-0.00001	-0.14503	-0.00037	0.20502
P	0.07629	-1.41972	-0.31843	-0.68419	0.06421	0.01341
Q	2.54761	0.02677	0.57144	0.12586	-1.31840	-0.16553
R	-0.21772	-0.15751	1.13901	-0.05023	-0.00735	-0.04199

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	-0.04431	0.04284	10.88094	-31.90117
2	0.18208	-0.34017	-32.82856	-4.37670
3	0.00498	-0.00447	-1.31840	0.00000
4	0.00000	0.00000	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

1	2
0.13510	1.22694
-0.09822	-8.22802
0.34340	0.01087
0.00000	0.00000

LATERAL F-MATRIX IS:

	1	2	3	4
1	-0.70016	0.00000	-0.06885	-0.00761
2	1.00000	0.00000	0.13720	0.00000
3	-0.04049	0.00000	-0.04729	-0.00330
	-9.75305	31.90117	33.24249	-0.14266

LATERAL G-MATRIX IS:

1	2
0.43462	-0.06633
0.00000	0.00000
0.04137	0.13992
1.16691	-0.07451

THE 8TH ORDER F-MATRIX IS:

	1	2	3	4	5	6	7	8
1	-0.04431	-0.00184	0.04284	0.07629	10.88094	-0.21772	-31.90117	0.00000
2	-0.00170	-0.14266	0.00272	-9.75305	0.02677	33.24249	0.03467	31.90117
3	0.18208	-0.00104	-0.34017	-0.31843	-32.82856	1.13901	-4.37670	0.00000
4	-0.00046	-0.00761	0.00061	-0.70016	0.06259	-0.06885	0.00000	0.00000
5	0.00498	0.00121	-0.00447	0.06421	-1.31840	-0.00735	0.00000	0.00000
6	0.00029	-0.00330	0.00030	-0.04049	-0.15072	-0.04729	0.00000	0.00000
7	0.00000	0.00000	0.00000	0.00000	0.99997	0.00792	0.00000	0.00000
8	0.00000	0.00000	0.00000	1.00000	0.00109	0.13719	0.00000	0.00000

THE 8TH ORDER G-MATRIX IS:

	1	2	3	4
1	0.13510	1.22694	-0.00025	-0.00013
2	-0.01042	0.06576	1.16691	-0.07451
3	-0.09822	-8.22802	0.00182	-0.00001
4	-0.01473	-0.01303	0.43462	-0.06633
5	0.34340	0.01087	0.00000	-0.00037
6	0.04736	-0.00294	0.04137	-0.01152
7	0.00000	0.00000	0.00000	0.00000
8	0.00000	0.00000	0.00000	0.00000

Figure G.10: **Linear Model for Airspeed of -20 knots, Climb Rate -500 ft/min.**

THIS IS DATA FOR ZDOT= 500 FT/MIN AND XDOT OR AIRSPEED= -20 KNOTS

	X	Y	Z	L	M	N
U	-0.04422	-0.00151	0.21206	-0.00063	0.01045	0.00008
V	-0.00058	-0.12523	0.00570	-0.00574	-0.00033	-0.00242
W	0.03283	0.00221	-0.27064	0.00530	-0.00731	0.00030
DB	0.12940	-0.02766	-0.10331	-0.03274	0.32931	0.03949
DC	1.20437	0.05345	-8.06621	-0.01071	0.03615	-0.00256
DS	0.00007	1.15921	-0.00050	0.41645	0.00001	0.00772
DR	0.00003	-0.07663	-0.00001	-0.14475	0.00009	0.20366
P	-0.05257	-1.76946	0.30099	-0.76640	-0.05053	0.00403
Q	2.46181	0.08166	0.93621	0.12011	-1.33744	-0.12984
R	0.00776	-0.18787	-0.45957	-0.06008	0.00643	-0.03976

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	-0.04422	0.03283	-5.87152	-31.90770
2	0.21206	-0.27064	-32.46379	-4.32879
3	0.01045	-0.00731	-1.33744	0.00000
4	0.00000	0.00000	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

	1	2
	0.12940	1.20437
	-0.10331	-8.06621
	0.32931	0.03615
	0.00000	0.00000

LATERAL F-MATRIX IS:

	1	2	3	4
1	-0.78875	0.00000	-0.07810	-0.00690
2	1.00000	0.00000	0.13567	0.00000
3	-0.05677	0.00000	-0.04578	-0.00295
	6.56387	31.90770	33.21213	-0.12523

LATERAL G-MATRIX IS:

	1	2
	0.43262	-0.06659
	0.00000	0.00000
	0.04107	0.19853
	1.15921	-0.07663

THE 8TH ORDER F-MATRIX IS:

	1	2	3	4	5	6	7	8
1	-0.04422	-0.00058	0.03283	-0.05257	-5.87152	0.00776	-31.90770	0.00000
2	-0.00151	-0.12523	0.00221	6.56387	0.08166	33.21213	0.02901	31.90699
3	0.21206	0.00570	-0.27064	0.30099	-32.46379	-0.45957	-4.32879	0.00000
4	-0.00062	-0.00690	0.00559	-0.78875	0.07115	-0.07810	0.00000	0.00000
5	0.01045	-0.00033	-0.00731	-0.05053	-1.33744	0.00643	0.00000	0.00000
6	0.00003	-0.00295	0.00073	-0.05677	-0.12436	-0.04578	0.00000	0.00000
7	0.00000	0.00000	0.00000	0.00000	0.99998	0.00670	0.00000	0.00000
8	0.00000	0.00000	0.00000	1.00000	0.00091	0.13566	0.00000	0.00000

THE 8TH ORDER G-MATRIX IS:

	1	2	3	4
1	0.12940	1.20437	0.00007	0.00003
2	-0.02766	0.05345	1.15921	-0.07663
3	-0.10331	-8.06621	-0.00050	-0.00001
4	-0.01773	-0.01208	0.43262	-0.06659
5	0.32931	0.03615	0.00001	0.00009
6	0.03812	-0.00349	0.04107	-0.01151
7	0.00000	0.00000	0.00000	0.00000
8	0.00000	0.00000	0.00000	0.00000

Figure G.9: **Linear Model for Airspeed of -20 knots, Climb Rate 500 ft/min.**

THIS IS DATA FOR ZDOT= 0 FT/MIN AND XDOT OR AIRSPEED= -20 KNOTS

	X	Y	Z	L	M	N
U	-0.04449	-0.00149	0.19817	-0.00059	0.00727	0.00023
V	-0.00075	-0.13255	0.00100	-0.00601	0.00054	-0.00254
W	0.03811	0.00238	-0.30703	0.00050	-0.00562	0.00026
DB	0.13262	-0.01824	-0.10291	-0.03269	0.33689	0.04375
DC	1.21170	0.05992	-8.12808	-0.01116	0.02013	-0.00218
DS	-0.00007	1.16217	0.00051	0.41715	0.00000	0.00782
DR	-0.00006	-0.07540	0.00014	-0.14475	-0.00012	0.20419
P	0.05290	-1.60055	-0.19944	-0.72706	0.05658	0.00866
Q	2.51458	0.05194	0.69186	0.12183	-1.31503	-0.14697
R	-0.12437	-0.17280	0.47219	-0.05530	-0.01058	-0.04088

LONGITUDINAL F-MATRIX IS:

	1	2	3	4
1	-0.04449	0.03811	2.51458	-31.90471
2	0.19817	-0.30703	-32.70814	-4.35079
3	0.00727	-0.00562	-1.31503	0.00000
4	0.00000	0.00000	1.00000	0.00000

LONGITUDINAL G-MATRIX IS:

1	2
0.13262	1.21170
-0.10291	-8.12808
0.33689	0.02013
0.00000	0.00000

LATERAL F-MATRIX IS:

	1	2	3	4
1	-0.74630	0.00000	-0.07363	-0.00723
2	1.00000	0.00000	0.13637	0.00000
3	-0.04887	0.00000	-0.04656	-0.00310
4	-1.60055	31.90471	33.22720	-0.13255

LATERAL G-MATRIX IS:

1	2
0.43338	-0.06638
0.00000	0.00000
0.04123	0.19907
1.16217	-0.07540

THE 8TH ORDER F-MATRIX IS:

	1	2	3	4	5	6	7	8
1	-0.04449	-0.00075	0.03811	0.05290	2.51458	-0.12437	-31.90471	0.00000
2	-0.00149	-0.13255	0.00238	-1.60055	0.05194	33.22720	0.03181	31.90385
3	0.19817	0.00100	-0.30703	-0.19944	-32.70814	0.47219	-4.35079	0.00000
4	-0.00052	-0.00723	0.00062	-0.74630	0.06597	-0.07363	0.00000	0.00000
5	0.00727	0.00054	-0.00562	0.05658	-1.31503	-0.01058	0.00000	0.00000
6	0.00019	-0.00310	0.00031	-0.04887	-0.14188	-0.04656	0.00000	0.00000
7	0.00000	0.00000	0.00000	0.00000	0.99997	0.00731	0.00000	0.00000
8	0.00000	0.00000	0.00000	1.00000	0.00100	0.13636	0.00000	0.00000

THE 8TH ORDER G-MATRIX IS:

	1	2	3	4
1	0.13262	1.21170	-0.00007	-0.00006
2	-0.01824	0.05992	1.16217	-0.07540
3	-0.10291	-8.12808	0.00051	0.00014
4	-0.01395	-0.01239	0.43338	-0.06638
5	0.33689	0.02013	0.00000	-0.00012
6	0.04252	-0.00314	0.04123	-0.01151
7	0.00000	0.00000	0.00000	0.00000
8	0.00000	0.00000	0.00000	0.00000

Figure G.8: **Linear Model for Airspeed of -20 knots, Climb Rate 0 ft/min.**

THIS IS DATA FOR ZDOT= -500 FT/MIN AND ... 60 KNOTS

Figure G.7: **Linear Model for Airspeed of 60 knots, Climb Rate -500 ft/min.**

Appendix I.

Flight Software

This appendix lists the flight computer software unique to this project. It is written in Sperry 1819A assembly code and internally documented. Three different sets of the code are shown. The initialization code was executed whenever the experimental control system was disengaged. It did such things as:

- reset the compensator states to zero
- set the trim values of controls and states to the current values of these variables in preparation for system engage

The experimental controller subroutines computed the control laws, described in Chapters 3 and 4, and were executed at 20 Hz. Both the longitudinal CAS and hover controller are shown. The last item shown in this appendix are the instructions which reserve memory for the variables and contants unique to the subroutines.

Initialisation Code.

```
1819A ASSEMBLER, VERSION 1.0   MOVR43  10/02/84   SECTION  1                                  PAGE  32

                        *
                        * ***********************************************************************
                        *
                        *    MODIFICATIONS TO INIT DONE ON 6 JUN 84
                        *
                        *
                        *      THESE LINES STORE INITIAL THETA AND AIRSPEED FOR THE CMSTR SUBR.
                        *      AND INITIALIZE COMPENSATOR INTEGRATORS.
                        *
 002600  120746             ENTAL   IWETH                     GET THETA AT ENGAGE
 002601  442156             STRAL   MIRPTH                    STORE THETA AT ENGAGE
 002602  442344             STRAL   NIRPTH                    STORE THETA AT ENGAGE
 002603  442603             STRAL   OIRPTH                    STORE THETA AT ENGAGE
 002604  443151             STRAL   PIRPTH                    STORE THETA AT ENGAGE
 002605  120753             ENTAL   INSPHI                    GET PHI AT ENGAGE
 002606  442604             STRAL   OIRPPH                    STORE PHI AT ENGAGE
 002607  443152             STRAL   PIRPPH                    STORE PHI AT ENGAGE
 002610  120752             ENTAL   AIRSPD                    GET THE AIRSPEED AT ENGAGE
 002611  442157             STRAL   MIRPAS                    STORE AIRSPEED AT ENGAGE
 002612  442345             STRAL   NIRPAS                    STORE AIRSPEED AT ENGAGE
 002613  442605             STRAL   OIRPAS                    STORE AIRSPEED AT ENGAGE
 002614  443153             STRAL   PIRPAS                    STORE AIRSPEED AT ENGAGE
 002615  120765             ENTAL   IVSI                      GET VERT VELOCITY AT ENGAGE
 002616  442160             STRAL   MIRPHD                    STORE VERTICAL VELOCITY AT ENGAGE
 002617  442346             STRAL   NIRPHD                    STORE VERTICAL VELOCITY AT ENGAGE
 002620  442606             STRAL   OIRPHD                    STORE VERTICAL VELOCITY AT ENGAGE
 002621  443154             STRAL   PIRPHD                    STORE VERTICAL VELOCITY AT ENGAGE
 002622  121134             ENTAL   XPILT                     GET RUNWAY X POSITION
 002623  442662             STRAL   OXREF                     CXREF=INITIAL RUNWAY X
 002624  443230             STRAL   PXREF                     PXREF=INITIAL RUNWAY X
 002625  121147             ENTAL   XBODY                     GET BODY X POSITION
 002626  442663             STRAL   OXBREF                    CXBREF=INITIAL BODY X
 002627  443231             STRAL   PXBREF                    PXBREF=INITIAL BODY X
 002630  121135             ENTAL   YPILT                     GET RUNWAY Y POSITION
 002631  442673             STRAL   OYREF                     CYREF=INITIAL Y POSITION
 002632  443241             STRAL   PYREF                     PYREF=INITIAL Y POSITION
 002633  121150             ENTAL   YBODY                     GET BODY Y POSITION
 002634  442674             STRAL   OYBREF                    CYBREF=INITIAL BODY Y
 002635  443242             STRAL   PYBREF                    PYBREF=INITIAL BODY Y
 002636  121136             ENTAL   ZPILT                     GET Z POSITION
 002637  442704             STRAL   OZREF                     CZREF=Z POSITION
 002640  443252             STRAL   PZREF                     PZREF=Z POSITION
 002641  402712             STRZ    OXDI                      CXDI=0
 002642  403200             STRZ    PXDI                      PXDI=0
 002643  402714             STRZ    OYDI                      CYDI=0
 002644  403202             STRZ    PYDI                      PYDI=0
 002645  402716             STRZ    OZDI                      CZDI=0
 002646  403204             STRZ    PZDI                      PZDI=0
 002647  402713             STRZ    OXDI+1                    CXDI+1=0
 002650  403201             STRZ    PXDI+1                    PXDI+1=0
 002651  402715             STRZ    OYDI+1                    CYDI+1=0
 002652  403203             STRZ    PYDI+1                    PYDI+1=0
 002653  402717             STRZ    OZDI+1                    CZDI+1=0
 002654  403205             STRZ    PZDI+1                    PZDI+1=0
 002655  402672             STRZ    OXDCLD                    CXDCLD=0
 002656  403240             STRZ    PXDCLD                    PXDCLD=0
 002657  402703             STRZ    OYDCLD                    CYDCLD=0
```

Initialisation Code. (contd)

```
1819A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION   1                              PAGE   33

  002660  403251            STRZ     PYDCLD                       PYDCLC=0
  002661  402711            STRZ     UZDCLD                       CZDCLC=0
  002662  403257            STRZ     PZDCLD                       PZDCLC=0
  002663  402671            STRZ     UXDPID                       CXDPIC=0
  002664  403237            STRZ     PXDPID                       PXDPIC=0
  002665  402702            STRZ     UYDPID                       CYDPIC=0
  002666  403250            STRZ     PYDPID                       PYDPIC=0
  002667  402710            STRZ     UZDPID                       CZDPIC=0
  002670  403256            STRZ     PZDPID                       PZDPIC=0
  002671  402720            STRZ     UXEZCN                       CXEZON=0 START PID FADE-IN AT ZERC
  002672  402721            STRZ     UYEZCN                       CYEZON=0 START PID FADE-IN AT ZERC
  002673  402722            STRZ     UZEZCN                       CZEZON=0 START PID FADE-IN AT ZERC
  002674  403266            STRZ     PXEZCN                       PXEZON=0 START PID FADE-IN AT ZERC
  002675  403267            STRZ     PYEZCN                       PYEZON=C START PID FADE-IN AT ZERC
  002676  403270            STRZ     PZEZCN                       PZEZON=0 START PID FADE-IN AT ZERC
                  *    INITIALIZATIONS OF THE BRANCHING FLAGS SINCE ESK USES CURRENT
                  *    MEMORY BANK, I.E. BANK 0.
  002677  122145            ENTAL    NNC                          AL:=(NNC) NUMBER OF CONTROLS, CMSTR1
  002700  102144            ENTAU    NR                           AU:=(NR) NUMBER OF COMP STATES, CPSTR1
  002701  507310            ENTSR    10                           USE BANK 0 LOCATIONS
  002702  717776            ADDALK   -1                           AL:=(AL)-1=NC-1
  002703  444457            STRAL    NNCP1                        NNCM1:=NC-1
  002704  507500            XFRUL                                 AL:=AU
  002705  717776            ADDALK   -1                           AL:=AL-1=NR-1
  002706  444454            STRAL    NRRP1                        NRRM1:=NR-1
  002707  507313            ENTSR    13                           USE BANK 3 AGAIN
  002710  122333            ENTAL    NNC                          AL:=(NNC) NUMBER OF CONTROLS, CMSTR2
  002711  102332            ENTAU    NRCATA                       AU:=(NRCATA) NUMBER OF COMP STATES, CMSTR2
  002712  507310            ENTSR    10                           USE BANK 0 LOCATIONS
  002713  717776            ADDALK   -1                           AL:=(AL)-1=NC-1
  002714  445170            STRAL    NNCP1                        NNCM1:=NC-1
  002715  507500            XFRUL                                 AL:=AU
  002716  717776            ADDALK   -1                           AL:=AL-1=NR-1
  002717  445165            STRAL    NRRP1                        NRRM1:=NR-1
  002720  507313            ENTSR    13                           USE BANK 3 AGAIN
  002721  122570            ENTAL    ONC                          AL:=(ONC) NUMBER OF CONTROLS, CPSTR3
  002722  102567            ENTAU    OR                           AU:=(CR) NUMBER OF COMP STATES, CPSTR3
  002723  507310            ENTSR    10                           USE BANK 0 LOCATIONS
  002724  717776            ADDALK   -1                           AL:=(AL)-1=NC-1
  002725  445701            STRAL    ONCP1                        CNCM1:=NC-1
  002726  507500            XFRUL                                 AL:=AU
  002727  717776            ADDALK   -1                           AL:=AL-1=CR-1
  002730  445676            STRAL    ORRP1                        CRRM1:=NR-1
  002731  507313            ENTSR    13                           USE BANK 3 AGAIN
  002732  123136            ENTAL    PNC                          AL:=(PNC) NUMBER OF CONTROLS, CMSTR4
  002733  103135            ENTAU    PR                           AU:=(PR) NUMBER OF COMP STATES, CPSTR4
  002734  507310            ENTSR    10                           USE BANK 0 LOCATIONS
  002735  717776            ADDALK   -1                           AL:=(AL)-1=NC-1
  002736  446715            STRAL    PNCP1                        PNCM1:=NC-1
  002737  507500            XFRUL                                 AL:=AU
  002740  717776            ADDALK   -1                           AL:=AL-1=NR-1
  002741  446712            STRAL    PRRP1                        PRRM1:=PR-1
  002742  507313            ENTSR    13                           USE BANK 3 AGAIN
                  *    DO THE CMSTR1 INITIALIZATIONS
  002743  507201            ENTICR   1                            USE ICR1 AS INDEX REGISTER
  002744  360000            ENTBK    0                            ICR1:=0
  002745  412034  MINIT1    STRZB    MUI                          (MUI+ICR1):=0
```

Initialisation Code. (contd)


```
002746  564457            ESK     MACP1                                IF P=MC-1 THEN SKIP A LINE
                 *                        ELSE INITIALIZE THE NEXT MUI AT ZERO, ICR1=ICR1+1
002747  342745            JP      MINIT1                               CONTINUE MUI INITIALIZATION
002750  360000            ENTBK   0                                    ICR1:=0  START MZK,MZKP1 INITIALIZATION
002751  412114   MINIT2   STRZB   MZK                                  (MZK+ICR1):=0
002752  412116            STRZB   MZKP1                                (MZKP1+ICR1):=0
002753  564454            ESK     MRRP1                                IF B=MP-1 THEN SKIP A LINE
                 *                        ELSE GO INITIALIZE NEXT TERM, ICR1=ICR1+1
002754  342751            JP      MINIT2                               CONTINUE INITIALIZATION
                 *   NOW DO THE CNSTR2 INITIALIZATIONS
002755  507201            ENTICR  1                                    USE ICR1 AS INDEX REGISTER
002756  360000            ENTBK   0                                    ICR1:=0
002757  412211   NINIT1   STRZB   NUI                                  (NUI+ICR1):=0
002760  565170            ESK     NNCP1                                IF P=NC-1 THEN SKIP A LINE
                 *                        ELSE INITIALIZE THE NEXT NUI AT ZERO, ICR1=ICR1+1
002761  342757            JP      NINIT1                               CONTINUE NUI INITIALIZATION
002762  360000            ENTBK   0                                    ICR1:=0  START NZK,NZKP1 INITIALIZATION
002763  412271   NINIT2   STRZB   NZK                                  (NZK+ICR1):=0
002764  412274            STRZB   NZKP1                                (NZKP1+ICR1):=0
002765  565165            ESK     NRRP1                                IF B=NR-1 THEN SKIP A LINE
                 * .                      ELSE GO INITIALIZE NEXT TERM, ICR1=ICR1+1
002766  342763            JP      NINIT2                               CONTINUE INITIALIZATION
                 *   DO THE CNSTR3 INITIALIZATIONS
002767  507201            ENTICR  1                                    USE ICR1 AS INDEX REGISTER
002770  360000            ENTBK   0                                    ICR1:=0  START OZK,OZKP1 INITIALIZATION
002771  412451   OINIT2   STRZB   OZK                                  (OZK+ICR1):=0
002772  412456            STRZB   OZKP1                                (OZKP1+ICR1):=0
002773  565676            ESK     ORRP1                                IF B=OR-1 THEN SKIP A LINE
                 *                        ELSE GO INITIALIZE NEXT TERM, ICR1=ICR1+1
002774  342771            JP      OINIT2                               CONTINUE INITIALIZATION
                 *   NOW DO THE CNSTR4 INITIALIZATIONS
002775  507201            ENTICR  1                                    USE ICR1 AS INDEX REGISTER
002776  360000            ENTBK   0                                    ICR1:=0  START PZK,PZKP1 INITIALIZATION
002777  413017   PINIT2   STRZB   PZK                                  (PZK+ICR1):=0
003000  413024            STRZB   PZKP1                                (PZKP1+ICR1):=0
003001  566712            ESK     PRRP1                                IF B=PR-1 THEN SKIP A LINE
                 *                        ELSE GO INITIALIZE NEXT TERM, ICR1=ICR1+1
003002  342777            JP      PINIT2                               CONTINUE INITIALIZATION
003003  343004            JP      MNINIT                               END THE INITIALIZATIONS
003004  504000   MNINIT   NOOP                                         END OF THE CNSTR INITIALIZATIONS
                 *
                 * ****************************************************************
003005  120753            ENTAL   INSFHI
003006  441203            STRAL   RCLIST
003007  440267            STRAL   INGL12                               ROLL MODEL FOLLOWING
003010  440777            STRAL   PMSENG
003011  400274            STRZ    INGL17
003012  400414            STRZ    TGDS14
003013  401277            STRZ    RCLCLD
003014  401270            STRZ    PTSCLD
003015  401454            STRZ    HASFLG
003016  400666            STRZ    LAMFLG                               DISABLE CLUTCH SLIP LIGHT ENABLE FLAG
003017  400664            STRZ    A/PFLG                               HHOLD DETENT ROLL AXIS LIGHT
003020  400665            STRZ    H/RFLG                               HHOLD DETENT PITCH AXIS LIGHT
003021  400663            STRZ    G/AFLG                               HHOLD COLLECTIVE DETENT LIGHT
003022  332307            IJP     CLEAR
003023  121366   CL1      ENTAL   VEZCN
```

Longitudinal CAS Subroutine.

```
1819A ASSEMBLER, VERSION 1.0   NOVR43  10/02/84   SECTION   1                                  PAGE  52

                     *
                     * ****************************************************************************
                     *          THIS IS THE START OF THE SUBROUTINE WHICH DOES THE
                     *          MINIMAL COMPENSATOR.  THE INPUTS ARE
                     *                   NPLT(PILOT COMMANDS)
                     *                   NYS(THE MEASUREMENT VECTOR)
                     *          THE OUTPUTS ARE:
                     *                   NUT(THE COMMANDS TO THE ACTUATORS)
                     *         THE EQUATIONS BEING DONE BY THIS SUBROUTINE ARE
                     *
                     *           NYDES = NYSCLE * NPLT
                     *           NUC = NNK * NYDES
                     *           NUI = NUI + NKINT*(NYDES-NYACT)
                     *           NZKP1 = NAMIN * NZK  +  NEMIN * NYS
                     *           NUR = NCMIN * NZKP1
                     *           NUT = NUR + NUC + NUI
                     *
                     *           WHERE:     NUC-- THE SETPOINT CONTROL VECTOR
                     *                      NNK-- THE FEEDFORWARD GAIN MATRIX(FOR SETPOINT
                     *                                  CONTROL
                     *                      NPLT-- THE PERTURBATION PILOT INPUT VECTOR
                     *                             (PERTURBED ABOUT THE CNTRL AT INITIALIZE)
                     *                      NZKP1-- THE PRESENT COMPENSATOR STATE VECTOR
                     *                      NAMIN-- THE COMPENSATOR DYNAMICS MATRIX
                     *                      NZK-- THE LAST COMPENSATOR STATE VECTOR
                     *                      NEMIN-- THE COMPENSATOR INPUT DIST. MATRIX
                     *                      NYS-- THE MEAS. VECTOR
                     *                      NUR-- THE REGULATOR/COMPENSATOR CONTROL VECTOR
                     *                      NCMIN-- THE COMPENSATOR OUTPUT MATRIX
                     *                      NUT-- THE TOTAL PERTURBATION CONTROL
                     * ****************************************************************************
                     *
                     *          RESERVE WORDS FOR USE IN THE BRANCHING INSTRUCTIONS
                     *
      005164  000000   NRWEND   RESERV   RESERV'1D                           ROW COUNTER
      005165  000000   NRRM1    RESERV   RESERV'1D                           ORDER OF COMPENSATOR - 1
      005166  000000   NRR      RESERV   RESERV'1D                           ORDER OF COMPENSATOR
      005167  000000   NRRP1    RESERV   RESERV'1D                           ORDER OF COMPENSATOR + 1
      005170  000000   NNCM1    RESERV   RESERV'1D                           NUMBER OF CONTROLS - 1
      005171  000000   NNCTRL   RESERV   RESERV'1D                           NUMBER OF CONTROLS
      005172  000000   NNMEAS   RESERV   RESERV'1D                           NUMBER OF MEASUREMENTS
      005173  000000   CHSTR2   O'0
                     *
                     *      INITIALIZE BRANCHING VARIABLES SINCE BSK DOESN'T USE
                     *      THE SPECIAL REGISTER
                     *
      005174  507313            ENTSR    13                                  USE MEMORY 3 REGISTER
      005175  122333            ENTAL    NNC                                 AL:=(NNC)
      005176  102334            ENTAU    NNP                                 AU:=(NNP)
      005177  507310            ENTSR    0                                   USE MEMORY BANK 0
      005200  445171            STRAL    NNCTRL                              NNCTRL:=NNC
      005201  717776            ADDALK   -1                                  AL:=NNC-1
      005202  445170            STRAL    NNCM1                               NNCM1:=NNC-1
      005203  465172            STRAU    NNMEAS                              NNMEAS:=NNR
      005204  507313            ENTSR    13                                  USE MEMORY BAN. 3
      005205  122332            ENTAL    NRCPTA                              AL:=(NRCPTA)
      005206  102337            ENTAU    NRR1                                AU:=(NRP1)
```

Longitudinal CAS Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION   1                                   PAGE  63

005207  507310            ENTSR    1C                               USE MEMORY BANK 0
005210  445166            STRAL    NRR                              NRR:=NRDATA
005211  717776            ADDALK   -1                               AL:=AL-1=NRDATA-1
005212  445165            STRAL    NRRP1                            NRRP1:=NRDATA-1
005213  465167            STRAU    NRRF1                            NRRP1:=NRF1
                  *
                  * ----------SECTION NSTPO--------------
                  *
                  *   THIS SECTION PUTS MEASUREMENTS NEEDED BY THE CONTROLLER
                  *   INTO THE MEASUREMENT VECTOR, NYS.  IT ALSO PUTS THE ACTUAL
                  *   VALUES OF THE DESIRED OUTPUTS INTO THE VECTOR, NYACT.
                  *
                  *   IN BASIC, THE CODE WOULD BE:
                  *
                  *          FOR I=1 TO NN                    ]
                  *             NYS(I)=MEAS(NYSSEL(I))        ]--NSTP01
                  *          NEXT I                           ]
                  *
                  *          FOR I=1 TO NC                    ]
                  *             NYACT(I)=MEAS(NYOSEL(I))      ]--NSTP02
                  *          NEXT I                           ]
                  *
                  *   NYSSEL IS A VECTOR CONTAINING, IN ORDER, THE INDEX NUMBERS
                  *   OF THE SELECTED MEASUREMENTS.  NYOSEL IS A VECTOR CONTAINING,
                  *   IN ORDER, THE INDEX NUMBERS OF THE DESIRED MEASUREMENTS(THOSE
                  *   BEING COMMANDED BY THE PILOT).  THE MEASUREMENTS COME FROM BANK 3.
                  *   THE INDEX NUMBERS AND THE RELATED POSSIBLE MEASUREMENTS ARE
                  *   SHOWN BELOW:
                  *
                  *      INDEX NUMBER            PARAMETER
                  *           1             THETA(+NOSE UP,500/DEG)
                  *           2             PHI(+RWD,500/DEG)
                  *           3             PSI(MAGNETIC,500/DEG)
                  *           4             Q(+NOSE UP,500/(DEG/SEC))
                  *           5             P(+RWD,500/(DEG/SEC))
                  *           6             R(+RIGHT,500/(DEG/SEC))
                  *           7             LONG. ACCEL.(NO GRAV,+FORW,128/(FT/SEC**2))
                  *           8             LAT. ACCEL.(NO GRAV,+RIGHT,128/(FT/SEC**2))
                  *           9             NORMAL ACCEL.(NO GRAV,+UP,128/(FT/SEC**2))
                  *          10             DELTA FORW. VEL.(+FORW,87/(FT/SEC))
                  *          11             VERT. VEL.(+UP,32/(FT/SEC))
                  *          12             BARO. ALT.(16/FT)
                  *
                  *   NOTE THAT THETA AND AIRSPEED ARE PERTURBATION QUANTITIES AND HAVE
                  *   TRIM VALUES SUBTRACTED FROM THEM.*
005214  507313  NSTPO     ENTSR    13                               USE MEMORY BANK 3
005215  120746            ENTAL    INSTH                            AL:=ANGTH(PITCH ANGLE)
005216  102344            SUBAL    NTRMTH                           AL:=AL-NTRMTH(PERTURBATION THETA)
005217  442347            STRAL    NDTHET                           NDTHET:=PERTURBATION PITCH ANGLE
                  *                  +NOSE UP, 500/DEG
005220  120753            ENTAL    INSPHI
005221  442350            STRAL    NPHI                             NPHI IS ROLL,+RWD,500/DEG
005222  120766            ENTAL    INSPSI
005223  442351            STRAL    NPSI                             NPSI IS HEADING, MAGNETIC,500/DEG
005224  120743            ENTAL    PITR/G
005225  442352            STRAL    NPITRT                           PITCH RATE,+ NOSE UP,500/(DEG/SEC)
005226  120744            ENTAL    RCLR/G
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Longitudinal CAS Subroutine. (contd)

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1019A ASSEMBLER, VERSION 1.0   NOVR43  10/02/84   SECTION   1                                  PAGE  64

005227  442353              STRAL    NROLRT          ROLL RATE,+ RWD,500/(DEG/SEC)
005230  120745              ENTAL    YAWF/G
005231  442354              STRAL    NYAWRT          YAW RATE,+RIGHT,500/(DEG/SEC)
005232  120747              ENTAL    ACCLNG
005233  442355              STRAL    NAX             LONG. ACCEL.,NO GRAV,+FORW,128/(FT/SEC**2)
005234  120750              ENTAL    ACCLAT
005235  442356              STRAL    NAY             LAT. ACCEL.,NO GRAV,+RIGHT128/(FT/SEC**2)
005236  120751              ENTAL    ACCNRM
005237  442357              STRAL    NAZ             NORMAL ACCEL.,NO GRAV,+UP,128/(FT/SEC**2)
005240  120752              ENTAL    AIRSPD
005241  162345              SUBAL    NTRMAS          AL:=AIRSPD-TRIM AIRSPEED
005242  442360              STRAL    NCVEL           NCVEL IS PERTURBATION VELOCITY,
                    *                 +FORW,8/(FT/SEC)
005243  120765              ENTAL    IVSI            VERT. SPEED,+UP,32/(FT/SEC)
005244  162346              SUBAL    NTRMHD          SUBTRACT HDOT AT ENGAGE
005245  442361              STRAL    NVVEL           PERTURBED VERT. SPEED,+UP,32/(FT/SEC)
005246  120754              ENTAL    BARC
005247  442362              STRAL    NBALT           BARO. ALT., 16/FT
                    *
                    *    THIS DOES THE NYS SELECTION
                    *
005250  507201              ENTICR   1               USE ICR1 AS INDEX I
005251  360001              ENTBK    1               START WITH ICR1=1 SO (I=2)
005252  132323   NSTP01     ENTALB   NYSSEL-1        AL:=(NYSSEL+ICR1-1)
005253  441650              STRAL    TMP             TMP:=NYSSEL(I)
005254  507202              ENTICR   2               USE ICR2 AS INDEX
005255  321650              ENTB     TMP             B:=TMP=NYSSEL(I)
005256  132346              ENTALB   NCTHET-1        AL:=MEAS(NYSSEL(I))=(NDTHET+TMP-1)
005257  507201              ENTICR   1               USE INDEX REGISTER 1 AGAIN
005260  452234              STRALB   NYS-1           AL:=(NYS+ICR1-1)=NYS(I)
005261  565172              PSK      NAMEAS          IF B=NAMEAS DO NEXT LINE
                    *                  ELSE ICR1=ICR1+1 AND DO NEXT LINE
005262  345252              JP       NSTP01          CONTINUE
                    *
                    *    THIS DOES THE NYACT SELECTION
                    *
005263  507201              ENTICR   1               USE ICR1 AS INDEX I
005264  360001              ENTBK    1               START WITH ICR1=1 SO (I=1)
005265  132327   NSTP02     ENTALB   NYDSEL-1        AL:=(NYDSEL+ICR1-1)
005266  441650              STRAL    TMP             TMP:=NYDSEL(I)
005267  507202              ENTICR   2               USE ICR2 AS INDEX
005270  321650              ENTB     TMP             B:=TMP=NYDSEL(I)
005271  132346              ENTALB   NCTHET-1        AL:=MEAS(NYDSEL(I))=(NDTHET+TMP-1)
005272  507201              ENTICR   1               USE INDEX REGISTER AGAIN
005273  452252              STRALB   NYACT-1         NYACT(I)=(NYACT+ICR1-1)
005274  565171              PSK      NNCTRL          IF B=NNCTRL SKIP A LINE
                    *                 ELSE ICR1=ICR1+1 AND DO THE NEXT LINE
005275  345265              JP       NSTP02          GET NEXT NYACT
005276  345277              JP       NSTP03          GO GET PILOT INPUTS
                    *
                    *     THIS SECION PUTS EXPERIMENTAL PILOT COMMANDS INTO THE NPLT VECTOR
                    *
005277  120755   NSTP03     ENTAL    EPLCN           AL:=EP LONG STICK
005300  504600              LRTAL    0               SCALE THE INPUT OF LONG CYLIC
005301  442231              STRAL    NPLT            NPLT(1)=LONG STICK,1024PER IN,+AFT
005302  120760              ENTAL    EPNPAV          AL:=EP COLLECTIVE
005303  504600              LRTAL    0               SCALE THE INPUT OF COLLECTIVE
```

Longitudinal CAS Subroutine. (contd)

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IBIYA ASSEMBLER, VERSION 1.0   NOVR43  10/02/84   SECTION   1                                    PAGE  65

005304  442232                    STRAL   NPLT+1     NPLT(2)=CCLLECTIVE,1024 PER IN,+UF
005305  120756                    ENTAL   EFLAT      AL:=EP LATERAL STICK
005306  504600                    LRTAL   0          SCALE THE LATERAL STICK
005307  442233                    STRAL   NPLT+2     NPLT(3)=LATERAL CYCLIC,1024 PER IN,+RIGHT
005310  120757                    ENTAL   EFYAW      AL:=EP YAW COMMANDS
005311  504600                    LRTAL   0          SCALE THE PEDALS
005312  442234                    STRAL   NPLT+3     NPLT(4)=YAW CONTROL,1024 PER IN,+RIGHT??
               *
               *  ----------SECTION NSTP1---------------
               *
               *    THIS SECTION PUTTS NPLT * COMMAND SCALING INTC THE NYDES
               *    (DESIREC OUTPUT VECTOR)
               *
               *            NYDES = NYSCLE * NPLT
               *
               *        WHERE NYSCLE IS THE DIAGONAL SCALING MATRIX
005313  507310    NSTP1   ENTSR   10         USE MENCRY BANK 0
005314  507201            ENTICR  1          USE ICR1 AS THE INDEX REG,(B)
005315  360000            ENTBK   0          INITIALIZE THE B REG TO 0
005316  507313            ENTSR   13         USE MENCRY BANK 3
005317  132231    NSTP10  ENTALB  NPLT       AL:=(NPLT+ICR1)
005320  252257            PULALB  NYSCLE     AI=ALP(NYSCLE + ICR1)
005321  504702            LRTA    2          NSTP1 SCALING WAS 2**16
005322  472247            STRAUB  NYCES      STORE RESULT IN (NYDES+ICR1),SCALING IS 2**16
005323  565170            ESK     NNCM1      IF ICR1=NNCM1(NC-1) THEN SKIP NEXT LINE
               *                   ELSE DO NEXT LINE AND ICR1=ICR1+1
005324  345317            JP      NSTP10     GO SCALE THE NEXT CONTROL
005325  345326            JP      NSTP2      GO TO THE INTEGRAL CONTROL SECTION
               *
               *  ===========SECTION NSTP2============
               *
               *    THIS SECTION DOES THE INTEGRAL CONTROL CALCULATION FOR
               *    THE CONTROLLER SUBRCUTINE.  FOR THE INTEGRATCRS WE USE
               *    FOLLOWING EQUIVALENT BASIC COMMANDS:
               *
               *         NUI = NUI + NFINT * (NYDES-NYACT)
               *
               *       WHERE NUI IS THE OUTPUT OF THE INTEGRATOR.
005326  507310    NSTP2   ENTSR   10         USE MENCRY BANK 0
005327  507201            ENTICR  1          USE ICR1 AS THE INDEX REG,(B)
005330  360000            ENTBK   0          INITIALIZE THE B REG, TO 0
005331  400002            STRZ    2          ICR2=0, THE COLUMN INDEX
005332  400003            STRZ    3          ICR3=0, THE ROW INDEX
005333  507313            ENTSR   13         USE MENCRY BANK 3
005334  122333            ENTAL   NNC        AL:=NUMBER OF CONTROLS
005335  717776            ADDALK  -1         AL:=NNC-1
005336  507310            ENTSR   10         USE MENCRY BANK 0
005337  445104            STRAL   NRWEND     NRWEND:=NNC-1
005340  507313            ENTSR   13         USE MENCRY BANK 3
005341  700000    NNXRW4  ENTALK  0          AL:=0
005342  507400            XFRLU              AU:=AL=0
005343  500800    NNXCL4  STRA    TPP        TMP1=A
005344  031650
005345  507202            ENTICR  2          GET THE CCLUMN INDEX
005346  370001            ENTBKB  1          INCREMENT COLUMN INDEX(ICR2=ICR2+1)
005347  132246            ENTALB  NYDES-1    AL:=(NYCES+ICR2-1)
005350  172252            SUBALB  NYACT-1    AL:=(NYCES+ICR2-1)-(NYACT+ICR2-1)
```

Longitudinal CAS Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.0   MOVR43  10/02/84   SECTION  1                                      PAGE  56

005351 507201           ENTICR   1                        USE ICR1 AS INDEX REG.(ELEMENT INDEX)
005352 252201           MULALB   MKINT                    A:=AL * (MKINT+ICR1)
005353 201650           ADDA     TMP                      A:=A + (TMP,TMP+1)
005354 505300           SKPNOV                            CHECK FOR OVERFLOW
005355 504000           NOOP                              CALL OVERFLOW HANDLER
005356 565164           ESK      NRWEND                   IF ICR1=NRWEND THEN SKIP NEXT LINE
                $                              ELSE DO NEXT LINE AND ICR1=ICR1+1
005357 345343           JP       MMXCL4                   JUMPS TO NEXT COLUMN OF MKINT
                $              AND NEXT ROW ELEMENT OF (NYDES-NYACT)
005360 370001           ENTBRB   1                        ICR1=ICR1+1
005361 507203           ENTICR   3                        USE ICR3 AS INDEX REG.(ROW INDEX)
005362 504703           ERTA     3C                       SCALING FOR NSTP2,2**15
005363 507500           XFRUL                             PUT AU(THE RESULT) INTO AL
005364 152211           ADDALB   NUI                      AL:=AL+(NUI+ICR1)
005365 452211           STRALB   NUI                      NUI+ICR3:=(AL)=(NUI+ICR3)+AL
005366 565170           ESK      NNCM1                    IF ICR3=NNCM1 THEN SKIP NEXT LINE
                $                              ELSE DO NEXT LINE AND ICR3=ICR3+1
005367 345371           JP       NRSET4                   GO RESET THE COUNTER
005370 345401           JP       NSTF3                    GO TO NEXT MATRIX MULT IF DONE
005371 507202   NRSET4  ENTICR   2                        SAVE ROW INDEX AND START USING COLUMN INDEX
005372 360000           ENTBK    0                        RESET COLUMN INDEX TO ZERO
005373 507310           ENTSR    1C                       BANK 0 TO USE NRWEND AND NNCTRL
005374 125164           ENTAL    NRWEND                   AL:=NRWEND
005375 145171           ADDAL    NNCTRL                   AL:=NRWEND+NNCTRL=NRWEND+# OF COLUMNS
005376 445164           STRAL    NRWEND                   NRWEND:=NRWEND+NNCTRL
005377 507313           ENTSR    13                       BANK 3 FOR DATA
005400 345341           JP       MMXRW4                   DO THE NEXT ROW
                $
                $  ----------SECTION NSTF3--------
                $
                $  FIRST DO THE SET POINT GENERATOR MATRIX MULTIPLICATION
                $                        NUC = NNK * NYDES
                $                        WHERE NUC = NNC X NNC    AND  NYDES = NNC X 1
005401 507310   NSTF3   ENTSR    1C                       USE MEMORY BANK 0
005402 507201           ENTICR   1                        USE ICR1 AS THE INDEX REG.(B)
005403 360000           ENTBK    0                        INITIALIZE THE B REG. TO 0
005404 400002           STRZ     2                        ICR2=0, THE COLUMN INDEX
005405 400003           STRZ     3                        ICR3=0, THE ROW INDEX
005406 507313           ENTSR    13                       USE MEMORY BANK 3
005407 122333           ENTAL    NNC                      AL:=NUMBER OF CONTROLS
005410 717776           ADDALK   -1                       AL:=NNC-1
005411 507310           ENTSR    1C                       USE MEMORY BANK 0
005412 445164           STRAL    NRWEND                   NRWEND:=NNC-1
005413 507313           ENTSR    13                       USE MEMORY BANK 3
005414 700000   NNXRW1  ENTALK   0                        AL:=0
005415 507400           XFRLU                             AU:=AL=0
005416 500600   NNXCL1  STRA     TMP                      TMP:=A
005417 031050
005420 507202           ENTICR   2                        GET THE COLUMN INDEX
005421 370001           ENTBRB   1                        INCREMENT COLUMN INDEX(ICR2=ICR2+1)
005422 132246           ENTALB   NYDES-1                  AL:=(NYDES+ICR2-1)
005423 507201           ENTICR   1                        USE ICR1 AS INDEX REG.(ELEMENT INDEX)
005424 252265           MULALB   NNK                      A:=AL * (NNK+ICR1)
005425 201650           ADDA     TMP                      A:=A + (TMP,TMP+1)
005426 505300           SKPNOV                            CHECK FOR OVERFLOW
005427 504000           NOOP                              CALL OVERFLOW HANDLER
005430 565164           ESK      NRWEND                   IF ICR1=NRWEND THEN SKIP NEXT LINE
```

Longitudinal CAS Subroutine. (contd)


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                       *                         ELSE DO NEXT LINE AND ICR1=ICR1+1
005431  345416                 JP       NNXCL1                               JUMPS TC NEXT COLUMN OF NNK
                       *                         AND NEXT RCW ELEMENT OF NFLT
005432  370001                 ENTBKB   1                                    ICR1=ICR1+1
005433  507203                 ENTICR   3                                    USE ICR3 AS INDEX REG.(ROW INDEX)
005434  504703                 LRTA     3                                    SCALING FCR NSTP3,2**15
005435  472215                 STRAUB   NUC                                  NUC+ICR3:=(AU)
005436  565170                 BSK      NNCPI                                IF ICR3=NNCPI THEN SKIP NEXT LINE
                       *                         ELSE DO NEXT LINE AND ICR3=ICR3+1
005437  345441                 JP       NRSET1                               GO RESET THE COUNTER
005440  345451                 JP       NSTP4                                GO TO NEXT MATRIX MULT IF DONE
005441  507202       NRSET1    ENTICR   2                                    SAVE ROW INDEX AND START USING COLUMN INDEX
005442  360000                 ENTBK    0                                    RESET CCLUMN INDEX TO ZERO
005443  507310                 ENTSR    S0                                   BANK 0 TO USE NRWEND AND NNCTRL
005444  125164                 ENTAL    NRWEND                               AL:=NRWENC
005445  165171                 ADDAL    NNCTRL                               AL:=NRWENC+NNCTRL=NRWEND+# OF COLUMNS
005446  445164                 STRAL    NRWEND                               NRWENC:=NRWENC+NNCTRL
005447  507313                 ENTSR    I3                                   BANK 3 FOR DATA
005450  345414                 JP       NNXRW1                               DO THE NEXT ROW
                       *
                       *   ---------------------------SECTION NSTP4--------
                       *
                       *             THIS IS THE 2ND MATRIX MULTIPLY IN THE CMSTR2
                       *             SUBROUTINE, I.E.
                       *                           NEPIN * NYS
005451  507310       NSTP4     ENTSR    S0                                   USE MEMCRY BANK 0
005452  507201                 ENTICR   1                                    USE ICR1 AS THE INDEX REG.(B)
005453  360000                 ENTBK    0                                    INITIALIZE THE B REG. TO 0
005454  400002                 STRZ     2                                    ICR2=0, THE COLUMN INDEX
005455  400003                 STRZ     3                                    ICR3=0, THE ROW INDEX
005456  507313                 ENTSR    13                                   USE MEMCRY BANK 3
005457  122334                 ENTAL    NNP                                  AL:=NUMBER OF MEASUREMENTS
005460  717776                 ADDALK   -1                                   AL:=NNM-1
005461  507310                 ENTSR    S0                                   USE MEMCRY BANK 0 SINCE NRWEND IS THERE
005462  445164                 STRAL    NRWEND                               NRWEND:=NNM-1
005463  507313                 ENTSR    I3                                   BACK TO MEMORY BANK 3 FOR DATA
005464  700000       NNXRW2    ENTALK   0                                    AL:=0
005465  507400                 XFRLU                                         AU:=AL=0
005466  500600       NNXCL2    STRA     TPP                                  TPP:=A
005467  031650
005470  507202                 ENTICR   2                                    GET THE CCLUMN INDEX
005471  370001                 ENTBKB   1                                    INCREMENT COLUMN INDEX(ICR2=ICR2+1)
005472  132234                 ENTALB   NYS-1                                AL:=(NYS+ICR2-1)
005473  507201                 ENTICR   1                                    USE ICR1 AS INDEX REG.(ELEMENT INDEX)
005474  252302                 MULALB   NEPIN                                A:=AL * (NEMIN+ICR1)
005475  201650                 ADDA     TPP                                  A:=A + (TPP,TMP+1)
005476  505300                 SKPNOV                                        CHECK FCR OVERFLOW
005477  508000                 HOOP                                          CALL OVERFLOW HANDLER
005500  565164                 BSK      NRWEND                               IF ICR1=NRWEND THEN SKIP NEXT LINE
                       *                         ELSE DO NEXT LINE AND ICR1=ICR1+1
005501  345466                 JP       NNXCL2                               JUMPS TC NEXT COLUMN OF NEMIN
005502  370001                 ENTBKB   1                                    ICR1=ICR1+1
005503  507203                 ENTICR   3                                    USE ICR3 AS INDEX REG.(ROW INDEX)
005504  504705                 LRTA     5C                                   NSTP4 SCALING IS 2**13
005505  472274                 STRAUB   NZKP1                                NZKP1+ICR3:=(AU)
005506  565103                 BSK      NNMP1                                IF ICR3=NNMP THEN SKIP NEXT LINE
                       *                         ELSE DO NEXT LINE AND ICR3=ICR3+1
```

Longitudinal CAS Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.0   NOVR43  10/02/84   SECTION  1                                    PAGE  68

005507  345511                   JP       NRSET2                    GO RESET THE COUNTER
005510  345521                   JP       NSTP5                     GO TO NEXT MATRIX MULT IF DONE
005511  507202         NRSET2    ENTICR   2                         SAVE ROW INDEX AND START USING COLUMN INDEX
005512  360000                   ENTBK    0                         RESET COLUMN INDEX TO ZERO
005513  507310                   ENTSR    10                        BANK 0 TO USE NPWEND AND NWMEAS
005514  125164                   ENTAL    NPWEND                    AL:=NPWEND
005515  145172                   ADDAL    NWMEAS                    AL:=NPWEND+NWMEAS
005516  445164                   STRAL    NPWEND                    NPWEND:=NPWEND+NWMEAS=NPWEND+NOF COLUMNS
005517  507313                   ENTSR    13                        BACK TO MEMORY BANK 3 FOR DATA
005520  345404                   JP       NNXRW2                    DO THE NEXT ROW
                       *
                       *  ==============SECTION NSTP5============
                       *
                       *          THIS STEP(NSTP5) DOES THE MATRIX MULTIPLICATION
                       *          DESCRIBED BY
                       *                   NAMIN*NZK
                       *          WHERE NAMIN IS THE MINIMAL FORM OF THE COMPENSATOR
                       *            DYNAMICS MATRIX
005521  507202         NSTP5     ENTICR   2                         SELECT ICR2(J=ICR2)
005522  360000                   ENTBK    0                         ICR2:=0
005523  507201                   ENTICR   1                         SELECT ICR1(I=ICR1)
005524  360000                   ENTBK    0                         ICR1:=1
005525  565166         NSTP50    BSK      NRR                       IF ICR=NR SKIP ONE
                       *                    LINE ELSE ICR1=ICR1+1(I=I+1) AND DO NEXT LINE
005526  345530                   JP       NSTP51                    GO CHECK FOR TYPE OF MINIMAL BLOCK
005527  345560                   JP       NSTP54                    GO TO SUMMATION WITH NZKP1
005530  507202         NSTP51    ENTICR   2                         USE ICR2 AS INDEX,J
005531  132335                   ENTALB   NADESC                    AL:=(NADESC+ICR2)
005532  022375                   CMAL     NONE                      COMPARE AL,I.E. NADESC(J), WITH 1
005533  615537                   JPEQ     NSTP52                    GOTO NSTP52 IF NADESC(J)=1
005534  022376                   CMAL     NTWC                      COMPARE AL TO 2
005535  615546                   JPEQ     NSTP53                    GOTO NSTP53 IF NADESC(J)=2
005536  504000                   NOCP                               A CALL TO AN ERROR HANDLER GOES HERE
                       *      THIS IS THE SECTION FOR 1X1 BLOCKS OF AMIN
005537  370001         NSTP52    ENTBKB   1                         ICR2=ICR2+1,I.E. J=J+1
005540  507201                   ENTICR   1                         ICR1 IS THE INDEX REG.
005541  132276                   ENTALB   NAMIN-1                   AL:=AL*(NAMIN+ICR1-1)
005542  252270                   PULALB   NZK-1                     A:=AL*(NZK+ICR1-1)
005543  504703                   LRTA     3                         SCALING FOR NSTP52 IS 2**15
005544  472362                   STRAUB   TMPNZ-1                   TMPNZ=1:=AU=A(I)*NZK(I),SCALING IS 2**15
005545  345525                   JP       NSTP50                    JUMP BACK TO GET NEXT AMIN DESCRIPTOR
                       *      THIS IS THE SECTION FOR 2X2 BLOCKS OF AMIN
005546  370001         NSTP53    ENTBKB   1                         ICR2=ICR2+1,I.E. J=J+1
005547  507201                   ENTICR   1                         ICR1 IS NOW THE INDEX REG.
005550  132271                   ENTALB   NZK                       AL:=(NZK+ICR1)
005551  452362                   STRALB   TMPNZ-1                   TMPNZ+ICR1-1:=(NZK+ICR1),I.E.
                       *                              TMPNZ(I)=NZK(I+1)
005552  132276                   ENTALB   NAMIN-1                   AL:=(NAMIN+ICR1-1)
005553  252270                   PULALB   NZK-1                     A:=AL*(NZK+ICR1-1)
005554  504703                   LRTA     3                         SCALING FOR NSTP53 IS 2**15
005555  461650                   STRAU    TMP                       TMP:=AU, I.E. TMP=NAMIN(I)*NZK(I),SCALING IS
                                                                    2**15
005556  132277                   ENTALB   NAMIN                     AL:=(NAMIN+ICR1)
005557  252271                   PULALB   NZK                       A:=AL*(NZK+ICR1);I.E.
005560  504703                   LRTA     3                         SCALING FOR NSTP53 IS 2**15
                       *                              A=NAMIN(I+1)*NZK(I+1)
005561  507500                   XFRUL                              PUT AU INTO AL
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Longitudinal CAS Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.0   NOVR43  10/02/84   SECTION   1                                                    PAGE  69

 005562  141650           ADDAL   TPP                                      AL:=AL+INF,I.E. AL=A(I)*Z(I)+A(I+1)*Z(I+1)
 005563  452363           STRALB  TPPNZ                                    TPPNZ+ICR1:=AL,SCALING IS 2**15
 005564  370001           ENTBKB  1                                        ICR1=ICR1+1 BUT THIS MEANS I=I+2
                *                               SINCE NSTF50 INCREMENTED   ICR1 ONCE ALREADY
 005565  345525           JP      NSTF50                                   GO GET THE NEXT AMIN DESCRIPTOR
 005566  360001  NSTP54   ENTBK   1                                        ICR1:=1
                *      THIS SECTION ADDS NBMIN*NYS + AAPIN*NZK
                *      AND PUTS THE RESULT IN THE NZKF1 VECTOR
 005567  132273  NSTP55   ENTALB  NZKF1-1                                  AL:=(NZKP1+ICR1-1)
 005570  152362           ADDALB  TPPNZ-1                                  AL:=AL+(TPPNZ+ICR1-1)
 005571  452273           STRALB  NZKP1-1                                  NZKP1+ICR1-1:=AL
 005572  565166           ESK     NRN                                      IF ICR1=NR+1 THEN SKIP ONE LINE
                *                               ELSE ICR1=ICR1+1 AND DO NEXT LINE
 005573  345567           JP      NSTF55                                   CONTINUE
 005574  345575           JP      NSTF6                                    GOTO NEXT STEP
                *
                * ------------SECTION NSTPL ---------
                *
                *          THIS IS THE 4TH MATRIX MULTIPLY IN THE CMSTR2
                *          SUBROUTINE, I.E.
                *                      NUR = TCMIN * NZKF1
 005575  507310  NSTP6    ENTSR   $C                                       USE MEMORY BANK 0
 005576  507201           ENTICR  1                                        USE ICR1 AS THE INDEX REG.(B)
 005577  360000           ENTBK   0                                        INITIALIZE THE E REG. TO 0
 005600  400002           STRZ    2                                        ICR2=0, THE COLUMN INDEX
 005601  400003           STRZ    3                                        ICR3=0, THE ROW INDEX
 005602  507313           ENTSR   $3                                       USE MEMORY BANK 3
 005603  122332           ENTAL   NRDATA                                   AL:=NUM OF COMPENSATOR STATES
 005604  717776           ADDALK  -1                                       AL:=NRDATA-1
 005605  507310           ENTSR   $0                                       USE MEMORY BANK 0 SINCE NRWEND IS THERE
 005606  445164           STRAL   NRWEND                                   NRWEND:=NRDATA-1
 005607  507313           ENTSR   $3                                       BACK TO MEMORY BANK 3 FOR DATA
 005610  700000  NNXRN3   ENTALK  0                                        AL:=0
 005611  507400           XFRLU                                            AU:=AL=0
 005612  500600  NNXCL3   STRA    TPP                                      TMP:=A
 005613  031650
 005614  507202           ENTICR  2                                        GET THE COLUMN INDEX
 005615  370001           ENTBKM  1                                        INCREMENT COLUMN INDEX(ICR2=ICR2+1)
 005616  132273           ENTALB  NZKF1-1                                  AL:=(NZKP1+ICR2-1)
 005617  507201           ENTICR  1                                        USE ICR1 AS INDEX REG.(ELEMENT INDEX)
 005620  252316           PULALB  NTCMIN                                   A:=AL * (NTCMIN+ICR1)
 005621  201650           ADDA    TPP                                      A:=A + (TPP,TMP+1)
 005622  505300           SKPNOV                                           CHECK FOR OVERFLOW
 005623  504000           NOOP                                             CALL OVERFLOW HANDLER
 005624  565164           ESK     NRWEND                                   IF ICR1=NRWEND THEN SKIP NEXT LINE
                *                               ELSE DO NEXT LINE AND ICR1=ICR1+1
 005625  345612           JP      NNXCL3                                   JUMPS TO NEXT COLUMN OF NTCMIN
                *                               AND NEXT ROW ELEMENT OF NZKP1
 005626  370001           ENTBKB  1                                        ICR1=ICR1+1
 005627  507203           ENTICR  3                                        USE ICR3 AS INDEX REG.(ROW INDEX)
 005630  504700           LRTA    0                                        SCALING FOR NSTP6 IS 2**18
 005631  472221           STRAUB  NUR                                      NUR+ICR3:=(AU),SCALING IS 2**18
 005632  565170           ESK     NNCP1                                    IF ICR3=NNCM1 THEN SKIP NEXT LINE
                *                               ELSE DO NEXT LINE AND ICR3=ICR3+1
 005633  345635           JP      NRSET3                                   GO RESET THE COUNTER
 005634  345643           JP      NSTF7                                    GO TO NEXT MATRIX MULT IF DONE
 005635  507202  NRSET3   ENTICR  2                                        SAVE ROW INDEX AND START USING COLUMN INDEX
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Longitudinal CAS Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.C   MOVR43  10/02/14   SECTION   1                                                PAGE  70

005636  360000                ENTBK    0                                   RESET COLUMN INDEX TO ZERO
005637  507320                ENTSR    IC                                  USE BANK 0 SINCE NRWEND AND NNCTRL ARE THERE
005640  125164                ENTAL    NRWEND                              AL:=NRWEND
005641  145166                ADDAL    NRR                                 AL:=NRWEND+NRR=NRWEND+NCF COLUMNS
005642  445164                STRAL    NRWEND                              NRWEND:=NRWEND+NNCTRL
005643  507313                ENTSR    T3                                  USE BANK 3 FOR DATA
005644  345610                JP       NAXRW3                              DO THE NEXT ROW
                        *
                        *  ------------SECTION NSTP7----------
                        *
                        *           THIS STEP DOES THE ADDITION NUT = NUC + NUR + NUI
                        *
005645  507201    NSTP7       ENTICR   1                                   USE ICR1
005646  360001                ENTBK    1                                   (ICR1=0) MEANS (I=1)
005647  132214    NSTP70      ENTALB   NUC-1                               AL:=(NUC+ICR1-1)
005650  152220                ADDALB   NUR-1                               AL:=AL+(NUR+ICR1-1)
005651  152210                ADDALB   NUI-1                               AL:=AL+(NUI+ICR1-1)
005652  505300                SKPNOV                                       SKIP A LINE IF NO OVERFLOW
005653  504000                NOOP                                         CALL OVERFLOW HANDLER
005654  452224                STRALB   NUT-1                               NUT:=AL, NUT(I)=NUC(I)+NUR(I)
005655  565171                BSK      NNCTRL                              IF BSK=NNCTRL SKIP THE NEXT LINE
                        *                               ELSE ICR1:=ICR1+1 AND DO NEXT LINE
005656  345647                JP       NSTP70                              CONTINUE
005657  345660                JP       NSTP8                               WRITE THE DATA OUT
                        *
                        *  ---------------SECTION NSTP8-----------
                        *
                        *           HERE GOES THE SECTION(NSTP8) WHICH WRITES NUT(ACTUATOR
                        *           COMMANDS) TO THE LOCATION  WHICH SENDS NUT TO THE
                        *           ACTUATORS.
                        *                                    NSTP8
005660  122225    NSTP8       ENTAL    NUT                                 AL:=NUT(1),LONG CYCLIC
005661  242340                MULAL    NLNGSC                              SCALE FOR OUTPUT(1IN/140.85BITS)
005662  460072                STRAU    OEP1                                STORE NUT(1) TO ECS PITCH COMMAND
005663  122226                ENTAL    NUT+1                               AL:=NUT(2),COLLECTIVE
005664  242341                MULAL    NCOLSC                              SCALE THE OUTPUT(1IN/206.24BITS)
005665  460075                STRAU    OEF4                                STORE NUT(2) TO ECS COLLECTIVE COMMAND
                        *           ENTAL'NUT+2 AL:=NUT(3), LATERAL CYCLIC
                        *           MULAL'NLATSC      SCALE THE OUTPUT(1IN/218.33BITS)
                        *           STRAU'OBF2  STORE NUT(3) TO ECS ROLL COMMAND
                        *           ENTAL'NUT+3 AL:=NUT(4), DIRECTIONAL COMMAND
                        *          MULAL'NTAWSC      SCALE THE OUTPUT(1IN/280.93BITS)
                        *           STRAU'OBF3  STORE NUT(4) TO ECS YAW COMMAND
                        *
                        *  -------------SECTION NSTP9
                        *
                        *           THIS SECTION OF CMSTR2 SETS THE PRESENT COMPENSATOR
                        *           STATES(NZKP1) TO OLD STATES(NZK)
                        *
005666  507201    NSTP9       ENTICR   1                                   USE ICR1 AS INDEX
005667  360001                ENTBK    1                                   ICR1=0  (I=0)
005670  132273    NSTP90      ENTALB   NZKP1-1                             AL:=(NZKP1+ICR1)
005671  452270                STRALB   NZK-1                               NZK+ICR1-1:=AL
005672  565166                BSK      NRR                                 IF ICR1=NRR THEN SKIP 1 LINE
                        *                                   ELSE ICR1=ICR1+1  AND DO NEXT LINE
005673  345670                JP       NSTP90                              CONTINUE
005674  555173                IJP      CPSTR2                              END THE CONTROLLER SUBROUTINE NUMBER 2
```

Hover Controller Subroutine.

```
1819A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION  1                                   PAGE  86

                 *
                 * ****************************************************************************
                 *          THIS IS THE START OF THE SUBROUTINE WHICH DOES THE
                 *          PINTNAL COMPENSATOR FOR THE HOVER CONTROLLER.
                 *          THE CONTROL STRATEGY IS "VELOCITY COMMAND/POSITION HOLD"
                 *          THE INPUTS TO THE SUBROUTINE ARE
                 *                   PPLT(PILOT COMMANDS)
                 *                   PYS(THE MEASUREMENT VECTOR)
                 *          THE OUTPUTS ARE:
                 *                   PUT(THE COMMANDS TO THE ACTUATORS)
                 *         THE EQUATIONS BEING DONE BY THIS SUBROUTINE ARE
                 *
                 *            P?DPID = P?DP + P?DI + P?DD + P?DOLD
                 *                  WHERE ? IS X, Y, AND Z.
                 *                  NOTE: THIS EQUATION IS DONE ONLY DURING
                 *                        POSITION HOLD
                 *            PYDES = PYSCLE * (PPLT+P?DPID)
                 *            PUC = PNK * PYDES
                 *            PZKP1 = PPIN * PZK   +  PBNIN * PYS
                 *            PUR = PCMIN * PZKP1
                 *            PUT = PUR + PUC
                 *
                 *              WHERE:    P?DP-- PROPORTIONAL CONTROL
                 *                        P?DI-- INTEGRAL CONTROL
                 *                        P?DD-- DERIVATIVE CONTROL
                 *                        P?DPID-- TOTAL PID CONTROL
                 *                        PUC-- THE SETPOINT CONTROL VECTOR
                 *                        PNK-- THE FEEDFORWARD GAIN MATRIX(FOR SETPOINT
                 *                              CONTROL
                 *                        PPLT-- THE PERTURBATION PILOT INPUT VECTOR
                 *                               (PERTURBED ABOUT THE CNTRL AT INITIALIZE)
                 *                        PZKP1-- THE PRESENT COMPENSATOR STATE VECTOR
                 *                        PAMIN-- THE COMPENSATOR DYNAMICS MATRIX
                 *                        PZK-- THE LAST COMPENSATOR STATE VECTOR
                 *                        PBMIN-- THE COMPENSATOR INPUT DIST. MATRIX
                 *                        PYS-- THE MEAS. VECTOR
                 *                        PUR-- THE REGULATOR/COMPENSATOR CONTROL VECTOR
                 *                        PCMIN-- THE COMPENSATOR OUTPUT MATRIX
                 *                        PUT-- THE TOTAL PERTURBATION CONTROL
                 * ****************************************************************************
                 *
                 *          RESERVE WORDS FOR USE IN THE BRANCHING INSTRUCTIONS
                 *
  006711  000000      PRNEND    RESERV    RESERV'1D                  RUN COUNTER
  006712  000000      PRRM1     RESERV    RESERV'1D                  ORDER OF COMPENSATOR - 1
  006713  000000      PRR       RESERV    RESERV'1D                  ORDER OF COMPENSATOR
  006714  000000      PRRP1     RESERV    RESERV'1D                  ORDER OF COMPENSATOR + 1
  006715  000000      PNCM1     RESERV    RESERV'1D                  NUMBER OF CONTROLS - 1
  006716  000000      PNCTRL    RESERV    RESERV'1D                  NUMBER OF CONTROLS
  006717  000000      PNMEAS    RESERV    RESERV'1D                  NUMBER OF MEASUREMENTS
  006720  000000      CPSTR4    0'0
                 *
                 *        INITIALIZE BRANCHING VARIABLES SINCE BSK DOESN'T USE
                 *        THE SPECIAL REGISTER
                 *
  006721  307313                ENTSN     S3                         USE MEMORY 3 REGISTER
  006722  123136                ENTAL     PNC                        AL:=(PNC)
```

AD-A151 946 A MODERN CONTROL DESIGN METHODOLOGY WITH APPLICATION TO THE CH-47 HELICOPTER(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH R D HOLDRIDGE JAN 85 3/3

UNCLASSIFIED AFIT/CI/NR-85-33D F/G 1/4 NL

END

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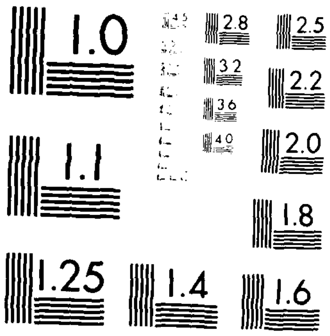
1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

Hover Controller Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION   1                                           PAGE  87

006723  103137          ENTAU    PNP                                    AU:=(PNP)
006724  507310          ENTSR    TC                                     USE MEMORY BANK 0
006725  446716          STRAL    PNCTRL                                 PNCTRL:=PNC
006726  717770          ADDALK   +1                                     AL:=PNC-1
006727  446715          STRAL    PNCP1                                  PNCM1:=PNC-1
006730  466717          STRAU    PKMEAS                                 PNMEAS:=PNM
006731  507313          ENTSR    13                                     USE MEMORY BANK 3
006732  123135          ENTAL    PR                                     AL:=(PR)
006733  103144          ENTAU    PRP1                                   AU:=(PRP1)
006734  507310          ENTSR    TO                                     USE MEMORY BANK 0
006735  446713          STRAL    PRR                                    PRR:=PR
006736  717770          ADDALK   -1                                     AL:=AL-1=PR-1
006737  446712          STRAL    PRRM1                                  PRRM1:=PR-1
006740  466714          STRAU    PRRP1                                  PRRP1:=PRP1
                 *
                 *  ----------SECTION PSTPO---------------
                 *
                 *   THIS SECTION PUTS MEASUREMENTS NEEDED BY THE CONTROLLER
                 *   INTO THE MEASUREMENT VECTOR, PYS.
                 *
                 *   IN BASIC, THE CODE WOULD BE:
                 *
                 *           FOR I=1 TO NM                          )
                 *             PYS(I)=MEAS(PTSSEL(I))               )<-PSTPO1
                 *           NEXT I                                 )
                 *
                 *   PTSSEL IS A VECTOR CONTAINING, IN ORDER, THE INDEX NUMBERS
                 *   OF THE SELECTED MEASUREMENTS.  THE MEASUREMENTS COME FROM BANK 3.
                 *   THE INDEX NUMBERS AND THE RELATED POSSIBLE MEASUREMENTS ARE
                 *   SHOWN BELOW:
                 *
                 *      INDEX NUMBER              PARAMETER
                 *           1            THETA(+NOSE UP,500/DEG)
                 *           2            PHI(+RWD,500/DEG)
                 *           3            PSI(MAGNETIC,500/DEG)
                 *           4            Q(+NOSE UP,500/(DEG/SEC))
                 *           5            P(+RWD,500/(DEG/SEC))
                 *           6            R(+RIGHT,500/(DEG/SEC))
                 *           7            LONG. ACCEL.(NO GRAV,+FORW,128/(FT/SEC**2))
                 *           8            LAT. ACCEL.(NO GRAV,+RIGHT,128/(FT/SEC**2))
                 *           9            NORMAL ACCEL.(NO GRAV,+UP,128/(FT/SEC**2))
                 *          10            DELTA FORW. VEL.(+FORW,8/(FT/SEC))
                 *          11            DELTA VERT. VEL.(+UP,32/(FT/SEC))
                 *          12            BARO. ALT.(16/FT)
                 *          13           X POSITION(+ FORW., 16/FT) IN HEADING INERTIAL AXIS
                 *          14           Y POSITION(+ RIGHT, 16/FT) IN HEADING INERTIAL AXIS
                 *          15           Z POSITION(+ DOWN, 16/FT) IN HEADING INERTIAL AXIS
                 *          16           X INERTIAL VEL.(+ FORW., 32/FPS) IN HEADING INERTIAL AXI
                 *
                 *          17           Y INERTIAL VEL.(+ RIGHT, 32/FPS) IN HEADING INERTIAL AXI
                 *
                 *          18           Z INERTIAL VEL.(+ DOWN, 32/FPS) IN HEADING INERTIAL AXIS
                 *          19           X POSITION(+ FORW., 16/FT) IN RUNWAY FRAME
                 *          20           Y POSITION(+ RIGHT, 16/FT) IN RUNWAY FRAME
                 *          21           X INERTIAL VEL.(+ FORW., 32/FPS) IN RUNWAY FRAME
                 *          22           Y INERTIAL VEL.(+ RIGHT, 32/FPS) IN RUNWAY FRAME
                 *
                 *   NOTE THAT THETA, VERT. VEL., AND AIRSPEED ARE PERTURBATION QUANTITIES AND MAY
```

Hover Controller Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.0   HOVR83  10/02/84   SECTION   1                                                  PAGE  88

4294                     $
4295  006741  307313  PSIPO    ENTSR    T3                                      USE MEMORY BANK 3
4296  006742  120746           ENTAL    INSTH                                   AL:=ANGTH(PITCH ANGLE)
4297  006743  163151           SUBAL    PTRPTH                                  AL:=AL-PTRPTH(PERTURBATION THETA)
4298  006744  443202           STRAL    PCTHET                                  FDTHET:=PERTURBATION PITCH ANGLE
4299                     $               +NOSE UP, 500/DEG
4300  006745  120753           ENTAL    INSPHI
4301  006746  163152           SUBAL    PTRPPH                                  AL:=AL-PTRPPH(PERTURBATION PHI)
4302  006747  443203           STRAL    PPHI                                    FPHI IS RCLL,+RWD,500/DEG
4303  006750  120760           ENTAL    INSPSI
4304  006751  443204           STRAL    PPSI                                    FPSI IS HEADING, MAGNETIC,500/DEG
4305  006752  120743           ENTAL    PITR/G
4306  006753  443205           STRAL    PPITRT                                  FITCH RATE,+ NOSE UP,500/(DEG/SEC)
4307  006754  120744           ENTAL    RCLR/G
4308  006755  443206           STRAL    PROLRT                                  ROLL RATE,+ RWD,500/(DEG/SEC)
4309  006756  120745           ENTAL    YAWR/G
4310  006757  443207           STRAL    PYAWRT                                  YAW RATE,+RIGHT,500/(DEG/SEC)
4311  006760  120747           ENTAL    ACCLNG
4312  006761  443210           STRAL    PAX                                     LONG. ACCEL.,NO GRAV,+FORW,128/(FT/SEC**2)
4313  006762  120750           ENTAL    ACCLAT
4314  006763  443211           STRAL    PAY                                     LAT. ACCEL.,NO GRAV,+RIGHT128/(FT/SEC**2)
4315  006764  120751           ENTAL    ACCNRM
4316  006765  443212           STRAL    PAZ                                     NORMAL ACCEL.,NO GRAV,+UP,128/(FT/SEC**2)
4317  006766  120752           ENTAL    AIRSPD
4318  006767  163153           SUBAL    PTRPAS                                  AL:=AIRSPC-TRIM AIRSPEED
4319  006770  443213           STRAL    PUVEL                                   PUVEL IS PERTURBATION VELOCITY,
4320                     $               +FORW,8/(FT/SEC)
4321  006771  120765           ENTAL    IVST                                    VERT. SPEED,+UP,32/(FT/SEC)
4322  006772  163154           SUBAL    PTRPHD                                  SUBTRACT HDOT AT ENGAGE
4323  006773  443214           STRAL    PVVEL                                   PERTURBEC VERT. SPEED,+UP,32/(FT/SEC)
4324  006774  120754           ENTAL    BARC
4325  006775  443215           STRAL    PFALT                                   BARO. ALT., 16/FT
4326  006776  121147           ENTAL    XPOCT
4327  006777  443216           STRAL    PXBCD                                   X POSITICN(+ FORW., 16/FT) IN HEADING FRAME
4328  007000  121150           ENTAL    YPOCT
4329  007001  443217           STRAL    PYBCD                                   Y POSITION(+ RIGHT, 16/FT) IN HEADING FRAME
4330  007002  121136           ENTAL    ZFILT
4331  007003  443220           STRAL    PZBCD                                   Z POSITION(+ DOWN, 16/FT) IN HEADING FRAME
4332  007004  121151           ENTAL    XPDCT
4333  007005  443221           STRAL    PXBCOT                                  X INERTIAL VEL.(+FORW, 32/FPS) IN HEADING FRA
                                                                                ME
4334  007006  121152           ENTAL    YPDCT
4335  007007  443222           STRAL    PYBCOT                                  Y INERTIAL VEL.(+RIGHT, 32/FPS) IN HEADING FR
                                                                                AME
4336  007010  121142           ENTAL    ZCOT
4337  007011  443223           STRAL    PZBCOT                                  Z INERTIAL VEL.(+DOWN, 32/FPS) IN HEADING FRA
                                                                                ME
4338  007012  121134           ENTAL    XPILT                                   X POSITION(+ FORW, 16/FT) RUNWAY AXIS
4339  007013  443224           STRAL    PX
4340  007014  121135           ENTAL    YPILT                                   Y POSITCN(+RIGHT, 16/FT) RUNWAY AXIS
4341  007015  443225           STRAL    PY
4342  007016  121140           ENTAL    XCOT                                    X INERTIAL VELOCITY(+ FORW, 32/FPS)RUNWAY AXIS
4343  007017  443226           STRAL    PXDCT
4344  007020  121141           ENTAL    YCOT                                    Y INERTIAL VELOCITY(+ RIGHT, 32/FPS)RUNWAY AX
                                                                                IS
4345  007021  443227           STRAL    PYDCT
```

Hover Controller Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION   1                                    PAGE  89

                      *
                      *   THIS SECTION DOES THE PYS SELECTION
                      *
007022  507201                    ENTICR    1                        USE ICRI AS INDEX I
007023  360001                    ENTBK     1                        START WITH ICR1=1 SO (I=2)
007024  133124        PSTP01      ENTALB    PYSSEL-1                 AL:=(PYSSEL+ICRI-1)
007025  441650                    STRAL     TPP                      TMP:=PYSSEL(I)
007026  507202                    ENTICR    2                        USE ICR2 AS INDEX
007027  321650                    ENTB      TPP                      B:=TMP=PYSSEL(I)
007030  133201                    ENTALB    PDTHET-1                 AL:=MEAS(PYSSEL(I))=(PDTHET+TMP-1)
007031  507201                    ENTICR    1                        USE INDEX REGISTER 1 AGAIN
007032  452784                    STRALB    PYS-1                    (PYS+ICRI-1)=PYS(I)=AL
007033  566717                    ESK       PNMEAS                   IF B=PNMEAS SKIP A LINE
                      *                       ELSE ICRI=ICRI+1 AND DO NEXT LINE
007034  347024                    JP        PSTP01                   CONTINUE
                      *
                      *
                      *   THIS SECION PUTS EXPERIMENTAL PILOT COMMANDS INTO THE PPLT VECTOR
                      *
007035  120755        PSTP03      ENTAL     EPLCN                    AL:=EP LONG STICK
007036  504600                    LRTAL     0                        SCALE THE INPUT OF LONG CYLIC
007037  442761                    STRAL     PPLT                     PPLT(1)=LONG STICK,1024PER IN,+AFT
007040  120760                    ENTAL     EFHEAV                   AL:=EP COLLECTIVE
007041  504600                    LRTAL     0                        SCALE THE INPUT OF COLLECTIVE
007042  442762                    STRAL     PPLT+1                   PPLT(2)=COLLECTIVE,1024 PER IN,+UP
007043  120756                    ENTAL     EPLAT                    AL:=EP LATERAL STICK
007044  504600                    LRTAL     0                        SCALE THE LATERAL STICK
007045  442763                    STRAL     PPLT+2                   PPLT(3)=LATERAL CYCLIC,1024 PER IN,+RIGHT
007046  120757                    ENTAL     EFYAW                    AL:=EP YAW COMMANDS
007047  504600                    LRTAL     0                        SCALE THE PEDALS
007050  442764                    STRAL     PPLT+3                   PPLT(4)=YAW CONTROL,1024 PER IN,+RIGHT??
                      *
                      *
                      *           *************SECTION PSTP1*****************
                      *
                      *     THIS SECTION DOES THE PID CONTROL CALCULATIONS IN EACH
                      *     OF THE 3 AXES.  IT FIRST CHECKS TO SEE IF THE APPROPRIATE
                      *     PILOT CONTROL IS OUT OF DETENT.  IF OUT OF DETENT, THE PID
                      *     CALCULATIONS ARE HELD AND THE PILOT'S CONTROL BECOMES A
                      *     VELOCITY COMMAND TO THE CM=47.  IF IN DETENT, THE PID CALCULATIONS
                      *     HOLD POSITION IN THAT AXIS.  THE 3 AXES ARE HANDLED INDEPENDENTLY.
                      *     THIS CODE ALSO PUTS A DEADZONE AROUND THE PILOT CONTROL TO
                      *     ELIMINATE TRANSIENTS WHEN GOING IN AND OUT OF DETENT.
                      *
                      *     THE FOLLOWING IS AN EQUIVALENT SET OF BASIC LANGUAGE
                      *     INSTRUCTIONS NEEDED TO DO THE JOB.
                      *
                      *   PSTP10     IF ABS(PPLT(1))<PXDINT THEN GO TO PSTP11
                      *              ELSE CONTINUE
                      *              PXREF=PXFILT
                      *              PXDOLD=PXCPID
                      *              IF PPLT(1)<0 THEN PPLT(1)=PPLT(1)+PXDINT
                      *              ELSE PPLT(1)=PPLT(1)-PXDINT
                      *              GO TO PSTP12
                      *   PSTP11     PDELX=PXFILT-PXREF
                      *              PXDP=PKXP*PDELX
                      *              PXDI=PXCI+PKXI*PDELX
```

Hover Controller Subroutine. (contd)

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1019A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION   1                                  PAGE  96

                       *              PXDD=PKXD*PXDOT
                       *              PXDPID=PXFP+PXKI+PXDD+PXDCLD
                       *
                       *    PSTP12  IDENTICAL EXCEPT FOR THE Y AXIS(PPLT(3) IS LAT. CONTROL)
                       *
                       *    PSTP14 IDENTICAL EXCEPT FOR THE Z AXIS(PPLT(2) IS COLLECTIVE)
                       *
                       *
                       *     X AXIS ***VELOCITY COMMAND/POSITION HOLD*** LOGIC
                       *
007051 122761   PSTP10    ENTAL    PFLT                                       AL:=PPLT(1)=PILOT LONG STICK
007052 700533             RJP      ABSVAL                                     GET ABS(PFLT(1))
007053 023172             CMAL     PXDINT                                     COMPARE PFLT(1) AND DETENT MAGNITUDE
007054 677115             JPMGR    PSTP11                                     IF DETENT IS LARGER GO TO PID CALCULATIONS
                       *                            ELSE THE PILOT IS COMMANDING A VELOCITY AND
                       *                            WE DO THE FOLLOWING INSTRUCTIONS
007055 400605             STRZ     H/RFLG                                     TURN OFF THE PITCH DETENT LIGHT
007056 703777             ENTALK   3777
007057 440111             STRAL    OPK16                                      PITCH BAR OUT OF VIEW IF NOT PID
007060 123210             ENTAL    PXBCD                                      THESE TWO LINES FORCE THE REFERENCE POSITION
                                                                              TO FOLLOW
007061 443231             STRAL    PXBREF                                     ACTUAL POSITION WHILE THE PILOT IS COMMANDING
                                                                               A RATE.
007062 123231             ENTAL    PXBREF                                     DO THE TRANSFORMATION FROM HEADING TO RUNWAY
007063 103242             ENTAU    PYBREF                                     GET XBREF AND YBREF IN THE A REGISTER
007064 703413             RJP      PROTAT
007065 443230             STRAL    PXREF
007066 403241             STRAU    PYREF
                       *
                       *       DO FADE OUT OF OLD PID CONTROL WHILE PILOT IS
                       *       COMMANDING A VELOCITY.
007067 123271             ENTAL    PXBCFF                                     AL:=FADE-OUT MULTIPLIER
007070 637074             JPALNZ   LCK+4                                      IF NOT RAMPED TO ZERO, GO DOWN AND CONTINUE R
                                                                              AMP
007071 403240             STRZ     PXDCLD                                     IF WE'VE RAMPED TO ZERO, HOLD PXDCLD AT ZERO
007072 403271             STRZ     PXBCFF                                     IF WE'VE RAMPED TO ZERO, KEEP RAMP AT ZERO
007073 347101             JP       LCK+6                                      SKIP AROUND THE FADE-OUT TO STRZ' COMMAND
007074 717776             ADDALK   -1                                         CONTINUE RAMP DOWN
007075 443271             STRAL    PXBCFF                                     STORE THE RAMPED DOWN VALUE
007076 243240             MULAL    PXDCLD                                     A:=RAMP*PXDOLC
007077 504706             LRTA     6C                                         DIVIDE BY NUMBER OF CYCLES IN RAMP DOWN
007100 403240             STRAU    PXDCLD                                     PXDOLCI= FADED VALUE
007101 403266             STRZ     PXEZON                                     GET READY FOR PID FADE-IN
007102 123240             ENTAL    PXDCLD                                     STORE THE FADED VALUE OF THE LAST PID
007103 443274             STRAL    PXCLST                                     COMMAND BEFORE COMING OUT OF DETENT
007104 403260             STRZ     PXDI                                       ZERO THE INTEGRATOR
007105 403261             STRZ     PXDI+1                                     *
                       *
                       *    NOW DO THE DEADZONE CALCULATIONS
007106 122701             ENTAL    PFLT                                       AL:=PPLT(1), PILOT LNG STICK
007107 677112             JPALNG   LOK+3                                      IF CONTROL NEGATIVE, SKIP A LINE
007110 163172             SUBAL    PXDINT                                     ELSE THE CONTROL IS POSITIVE SO SUBTRACT
                       *                            THE DETENT VALUE.
007111 347113             JP       LCK+2                                      GO STORE THE DEADZONED VALUE
007112 143172             ADDAL    PXDINT                                     FOR NEG.CONTROL, ADD DETENT
007113 442701             STRAL    PFLT                                       PUT THE MODIFIED CONTROL BACK IN PPLT
007114 347205             JP       PSTP12                                     GO TO THE Y AXIS
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Hover Controller Subroutine. (contd)

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1819X ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION   1                                        PAGE   91

 4457  007115  123230  PSTP11  ENTAL    PXREF          DO THE TRANSFORMATION FROM RUNWAY TO HEADING
 4458  007116  103201          ENTAU    PYREF          GET XREF  AND YREF  IN THE A REGISTER
 4459  007117  763366          RJP      RCTATE
 4460  007120  463202          STRAU    PYBREF
 4461  007121  700001          ENTALK   1              TURN CN THE  PITCH DETENT LIGHT
 4462  007122  440665          STRAL    R/XFLG
 4463  007123  402761          STRZ     PPLT           STORE ZERO IN PILOT COMMAND WHEN IN PID
 4464  007124  123216          ENTAL    PXBCD          THESE 3 LINES CALCULATE
 4465  007125  163231          SUBAL    PXBREF         THE PCSITION ERROR, AL=PDELX
 4466  007126  443232          STRAL    PDELX          STORE PDELX
 4467  007127  506100          CPAL                    USE PITCH BAR TO SHOW XPOSN ERROR
 4468  007130  760623          RJP      BATCHK         IN PIC MCDE
 4469  007131  440111          STRAL    OPR16          SCALING 3.33V=682 COUNTS=42.6 FEET=1 INCH?
 4470  007132  123232          ENTAL    PDELX
 4471  007133  243155          MULAL    PKXP           MULTIPLY PKXP*PDELX(DO PROPORTIONAL CONTROL)
 4472  007134  504707          LRTA     7C             SCALING CN KXP IS 1 FPS PER FT ERRCR = 1024 B
                                                       ITS
 4473  007135  463233          STRAU    PXDF           STORE THE RESULT
 4474  007136  123232          ENTAL    PDELX          GET PCSITION ERRCR TO BE INTEGRATED(1FT=16BIT
                                                       S)
 4475  007137  760533          RJP      ABSVAL         HOLD INTEGRATOR TERM IF ERROR GT 15FT
 4476  007140  023176          CMAL     PK240
 4477  007141  657147          JPMLEQ   PS3115
 4478  007142  123232          ENTAL    PDELX
 4479  007143  243160          MULAL    PKXI           MULTIPLY BY DIGITIZED INTEGRAL GAIN(1FPS/FT=2
                                                       **19BITS)
 4480  007144  203260          ADDA     PXDI           CO SUMMATION(THE INTEGRATION)
 4481  007145  500600          STRA     PXCI           AU GOES TC PXKI+1, AL TO PXKI
       007146  033260
 4482  007147  123226  PS3115  ENTAL    PXDCT          DO DERIVATIVE CONTROL
 4483  007150  243163          MULAL    PKXC           FXDD=PKXD*PXDOT
 4484  007151  504706          LRTA     6C             SCALING CN PKXD IS 1 FPS PER FPS = 1024 BITS
 4485  007152  463234          STRAU    PXDC           STORE RESULT
 4486  007153  123202          ENTAL    PCTHET         GET THETA FOR 2ND DERIVATIVE CONTROL
 4487  007154  243166          MULAL    PKXTH          FXDTH=PCTHET*PKXTH
 4488  007155  504704          LRTA     4C             SCALING CN PKXTH IS 1 FPS PER DEG = 1048 BITS
 4489  007156  463235          STRAU    PXDTH          STORE THE RESULT
 4490  007157  123205          ENTAL    PPITRT         GET Q FCR 3RD DERIVATIVE CONTROL
 4491  007160  243170          MULAL    PKXPR          FXDPR=PPITRT*PKXPR
 4492  007161  504704          LRTA     4C             SCALING CN PKXPR IS 1 FPS PER DEG/SEC = 1048
                                                       BITS
 4493  007162  463236          STRAU    PXDPR          STORE THE RESULT
 4494  007163  123233          ENTAL    PXDF           BEGIN THE PXDPIC EQUATION
 4495  007164  143261          ADDAL    PXDI+1
 4496  007165  143234          ADDAL    PXCC
 4497  007166  143235          ADDAL    PXDTH
 4498  007167  143236          ADDAL    PXDFR
 4499  007170  443237          STRAL    PXDPID         FXDPIC=PXCP+PXDI+PXDD+PXDTH+PXDPR
 4500                 *
 4501                 *  DO RAMP FADE-IN CF PID COMMAND WHEN THE PILOT
 4502                 *  GOES BACK INTO DETENT
 4503  007171  123200          ENTAL    PXEZCN         AL= FADER MULTIPLIER
 4504  007172  710001          ADDALK   1              DO RAMP UP
 4505  007173  103201          ENTAU    PK320          USE 128 CYCLES AS THE RAMP UP TIME
 4506  007174  760537          RJP      LIMIR          LIMIT PXEZCN TO PK128 (LIMIT AL TC AU)
 4507  007175  443200          STRAL    PXEZCN         STORE RAMP FADER VALUE
 4508  007176  243237          MULAL    PXDPID         A:=RAMP*PID CONTROL
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Hover Controller Subroutine. (contd)

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1019A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION   1                                    PAGE  97

   007177  504307            RSHA     7C            DIVIDE BY NUMBER OF CYCLES IN RAMP
   007200  143274            ADDAL    PXCEST        ADD LAST PID COMMAND(FADED) TO AVCIC TRANSIENT
   007201  443237            STRAL    PXDFID        PUT SUM BACK INTO PID COMMAND
   007202  443240            STRAL    PXDCLD        STORE PID COMMAND FOR LATER FADE-OUT
   007203  123200            ENTAL    PK64          GET READY FOR THE PXDOLD FADE-OUT ABOVE
   007204  443271            STRAL    PXECFF        CXECFF GET START OF FADE-OUT VALUE
                     *
                     *     Y AXIS ***VELOCITY COMMAND/POSITION HOLD***
                     *
   007205  122763  PSTP12   ENTAL    PPLT+2        AL:=PPLT(3)=PILOT LAT STICK
   007206  760533            RJP      ABSVAL        GET ABS(PPLT(3))
   007207  023173            CMAL     PYDINT        COMPARE PPLT(3) AND DETENT MAGNITUDE
   007210  677251            JPMGR    PSTF13        IF DETENT IS LARGER GO TO PID CALCULATIONS
                     *                       ELSE THE PILOT IS COMMANDING A VELOCITY AND
                     *                       WE DO THE FOLLOWING INSTRUCTIONS
   007211  400004            STRZ     R/PPLG        TURN OFF THE ROLL DETENT LIGHT
   007212  703777            ENTALK   3777          ROLL BAR OUT OF VIEW IF NOT IN PID
   007213  440112            STRAL    OPR17
   007214  123217            ENTAL    PYBCD         THESE TWO LINES FORCE THE REFERENCE POSITION
                                                    TO FOLLOW
   007215  443242            STRAL    PYBREF        ACTUAL POSITION WHILE THE PILOT IS COMMANDING
                                                     A RATE.
   007216  123231            ENTAL    PXBREF        DO THE TRANSFORMATION FROM HEADING TO RUNWAY
   007217  103242            ENTAU    PYBREF        GET XRREF AND YRREF IN THE A REGISTER
   007220  763413            RJP      BROTAT
   007221  443230            STRAL    PXREF
   007222  463241            STRAU    PYREF
                     *
                     *     DO FADE OUT OF OLD PID CONTROL WHILE PILOT IS
                     *     COMMANDING A VELOCITY.
   007223  123272            ENTAL    PYECFF        AL:=FADE-OUT MULTIPLIER
   007224  037230            JPALNZ   LCK+4         IF NOT RAMPED TO ZERO, GO DOWN AND CONTINUE R
                                                    AMP
   007225  403251            STRZ     PYDCLD        IF WE'VE RAMPED TO ZERO, HOLD PYDCLD AT ZERO
   007226  403272            STRZ     PYECFF        IF WE'VE RAMPED TO ZERO, KEEP RAMP AT ZERO
   007227  347235            JP       LCK+8         SKIP AROUND THE FADE-OUT TO STRZ' COMMAND
   007230  717776            ADDALK   -1            CONTINUE RAMP DOWN
   007231  443272            STRAL    PYECFF        STORE THE RAMPED DOWN VALUE
   007232  243251            MULAL    PYDCLD        A:=RAMP*PYDOLD
   007233  300706            LRTA     6C            DIVIDE BY NUMBER OF CYCLES IN RAMP DOWN
   007234  463251            STRAU    PYDCLD        PYDOLD:= FADED VALUE
   007235  403267            STRZ     PYEZON        GET READY FOR PID FADE-IN
   007236  123251            ENTAL    PYDCLD        STORE THE FADED VALUE OF THE LAST PID
   007237  443275            STRAL    PYDIST        COMMAND BEFORE COMING OUT OF DETENT
   007240  403262            STRZ     PYCI          ZERO THE INTEGRATOR
   007241  403263            STRZ     PYCI+1        *
                     *
                     *     NOW DO THE DEADZONE CALCULATIONS
   007242  122763            ENTAL    PPLT+2        AL:=PPLT(3), PILOT LATERAL STICK
   007243  077246            JPALNG   LCK+3         IF CONTROL NEGATIVE, SKIP A LINE
   007244  163173            SUBAL    PYDINT        ELSE THE CONTROL IS POSITIVE SO SUBTRACT
                     *                       THE DETENT VALUE.
   007245  347247            JP       LCK+2         GO STORE THE DEADZONED VALUE
   007246  143173            ADDAL    PYDINT        FOR NEG.CONTROL, ADD DETENT
   007247  442763            STRAL    PPLT+2        PUT THE MODIFIED CONTROL BACK IN PPLT
   007250  347333            JP       PSTP14        GO TO THE Z AXIS
```

Hover Controller Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.0   HCVR43  10/02/84   SECTION  1                                           PAGE  93

4562 007251 123230  PSTP13  ENTAL   PXREF          DO THE TRANSFORMATION FROM RUNWAY TC HEADING
4563 007252 103231          ENTAU   PYREF          GET XREF  AND YREF  IN THE A REGISTER
4564 007253 763366          RJP     ROTATE
4565 007254 443231          STRAL   PXEREF
4566 007255 700001          ENTALK  1              TURN CN THE ROLL DETENT LIGHT
4567 007256 440664          STRAL   A/PFLG
4568 007257 402763          STRZ    PFL1+2         STORE ZERC IN THE PILOT COMMAND WHEN IN PID
4569 007260 123217          ENTAL   PYBCC          THESE 3 LINES CALCULATE
4570 007261 163242          SUBAL   PYEREF         THE PCSITIN ERROR, AL=PDELY
4571 007262 443243          STRAL   PDELY          STORE PDELY
4572 007263 506100          CPAL                   SHOW Y PCSN ERROR ON ROLL BAR
4573 007264 760623          RJP     BRYCHK         IF IN PIC
4574 007265 440112          STRAL   OPF17          SCALING 3.33V=682 COUNTS=42.6 FEET=1 INCH?
4575 007266 123243          ENTAL   PDELY
4576 007267 243156          MULAL   PKYP           MULTIPLY PKYP*PDELY(DO PROPORTIONAL CONTROL)
4577 007270 504707          LRTA    7C             SCALING CN KYP IS 1 FPS PER FT ERROR = 1024 B
                                                   ITS
4578 007271 463244          STRAU   PYDP           STORE THE RESULT
4579 007272 123243          ENTAL   PDELY          GET PCSITICN ERROR TO BE INTEGRATED(1FT=16BIT
                                                   S)
4580 007273 243161          MULAL   PKYI           MULTIPLY BY DIGITIZED INTEGRAL GAIN(1FPS/FT=2
                                                   **19BITS)
4581 007274 203262          ADDA    PYDI           DO SUMMATION(THE INTEGRATION)
4582 007275 500600          STRA    PYDI           AU GOES TC PYKI+1, AL TO PYKI
     007276 033262
4583 007277 123227          ENTAL   PYDCT          DO DERIVATIVE CONTROL
4584 007300 243164          MULAL   PKYD           PYDD=PKYD*PYDOT
4585 007301 504706          LRTA    6C             SCALING ON PKYD IS 4 FPS PER FPS = 4096 BITS
4586 007302 463245          STRAU   PYDD           STORE RESULT
4587 007303 123203          ENTAL   PPHI           GET PHI(ROLL ANGLE) FOR 2ND DERIVATIVE CONTROL
4588 007304 243167          MULAL   PKYPH          PYDPH=PPHI*PKYPH
4589 007305 504704          LRTA    4C             SCALING ON PKYPH IS 1 FPS PER DEG = 1040 BITS
4590 007306 463246          STRAU   PYDPH          STORE THE RESULT
4591 007307 123208          ENTAL   PROLRT         GET P FOR 3RD DERIVATIVE CONTROL
4592 007310 243171          MULAL   PKYRR          PYDRR=PROLRT*PKYRR
4593 007311 504704          LRTA    4C             SCALING CN PKYRR IS 1FPS PER DEG/SEC = 1040 B
                                                   ITS
4594 007312 463247          STRAU   PYDRR          STORE THE RESULT
4595 007313 123244          ENTAL   PYDP           BEGIN THE PYDPIC EQUATION
4596 007314 143263          ADDAL   PYDI+1
4597 007315 143245          ADDAL   PYDD
4598 007316 143246          ADDAL   PYDPH
4599 007317 143247          ADDAL   PYDRR
4600 007320 443250          STRAL   PYDPID         PYDPIC=PYDP+PYDI+PYDD+PYDPH+PYDRR
4601                    *
4602                    *  DO RAMP FADE-IN CF PID COMMAND WHEN THE PILOT
4603                    *  GOES BACK INTO DETENT
4604 007321 123207          ENTAL   PYEZCN         ALIGN FADER MULTIPLIER
4605 007322 710001          ADDALK  1              DO RAMP UP
4606 007323 103201          ENTAU   PK520          USE 170 CYCLES AS THE RAMP UP TIME
4607 007324 760537          RJP     LIMIR          LIMIT PYEZCN TO PK128 (LIMIT AL TC AU)
4608 007325 443207          STRAL   PYEZCN         STORE RAMP FADER VALUE
4609 007326 243250          MULAL   PYDPID         AI=RAMP*PID CONTROL
4610 007327 504307          RSHA    7C             DIVIDE BY NUMBER OF CYCLES IN RAMP
4611 007330 143275          ADDAL   PYDLST         ADD LAST PID COMMAND(FADED) TO AVCID TRANSIENT
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Hover Controller Subroutine. (contd)

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1019A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION   1                                    PAGE  98

007331 443250           STRAL   PYDFID          PUT SUM BACK INTO PID COMMAND
007332 443251           STRAL   PYDCLD          STORE PID COMMAND FOR LATER FADE-OUT
007333 123200           ENTAL   PK64            GET READY FOR THE PYDOLD FADE-OUT ABOVE
007334 443272           STRAL   PYECFF          PYECFF GET START OF FADE-OUT VALUE
              *
              *   Z AXIS ***VELOCITY COMMAND/POSITION HOLD***
              *
007335 122762  PSTP14   ENTAL   PPLT+1          AL=PPLT(2)=PILOT COLLECTIVE
007336 760533           RJP     ABSVAL          GET ABS(PPLT(2))
007337 023174           CMAL    PZDTNT          COMPARE PPLT(2) AND DETENT MAGNITUDE
007340 677372           JPMGR   PSTF15          IF DETENT IS LARGER GO TO PID CALCULATIONS
              *                 ELSE THE PILOT IS COMMANDING A VELOCITY AND
              *                 WE DO THE FOLLOWING INSTRUCTIONS
007341 000003           STRZ    G/NFLG          TURN OFF THE COLLECTIVE DETENT LIGHT
007342 123220           ENTAL   PZBCD           THESE TWO LINE FORCE THE REFERENCE POSITION T
                                                O FOLLOW
007343 443252           STRAL   PZREF           ACTUAL POSITION WHILE THE PILOT IS COMMANDING
                                                 A RATE.
              *
              *    DO FADE OUT OF OLD PID CONTROL WHILE PILOT IS
              *    COMMANDING A VELOCITY.
007344 123273           ENTAL   PZECFF          AL=FADE-OUT MULTIPLIER
007345 637351           JPALNZ  LCR+4           IF NOT RAMPED TO ZERO, GO DOWN AND CONTINUE R
                                                AMP
007346 403257           STRZ    PZDCLD          IF WE'VE RAMPED TO ZERO, HOLD PZDCLD AT ZERO
007347 403273           STRZ    PZECFF          IF WE'VE RAMPED TO ZERO, KEEP RAMP AT ZERO
007350 347356           JP      LCR+6           SKIP AROUND THE FADE-OUT TO STRZ' COMMAND
007351 717776           ADDALK  -1              CONTINUE RAMP DOWN
007352 443273           STRAL   PZECFF          STORE THE RAMPED DOWN VALUE
007353 243257           PULAL   PZDCLD          A=RAMP*PZDOLD
007354 504706           LRTA    6D              DIVIDE BY NUMBER OF CYCLES IN RAMP DOWN
007355 403257           STRAU   PZDCLD          PZDOLD= FADED VALUE
007356 403270           STRZ    PZEZON          GET READY FOR PID FADE-IN
007357 123257           ENTAL   PZDCLD          STORE THE FADED VALUE OF THE LAST PID
007360 443276           STRAL   PZCLST          COMMAND BEFORE COMING OUT OF DETENT
007361 403264           STRZ    PZCI            ZERO THE INTEGRATOR
007362 403265           STRZ    PZCI+1          *
              *
              *   NOW DO THE DEADZONE CALCULATIONS
007363 122762           ENTAL   PPLT+1          AL=PPLT(2), PILOT COLLECTIVE
007364 677367           JPALNG  LCR+3           IF CONTROL NEGATIVE, SKIP A LINE
007365 163174           SUBAL   PZDTNT          ELSE THE CONTROL IS POSITIVE SO SUBTRACT
              *                 THE DETENT VALUE.
007366 347370           JP      LCR+2           GO STORE THE DEADZONED PILOT COMMAND
007367 143174           ADDAL   PZDTNT          FOR NEG.CONTROL, ADD DETENT
007370 442762           STRAL   PPLT+1          PUT THE MODIFIED CONTROL BACK IN PPLT(2)
007371 347434           JP      PSTF2           GO TO THE PILOT SCALING ROUTINE
007372 402762  PSTP15   STRZ    PPLT+1          STORE ZERO IN THE PILOT COMMAND WHEN IN PID
007373 700001           ENTALK  1               TURN ON THE COLLECTIVE DETENT LIGHT
007374 440003           STRAL   G/NFLG
007375 123220           ENTAL   PZBCD           THESE 3 LINES CALCULATE
007376 163252           SUBAL   PZREF           THE POSITION ERROR, AL=PDELZ
007377 443253           STRAL   PDELZ           STORE PDELZ
007400 243157           PULAL   PKZP            MULTIPLY PKZP*PDELZ(DO PROPORTIONAL CONTROL)
007401 504707           LRTA    7D              SCALING ON KZP IS 1 FPS PER FT ERROR = 1024 B
                                                ITS
007402 403254           STRAU   PZDP            STORE THE RESULT
```

Hover Controller Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION  1                                              PAGE  95

007403  123253              ENTAL   PEELZ       GET POSITION ERROR TO BE INTEGRATED(1FT=16BIT
                                                S)
007404  243162              MULAL   PKZI        MULTIPLY BY DIGITIZED INTEGRAL GAIN(1FPS/FT=2
                                                **19BITS)
007405  203264              ADDA    PZDI        DO SUMMATION(THE INTEGRATION)
007406  500600              STRA    PZCI        AU GOES TC PZKI+1, AL TO PZKI
007407  033264
007410  123223              ENTAL   PZBDOT      DO DERIVATIVE CONTROL
007411  243165              MULAL   PKZC        PZDD=PKZD*PZBDOT
007412  504706              LRTA    6C          SCALING CN PKZD IS 1 FPS PER FPS = 1024 BITS
007413  463255              STRAU   PZDC        STORE RESULT
007414  123254              ENTAL   PZDF        BEGIN THE PZDPIC EQUATION
007415  143265              ADDAL   PZCI+1
007416  143255              ADDAL   PZDC
007417  443256              STRAL   PZDFID      PZDPIC=PZCP+PZDI+PZDD
                     *
                     *       DO RAMP FADE-IN CF PIC COMMAND WHEN THE PILOT
                     *       GOES BACK INTO DETENT
007420  123270              ENTAL   PZEZCN      AL1= FACER MULTIPLIER
007421  710001              ADDALK  1           DO RAMP UP
007422  103201              ENTAU   PK128       USE 128 CYCLES AS THE RAMP UP TIME
007423  760537              RJP     LIMIR       LIMIT PZEZCN TO PK64 (LIMIT AL TO AU)
007424  443270              STRAL   PZEZCN      STORE RAMP FACER VALUE
007425  243256              MULAL   PZDFID      AI=RAMP*PID CONTROL
007426  504307              RSHA    7C          DIVIDE BY NUMBER OF CYCLES IN RAMP
007427  143276              ADDAL   PZCLST      ADD LAST PID COMMAND(FADEC) TO AVCID TRANSIENT
007430  443256              STRAL   PZDFID      PUT SUM BACK INTO PID COMMAND
007431  443257              STRAL   PZDCLD      STORE PIC COMMAND FOR LATER FADE-CUT
007432  123200              ENTAL   PK64        GET READY FOR THE PZDOLD FADE-OUT ABOVE
007433  443273              STRAL   PZECFF      PZEOFF GET START OF FADE-OUT VALUE
                     *
                     * --------SECTION PSTP2--------------
                     *
                     *    THIS SECTION PUTS (PPLT * COMMAND SCALING) INTO THE PYDES
                     *    (DESIRED OUTPUT) VECTOR.
                     *
                     *         PYDES = PYSCLE * PPLT
                     *
                     *     WHERE PYSCLE IS THE DIAGONAL SCALING MATRIX
007434  507310      PSTP2   ENTSR   1C          USE MEMCRY BANK 0
007435  507201              ENTICR  1           USE ICR1 AS THE INDEX REG.(B)
007436  300000              ENTBK   0           INITIALIZE THE B REG TO 0
007437  507313              ENTSR   13          USE MEMCRY BANK 3
007440  132761      PSTP20  ENTALB  PPLT        AL1=(PPLT+ICR1)
007441  253003              MULALB  PYSCLE      AI=AL*(PYSCLE + ICR1)
007442  504702              LRTA    2           SCALING WAS 2**16 FOR PSTP2
007443  472777              STRAUB  PYDES       STORE RESULT IN (PYDES+ICR1),SCALING IS 2**16
007444  300713              EBK     PNCP1       IF ICR1=PNCP1(NC-1) THEN SKIP NEXT LINE
                     *                  ELSE DO NEXT LINE AND ICR1=ICR1+1
007445  347440              JP      PSTP20      GO SCALE THE NEXT CONTROL
007446  347447              JP      PSTP3       GO TO THE INTEGRAL CONTROL SECTION
                     *
                     * --------SECTION PSTP3----------
                     *
                     * FIRST DO THE SET POINT GENERATOR MATRIX MULTIPLICATION
                     *                    PUC = PNK * PYDES
```

Hover Controller Subroutine. (contd)

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                                                                                  PAGE  96
                       *             WHERE PUC = PNC X PNC   AND  FYDES = PNC X 1
                       *
                       *     PYDES INCLUDES BOTH PILOT COMMANDS AND THE
                       *     PIC CONTROLLER COMMANDS.
                       *
007447  507310  PSTP3   ENTSR    $C                        USE MEMORY BANK 0
007450  507201          ENTICR   1                         USE ICR1 AS THE INDEX REG.(B)
007451  360000          ENTBR    0                         INITIALIZE THE B REG. TO 0
007452  400002          STRZ     2                         ICR2=0, THE COLUMN INDEX
007453  400003          STRZ     3                         ICR3=0, THE ROW INDEX
007454  507313          ENTSR    13                        USE MEMORY BANK 3
007455  123237          ENTAL    PXDPID                    AL:=PXDFIC
007456  142777          ADDAL    PYDES                     PYDES(1)=PYDES(1)+PXDPID
007457  442777          STRAL    PYDES                     STORE RESULT
007460  123256          ENTAL    PZDPID                    AL:=PZDFIC
007461  143000          ADDAL    PYDES+1                   AL:=PYDES(2)+PYDPID, LATERAL
007462  443000          STRAL    PYDES+1                   STORE RESULT IN PYDES(2)
007463  123250          ENTAL    PYDPID                    AL:=PYDFIC
007464  143001          ADDAL    PYDES+2                   AL:=PYDES(3)+PZDPID
007465  443001          STRAL    PYDES+2                   STORE IN PYDES(3), COLLECTIVE
007466  123136          ENTAL    PNC                       AL:=NUMBER OF CONTROLS
007467  717770          ADDALK   =1                        AL:=PNC-1
007470  507310          ENTSR    $C                        USE MEMORY BANK 0
007471  446711          STRAL    PRWEND                    PRWEND:=PNC-1
007472  507313          ENTSR    13                        USE MEMORY BANK 3
007473  700000  PNXRW1  ENTALK   0                         AL:=0
007474  507400          XFRLU                              AU:=AL=0
007475  500600  PNXCL1  STRA     TPP                       TMP:=A
007476  031650
007477  507202          ENTICR   2                         GET THE COLUMN INDEX
007500  370001          ENTBKP   1                         INCREMENT COLUMN INDEX(ICR2=ICR2+1)
007501  132776          ENTALB   PYDES-1                   AL:=(PYDES+ICR2-1)
007502  507201          ENTICR   1                         USE ICR1 AS INDEX REG.(ELEMENT INDEX)
007503  253000          PULALB   PNR                       A:=AL * (PNR+ICR1)
007504  201650          ADDA     TPP                       A:=A + (TMP,TMP+1)
007505  505300          BKPNOV                             CHECK FOR OVERFLOW
007506  504000          NOOP                               CALL OVERFLOW HANDLER
007507  566711          EON      PRWEND                    IF ICR1=PRWEND THEN SKIP NEXT LINE
                       *                      ELSE DO NEXT LINE AND ICR1=ICR1+1
007510  347475          JP       PNXCL1                    JUMPS TO NEXT COLUMN OF PNR
                       *                      AND NEXT ROW ELEMENT OF PPLT
007511  370001          ENTBKB   1                         ICR1=ICR1+1
007512  507203          ENTICR   3                         USE ICR3 AS INDEX REG.(ROW INDEX)
007513  504705          LRTA     5C                        SCALING FOR PSTP3,2**13
007514  472745          STRAUB   PUC                       PUC+ICR3:=(AU)
007515  566715          EON      PNCM1                     IF ICR3=PNCM1 THEN SKIP NEXT LINE
                       *                      ELSE DO NEXT LINE AND ICR3=ICR3+1
007516  347530          JP       PRSET1                    GO RESET THE COUNTER
007517  347530          JP       P2TF4                     GO TO NEXT MATRIX MULT IF DONE
007520  507202  PRSET1  ENTICR   2                         SAVE ROW INDEX AND START USING COLUMN INDEX
007521  360000          ENTBR    0                         RESET COLUMN INDEX TO ZERO
007522  507310          ENTSR    $0                        BANK 0 TO USE PRWEND AND PNCTRL
007523  126711          ENTAL    PRWEND                    AL:=PRWEND
007524  146716          ADDAL    PNCTRL                    AL:=PRWEND+PNCTRL=PRWEND+# PP COLUMNS
007525  446711          STRAL    PRWEND                    PRWEND:=PRWEND+PNCTRL
007526  507313          ENTSR    13                        BANK 3 FOR DATA
007527  347473          JP       PNXRW1                    DO THE NEXT ROW
```

Hover Controller Subroutine. (contd)

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1819A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION   1                                      PAGE   97

                      *
                      *  ---------------SECTION PSTP4--------------------
                      *
                      *              THIS IS THE 2ND MATRIX MULTIPLY IN THE CMPSTR
                      *              SUBROUTINE, I.E.
                      *                          PFMIN * PYS
 007530   507310   PSTP4    ENTSR    $C                           USE MEMORY BANK 0
 007531   507201            ENTICR   1                            USE ICR1 AS THE INDEX REG.(B)
 007532   360000            ENTBK    0                            INITIALIZE THE B REG. TO 0
 007533   400002            STRZ     2                            ICR2=0, THE COLUMN INDEX
 007534   400003            STRZ     3                            ICR3=0, THE ROW INDEX
 007535   507313            ENTSR    $3                           USE MEMORY BANK 3
 007536   123137            ENTAL    PMM                          AL:=NUMBER OF MEASUREMENTS
 007537   717776            ADDALK   -1                           AL:=PMP-1
 007540   507310            ENTSR    $0                           USE MEMORY BANK 0 SINCE PPWEND IS THERE
 007541   446711            STRAL    PPWEND                       PRWEND:=PMM-1
 007542   507313            ENTSR    $3                           BACK TO MEMORY BANK 3 FOR DATA
 007543   700000   PMXRW2   ENTALK   0                            AL:=0
 007544   507400            XFRLU                                 AU:=AL=0
 007545   500600   PMXCL2   STRA     TPP                          TMP:=A
 007546   031650
 007547   507202            ENTICR   2                            GET THE COLUMN INDEX
 007550   370001            ENTBKB   1                            INCREMENT COLUMN INDEX(ICR2=ICR2+1)
 007551   132764            ENTALB   PYS-1                        AL:=(PYS+ICR2-1)
 007552   507201            ENTICR   1                            USE ICR1 AS INDEX REG.(ELEMENT INDEX)
 007553   253036            MULALB   PFMIN                        A:=AL * (PBMIN+ICR1)
 007554   201650            ADDA     TPP                          A:=A + (TMP,TMP+1)
 007555   505300            SKPNOV                                CHECK FOR OVERFLOW
 007556   504000            NOOP                                  CALL OVERFLOW HANDLER
 007557   566711            BSK      PPWEND                       IF ICR1=PRWEND THEN SKIP NEXT LINE
                      *                                ELSE DO NEXT LINE AND ICR1=ICR1+1
 007560   347545            JP       PMXCL2                       JUMPS TO NEXT COLUMN OF PBMIN
 007561   370001            ENTBKB   1                            ICR1=ICR1+1
 007562   507203            ENTICR   3                            USE ICR3 AS INDEX REG.(ROW INDEX)
 007563   504704            LRTA     4C                           PSTP4 SCALING IS 2**14
 007564   473024            STRAUB   PZKPI                        PZKPI+ICR3I=(AU)
 007565   566712            BSK      PRRP1                        IF ICR=PRR THEN SKIP NEXT LINE
                      *                           ELSE DO NEXT LINE AND ICR3=ICR3+1
 007566   347570            JP       PRSET2                       GO RESET THE COUNTER
 007567   347600            JP       PSTP5                        GO TO NEXT MATRIX MULT IF DONE
 007570   507202   PRSET2   ENTICR   2                            SAVE ROW INDEX AND START USING COLUMN INDEX
 007571   360000            ENTBK    0                            RESET COLUMN INDEX TO ZERO
 007572   507310            ENTSR    $0                           BANK 0 TO USE PRWEND AND PNMEAS
 007573   126711            ENTAL    PRWEND                       AL:=PRWEND
 007574   146717            ADDAL    PNMEAS                       AL:=PRWEND+PNMEAS
 007575   446711            STRAL    PRWEND                       PRWEND:=PRWEND+PNMEAS=PRWEND+#OF COLUMNS
 007576   507313            ENTSR    $3                           BACK TO MEMORY BANK 3 FOR DATA
 007577   347543            JP       PMXRW2                       DO THE NEXT ROW
                      *
                      *  -----------------------SECTION PSTP5----------
                      *
                      *              THIS STEP(PSTP5) DOES THE MATRIX MULTIPLICATION
                      *              DESCRIBED BY
                      *                   PAMIN*PZK
                      *              WHERE PAMIN IS THE MINIMAL FORM OF THE COMPENSATOR
                      *                DYNAMICS MATRIX
 007600   507202   PSTP5    ENTICR   2                            SELECT ICR2(J=JCR2)
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Hover Controller Subroutine. (contd)

```
1819A ASSEMBLER, VERSION 1.0   HOVR43  10/02/84   SECTION   1                                             PAGE   98

007601 360000             ENTBK     0                                           ICR2:=0
007602 507201             ENTICR    1                                           SELECT ICR1(I=ICR1)
007603 360000             ENTBK     0                                           ICR1:=1
007604 566713    PSTP50   ESK       PPR                                         IF ICR=PR SKIP ONE
                 *                    LINE ELSE ICR1=ICR1+1(I=I+1) AND          DO NEXT LINE
007605 347607             JP        PSTP51                                      GO CHECK FOR TYPE OF MINIMAL BLOCK
007606 347645             JP        PSTP54                                      GO TO SUMMATION WITH PZKP1
007607 507202    PSTP51   ENTICR    2                                           USE ICR2 AS INDEX,J
007610 133140             ENTALB    PADESC                                      AL:=(PADESC+ICR2)
007611 023311             CMAL      PCNE                                        COMPARE AL,I.E. PADESC(J), WITH 1
007612 617616             JPEQ      PSTP52                                      GOTO PSTP52 IF PADESC(J)=1
007613 023312             CMAL      PTWC                                        COMPARE AL TO 2
007614 617625             JPEQ      PSTP53                                      GOTO PSTP53 IF PADESC(J)=2
007615 504000             NOOP                                                  A CALL TO AN ERROR HANDLER GOES HERE
                 *        THIS IS THE SECTION FOR 1X1 BLOCKS OF AMIN
007616 370001    PSTP52   ENTBKB    1                                           ICR2=ICR2+1,I.E. J=J+1
007617 507201             ENTICR    1                                           ICR1 IS THE INDEX REG.
007620 133030             ENTALB    PAMIN-1                                     AL:=AL*(PAMIN+ICR1-1)
007621 253016             MULALB    PZK-1                                       A:=AL*(PZK+ICR1-1)
007622 504703             LRTA      3                                           SCALING FOR PSTP52 IS 2**15
007623 473276             STRAUB    TMPPZ-1                                     TMPPZ=1:=AU=A(I)*PZK(I),SCALING IS 2**15
007624 347604             JP        PSTP50                                      JUMP BACK TO GET NEXT AMIN DESCRIPTOR
                 *        THIS IS THE SECTION FOR 2X2 BLOCKS OF AMIN
007625 370001    PSTP53   ENTBKB    1                                           ICR2=ICR2+1,I.E. J=J+1
007626 507201             ENTICR    1                                           ICR1 IS NOW THE INDEX REG.
007627 133017             ENTALB    PZK                                         AL:=(PZK+ICR1)
007630 453276             STRALB    TMPPZ-1                                     TMPPZ+ICR1-1:=(PZK+ICR1),I.E.
                 *                                  TMPPZ(I)=PZK(I+1)
007631 133030             ENTALB    PAMIN-1                                     AL:=(PAMIN+ICR1-1)
007632 253016             MULALB    PZK-1                                       A:=AL*(PZK+ICR1-1)
007633 504703             LRTA      3                                           SCALING FOR PSTP53 IS 2**15
007634 461050             STRAU     TMP                                         TMP:=AU, I.E. TMP=PAMIN(I)*PZK(I),SCALING IS
                                                                                2**15
007635 133031             ENTALB    PAMIN                                       AL:=(PAMIN+ICR1)
007636 253017             MULALB    PZK                                         A:=AL*(PZK+ICR1),I.E.
007637 504703             LRTA      3                                           SCALING FOR PSTP53 IS 2**15
                 *                                  A=PAMIN(I+1)*PZK(I+1)
007640 507300             XPROD                                                 PUT AU INTO AL
007641 141050             ADDAL     TMP                                         AL:=AL+TMP,I.E. AL=A(I)*Z(I)+A(I+1)*Z(I+1)
007642 453277             STRALB    TMPPZ                                       TMPPZ+ICR1:=AL,SCALING IS 2**15
007643 370001             ENTBKB    1                                           ICR1=ICR1+1 BUT THIS MEANS I=I+2
                 *                                  SINCE PSTP50 INCREMENTED    ICR1 ONCE ALREADY
007644 347604             JP        PSTP50                                      GO GET THE NEXT AMIN DESCRIPTOR
007645 360001    PSTP54   ENTBK     1                                           ICR1:=1
                 *        THIS SECTION ADDS PBMIN*PYS + PAMIN*PZK
                 *        AND PUTS THE RESULT IN THE PZKP1 VECTOR
007646 133023    PSTP55   ENTALB    PZKP1-1                                     AL:=(PZKP1+ICR1-1)
007647 153276             ADDALB    TMPPZ-1                                     AL:=AL+(TMPPZ+ICR1-1)
007650 453023             STRALB    PZKP1-1                                     PZKP1+ICR1-1:=AL
007651 566713             ESK       PPR                                         IF ICR1=PR+1 THEN SKIP ONE LINE
                 *                                  ELSE ICR1=ICR1+1 AND DO NEXT LINE
007652 347646             JP        PSTP55                                      CONTINUE
007653 347654             JP        PSTP6                                       GOTO NEXT STEP
                 *
                 *   -----------SECTION PSTP6----------
                 *
                 *           THIS IS THE 4TH MATRIX MULTIPLY IN THE CMPSTR
```

Example Data File for Using the ROPTSYS Computer Program.

```
DATA FOR OPTSYS FOR THE CHAPTER 2 NAVION EXAMPLE
I L IQ INQ.IR.IOMF ISS.IM.ITF1.DM.ITF3.IFDFW.IE.IDSTB.IDBG.ISET.ILNG.ISCLE.IMIN
1 1 0.0.0.0.0.0 0 3.0.0.0 2.0.1.1.1
NS NC NM NPD NO.NMOD.IREG
4 2 3 2.2.0 0
TS MATRIX(NS)
1 0 1 0. 01. 01
TC MATRIX(NC)
 01 1 0
TD MATRIX(NPD)
1 0.1 0
TM MATRIX(NM)
1 0 1 0. 01
TP MATRIX(NO)
1 0.1 0
F MATRIX(NS X NS)
- 045. 036.0.-32 2
- 37.-2 02.176 0.0
 00191.- 0396.-2 98.0
0.0.1 0.0
HO MATRIX(NO X NS)
1 0.0.0.0
0.-1 0.0.176 0
RL MATRIX(NO X NC)
0.0
0.0
(AX.AM) MATRIX(NO)
1 1
G MATRIX(NS X NC)
0.1 0
-28 2.0
-11 0.0
0.0
B MATRIX(NC)
1.1
HM MATRIX(NM X NS)
1 0.0.0.0
0.-1 0.0.176 0
0.0 0.1 0
RN MATRIX(NM X NPD)
0.0
0 0
0.0
GAMMA MATRIX(NS X NPD)
 045.- 036
 37.2 02
- 00191. 0396
0.0
Q MATRIX(NPD)
24 6.9 98
R MATRIX(NM)
 318. 318. 00039
```

ROPTSYS User's Manual. (contd)

```
    FOR OMF REGULATOR SYNTHESIS USE
       F HO FM HS AM C B
    FOR FILTER SYNTHESIS USE
       F HO CAM Q R
    DSTAB R ENTER DIAGONAL ELEMENTS ONLY
    (AX AM) B Q ARE DIAGONAL OR FULL (SELECT IR)
    HO IS A VECTOR

  IF LAST CARD COL 1 IS *  THEN CONTINUE TO NEXT CASE
  each case expects complete title lines  options  sizes  and matrices

SUBROUTINE LISTING
  SETUP USER CAN SET UP OPEN LOOP DYNAMICS MARTIX
  INNER OPTIMAL CONTROLLER/OPTIMAL ESTIMATOR DESIGN
  OMF OPTIMAL MODEL FOLLOWING DESIGN OPTION
  CDIV COMPLEX DIVISION
  RAPRINT MATRIX PRINTING
  RGAIN REFORMATS EIGENVALUES CALCULATES MODAL SUBMATRICES
  MULT MATRIX MULTIPLICATION
  MADD MATRIX ADDITION
  MTRN MATRIX TRANSPOSITION
  MINV MATRIX INVERSION
  SLOV SOLVES LYAPUNOV EQUATION FOR SS COVARIANCE
  MODE COMPUTES MODAL COORDINATE MATRICES
  NORM FORMATS EIGENVALUE/EIGENVECTOR OUTPUT
  TF COMPUTES TRANSFER FUNCTIONS
  CHECK CHECK CONSISTENCY OF INPUTS
  POLES PRINT OUT TF POLES
  ZEROS COMPUTE SISO TF ZEROS
  ACOMP COMPUTE ZEROS BY BROCKETT'S METHOD (3 SUBROUTINES)
  CCOMP
  SCL FUNCTION
  RESID COMPUTE (TIME RESPONSE) RESIDUES
  BALANC FIND EIGENVALUES AND EIGENVECTORS VIA
  ORTHES    THE QR ALGORITHM (6 SUBROUTINES)
  ORTRAN
  HQR2
  BALBAK
  HQR
  MODCOM CALCULATES THE MODAL FORM OF THE COMPENSATOR (HOLDRIDGE)
  MINCOM CALCULATES THE MINIMAL FORM OF THE COMPENSATOR (HOLDRIDGE)
```

ROPTSYS User's Manual.

```
C (5-11-83) print Ric att equation solution if IDEBUG = 2
C  input free format  expect and neglect one line title at line 1 2 4
C  and before each matrix
C  output use E instead of D (C input compatible)
C
C    IMPLICIT REAL*8(A H O Z)
C
C
C
C           OPTSYS 6
C
C         JEFFERY A  QUIRK
C
C       VERSION   22 JULY 1981
C
C       REVISED BY RICK HOLDRIDGE 11 Mar 84
C
C
C
C  THIS VERSION OF OPTSYS WILL COMPUTE
C     OPTIMAL CONTROLLERS
C     OPTIMAL MODEL FOLLOWING CONTROLLERS
C     OPTIMAL ESTIMATORS
C     SYSTEM TRANSFER FUNCTIONS
C     SYSTEM EIGENVALUES  EIGENVECTORS  AND MODAL MATRICES
C  FEATURES
C     NON DIAGONAL A B Q MATRICES ARE ALLOWED
C  OPTIMAL CONTROLLER EQUATIONS
C     DYNAMICS  DX F*X+G*U
C     OUTPUT     Y HO*X+RL*U
C     WEIGHTING MATRICES  A AND B      = INT(YT*A*Y+UT*B*U)
C     CONTROLLER GAINS  C               NOTE   U =  C*X
C  OMF CONTROLLER EQUATIONS
C     MODEL DYNAMICS  DXM FM*XM
C     DESIGN STATES   XD HS*X
C     WEIGHTING MATRICES  AM AND B
C     CONTROLLER GAINS  C
C  ESTIMATOR EQUATIONS
C     DYNAMICS  DX F*X+GAM*W
C     MEASUREMENTS  Y HM*X+RN*W+V
C     WEIGHTING MATRICES  Q AND R
C     ESTIMATOR GAINS  K
C
C
C
C         USER'S MANUAL
C
C
C
C  INPUTS
C
C     line 1  title or comment for the data set
C     line 2  comment for the options
C     CARD 3 (free format)
C        IOL IQ INQ IR IOMF ISS IM ITF1 DUM ITF3 IE IDSTAB
C        IDEBUG ISET ILONG ISCALE IMIN
C
C        DEFAULT VALUES ARE ZERO
C         IOL=1 OPEN LOOP EIGENSYSTEM IS DESIRED
C            =2 OPEN LOOP EIGENSYSTEM ONLY (THEN TERMINATE)
C            =3 MODAL DISTRIBUTION MATRICES ONLY
C                (NO REGULATOR OR FILTER SYNTHESIS)
C         IQ=1 IF THE RMS VALUES OF THE CONTROL AND STATE ARE TO BE FOUND
C         INQ 0 IF A B Q AND R ARE DIAGONAL
C             1 IF ONLY B AND R ARE DIAGONAL
C             2 IF ONLY R IS DIAGONAL
C         IR 0 IF OPTIMAL FILTER AND REGULATOR EIGENSYSTEMS ARE TO BE FOUND
C            1 IF EXTERNAL C MATRIX IS SUPPLIED
C            2 IF EXTERNAL K IS SUPPLIED
C            3 IF EXTERNAL C AND K ARE SUPPLIED
C         IOMF 0 IF OPTIMAL CONTROL REGULATOR DESIGN IS DESIRED
C              1 IF OPTIMAL MODEL FOLLOWING REGULATOR DESIGN DESIRED
C         ISS 1 IF STEADY STATE VALUES (FOR A CONSTANT DISTURBANCE)
C               ARE TO BE DETERMINED
C         IM 1 IF MODAL CONTOL DISTRIBUTION AND GAINS ARE DESIRED
C         ITF1 0 IF NO OPEN LOOP TRANSFER FUNCTIONS ARE DESIRED
C              1 IF POLES  RESIDUES  AND ZEROS ARE DESIRED
C              2 IF POLES AND ZEROS ARE DESIRED
C              3 IF POLES AND RESIDUES ARE DESIRED
C        DUM 0
C         ITF3 0 IF NO COMPENSATOR TRANSFER FUNCTIONS ARE DESIRED
C                COMPENSATOR TRANSFER FUNCTIONS CAN BE COMPUTED ONLY
C                IF BOTH REGULATOR AND FILTER ARE SYNTHESIZED OR INPUT
C              1 IF POLES  RESIDUES  AND ZEROS ARE DESIRED
C              2 IF POLES AND ZEROS ARE DESIRED
C              3 IF POLES AND RESIDUES ARE DESIRED
C         IDFDW 0 UNKNOWN PARAMETER USED IN THE TF CALLS
C         IE 0 DEFAULT CRITERIA FOR ZERO VALUES IS 10E-06
C         IE-  SETS THE ZERO CRITERIA FOR THE MARKOV PARAMETERS OF THE
C              NUMERATOR POLYNOMIAL OF THE TRANSFER FUNCTIONS
C         IDSTAB 1 IF FILTER (OR REGULATOR) SYNTHESIS BY THE
C                  DESTABILIZATION TECHNIQUE IS DESIRED
C         IDEBUG 1 PRINTS THE EULER LAGRANGE EIGENSYSTEM PRIOR TO
C                  THE MODAL DECOMPOSITION PROCEDURE
C                2 PRINTS THE RICCATI EQUATION SOLUTION MATRIX
C         ISET 1 IF THE SETUP SUBROUTINE IS TO BE USED TO DETERMINE
C                THE F MATRIX
C         ILONG 0 DOES NOT PRINT OUT EIGENVECTORS MATRICES (WHEN IM 1)
C         ISCALE 0 NO SCALING IS DONE  MATRICES TS TC TD TM TP AREN'T ENTERED
C                =1 SCALING IS DONE  THE TS TC TD TM TP MATRICES MUST BE IN DATA
C
C         IMIN 0 THE MINIMAL FORM OF THE COMPENSATOR IS NOT FOUNE
C             =1 THE MINIMAL FORM OF THE COMPENSATOR IS CALCULATED
C
C     line 4  comment for the numbers
C     CARD 5 (free format)
C        NS NC NOB NG NOUT NMOD IREG
C
C         NS = NUMBER OF STATES (MAX 20)
C         NC = NUMBER OF CONTROLS (MAX 8)
C         NOB   NUMBER OF MEASUREMENTS (MAX 8)
C         NG = NUMBER OF DISTURBANCES (MAX 8)
C         NOUT = NUMBER OF OUTPUTS (MAX 8)
C         NMOD = NUMBER OF MODEL STATES (MAX 10)
C         IREG = 1 FOR REGULATOR SYNTHESIS ONLY
C              = 0 FOR BOTH REGULATOR AND FILTER SYNTHESIS
C
C     MATRIX CARDS
C        one line title
C        free format, by row, wrap around if needed, new line for next row
C
C        TS TC TD TM TP F DSTAB HO RL D C
C        FM (AX AM) G B GAM HM RN Q R K MC
C
C        DELETE THOSE MATRICES NOT REQUIRED
C        FOR OPTIMAL REGULATOR SYNTHESIS USE
C           F HO AX G B
```

Appendix J.

ROPTSYS Computer Program

This appendix includes the users manual for the ROPTSYS computer program, which is located on the FSD VAX at NASA Ames Research center, and an example data file. The data file was used to calculate the full order compensator in the Navion example in Chapter 2. The lengthy FORTRAN listing is not shown.

Memory Allocation. (contd)

```
[illegible] ASSEMBLER, VERSION 1.0   NOVR43  10/02/84   SECTION   3                                PAGE  165

   033266  000000   PXEZCN   RESERV   RESERV'1D                  RESERVE MEMORY FOR THE FADER RAMPS
   033267  000000   PYEZCN   RESERV   RESERV'1D
   033270  000000   PZEZCN   RESERV   RESERV'1D
   033271  000000   PXEOFF   RESERV   RESERV'1D
   033272  000000   PYEOFF   RESERV   RESERV'1D
   033273  000000   PZEOFF   RESERV   RESERV'1D
   033274  000000   PXCLST   RESERV   RESERV'1D
   033275  000000   PYCLST   RESERV   RESERV'1D
   033276  000000   PZCLST   RESERV   RESERV'1D
   033277  000000   TPPPZ    RESERV   RESERV'10D                 TEMPORARY USED IN PSTPS2 AND PSTPS3
                    *
                    *        CONSTANTS FOR CNSTNG SUBROUTINE
                    *
   033311  000001   PONE     1D
   033312  000002   PTWO     2D
                    *
                    *     COMPLEMENTARY FILTER FREQUENCIES AND DAMPINGS
                    *
   033313  000310   KFREQH   200D
   033314  000620   KFREQX   400D                                KALMAN FREQ 1000/RPS
   033315  000620   KFREQY   400D
   033316  000620   KFREQZ   400D
   033317  001303   KZETAH   707D
   033320  001303   KZETAX   707D                                KALMAN DAMPING 1000/UNIT
   033321  001303   KZETAY   707D
   033322  001303   KZETAZ   707D
   033323  037200   KERLIN   16000D                              KALMAN OVFLO LIMITER
                    *
```

Memory Allocation. (contd)

```
IB19A ASSEMBLER, VERSION 1.0   NOVR43  10/02/84   SECTION

7911  033200  000100   PK64     DATA     64C                        64 CYCLE FADE VALUE
7912  033201  000200   PK128    DATA     128C                       128 CYCLE FADE VALUE
7913                 $ THE FOLLOWING 22 VARIABLE DECLARATIONS MUST STAY IN
7914                 $ THE ORDER HERE TO MAKE THE MEASUREMENT SELECTION LOGIC
7915                 $ IN CPPSTR4 CORRECT
7916                 $ ------------------------------------------------------------
7917  033202  000000   PDTHET   RESERV   RESERV'1D                  PERTURBATION PITCH ANGLE
7918  033203  000000   PPHI     RESERV   RESERV'1D                  ROLL ANGLE
7919  033204  000000   PPSI     RESERV   RESERV'1D                  YAW ANGLE
7920  033205  000000   PPITRT   RESERV   RESERV'1D                  PITCH RATE
7921  033206  000000   PROLRT   RESERV   RESERV'1D                  ROLL RATE
7922  033207  000000   PYAWRT   RESERV   RESERV'1D                  YAW RATE
7923  033210  000000   PAX      RESERV   RESERV'1D                  LONG. ACCELERATION
7924  033211  000000   PAY      RESERV   RESERV'1D                  LATERAL ACCELERATION
7925  033212  000000   PAZ      RESERV   RESERV'1D                  NORMAL ACCELERATION
7926  033213  000000   PDVEL    RESERV   RESERV'1D                  PERTURBATION AIRSPEED
7927  033214  000000   PVVEL    RESERV   RESERV'1D                  VERTICAL VELOCITY
7928  033215  000000   PBALT    RESERV   RESERV'1D                  BAROMETRIC ALTITUDE
7929  033216  000000   PXBOD    RESERV   RESERV'1D                  X POSITION IN HEADING INERTIAL FRAME
7930  033217  000000   PYBOD    RESERV   RESERV'1D                  Y POSITION IN HEADING INERTIAL FRAME
7931  033220  000000   PZBOD    RESERV   RESERV'1D                  Z POSITION IN HEADING INERTIAL FRAME
7932  033221  000000   PXBDCT   RESERV   RESERV'1D                  INERTIAL X VEL. IN HEADING INERTIAL FRAME
7933  033222  000000   PYBDCT   RESERV   RESERV'1D                  INERTIAL Y VEL. IN HEADING INERTIAL FRAME
7934  033223  000000   PZBDCT   RESERV   RESERV'1D                  INERTIAL Z VEL. IN HEADING INERTIAL FRAME
7935  033224  000000   PX       RESERV   RESERV'1D                  RUNWAY FRAME X POSITION
7936  033225  000000   PY       RESERV   RESERV'1D                  RUNWAY FRAME Y POSITION
7937  033226  000000   PXDOT    RESERV   RESERV'1D                  RUNWAY FRAME X INERTIAL VELOCITY
7938  033227  000000   PYDOT    RESERV   RESERV'1D                  RUNWAY FRAME Y INERTIAL VELOCITY
7939                 $ ------------------------------------------------------------
7940  033230  000000   PXREF    RESERV   RESERV'1D                  REFERENCE POSITION
7941  033231  000000   PXBREF   RESERV   RESERV'1D                  ROTATED REFERENCE POSITION
7942  033232  000000   PDELX    RESERV   RESERV'1D                  X POSITION ERROR
7943  033233  000000   PXDP     RESERV   RESERV'1D                  X PROPORTIONAL CONTROL
7944  033234  000000   PXDD     RESERV   RESERV'1D                  X DERIVATIVE CONTROL
7945  033235  000000   PXCTH    RESERV   RESERV'1D                  X 2ND DERIVATIVE CONTROL(THETA FEEDBACK)
7946  033236  000000   PXCPR    RESERV   RESERV'1D                  X 3RD DERIVATIVE CONTROL(PITCH RATE FEEDBACK)
7947  033237  000000   PXDPID   RESERV   RESERV'1D                  X TOTAL PID CONTROL
7948  033240  000000   PXCOLD   RESERV   RESERV'1D                  OLD X TOTAL PID CONTROL
7949  033241  000000   PYREF    RESERV   RESERV'1D                  REFERENCE POSITION
7950  033242  000000   PYBREF   RESERV   RESERV'1D                  ROTATED REFERENCE POSITION
7951  033243  000000   PDELY    RESERV   RESERV'1D                  Y POSITION ERROR
7952  033244  000000   PYDP     RESERV   RESERV'1D                  Y PROPORTIONAL CONTROL
7953  033245  000000   PYDD     RESERV   RESERV'1D                  Y DERIVATIVE CONTROL
7954  033246  000000   PYCPH    RESERV   RESERV'1D                  Y 2ND DERIVATIVE CONTROL(PHI FEEDBACK)
7955  033247  000000   PYCRR    RESERV   RESERV'1D                  Y 3RD DERIVATIVE CONTROL(ROLL RATE FEEDBACK)
7956  033250  000000   PYDPID   RESERV   RESERV'1D                  Y TOTAL PID CONTROL
7957  033251  000000   PYDOLD   RESERV   RESERV'1D                  OLD Y TOTAL PID CONTROL
7958  033252  000000   PZREF    RESERV   RESERV'1D                  REFERENCE POSITION
7959  033253  000000   PDELZ    RESERV   RESERV'1D                  Z POSITION ERROR
7960  033254  000000   PZDP     RESERV   RESERV'1D                  Z PROPORTIONAL CONTROL
7961  033255  000000   PZDD     RESERV   RESERV'1D                  Z DERIVATIVE CONTROL
7962  033256  000000   PZDPID   RESERV   RESERV'1D                  Z TOTAL PID CONTROL
7963  033257  000000   PZCOLD   RESERV   RESERV'1D                  OLD Z TOTAL PID CONTROL
7964                 $          COLSET
7965  033260  000000   PXDI     RESERV   RESERV'2                   X INTEGRAL CONTROL
7966  033262  000000   PYDI     RESERV   RESERV'2                   Y INTEGRAL CONTROL
7967  033264  000000   PZDI     RESERV   RESERV'2                   Z INTEGRAL CONTROL
```

Memory Allocation. (contd)

```
1019A ASSEMBLER, VERSION 1.0   MOVR43  10/02/84   SECTION   3                                      PAGE  163

 7876  033113  000325                 DATA    213D,-76D,755D,2048D,229D
       033114  777663
       033115  001363
       033116  004000
       033117  000345
 7877  033120  000000                 DATA    0,2048D,1024D,73D,186D
       033121  004000
       033122  003130
       033123  000111
       033124  000272
 7878  033125  000020    PYSSEL       DATA    16D,17D,18D,5D,4D,6D,1D,2D
       033126  000021
       033127  000022
       033130  000005
       033131  000004
       033132  000006
       033133  000001
       033134  000002
 7879  033135  000005    PR           5D
 7880  033136  000003    PNC          3D
 7881  033137  000010    PNM          8D
 7882  033140  000002    PACESC       DATA    2,1,1,1
       033141  000001
       033142  000001
       033143  000001
 7883  033144  000010    PRP1         8D
 7884  033145  106332    PLNGSC       36058D                                LONG. CYCLIC OUTPUT SCALING TERM(SCALED 2**18)
 7885  033146  147075    PCCLSC       52797D                                COLL. OUTPUT SCALING TERM(SCALED 2**18)
 7886  033147  155124    PLATSC       55892D                                LAT. CYCLIC OUTPUT SCALING TERM(SCALED 2**18)
 7887  033150  214356    PYAWSC       71918D                                YAW OUTPUT SCALING TERM(SCALED 2**18)
 7888  033151  000000    PIRNTH       C                                     THETA AT ENGAGE
 7889  033152  000000    PIRNPH       0                                     PHI AT ENGAGE
 7890  033153  000000    PIRNAS       0                                     AIRSPEED AT ENGAGE
 7891  033154  000000    PIRNHD       0                                     HDOT AT ENGAGE
 7892  033155  777467    PKXP         DATA    -200D                         X PROPORTIONAL GAIN (1 FPS PER FT ERROR = 102
                                                                            4)
 7893  033156  776027    PKYP         DATA    -1000D                        Y PROPORTIONAL GAIN (1 FPS PER FT ERROR = 102
                                                                            4)
 7894  033157  774057    PKZP         DATA    -2000D                        Z PROPORTIONAL GAIN (1 FPS PER FT ERROR = 102
                                                                            4)
 7895  033160  777753    PKXI         DATA    -20D                          X INTEGRAL GAIN
 7896  033161  777467    PKYI         DATA    -200D                         Y INTEGRAL GAIN
 7897  033162  777715    PKZI         DATA    -50D                          Z INTEGRAL GAIN
 7898  033163  774057    PKXD         DATA    -2000D                        X DERIVATIVE GAIN (1 FPS PER FPS =1024)
 7899  033164  776027    PKYD         DATA    -1000D                        Y DERIVATIVE GAIN (1 FPS PER FPS =1024)
 7900  033165  767153    PKZD         DATA    -4500D                        Z DERIVATIVE GAIN (1 FPS PER FPS =1024)
 7901  033166  001750    PKXTH        DATA    1000D                         X THETA GAIN(1 FPS PER DEG = 1048)
 7902  033167  777013    PKYPH        DATA    -500D                         Y PHI GAIN(1 FPS PER DEG = 1048)
 7903  033170  005670    PKXPR        DATA    3000D                         X PITCH RATE GAIN(1 FPS PER DEG/SEC = 1048)
 7904  033171  777013    PKYRR        DATA    -500D                         Y ROLL RATE GAIN(1 FPS PER DEG/SEC =1048)
 7905  033172  000372    PXLTNT       DATA    250D                          LONGITUDINAL STICK DETENT(1024/IN)
 7906  033173  000372    PYDTNT       DATA    250D                          LATERAL STICK DETENT(1024/IN)
 7907  033174  000372    PZLTNT       DATA    250D                          COLLECTIVE DETENT(1024/IN)
 7908  033175  000010    PN8          DATA    8D                            8 CYCLE FADE VALUE
 7909  033176  000360    PK240        DATA    240D                          15FT X POSITION INTEGRATOR HOLD THRESHOLD
 7910  033177  000040    PN32         DATA    32D                           32 CYCLE FADE VALUE
```

Memory Allocation. (contd)

```
1819A ASSEMBLER, VERSION 1.0   MOVF43  10/02/84   SECTION   3                                PAGE  162

       033021  000000
       033022  000000
       033023  000000
 7868  033024  000000   PZKP1   DATA    0,0,0,0,0
       033025  000000
       033026  000000
       033027  000000
       033030  000000
 7869  033031  715722   PAKIN   DATA    -25645D,57115D,29685C,31459C,23903C
       033032  157433
       033033  071765
       033034  075343
       033035  056537
 7870  033036  751556   PBPIN   DATA    -11409D,4027D,-12415C,-217C,933D,342D,1960C,-35796C
       033037  007673
       033040  747600
       033041  777446
       033042  001645
       033043  000526
       033044  003650
       033045  672053
 7871  033046  747060           DATA    -12751D,-13925D,-14768D,-235C,932C,150C,1513C,-32809D
       033047  744632
       033050  743123
       033051  777424
       033052  001644
       033053  000226
       033054  002751
       033055  677726
 7872  033056  100077           DATA    35903D,-8724D,16093C,-13D,-2021D,-1111D,-90C,6944D
       033057  756753
       033060  033415
       033061  777762
       033062  774032
       033063  775650
       033064  777645
       033065  015440
 7873  033066  700212           DATA    -8093D,160D,26173C,1D,131C,24C,52C,144C
       033067  000250
       033070  003075
       033071  000001
       033072  000203
       033073  000030
       033074  000064
       033075  000220
 7874  033076  613200           DATA    -59727D,19294D,1007C,109D,-12582D,2449C,-51995D,-30852D
       033077  045536
       033100  001757
       033101  000155
       033102  747331
       033103  004621
       033104  032344
       033105  703573
 7875  033106  770635   PICNIN  DATA    -3682D,3740D,2048C,-337D,2048C
       033107  007234
       033110  004000
       033111  777256
       033112  004000
```

Memory Allocation. (contd)

```
1819A ASSEMBLER, VERSION 1.0   MOVR43  10/02/84   SECTION   3                                            PAGE  161

  7820  032710  000000   OZCPID   RESERV   RESERV'1D                         Z TOTAL PID CONTROL
  7821  032711  000000   OZCCLD   RESERV   RESERV'1D                         CLD Z TOTAL PID CONTROL
  7822                 $          CBLSET
  7823  032712  000000   OXDI     RESERV   RESERV'2                          X INTEGRAL CONTROL
  7824  032714  000000   CYDI     RESERV   RESERV'2                          Y INTEGRAL CONTROL
  7825  032716  000000   OZDI     RESERV   RESERV'2                          Z INTEGRAL CONTROL
  7826  032720  000000   CXEZCN   RESERV   RESERV'1D                         RESERVE MEMORY FOR THE FADER RAMPS
  7827  032721  000000   OYEZCN   RESERV   RESERV'1D
  7828  032722  000000   OZEZCN   RESERV   RESERV'1D
  7829  032723  000000   OXEOFF   RESERV   RESERV'1D
  7830  032724  000000   OYEOFF   RESERV   RESERV'1D
  7831  032725  000000   CZEOFF   RESERV   RESERV'1D
  7832  032726  000000   CXCLST   RESERV   RESERV'1D
  7833  032727  000000   CYCLST   RESERV   RESERV'1D
  7834  032730  000000   CZCLST   RESERV   RESERV'1D
  7835  032731  000000   TMPO2    RESERV   RESERV'10D                        TEMPORARY USED IN CSTP52 AND CSTP53
  7836                 $
  7837                 $          CONSTANTS FOR CMPSTR SUBROUTINE
  7838                 $
  7839  032743  000001   OONE     1D
  7840  032744  000002   OTWO     2D
  7841                 $ ********************************************************************
  7842                 $
  7843                 $          THIS CODE RESERVES THE CONSTANTS AND
  7844                 $          VARIABLES NEEDED BY THE CMSTR4 SUBROUTINE
  7845                 $          WHICH IS ASSEMBLED IN MEMORY AREA #1.
  7846                 $
  7847  032745  000000   PUC      RESERV   RESERV'4D                         SET POINT BIAS COMMAND TO ACTUATOR
  7848  032751  000000   PUR      RESERV   RESERV'4D                         REGULATOR COMMANDS TO ACTUATOR
  7849  032755  000000   PUT      RESERV   RESERV'4D                         TOTAL ACTUATOR COMMANDS
  7850                 $                             PUT(1)=CELB(LONG CYCLIC)
  7851                 $                             PUT(2)=CELC(COLLECTIVE)
  7852                 $                             PUT(3)=CELS(LAT CYCLIC)
  7853                 $                             PUT(4)=CELR(DIRECTIONAL)
  7854  032761  000000   PPLT     RESERV   RESERV'4D                         PILOT COMMANDS
  7855                 $                             PPLT(1)=FOR-AFT STICK
  7856                 $                             PPLT(2)=COLLECTIVE
  7857                 $                             PPLT(3)=LEFT-RIGHT STICK
  7858                 $                             PPLT(4)=RUDDER PEDALS
  7859  032765  000000   PYS      RESERV   RESERV'10D                        MEASUREMENTS
  7860  032777  000000   PYDES    RESERV   RESERV'4D                         DESIRED OUTPUT VECTOR
  7861  033003  661677   PYSCLE   DATA     -40000D,-20000D,40000D
                                                                           LNG. CYCLIC SCALING(20000=10FPS/IN)
        033004  730737
        033005  116100
  7862                 $                                   COLLECTIVE SCALING
  7863                 $                                   LATERAL CYCLIC SCALING
  7864  033006  747214   PNK      DATA     -12659D,-2565D,-823D
        033007  772772
        033010  776020
  7865  033011  003454            DATA     1836D,-20665D,550D
        033012  727506
        033013  001046
  7866  033014  771767            DATA     -3080D,-897D,15430D
        033015  776176
        033016  036100
  7867  033017  000000   PZK      DATA     0,0,0,0,0
        033020  000000
```

Memory Allocation. (contd)

```
1819A ASSEMBLER, VERSION 1.0   MOVR43  10/02/84   SECTION   3                                   PAGE  157

032344  000000   NIRNTN   0                                        THETA AT ENGAGE
032345  000000   NIRNAS   0                                        AIRSPEED AT ENGAGE
032346  000000   NIRNHC   0                                        HDOT AT ENGAGE
                 $  THE FOLLOWING 12 VARIABLE DECLARATIONS MUST STAY IN
                 $  THE ORDER HERE TO MAKE THE MEASUREMENT SELECTION LOGIC
                 $  IN CMPSTR2 CORRECT
                 $  ------------------------------------------------------------
032347  000000   NDTHET   RESERV   RESERV'1D                      PERTURBATION PITCH ANGLE
032350  000000   NPHI     RESERV   RESERV'1D                      ROLL ANGLE
032351  000000   NPSI     RESERV   RESERV'1D                      YAW ANGLE
032352  000000   NPITRT   RESERV   RESERV'1D                      PITCH RATE
032353  000000   NROLRT   RESERV   RESERV'1D                      ROLL RATE
032354  000000   NYAWRT   RESERV   RESERV'1D                      YAW RATE
032355  000000   NAX      RESERV   RESERV'1D                      LONG. ACCELERATION
032356  000000   NAY      RESERV   RESERV'1D                      LATERAL ACCELERATION
032357  000000   NAZ      RESERV   RESERV'1D                      NORMAL ACCELERATION
032360  000000   NDVEL    RESERV   RESERV'1D                      PERTURBATION AIRSPEED
032361  000000   NVVEL    RESERV   RESERV'1D                      VERTICAL VELOCITY
032362  000000   NBALT    RESERV   RESERV'1D                      BAROMETRIC ALTITUDE
                 $  ------------------------------------------------------------
032363  000000   TMPN2    RESERV   RESERV'10D                     TEMPORARY USED IN NSTP52 AND NSTP53
                 $
                 $              CONSTANTS FOR CMSTR2 SUBROUTINE
                 $
032375  000001   NONE     1D
032376  000002   NTWO     2D
                 $
                 $  ************************************************************
                 $
                 $              THIS CODE RESERVES THE CONSTANTS AND
                 $              VARIABLES NEEDED BY THE CMPSTR3 SUBROUTINE
                 $              WHICH IS ASSEMBLED IN MEMORY AREA V1.
                 $
032377  000000   OUC      RESERV   RESERV'4D                      SET POINT BIAS COMMAND TO ACTUATOR
032403  000000   OUR      RESERV   RESERV'4D                      REGULATOR COMMANDS TO ACTUATOR
032407  000000   OUT      RESERV   RESERV'4D                      TOTAL ACTUATOR COMMANDS
                 $                          OUT(1)=DELB(LONG CYCLIC)
                 $                          OUT(2)=DELC(COLLECTIVE)
                 $                          OUT(3)=DELS(LAT CYCLIC)
                 $                          OUT(4)=DELR(DIRECTIONAL)
032413  000000   OPLT     RESERV   RESERV'4D                      PILOT COMMANDS
                 $                          OPLT(1)=FOR-AFT STICK
                 $                          OPLT(2)=COLLECTIVE
                 $                          OPLT(3)=LEFT-RIGHT STICK
                 $                          OPLT(4)=RUDDER PEDALS
032417  000000   OYS      RESERV   RESERV'10D                     MEASUREMENTS
032431  000000   OYDES    RESERV   RESERV'4D                      DESIRED OUTPUT VECTOR
032435  730737   OYSCLE   DATA     -20000D,-20000D,20000D
                                                                  LNG. CYCLIC SCALING(20000=10FPS/IN)
032436  730737
032437  047040
                 $                                  COLLECTIVE SCALING
                 $                                  LATERAL CYCLIC SCALING
032440  733416   ONN      DATA     -10673D,3507D,-1591D
032441  006663
032442  774710
032443  003457            DATA     1839D,-20664D,549D
032444  727507
```

Memory Allocation. (contd)

```
1819A ASSEMBLER, VERSION 1.0   MCVR43  10/02/84   SECTION   3                                         PAGE  156

 7644                          8                        NPLT(4)=RUDDER PEDALS
 7645  032235  000000  NYS      RESERV   RESERV'10D                                  MEASUREMENTS
 7646  032247  000000  NYDES    RESERV   RESERV'4D                                   DESIRED OUTPUT VECTOR
 7647  032253  000000  NYACT    RESERV   RESERV'4D                                   ACTUAL OUTPUTS CORRESPONDING TO NYDES
 7648  032257  742547  NYSCLE   DATA     -15000D,20000D                              COMMAND SCALING TERMS(20000=1 FPS PER INCH)
       032260  047040
 7649  032261  775614  NKINT    DATA     -1139D,515D                                 INTEGRAL CONTROL GAINS
       032262  001003
 7650  032263  774474           DATA     -1731D,2576D
       032264  005020
 7651  032265  413627  NNK      DATA     -125032D,-32537D
       032266  700346
 7652  032267  714511           DATA     -26294D,91551D
       032270  262637
 7653  032271  000000  NZK      DATA     0,0,0
       032272  000000
       032273  000000
 7654  032274  000000  NZKP1    DATA     0,0,0
       032275  000000
       032276  000000
 7655  032277  744311  NAMIN    DATA     -14134D,34775D,28947D
       032300  103727
       032301  070423
 7656  032302  776215  NBMIN    DATA     -882D,-89943D,713D,26005D
       032303  520250
       032304  001311
       032305  062625
 7657  032306  767456           DATA     -4305D,-61197D,-10863D,45634D
       032307  610362
       032310  752620
       032311  131102
 7658  032312  000631           DATA     409D,1320D,27053D,53016D
       032313  002450
       032314  064655
       032315  147430
 7659  032316  012545  NICMIN   DATA     5477D,10596D,16384D
       032317  024544
       032320  040000
 7660  032321  000000           DATA     0,16384D,-6644D
       032322  040000
       032323  763013
 7661  032324  000004  NYSSEL   DATA     4D,1D,11D,10D
       032325  000001
       032326  000013
       032327  000012
 7662  032330  000012  NYDSEL   DATA     10D,11D                                     DESIRED COMMANDS ARE VELOCITY AND HDOT
       032331  000013
 7663  032332  000003  NRDATA   3D
 7664  032333  000002  NNC      2D
 7665  032334  000004  NNN      4D
 7666  032335  000002  NACESC   DATA     2,1
       032336  000001
 7667  032337  000004  NRP1     4D
 7668  032340  100332  NLNGSC   38038D                                               LONG.CYCLIC SCALING TERM(SCALED 2**18)
 7669  032341  147075  NCCLSC   52797D                                               COLL. SCALING TERM(SCALED 2**18)
 7670  032342  105124  NLATSC   35892D                                               LAT SCALING TERM(SCALED 2**18)
 7671  032343  214356  NYAWSC   71918D                                               YAW SCALING TERM(SCALED 2**18)
```

Memory Allocation.

```
18198 ASSEMBLER, VERSION 1.0   MOVP43  10/02/84   SECTION   3                                              PAGE 158

032142  000012  MYCSEL   CATA     1CC,11C                          CESIRED CCMMANDS ARE VELOCITY AND HCOT
032143  000013
032144  000002  MR       2D
032145  000002  MMC      2D
032146  000004  MMM      4D
032147  000001  MACESC   CATA     1,1
032150  000001
032151  000003  MMPI     3D
032152  106332  MLNGSC   36058D                                    LONG. CYCLIC OUTPUT SCALING TERM(SCALED 2**18)
032153  147075  MCOLSC   52797D                                    COLL. OUTPUT SCALING TERM(SCALED 2**18)
032154  155124  MLATSC   55092D                                    LAT. CYCLIC OUTPUT SCALING TERM(SCALED 2**18)
032155  214356  MYAWSC   71918D                                    YAW OUTPUT SCALING TERM(SCALED 2**18)
032156  000000  MTHMTH   0                                         THETA AT ENGAGE
032157  000000  MTHMAS   0                                         AIRSPEED AT ENGAGE
032160  000000  MTHMHC   0                                         HDOT AT ENGAGE
                *  THE FOLLOWING 12 VARIABLE DECLARATIONS MUST STAY IN
                *  THE ORDER HERE TO MAKE THE MEASUREMENT SELECTION LOGIC
                *  IN CMPSTR1 CORRECT
                *  ---------------------------------------------------------
032161  000000  MDTHET   RESERV   RESERV'1D                        PERTURBATION PITCH ANGLE
032162  000000  MPHI     RESERV   RESERV'1C                        ROLL ANGLE
032163  000000  MPSI     RESERV   RESERV'1D                        YAW ANGLE
032164  000000  MPITRT   RESERV   RESERV'1D                        PITCH RATE
032165  000000  MROLRT   RESERV   RESERV'1D                        ROLL RATE
032166  000000  MYAWRT   RESERV   RESERV'1C                        YAW RATE
032167  000000  MAX      RESERV   RESERV'1D                        LONG. ACCELERATION
032170  000000  MAY      RESERV   RESERV'1D                        LATERAL ACCELERATION
032171  000000  MAZ      RESERV   RESERV'1D                        NORMAL ACCELERATION
032172  000000  MDVEL    RESERV   RESERV'1D                        PERTURBATION AIRSPEED
032173  000000  MVVEL    RESERV   RESERV'1D                        VERTICAL VELOCITY
032174  000000  MBALT    RESERV   RESERV'1D                        BAROMETRIC ALTITUDE
                *  ---------------------------------------------------------
032175  000000  TMPM2    RESERV   RESERV'10D                       TEMPORARY USED IN MSTP52 AND MSTP53
                *
                *           CCNSTANTS FCR CMPSTR SUBROUTINE
                *
032207  000001  MONE     1D
032210  000002  MTWO     2D
                *  **************************************************************
                *
                *           THIS CODE RESERVES THE CONSTANTS AND
                *           VARIABLES NEEDED BY THE CMSTR2 SUBROUTINE
                *           WHICH IS ASSEMBLED IN MEMORY AREA 01.
                *
032211  000000  MUI      RESERV   RESERV'4D                        INTEGRAL CONTROL COMPONENTS
032215  000000  MUC      RESERV   RESERV'4D                        SET POINT BIAS COMMAND TC ACTUATOR
032221  000000  MUR      RESERV   RESERV'4D                        REGULATCR COMMANDS TO ACTUATOR
032225  000000  MUT      RESERV   RESERV'4D                        TOTAL ACTUATOR COMMANDS
                *                             NUT(1)=CELB(LONG CYCLIC)
                *                             NUT(2)=CELC(COLLECTIVE)
                *                             NUT(3)=CELS(LAT CYCLIC)
                *                             NUT(4)=CELR(DIRECTIONAL)
032231  000000  MPLT     RESERV   RESERV'4D                        PILCT CCMMANDS
                *                             MPLT(1)=FOR-AFT STICK
                *                             MPLT(2)=CCLLECTIVE
                *                             MPLT(3)=LEFT-RIGHT STICK
```

Hover Controller Subroutine. (contd)

```
1819A ASSEMBLER, VERSION 1.0   HCVP43  10/02/84   SECTION   1                                    PAGE  100

007733 566716           ESK     PACTRL                     IF PSK=PACTRL SKIP THE NEXT LINE
                 *                     ELSE ICR1I=ICR1+1 AND DO NEXT LINE
007734 347726           JP      PSTF70                     CONTINUE
007735 347730           JP      PSTF8                      WRITE THE DATA OUT
                 *
                 *  -------------SECTION PSTP8-------------
                 *
                 *          HERE GOES THE SECTION(PSTP8) WHICH WRITES PUT(ACTUATOR
                 *          COMMANDS) TO THE LOCATION WHICH SENDS PUT TO THE
                 *          ACTUATORS.
                 *                          PSTP8
007736 122755  PSTP8    ENTAL   PUT                        AL:=PUT(1),LONG CYCLIC
007737 243145           MULAL   PLNGSC                     SCALE FOR OUTPUT(1IN/140.85BITS)
007740 460072           STRAU   OEF1                       STORE PUT(1) TO ECS PITCH COMMAND
007741 122756           ENTAL   PUT+1                      AL:=PUT(2),COLLECTIVE
007742 243146           MULAL   PCOLSC                     SCALE FOR OUTPUT(1IN/206.24BITS)
007743 460075           STRAU   OEF4                       STORE PUT(2) TO ECS COLLECTIVE COMMAND
007744 122757           ENTAL   PUT+2                      AL:=PUT(3), LATERAL CYCLIC
007745 243147           MULAL   PLATSC                     SCALE FOR OUTPUT(1IN/218.33BITS)
007746 460073           STRAU   OEF2                       STORE PUT(3) TO ECS ROLL COMMAND
                 *          ENTAL'PUT+3 AL:=PUT(4), DIRECTIONAL COMMAND
                 *          MULAL'PYAWSC      SCALE FOR OUTPUT(1IN/280.93BITS)
                 *          STRAU'OBF3  STORE PUT(4) TO ECS YAW COMMAND
                 *
                 *  -------------SECTION PSTP9
                 *
                 *          THIS SECTION OF CMPSTR SETS THE PRESENT COMPENSATOR
                 *          STATES(PZKP1) TO OLD STATES(PZK)
                 *
007747 507201  PSTP9    ENTICR  1                          USE ICR1 AS INDEX
007750 360001           ENTBK   1                          ICR1=0  (I=0)
007751 133023  PSTP90   ENTALB  PZKP1-1                    AL:=(PZKP1+ICR1)
007752 453016           STRALB  PZK-1                      PZK+ICR1-1:=AL
007753 566713           ESK     PPR                        IF ICR1=PPR THEN SKIP 1 LINE
                 *                     ELSE ICR1=ICR1+1  AND DO NEXT LINE
007754 347751           JP      PSTP90                     CONTINUE
007755 556720           IJP     CMSTR4                     END THE CONTROLLER SUBROUTINE NUMBER 4
```

Hover Controller Subroutine. (contd)

```
1819A ASSEMBLER, VERSION 1.0   MOVR43  10/02/84   SECTION   1                                         PAGE  55

                    *           SUBROUTINE, I.F.
                    *                     PUR = ICFIN * PZKPI
007654   507310   PSTP6     ENTSR    10                          USE MEMORY BANK 0
007655   507201             ENTICR   1                           USE ICR1 AS THE INDEX REG.(B)
007656   360000             ENTBK    0                           INITIALIZE THE B REG. TO 0
007657   400002             STZ      2                           ICR2=0, THE COLUMN INDEX
007660   400003             STZ      3                           ICR3=0, THE ROW INDEX
007661   507313             ENTSR    13                          USE MEMORY BANK 3
007662   123135             ENTAL    PR                          AL:=NUM OF COMPENSATOR STATES
007663   717776             ADDALK   -1                          AL:=PR-1
007664   507310             ENTSR    10                          USE MEMORY BANK 0 SINCE PRWEND IS THERE
007665   440711             STRAL    PRWEND                      PRWEND:=PR-1
007666   507313             ENTSR    13                          BACK TO MEMORY BANK 3 FOR DATA
007667   700000   PRXRW3    ENTALK   0                           AL:=0
007670   507400             XFRLU                                AU:=AL=0
007671   500600   PRXCL3    STRA     TPP                         TPP:=A
007672   031650
007673   507202             ENTICR   2                           GET THE COLUMN INDEX
007674   370001             ENTBKB   1                           INCREMENT COLUMN INDEX(ICR2=ICR2+1)
007675   133023             ENTALB   PZKPI-1                     AL:=(PZKPI+ICR2-1)
007676   507201             ENTICR   1                           USE ICR1 AS INDEX REG.(ELEMENT INDEX)
007677   253106             MULALB   PTCFIN                      A:=AL * (PTCFIN+ICR1)
007700   201650             ADDA     TPP                         A:=A + (TPP,TMP+1)
007701   505300             SKPNOV                               CHECK FOR OVERFLOW
007702   504000             NOOP                                 CALL OVERFLOW HANDLER
007703   566711             CSK      PRWEND                      IF ICR1=PRWEND THEN SKIP NEXT LINE
                    *                     ELSE DO NEXT LINE AND ICR1=ICR1+1
007704   347671             JP       PRXCL3                      JUMPS TO NEXT COLUMN OF PTCFIN
                    *                     AND NEXT ROW ELEMENT OF PZKPI
007705   370001             ENTBKB   1                           ICR1=ICR1+1
007706   507203             ENTICR   3                           USE ICR3 AS INDEX REG.(ROW INDEX)
007707   504702             LRIA     2                           SCALING FOR PSTP6 IS 2**16
007710   472751             STRAUB   PUR                         PUR+ICR1:=(AU),SCALING IS 2**16
007711   566715             CSK      PNCPI                       IF ICR3=PNCPI THEN SKIP NEXT LINE
                    *                     ELSE DO NEXT LINE AND ICR3=ICR3+1
007712   347714             JP       PRSET3                      GO RESET THE COUNTER
007713   347724             JP       PSTP7                       GO TO NEXT MATRIX MULT IF DONE
007714   507202   PRSET3    ENTICR   2                           SAVE ROW INDEX AND START USING COLUMN INDEX
007715   360000             ENTBK    0                           RESET COLUMN INDEX TO ZERO
007716   507310             ENTSR    10                          USE BANK 0 SINCE PRWEND AND PNCTRL ARE THERE
007717   126711             ENTAL    PRWEND                      AL:=PRWEND
007720   160713             ADDAL    PRR                         AL:=PRWEND+PRR=PRWEND+NUM COLUMNS
007721   446711             STRAL    PRWEND                      PRWEND:=PRWEND+PNCTRL
007722   507313             ENTSR    13                          USE BANK 3 FOR DATA
007723   347667             JP       PRXRW3                      DO THE NEXT ROW
                    *
                    *     ------------SECTION PSTP7--------------
                    *
                    *           THIS STEP DOES THE ADDITION PUT = PUC + PUR
                    *
007724   507201   PSTP7     ENTICR   1                           USE ICR1
007725   360001             ENTBK    1                           (ICR1=60) MEANS (I=1)
007726   132744   PSTP70    ENTALB   PUC-1                       AL:=(PUC+ICR1-1)
007727   152750             ADDALB   PUR-1                       AL:=AL+(PUR+ICR1-1)
007730   505300             SKPNOV                               SKIP IF NO OVERFLOW
007731   504000             NOOP                                 CALL THE OVERFLOW HANDLER
007732   452754             STRALB   PUT-1                       PUT:=AL, PUT(I)=PUC(I)+PUR(I)
```

Appendix K.

RSANDY Computer Program

The RSANDY computer program is a modified version of the SANDY computer program written by Uy-Loi Ly as part of his PhD dissertation at Stanford [3] and later modified first by Gardner [16]. It is stored on the FSD VAX at NASA Ames Research Center. Ly also wrote a user's guide for the SANDY program.[8] This appendix gives the input format changes to make the SANDY user's guide correct for the RSANDY program. The major capabilities added by the RSANDY program are:

- an optional gradient step-size reducer from Gardner [16]
- a linear discrete model of the closed loop system can be created for later simulation studies
- a leading free line and free lines before all the data items are included to help in documenting the data files

The changes which follow apply to page numbers in the SANDY User's Guide. Other than these changes, the program is exactly like the SANDY program. Also included here is an example data set for running the program. This data was used to find the reduced order Navion compensator in Chapter 2. In the following changes, the new variables needed by the program are italicized.

Change 1, page 117a. Running the RSANDY Program

@RSANDY Infile Outfile Simfile

where:

RSANDY– A VMS command file which runs the RSANDY.EXE file with Infile, Outfile, and Simfile as data files.

Infile– A file containing the input data; an example is shown at the end of this appendix.

Outfile– A filename where the program will write the output.

Simfile– A filename written by program, if IPLOT=1, which contains the linear simulation models used by the SIMPLOT program, described in Appendix M.

Change 2, page 119a. Item 1

Np,n,m,m',p,p',p",r,flag,*NNS,IPPSS,ICF,ISS*

where:

NNS– Set to 0.

IPPSS– Set to 0.

ICF– Set to 0.

ISS– Set to 0.

Change 3, page 119a. Item 2

Maxfn,Nvar,Tol,*MSTEP*,Nlinear,Tf,Print,*IDPRN,ICLPRN,MAPRN,IPLOT, DT,IBG*

where:

MSTEP– Maximum step size for the gradient algorithm. Start at 100 and make it smaller if there are convergence problems.

IDPRN– $= 0$ for no input data printout.

ICLPRN– $= 0$ for no closed loop data printout.

MAPRN– $= 0$ for no modal analysis printout.

IPLOT– $= 0$ for not creating a simulation model. $= N$ for creating a simulation model of the N^{th} plant condition.

DT– Cycle time for the discrete simulation model. Rule of Thumb, $DT \approx .2(\frac{2\pi}{\omega_{fastest}})$.

Change 4, page 126. Add Item 9

Data: *XO*

Description:

XO– A vector with $(n + r + m')$ zeros.

RSANDY Example Data File.

```
DATA FOR RSANDY FOR THE CHAP 2 EX. THE NAVION AT 100 KNOTS(REDUCED ORDER COMP)
#PLNT.N.M.M'.P.P'.P''.R.FLAG.NNS.IPPSS.ICE.ISS
   1.4.2. 4.2. 2.  5.2.   0.  0.    0.  0.0
Maxfn.Nvar.Tol.MSTEP.NLINEAR.Tf.Princ.IDPRN.ICLPRN.MAPRN.IPLOT. DT.IBC
   00.   8.1 OE-01.100.0.999 DO.   -1.    0.     0.     0.    0. 05.1
PROBABILITY DENSITY OF PLANT CONDITION 1
1 0
F MATRIX(N X N)U.W.Q.THETA
- 045. 036.0.-32 2
- 37. -2 02.176 0.0
 00191.- 0396.-2 98.0
0.0.1 0.0
C MATRIX( n X m )
0 1 0
-28 2.0
-11 0.0
0.0
GAMMA MATRIX( n X m' )
 045.- 036.0.0
 37.2 02.0.0
- 00191. 0396.0.0
0.0 0.0
HS MATRIX( p X n )VELOCITY.HDOT
1 0.0.0.0
0. -1 0.0.176 0
DSU MATRIX( p X m )
0.0
0 0
DSW MATRIX( p X m' )
0 0.1 0.0
0 0 0.1 0
HC MATRIX( p' x n )VELOCITY.HDOT
1 0 0.0.0
0 -1 0.0.176 0
DCU MATRIX( p' x m )
0 0
0 0
DCW MATRIX( p' x m' )
0 0 0 0.0
0 0 0 0.0
HP MATRIX( p'' x n )U.W.Q.THETA HDOT
1 0 0.0 0
0 1 0.0.0
0 0 57 3 0
0 0 0 57 3
0 -1 0 0.176 0
DPU MATRIX( p'' x m )
0 0
0 0
0 0
0 0
0 0
DPW MATRIX( p'' X m' )
0.0 0.0
0 0 0 0
0.0.0 0
0 0 0.0
0 0.0.0
UW NOISE  TYPE ORDER RMS
2.1 2 3
FILTER CONSTANT
 43
WW NOISE  TYPE ORDER RMS
2 1 2 3
FILTER CONSTANT
1 06
U MEAS  NOISE  TYPE.ORDER.RMS
2 1.1 0
FILTER CONSTANT(1HZ)
6 28
HDOT MEAS  NOISE  TYPE.ORDER.RMS
2 1.1 0
FILTER CONSTANT
6 28
ALPHA
0 DO
Q MATRIX( p' x p' )VELOCITY.HDOT
1 0 0
0 1 0
R MATRIX( m x m )ELEVATOR.THROTTLE
10000 0.0
0.1 0
 A MATRIX
0 0000E+00   1 000    -13 59      -16 93
 B MATRIX
-0 1366      0 2124
2 676      -3 241
 C MATRIX
0 0000E+00 -0 1000E-01
-13 14       -1 228
IDVAR( Nvar )
3 4.5.6.7.8.11.12
ITEM 9  XO
0.0.0.0.0.0.0.0.0.0 0 0.0.0
```

Appendix L.

SETPNT Computer Program

This appendix lists the computer program which calculates the feedforward matrix described in Appendix D. This version does not have the G_z matrix. The data formats and data sequence are described at the beginning of the program. Also included is an example data set (the full-order Navion of Chapter 2).

SETPNT Computer Program.

```
***************************************************************

THIS PROGRAM TAKES  AS INPUT  A DYNAMIC SYSTEM AND FINDS THE
"FEEDFORWARD MATRIX" WHICH WHEN MULTIPLIED BY A DESIRED OUTPUT
GIVES THE STEADY CONTROL FOR THE NEW EQUILIBRIUM POINT DEFINED
BY THE DESIRED OUTPUT  YD   IT ALSO FINDS THE TRANSFER FUNCTIONS
OF THE COMPENSATOR

THE DYNAMIC SYSTEM IS DEFINED BY THE FOLLOWING SET OF EQUATIONS

          XDOT = F * X  + G * U                 PLANT
            YS = HS * X  + DSU * U              SENSORS
          ZDOT = A * Z  + B * YS                COMPENSATOR DYNAMICS
             U = C * Z  + D * YS  + UC          CONTROLS

WHERE THE DESIRE IS TO FIND US AS A FUNCTION OF THE SYSTEM MATRICES
AND THE DESIRED OUTPUT VECTOR  YD

           YD = HD * XT  + LD * UC

          WHERE   XT= X
                      Z

SO AT STEADY STATE      UC = RN* YD
                        XT(STEADY STATE) = RM * YD

          WHERE M AND N COME FROM THE INVERSE OF THE FOLLOWING
                MATRIX
                                                          1
              | F+G*D*HS           G*C          G     |     :  O  :
  | RM |      | B*(IP+DSU*D)*HS   A+B*DSU*C   B*DSU   |  *  :  O  :
  | RN |      |              HD                LD     |     :  IM :
              |_                                      |     :     :

THE FOLLOWING IS THE DATA REQUIRED BY THE PROGRAM   THE DATA MUST
BE IN THE ORDER SHOWN   THE DATA IS ASSUMED TO BE IN FOR003 DAT

      DESCRIPTION OF N,M P R(ONE LINE)
      N M P R
            WHERE  N IS THE NUMBER OF STATES
                   M IS THE NUMBER OF CONTROLS AND THE NUMBER OF DESIRED
                                                            OUTPUTS
                   P IS THE NUMBER OF MEASUREMENTS
                   R IS THE ORDER OF THE COMPENSATOR
      TITLE OF F MATRIX
      F MATRIX(N X N) ENTERED BY ROW
      TITLE OF G MATRIX
      G MATRIX(N X M) ENTERED BY ROW
      TITLE OF HS MATRIX
      HS MATRIX(P X N) ENTERED BY ROW
      TITLE OF DSU MATRIX
      DSU MATRIX(P X M) ENTERED BY ROW
      TITLE OF A MATRIX
      A MATRIX(R X R) ENTERED BY ROW
      TITLE OF B MATRIX
      B MATRIX(R X P) ENTERED BY ROW
      TITLE OF C MATRIX
      C MATRIX(M X R) ENTERED BY ROW
C           TITLE OF D MATRIX
C           D MATRIX(M X P) ENTERED BY ROW
C           TITLE OF HD MATRIX
C           HD MATRIX(M X N+R) ENTERED BY ROW
C           TITLE OF LD MATRIX
C           LD MATRIX(M X M) ENTERED BY ROW
C
C**************************************************************
        IMPLICIT REAL*8(A H O Z)
        REAL*8 LD(20 20)
        INTEGER P R
        CHARACTER*20 FNAME
        DIMENSION F(20 20),G(20 20) HS(20 20) DSU(10 20),
       *A(20,20),B(20 20),C(20 20) D(20,20) HD(20,40)
       *BIGM(44 44) TMP(44 44) IPS(44) RM(40,20) RN(20 20)
       *BIGMIN(44,44),WKAREA(2068) ADIG(20 20),BDIG(20,10) CDIG(4 20)
       *BTMP(44 4) BTMP1(44 4) TMP1(20 20) TMP2(20,20) TMP3(20 20)
       *TMP4(20 20) TMP5(20,20) TMP6(20,20),TMP7(20,20),
       *TMP8(20 20),TMP9(20 20),TMP10(20,20),TMP11(20,20)
C
C   INPUT THE DATA
C
C   N M,P,R
 1020 FORMAT('O',2X 'N=',I2,'  M=',I2,'  P=',I2,'  R=',I2,
     *'  SAMPLE PERIOD(SEC) = ',F7 4)
 1000 FORMAT('O',// 2X,'THE BIGM MATRIX IS SINGULAR')
 1010 FORMAT('O' // 2X,'THE BIGM MATRIX IS ILL CONDITIONED')
 1030 FORMAT(1X,// 2X 'THE BIGM MATRIX IS')
        READ(3 *)
        READ(3,*)N,M,P,R,T
        WRITE(6 1020)N,M,P,R,T
        NPLR=N+R
        CALL DATAIN(N M P,R NPLR FNAME F,G HS,DSU A B C D HD LD)
C
C   THESE STATEMENTS ARE COMMENTED BECAUSE THE THEORY BEHIND
C   GETTING M AND N IS WRONG
C
C   FILL THE BIGM MATRIX USING THE DATA
C
        NSUM N+R+M
        CALL FILLEM(N M,P R,NPLR NSUM,F,G HS,DSU A,B,C,D HD
       *,LD BIGM,TMP1 TMP2 TMP3,TMP4 TMP5,TMP6 TMP7 TMP8,TMP9 TMP10
       *,TMP11)
        WRITE(6 1030)
        CALL PRNTM(BIGM NSUM NSUM NSUM)
C
C   INVERT THE BIGM MATRIX
C
        CALL LINV2F(BIGM NSUM NSUM BIGMIN,5,WKAREA,IER)
        IF (IER EQ 129) WRITE(6,1000)
        IF (IER EQ 131) WRITE(6 1010)
C        CALL MATPNT(BIGMIN NSUM,NSUM,'INVERSE(BIGM)')
C
C   CHECK CORRECTNESS OF THE INVERSION
C
C        CALL MULT(BIGMIN BIGM TMP,NSUM NSUM NSUM)
C        CALL MATPNT(TMP NSUM,NSUM,'IDENTITY(NSUM)')
C
C   EXTRACT THE DATA AND PRINT THE RESULTS
C
        CALL GETMN(N M P R,NPLR NSUM,BIGMIN BTMP BTMP1 RM RN)
C
C   CALL THE SUBROUTINE WHICH DOES THE MATRIX POLYNOMIAL AND
C   PARTIAL FRACTION EXPANSION OF THE COMPENSATOR   THIS ALSO
```

SETPNT Computer Program. (contd)

```
C  FINDS THE ZEROS OF THE TRANSFER FUNCTIONS OF THE COMPENSATOR
      CALL TRANAL(A B C M P R)
C
C  THIS SUBROUTINE CALL FINDS THE DISCRETE FORM OF THE COMPENSATOR
C  AND ALSO FINDS THE MINIMAL FORM OF THE DISCRETE COMPENSATOR
C
      CALL DIGITL(A B C ADIG BDIG CDIG T R M P)
      STOP
      END
C*****************DATAIN*********************************************
C
C  THIS SUBROUTINE READS THE DATA FROM A DATA FILE IN
C  FREE FORMAT   IT FIRST ASKS FOR THE NAME OF THE FILE
C
C********************************************************************
      SUBROUTINE DATAIN(N M P R NPLR FNAME F G HS DSU A B
     *C D HD LD)
      IMPLICIT REAL*8(A H O Z)
      REAL*8 LD(M M)
      INTEGER P R
      CHARACTER*20 FNAME
      DIMENSION F(N N) G(N M) HS(P N) DSU(P M)
     *A(R R) B(R P) C(M R) D(M P) HD(M NPLR)
1000  FORMAT(' INPUT FILE NAME  '\) USED FOR IBM PC VERSION
1010  FORMAT(A)
1030  FORMAT('O' 2X 'HD(' I2 I2 ') ' F11 5)
C
C  PROMPT THE USER FOR THE FILENAME
C
      WRITE(6 1000)
      READ(6 1010)
C
C  OPEN UNIT 3 FOR INPUT
C
      OPEN(3 FILE FNAME)
C
C  READ THE DATA
C
      READ(3 *)
      DO 100 I=1 N
100      READ(3 *) (F(I J) J=1 N)
      CALL MATPNT(F N N 'F')
      READ(3 *)
      DO 110 I=1 N
110      READ(3 *) (G(I J) J 1 M)
      CALL MATPNT(G N M 'G')
      READ(3 *)
      DO 120 I=1 P
120      READ(3 *) (HS(I J) J 1 N)
      CALL MATPNT(HS P N 'HS')
      READ(3 *)
      DO 130 I=1 P
130      READ(3 *) (DSU(I J) J=1 M)
      CALL MATPNT(DSU P M 'DSU')
      READ(3 *)
      DO 140 I=1 R
140      READ(3 *) (A(I J) J 1 R)
      CALL MATPNT(A R R 'A')
      READ(3 *)
      DO 150 I=1 R
150      READ(3 *) (B(I J) J=1 P)
      CALL MATPNT(B R P 'B')
      READ(3 *)
      DO 160 I 1 M
160      READ(3 *) (C(I J) J 1 R)
      CALL MATPNT(C M R 'C')
      READ(3 *)
      DO 170 I 1 M
170      READ(3 *) (D(I J) J 1 P)
      CALL MATPNT(D M P 'D')
      READ(3 *)
      NPR N+R
      DO 180 I 1 M
180         READ(3 *) (HD(I J) J 1 NPR)
      CALL MATPNT(HD M NPR 'HD')
      READ(3 *)
      DO 190 I 1 M
190      READ(3 *) (LD(I J) J 1 M)
      CALL MATPNT(LD M M 'LD')
      RETURN
      END
C**************************FILLEM*************************************
C
C  THIS SUBROUTINE USES THE DATA READ IN IN THE SUBROUTINE DATAIN
C  TO FILL THE BIGM MATRIX
C
C*********************************************************************
      SUBROUTINE FILLEM(N M P R NPLR NSUM F G HS DSU A B C D HD
     * LD BIGM TMP1 TMP2 TMP3 TMP4 TMP5 TMP6 TMP7 TMP8 TMP9 TMP10
     * TMP11)
      IMPLICIT REAL*8(A H O Z)
      REAL*8 LD(M M)
      INTEGER P R
      DIMENSION F(N N) G(N M) HS(P N) DSU(P M)
     *A(R R) B(R P) C(M R) D(M P) HD(M NPLR)
     *BIGM(NSUM NSUM) TMP1(M N) TMP2(N N)
     *TMP3(N N) TMP4(N R) TMP5(P P) TMP6(P N)
     *TMP7(R N) TMP8(P R) TMP9(R R) TMP10(R R)
     *TMP11(R M)
1000  FORMAT(10(2X 1PE10 3) / 2X 10(2X 1PE10 3))
1010  FORMAT('O' 2X 'THE BIGM MATRIX IN FILLEM IS')
C  TMP1 D*HS
      CALL MULT(D HS TMP1 M P N)
C  TMP2=G*D*HS-G*TMP1
      CALL MULT(G TMP1 TMP2 N M N)
C  TMP3 F+G*D*HS=F+TMP2
      CALL MADD(F TMP2 TMP3 N N 1 0)
C  LOAD THE BIGM MATRIX
      DO 100 I=1 N
      DO 100 J 1 N
100      BIGM(I J) TMP3(I J)
C  TMP4 G*C AND LOAD THE BIGM MATRIX
      CALL MULT(G C TMP4 N M R)
      DO 110 I=1 N
      DO 110 J 1 R
110      BIGM(I N+J)=TMP4(I J)
C  LOAD THE BIGM MATRIX
      NPR N+R
      DO 120 I 1 N
      DO 120 J 1 M
120      BIGM(I NPR+J) G(I J)
C  TMP5 DSU*D
      CALL MULT(DSU D TMP5 P M P)
C  TMP5 TMP5+I DSU*D+I
      DO 130 I 1 P
130      TMP5(I I) TMP5(I I)+1 0
```

SETPNT Computer Program. (contd)

```
      TMP6 TMP5*HS (I+DSU*D)*HS
         CALL MULT(TMP5 HS TMP6 P P N)
      TMP7 B*TMP6 B*(I+DSU*D)*HS
         CALL MULT(B TMP6 TMP7 R P N)
      LOAD THE BIGM MATRIX
         DO 140 I 1 R
         DO 140 J 1 N
140         BIGM(N+I J) TMP7(I J)
      TMP8 DSU*C
         CALL MULT(DSU C TMP8 P M R)
      TMP9 B*TMP8 B*DSU*C
         CALL MULT(B TMP8 TMP9 R P R)
      TMP10 A+TMP9=A+B*DSU*C
         CALL MADD(A TMP9 TMP10 R R 1 0)
      LOAD THE BIGM MATRIX
         DO 150 I 1 R
         DO 150 J 1 R
150         BIGM(N+I N+J) TMP10(I J)
      TMP11 B*DSU
         CALL MULT(B DSU TMP11 R P M)
      LOAD THE BIGM MATRIX
         DO 160 I=1 R
         DO 160 J=1 M
160         BIGM(N+I NPR+J) TMP11(I J)
         DO 170 I=1 M
         DO 170 J 1 NPR
170         BIGM(NPR+I J) -HD(I J)
         DO 180 I-1 M
         DO 180 J 1 M
180         BIGM(NPR+I NPR+J) LD(I J)

      PRINT THE BIGM MATRIX

          WRITE(6 1010)
          DO 190 I=1 NSUM
190          WRITE(6 1000)(BIGM(I J) J=1 NSUM)
         RETURN
         END
****************************MATPNT*******************************

      THIS SUBROUTINE PRINTS A MATRIX AND LABELS THE PRINTING OF
      THE MATRIX

                     F     THE MATRIX TO BE PRINTED(LIMITED TO 20X20)
                     N     THE ROW DIMENSION OF THE MATRIX
                     M     THE COLUMN DIMENSION OF THE MATRIX
                     NAME   THE ASCII NAME OF THE MATRIX

*****************************************************************
         SUBROUTINE MATPNT(F N M NAME)
         IMPLICIT REAL*8(A H O Z)
         CHARACTER*(*) NAME
         DIMENSION F(N,M)
1000  FORMAT('0',//,2X,'THE ',A,' MATRIX IS ')
1010  FORMAT(10(2X,1PE10 3) /,2X,10(2X,1PE10 3))
         WRITE(6,1000)NAME
         DO 100 I=1 N
100         WRITE(6,1010)(F(I J),J=1 M)
         RETURN
         END
C
C
         SUBROUTINE MULT(A B C N1 N2 N3)
C
C  THIS SUBROUTINE MULTIPLIES MATRIX A(N1 X N2) BY MATRIX
C  B(N2 X N3)
C                         C A*B
         IMPLICIT REAL*8 (A H O Z)
         DIMENSION A(N1 N2) B(N2 N3) C(N1 N3)
         DO 7901 I 1 N1
         DO 7901 J 1 N3
         TEMP 0
         DO 7900 K 1 N2
 7900 TEMP TEMP+A(I K)*B(K J)
 7901 C(I J) TEMP
         RETURN
         END
C
C
C
         SUBROUTINE MADD(A B C N1 N2 SCALE)
C
C THIS SUBROUTINE PERFORMS MATRIX (N1 X N2) ADDITION
C                      C A+(SCALE)*B
C
         IMPLICIT REAL*8 (A H O Z)
         DIMENSION A(N1 N2) B(N1 N2) C(N1 N2)
         DO 7902 I 1 N1
         DO 7902 J 1 N2
 7902 C(I J) A(I J)+SCALE*B(I J)
         RETURN
         END
C
C
C
C***************GETMN*********************************************
C
C   THIS SUBROUTINE EXTRACTS THE M AND N MATRICES AS DESCRIBED
C   IN THE MAIN PROGRAM INTRODUCTION   IT THEN PRINTS THESE
C
C*****************************************************************
         SUBROUTINE GETMN(N M P R,NPLR NSUM BIGMIN BTMP BTMP1
        * RM RN)
         IMPLICIT REAL*8(A H O Z)
         INTEGER P R
         DIMENSION BIGMIN(NSUM NSUM) BTMP(NSUM M)
        *BTMP1(NSUM M),RM(NPLR M) RN(M M)
C   SET UP THE BTMP MATRIX
         DO 10 I-1,N
         DO 10 J-1,M
 10            BTMP(I J) 0 0
         DO 20 I-1 R
         DO 20 J-1 M
 20            BTMP(N+I J) 0 0
         DO 30 I 1 M
 30            BTMP(NPLR+I I) 1 0
C
   DO THE FINAL MATRIX MULTIPLY
C
         CALL MULT(BIGMIN BTMP BTMP1,NSUM NSUM M)
C   LOAD THE RM AND RN MATRICES
C
         DO 100 I=1,NPLR
         DO 100 J=1 M
 100           RM(I,J) BTMP1(I J)
         DO 110 I 1 M
         DO 110 J 1 M
```

SETPNT Computer Program. (contd)

```
 1    RN(I J) BTMP1(NPLR+I J)
C
C   PRINT THE RESULTS
C
      CALL MATPNT(RM NPLR M 'RM')
      CALL MATPNT(RN M M 'RN')
      RETURN
      END


      SUBROUTINE TFANAL(A B C M P R)
C
C   THIS SUBROUTINE FINDS THE MATRIX POLYNOMIAL AND RESIDUE POLE
C   REPRESENTATION OF THE COMPENSATOR DYNAMIC SYSTEM SHOWN BELOW
C
C              ZDOT = A * Z  +  B * YS
C                 U = C * Z
C
C   THE SUBROUTINE CALLS ARE BASED ON DOUG BERNARD'S
C   "CONTROLS PLAYPEN" LIBRARY
C
      IMPLICIT REAL*8(A H O Z)
      INTEGER DA(20) DB(20) DC(20) N(20) DN(20) DR(20) DENOM(20)
     *D(20) RR(20) LAMBDA(20) JMAT(20) NO(20) CLASS(64) RO(20)
      INTEGER P R
      COMPLEX*16 Z(10)
      DIMENSION A(R R) B(R P) C(M R) POLY(12)
      LODIM1=1
      LODIM2 1
      LODIM3 1
      L1DIM1 R
      L1DIM2 R
      L1DIM3 M
      L2DIM1=R
      L2DIM2=P
      L2DIM3=R
C
C   INITIALIZE DESCRIPTORS FOR DOUG'S PROGRAMS
C
      CALL INIT_DESCRIPTOR(DA)
      CALL INIT_DESCRIPTOR(DB)
      CALL INIT_DESCRIPTOR(DC)
      CALL INIT_DESCRIPTOR(N)
      CALL INIT_DESCRIPTOR(DN)
      CALL INIT_DESCRIPTOR(DR)
      CALL INIT_DESCRIPTOR(DENOM)
      CALL INIT_DESCRIPTOR(D)
      CALL INIT_DESCRIPTOR(RR)
      CALL INIT_DESCRIPTOR(LAMBDA)
      CALL INIT_DESCRIPTOR(JMAT)
      CALL INIT_DESCRIPTOR(NO)
      CALL INIT_DESCRIPTOR(RO)
      CALL COPY_STATIC_TO_DYNAMIC(A DA 1 R R LODIM1 L1DIM1 L2DIM1)
      CALL COPY_STATIC_TO_DYNAMIC(B DB 1 R P LODIM2 L1DIM2 L2DIM2)
      CALL COPY_STATIC_TO_DYNAMIC(C DC 1 M R LODIM3 L1DIM3 L2DIM3)
      CALL PRT(DA 1 FALSE )
      CALL PRT(DB 1 FALSE )
      CALL PRT(DC 1 FALSE )
C
C   FIND THE MATRIX POLYNOMIAL FORM OF THE COMPENSATOR
C
      CALL FGH_TO_MAT_POLY_SEP(DA DB DC JMAT N D NO)
C      WRITE(6 1200)
      CALL PRT(N 1 FALSE )
      CALL PRT(D 1 FALSE )
C
C   FIND THE POLES OF THE COMPENSATOR
C
      POLY(1) 1 0
      DO 200 I=1 R
 200      POLY(I+1)=ELF(D I 1 1)
      CALL ZPOLR(POLY R Z IERR)
      WRITE(6 1500)
      DO 210 II 1 R
 210      WRITE(6 1100) Z(II)
C
C   FIND THE ZEROS OF EACH NUMERATOR T F
C   M IS # OF CONTROLS  P IS # OF MEAS
C
      DO 130 I 1 M
      DO 130 J 1 P
         KK 0
         K=1
 160     IF (K EQ R+1) GO TO 150
         TMP ELF(N I J K)
         IF (DABS(TMP) LT  00001) GO TO 140
         KK KK+1
         POLY(KK)=TMP
 140     K=K+1
         GO TO 160
 150        WRITE(6 1400) (POLY(JJ) JJ 1 KK)
            CALL ZPOLR(POLY KK 1 Z IER)
            WRITE(6 1000) J I
            DO 170 II=1 KK 1
 170           WRITE(6 1100) Z(II)
 130  CONTINUE
C
C   FIND THE RESIDUE POLE FORM OF THE COMPENSATOR
C
      CALL MAT_POLY_TO_RESIDUE_SEP(N D NO RR LAMBDA CLASS RO)
      WRITE(6 1300)
      CALL PRT(RR 1 FALSE )
      CALL PRT(LAMBDA 1 FALSE )
 1000 FORMAT(' ' // 2X 'THE T F  ZEROS FROM INPUT ' I2 ' TO OUTPUT '
     * I2 / 2X 'REAL' 9X 'IMAGINARY')
 1100 FORMAT(' ' 2X G12 5 3X G12 5)
 1200 FORMAT(' ' // 2X 'THE MATRIX POLYNOMIAL REPRESENTATION OF
     * THE COMPENSATOR N(s)/d(s) IS' /)
 1300 FORMAT(' ' // 2X 'THE RESIDUE FORM OF THE COMPENSATOR IS' /)
 1400 FORMAT(' ' // 2X 'THE NUMERATOR COEFFICIENTS ARE' 10G12 4)
 1500 FORMAT(' ' // 2X 'THE POLES OF THE COMPENSATOR ARE' /
     *'REAL' 9X 'IMAGINARY')
      RETURN
      END

c  ****************digit1******11/9/83)**********************************
c
c   Written by Rick Holdridge
c
c   This subroutine accepts the analog form of a compensator in
c   block minimal form  then discretizes it using sample
c   time dtime   Then the discrete compensator is transformed
c   back into minimal form to speed up the calculations on the
c   real time computer
c
c   The form of the compensator is
c
c                 zdot = a * z + b * ys
```

SETPNT Computer Program. (contd)

```
                u   r * z

        where    a    r x r  (compenator dynamics matrix)
                 b    r x p  (compensator input dist  matrix)
                 c    m x r  (compensator output dist  matrix)
                ys    p x 1  (measurement vector)
                 u    m x 1  (control vector)

*********************************************************************
      SUBROUTINE DIGITL(A B C ADIG BDIG CDIG DTIME R M P)
      implicit real*8 (a h o z)
      integer p r
      dimension a(r 1) b(r 1) c(m 1) adig(r 1) bdig(r 1)
     *cdig(m 1)
      do 50 i 1 r
      do 50 j 1 r
 50      adig(i j) 0 0

  Print out the input matrices for check purposes

       write(6 1000)
       call prnte(a r r r)
       write(6 1100)
       call prnte(b r r p)
       write(6 1200)
       call prnte(c m m r)
 1000 format(// 1x 'The A matrix in digitl is')
 1100 format(// 1x 'The B matrix in digitl is')
 1200 format(// 1x 'The C matrix in digitl is')

  Begin an outer loop which checks for 1x1 or 2x2 blocks
      i=1
 100  if ((i+1) gt r) go to 200
      if ((dabs(a(i+1 i)) lt  0001) and (dabs(a(i i+1)) lt  0001))
     *go to 200
      go to 300

  **200** This finds the part of the transition matrix
          associated with a real mode

 200  adig(i i)=exp(a(i i)*dtime)
      do 220 j=1 p
 220      bdig(i j)=((exp(a(i i)*dtime) 1 0)/a(i i))*b(i j)
      do 230 j=1 m
 230      cdig(j i) c(j i)
      i i+1
      if (i gt r) go to 400
      go to 100

 **300** This section finds the transision matrix for the
         2x2 blocks

 300  call phi(a(i+1,i) a(i+1 i+1) dtime adig(i i) adig(i i+1)
     * adig(i+1,i) adig(i+1 i+1) gam11 gam12 gam21 gam22)

   fill the bdig matrix  I is the index of the phi(1 1) element
   in the big phi matrix

      do 310 j=1.p
             bdig(i j)=gam12*b(i j)+gam11*b(i+1 j)
 310         bdig(i+1 j)=gam22*b(i j)+gam21*b(i+1 j)
      do 320 j=1.m
             cdig(j i)=c(j i)
 320         cdig(j i+1)=c(j i+1)
      i i+2
      if (i gt r) go to 400
      go to 100

c  **400**  this last section minimalizes the matrix
c
  400 CONTINUE
c      write(6 1300)
c      call prnte(adig r r r)
c      write(6 1400)
c      call prnte(bdig r r p)
c      write(6 1500)
c      call prnte(cdig m m r)
 1300 format(// 1x 'The compensator phi matrix is')
 1400 format(// 1x 'The compensator gamma matrix is')
 1500 format(// 1x 'The compensator output matrix is')
      call minicom(adig bdig cdig a b c r p m)
c
c  Now the a b c matrices have the digital form
c  of the compensator
c
      STOP
      end
c
c
c
        subroutine phi(a1 a2 T  phi11 phi12 phi21 phi22
     1                          gam11 gam12 gam21 gam22)
c
c
comment  This subroutine accepts a continuous 2 by 2 block in real
c         modal form and discretizes it
c
c        The continuous equations are
c
c        |z1dot|    |  0    1| |z1| + |0| * u1 + |1| * u2
c        |z2dot|    | a1   a2| |z2|   |1|         |0|
c
c        the discrete equations are
c
c        |z1|          |phi11 phi12| |z1|    + |gam11 gam12| |u1|
c        |z2|(k+1)     |phi21 phi22| |z2|(k)   |gam21 gam22| |u2|k
c
c        the sample period is T in units of seconds
c
c       note that the program returns unit solutions for the gamma matrix
c       For a real problem simply multiply the columns by the elements
c       of the continuous C matrix
c
        IMPLICIT REAL*8(A H O Z)
        REAL*8 NUM
        logical comp
        comp =  TRUE
c
c
comment check discriminant
c
c  these statements are needed since I enter a matrix of the
c  form
c        0    1
c       a1   a2
c                 not in the form used by Dan Rosenthal who
c                 wrote this subroutine
c
```

SETPNT Computer Program. (contd)

```
      a1  a1
      a2  a2
      disc  a2 * a2   4  * a1
      if ( disc  gt  0 ) comp   FALSE

      if ( comp  eq   true ) goto 1000

      a   0 5 * (a2 + sqrt(disc))
      b   0 5 * (a2   sqrt(disc))

      c   1
      d   a2
       call sub1(a b c d T x)
       phi11   x

      c   0
      d   1
       call sub1(a b c d T x)
       phi12 = x

      c = 0
      d =  a1
       call sub1(a b c d T x)
       phi21 - x

      c = 1
      d   0
       call sub1(a b c d T x)
       phi22 = x

      num = 1
      call sub2(a b,T num x)
      gam11 = x

      gam21 = phi12

      gam12 = gam21 + a2 * gam11

      gam22 =   a1 * gam11

      goto 2000
1000  continue
c
c omment two complex roots
c
       a = 0 5 * a2
       b = sqrt(a1   a*a)
c
       c = 1
       d = a2
        call sub3(a b c d T x)
        phi11 = x

      c = 0
      d = 1
        call sub3(a.b.c.d.T x)
        phi12 = x
c
      c = 0
      d =  a1
        call sub3(a.b c.d.T x)
        phi21 = x
c
      c = 1
      d   0
        call sub3(a b c d T x)
        phi22   x
c
      num   1
      call sub4(a b T num x)
      gam11   x
c
      gam21   phi12
c
      gam12   gam21 + a2 * gam11
      gam22      a1 * gam11
c
2000  RETURN
      end
      subroutine sub1(a b,c d T x)
      IMPLICIT REAL*8(A H O Z)
               x    (d a*c)/(b a)* exp( a*T)
               x    x + (d   b*c)/(a  b)* exp( b*T)
      return
      end
      subroutine sub2(a b T num.x)
      IMPLICIT REAL*8(A H O Z)
      REAL*8 NUM
         c = 1
         d = a + b
         call sub1(a.b.c.d.T.temp)
         x = num/(a*b)* (1    temp)
      return
      end
      subroutine sub3(a b.c d.T.x)
      IMPLICIT REAL*8(A H.O Z)
         x = c* cos(b*t) + (d   a*c)/b*sin(b*t)
         x = x * exp(  a*t)
       return
       end
       subroutine sub4( a.b T num x)
       IMPLICIT REAL*8(A H O Z)
       REAL*8 NUM
          c = 1 0
          d = 2 * a
          call sub3( a b.c d.T temp)
          x = num/(a*a +b*b)*( 1   temp)
       return
       end

      SUBROUTINE MINCOM(FMOD.GMOD HMOD.EMIN.GMIN.HMIN.NS.NC.NM)
C  *************MINCOM********11/9/83********************************************
C     WRITTEN BY RICK HOLDRIDGE
C
C     THIS PROGRAM CONVERTS A SYSTEM OF THE FORM
C             XDOT=FMOD*X + GMOD*U
C             Y HMOD*X
C     WHERE FMOD.GMOD AND HMOD ARE IN ARBITRARY FORM TO THE MINIMAL
C     FORM WHERE THE SYSTEM MATRICES TAKE THE FORM SHOWN BELOW
C
C           ! O   I                       !
C           ! A1 A2                       !
C           !       O   1      O          !
C           !       A1 A2                 !
C     FMIN  !            \                !   GMIN=NS X NC. FULL MATRIX
C           !              \              !
C           !       O        O   1        !
C           !                A1 A2        !
```

SETPNT Computer Program. (contd)

```
C
C                                          \
C                                           A1  :
C      :  .   .   .   .                         :
C      :  0   1   .   .                         :
C      :  .   .   .   .   \                     :
C HMIN :  .   .   0   1    \                    :
C      :  .   .   .   .     \                   :
C      :  .   .   .   .                         :
C      :  .   .   .   .                     1   :
C
C  THE SUBROUTINE FINDS A TRANSFORMATION MATRIX TM SUCH THAT
C          FMIN  TMINV*FMOD*TM
C          GMIN  TMINV*GMOD
C          HMIN  HMOD*TM
C
C ......................................................................
C
C  DO THE DIMENSIONING OF THE MATRICES
C
      IMPLICIT REAL*8(A H,O Z)
      DIMENSION FMOD(NS 1) HMOD(NM 1) GMOD(NS 1).
     *FMIN(NS.1) HMIN(NM.1) GMIN(NS 1)
      DIMENSION TMIN(20.20) TMININV(20 20) FTEMP(20 20)
C
C  Print out the input matrices for check purposes
C
       write(6.1001)
       call prntm(FMOD NS NS.NS)
       write(6 1101)
       call prntm(HMOD.NM.NM NS)
       write(6 1201)
       call prntm(GMOD.NS NS NC)
 1001 format(// 1x.'The FMOD matrix in MINCOM is')
 1101 format(// 1x.'The HMOD matrix in MINCOM is')
 1201 format(//.1x.'The GMOD matrix in MINCOM is')
C
C        CALCULATE THE TRANSFORMATION MATRIX  TMIN(NS NS)
C
      I=1
C
C   ***********100************
C   CHECK FOR REAL BLOCKS(NO OFF DIAGONAL TERMS)
C
  100 IF ((I+1) GT NS) GO TO 200
      IF ((DABS(FMOD(I+1 I)) LT  0001) AND
     *(DABS(FMOD(I.I+1)) LT  0001)) GO TO 200
      GO TO 300
C
C   ***********200***********
C
  200 M=1
      RMM=ABS(HMOD(1 1))
      IF (NM EQ 1) GO TO 250
      DO 220 J=2.NM
         RMA=ABS(HMOD(J 1))
         IF (RMA LT RMM) GO TO 220
         RMM RMA
         M=J
C
C   ***********220*********
C
  220   CONTINUE
C
C   ***********250********
C
  250 THIN(I 1) 1/HMOD(M 1)
      TMININV(I I) HMOD(M I)
      I I+1
      IF (I GT NS) GO TO 400
      GO TO 100
C
C   ************300*********
C
  300  M 1
      RMM HMOD(1 1)**2+HMOD(1 I+1)**2
      IF (NM EQ 1) GO TO 350
      DO 320 J 2 NM
         RMA HMOD(J 1)**2+HMOD(J I+1)**2
         IF (RMA LT RMM) GO TO 320
         M J
         RMM RMA
C
C   *******320********
C
  320 CONTINUE
C
C   ***************350*************
C
  350 A FMOD(I I)
      B FMOD(I.I+1)
      C FMOD(I+1 I)
      D FMOD(I+1 I+1)
      H1=+HMOD(M.I)
      H2-+HMOD(M.I+1)
      DENOM= B*H1**2+(A D)*H1*H2+C*H2**2
C
C  FOR DEBUGGING
C
C       WRITE(6.2000)A.B.C.D.H1.H2.DENOM.I.J.M NS.NC.NM
 2000 FORMAT(1X.'A=' F11 5 ' B=' F11 5 ' C ' F11 5.' D=' F11 5./.
     *1X.' H1=' F11 5 ' H2=' F11 5.' DENOM ' F11 5./.
     *1X.' I=' I1.'  J=' I1.'  M=' I1.'  NS=' I1.'  NC=' I1.
     *'  NM=' I1)
      TMIN(I.I)=H2*(B*C A*D)/DENOM
      TMIN(I.I+1)=(A*H2 B*H1)/DENOM
      TMIN(I+1.I+1)-(C*H2 D*H1)/DENOM
      TMIN(I+1.I)= H1*(B*C-A*D)/DENOM
C
C        FIND THE INVERSE OF THIN
C
      DENOM=TMIN(I+1.I+1)*TMIN(I.I)-TMIN(I I+1)*TMIN(I+1.I)
      TMININV(I.I)=TMIN(I+1.I+1)/DENOM
      TMININV(I+1.I+1)=TMIN(I.I)/DENOM
      TMININV(I I+1)= TMIN(I.I+1)/DENOM
      TMININV(I+1.I)= TMIN(I+1.I)/DENOM
      I=I+2
      IF (I GT NS) GO TO 400
      GO TO 100
C
C   **************400************
C
C        TRANSFORM TO THE MINIMAL FORM
C
```

SETPNT Computer Program. (contd)

```
      FMIN   TMININV*FMOD*TMIN

 400  DO 410 I 1 NS
      DO 410 J 1 NS
         FTEMP(I J) 0.0
      DO 410 K 1 NS
        FTEMP(I J) FTEMP(I J)+FMOD(I K)*TMIN(K J)
 410  CONTINUE
      DO 420 I 1 NS
      DO 420 J 1 NS
         FMIN(I J) 0.0
      DO 420 K 1 NS
        FMIN(I J) FMIN(I J)+TMININV(I K)*FTEMP(K J)
 420  CONTINUE

      QMIN   TMININV*QMOD

      DO 430 I 1 NS
      DO 430 J=1 NC
         QMIN(I J) 0.0
      DO 430 K=1 NS
        QMIN(I J)=QMIN(I J)+TMININV(I K)*QMOD(K J)
 430  CONTINUE

      HMIN = HMOD*TMIN

      DO 440 I=1 NM
      DO 440 J=1 NS
         HMIN(I J) 0.0
      DO 440 K 1 NS
        HMIN(I J) HMIN(I J)+HMOD(I K)*TMIN(K J)
 440  CONTINUE

      PRINT THE RESULTS

 1000 FORMAT('0' // 2X 'THE OUTPUT OF THE MINIMALIZING
     *SUBROUTINE IS ')
 1010 FORMAT('0' // 2X 'THE MINIMAL DISCRETE COMPENSATOR DYNAMICS
     *MATRIX PHI IS ')
 1020 FORMAT('0' // 2X 'THE MINIMAL DISCRETE COMPENSATOR INPUT
     *MATRIX GAMMAMIN IS ')
 1030 FORMAT('0' // 2X 'THE MINIMAL COMPENSATOR OUTPUT
     *MATRIX HMIN IS ')
 1050 FORMAT('0' // 2X 'THE TMIN MATRIX IS ')
 1060 FORMAT('0' // 2X 'THE TMININV MATRIX IS ')
 1070 FORMAT(10(2X F11 5) / 2X 10(2X F11 5))
      WRITE(6 1000)
      WRITE(6 1010)
      DO 600 I=1 NS
 600  WRITE(6 1070) (FMIN(I J) J=1 NS)
      WRITE(6 1020)
      DO 610 I=1 NS
 610  WRITE(6 1070) (QMIN(I J) J=1 NC)
      WRITE(6 1030)
      DO 620 I=1 NM
 620  WRITE(6 1070) (HMIN(I J) J=1 NS)
      WRITE(6 1050)
      DO 640 I=1 NS
 640  WRITE(6 1070) (TMIN(I J) J=1 NS)
      WRITE(6 1060)
      DO 650 I=1 NS
 650  WRITE(6 1070) (TMININV(I J) J=1 NS)
      RETURN
      END
```

```
      SUBROUTINE PRNTM(X MX N M)
      IMPLICIT REAL*8(A H O Z)
      INTEGER COL1 COL10
      DIMENSION X(MX 1)
      COL1 1
      COL10 0
 1000 COL10 COL10+10
      IF (COL10 GT M)COL10 M
      WRITE(6 1) (J J COL1 COL10)
      DO 450 I 1 N
 450  WRITE(6 3)I (X(I J) J COL1 COL10)
      COL1 COL1+10
      IF (COL1 GT M) RETURN
      GO TO 1000
 1    FORMAT(/ T9 10(9X I3) /)
 3    FORMAT(T6 I3 T13 10(1X G11 4))
      END
```

AppendixL

SETPNT Computer Program Example Data Set.

```
N M.P.R.SAMPLE TIME FOR SPHOV5 DAT
4 2,3,4,.5
F MATRIX( n X n )--U,W,Q,THETA
-.045,.036,0,-32.2
-.37,-2.02,176.0,0
.00191,-.0396,-2.98,0
0,0,1.0,0
G MATRIX( n X m )
0,1
-28.2,0
-11.0,0
0,0
HS MATRIX( p X n )--U,HDOT,THETA
1.0,0,0,0
0,-1.0,0,176.0
0,0,0,1.0
DSU MATRIX, PXM
0,0
0,0
0,0
 A MATRIX
0.0000E+00    1.000        0.0000E+00   0.0000E+00
-14.69        -6.072       0.0000E+00   0.0000E+00
0.0000E+00    0.0000E+00   -11.34       0.0000E+00
0.0000E+00    0.0000E+00   0.0000E+00   -1.816
 B MATRIX
-0.2781       -0.8863E-01   6.515
1.485         0.8725       -33.66
-0.1334E-01   -2.622         2.441
0.7711        -0.4641E-01   -10.10
 C MATRIX
0.000       -0.1000E-01  -0.1000E-01   0.3600E-02
-0.1978     -0.2163E-01   0.3446E-01   -1.000
D MATRIX, MXP
0,0,0
0,0,0
HD MATRIX, M X N+R,--U,HDOT,THETA
1,0,0,0,0,0,0,0,0
0,-1.0,0,176.0,0,0,0,0
LD MATRIX, M X M
0,0
0,0
```

SCALEM2 Computer Program. (contd)

```
1080 INPUT #1 TEMP$
1090 MAT INPUT #1 YSCALE
1100 INPUT #1 TEMP$
1110 MAT INPUT #1 CNTRLSCALE
1120 INPUT #1 TEMP$
1130 MAT INPUT #1 YDSCALE
1140 INPUT #1 TEMP$
1150 MAT INPUT #1 YMAX
1160 INPUT #1 TEMP$
1170 MAT INPUT #1 YIMAX
1180 REM
1190 REM  NOW FIND THE SCALING FOR THE COMPENSATOR STATES
1200 REM
1210 MAXELE=O
1220 MAXVEC=O
1230 FOR I=1 TO NR
1240        BVEC(I)=O'
1250 FOR J=1 TO NM
1260        BELEMENT=B(I,J)*BSCALE(J)*YMAX(J)
1270        BVEC(I)=BVEC(I)+BELEMENT
1280        IF ABS(BELEMENT)>MAXELE THEN MAXELE=ABS(BELEMENT)\IE=I\JE=J
1290 NEXT J
1300        IF ABS(BVEC(I))>MAXVEC THEN MAXVEC=ABS(BVEC(I))\IV=I
1310 NEXT I
1320 MAXELE2=LOG(ABS(MAXELE))/LOG(2)
1330 MAXVEC2=LOG(ABS(MAXVEC))/LOG(2)
1340 PRINT "POSSIBLE SCALING FOR Z(K) AND Z(K+1) BASED ON MAXIMUM ELEMENT OF B*Y
 IS"
1350 PRINT "            2^17/2 " MAXELE2
1360 PRINT "POSSIBLE SCALING FOR Z(K) AND Z(K+1) BASED ON MAXIMUM VECTOR OF B*Y
IS"
1370 PRINT "            2^17/2^" MAXVEC2
1380 INPUT "PLEASE TYPE IN THE DESIRED SCALING AS POWER OF 2",ZSCALE2
1390 ZSCALE=2^ZSCALE2
1400 REM
1410 REM  NOW DO THE CALCULATION OF THE MATRICES IN COMPUTER SCALED
1420 REM  VARIABLES
1430 REM
1440 MAXB=O
1450 MAXC=O
1460 MAXN=O
1470 MAXKI=O
1480 FOR I=1 TO NR
1490 FOR J=1 TO NM
1500        BCS(I,J)=B(I,J)*BSCALE(J)*ZSCALE/YSCALE(J)
1510        IF ABS(BCS(I,J))>MAXB THEN MAXB=ABS(BCS(I,J))
1520 NEXT J\NEXT I
1530 FOR I=1 TO NC
1540 FOR J=1 TO NR
1550        CCS(I,J)=C(I,J)*CSCALE(J)*CNTRLSCALE(I)/ZSCALE
1560        IF ABS(CCS(I,J))>MAXC THEN MAXC=ABS(CCS(I,J))
1570 NEXT J\NEXT I
1580 FOR I=1 TO NC
1590 FOR J=1 TO NC
1600        NCS(I,J)=N(I,J)*NSCALE(J)*CNTRLSCALE(I)/YDSCALE(J)
1610        IF ABS(NCS(I,J))>MAXN THEN MAXN=ABS(NCS(I,J))
1660 NEXT J\NEXT I
1670 MAXC2=LOG(MAXC)/LOG(2)
1680 MAXB2=LOG(MAXB)/LOG(2)
1690 MAXN2=LOG(MAXN)/LOG(2)
1700 PRINT
1710 PRINT "THE A MATRIX SCALE FACTOR WILL BE 2^15 OR 32768"
1720 PRINT "POSSIBLE SCALING FOR MATRIX B BASED ON MAX ELEMENT OF COMPUTER SCALE
D B IS"
1730 PRINT "            2^17/2 " MAXB2
1740 PRINT "POSSIBLE SCALING FOR MATRIX C BASED ON MAX ELEMENT OF COMPUTER SCALE
D C IS"
1750 PRINT "            2^17/2 " MAXC2
1760 PRINT "POSSIBLE SCALING FOR MATRIX N BASED ON MAX ELEMENT OF COMPUTER SCALE
D N IS"
1770 PRINT "            2^17/2 " MAXN2
1780 INPUT "PLEASE TYPE IN THE DESIRED SCALE FACTORS FOR MATRICES B C N " SCALEB
2,SCALEC2,SCALEN2
1790 REM
1800 REM NOW DO THE CALCULATION OF SCALE FACTORS FOR KX AND KXI
1810 REM NOTE   I ALSO DISCRETIZE THE KXI HERE BY MULTIPLYING BY TP(THE CYCLE TI
ME)
1820 REM          THE SCALED KXI MATRIX HAS A SAFETY FACTOR OF 5 TO AVOID OVERFLOW
S
1830 FOR I=1 TO NC
1840        SCALEKX(I)=INT(LOG(ABS(2^6/KX(I)))/LOG(2))
1850        SCALEKXI(I)=18
1855        SCALEKXD(I)=INT(LOG(ABS(2^12/KXD(I)))/LOG(2))
1860 NEXT I
1870 PRINT
1880 PRINT "THE KX SCALE FACTORS ARE"
1890 PRINT "  SCALEKX(1) " SCALEKX(1) "SCALEKX(2) " SCALEKX(2) "SCALEKX(3) " SCA
LEKX(3)
1900 PRINT "THE KXI SCALE FACTORS ARE"
1910 PRINT "  SCALEKXI(1) " SCALEKXI(1) "SCALEKXI(2) " SCALEKXI(2) "SCALEKXI(3)
" SCALEKXI(3)
1915 PRINT
1912 PRINT "THE KXD SCALE FACTORS ARE"
1914 PRINT "  SCALEKXD(1) " SCALEKXD(1),"SCALEKXD(2) " SCALEKXD(2) "SCALEKXD(3)
",SCALEKXD(3)
1920 REM
1930 REM  NOW DO THE FINAL SCALING OF THE MATRICES AND PRINT THEM
1940 REM
1950 FOR I=1 TO NR
1960          AFINAL(I)=A(I)*2^15
1970 NEXT I
1980 FOR I=1 TO NR
1990 FOR J=1 TO NM
2000          BFINAL(I,J)=BCS(I,J)*(2^SCALEB2)
2010 NEXT J\NEXT I
2020 FOR I=1 TO NC
2030 FOR J=1 TO NR
2040          CFINAL(I,J)=CCS(I,J)*(2^SCALEC2)
2050 NEXT J\NEXT I
2060 FOR I=1 TO NC
2070 FOR J=1 TO NC
2080          NFINAL(I,J)=NCS(I,J)*(2^SCALEN2)
2100 NEXT J\NEXT I
2110 FOR I=1 TO NC
2120          KXFINAL(I)=KX(I)*2^SCALEKX(I)
2130          KXIFINAL(I)=KXI(I)*2^SCALEKXI(I)
2135          KXDFINAL(I)=KXD(I)*2^SCALEKXD(I)
2140 NEXT I
2150 PRINT
2160 PRINT
2170 PRINT TAB(10),"THE PHYSICAL VARIABLE MATRICES ARE"
2180 PRINT TAB(10),"THE A MATRIX IS"
2190 FOR I=1 TO NR\ PRINT TAB(I*8),FNR(A(I)),\ NEXT I
2200 PRINT TAB(10),"THE B MATRIX IS"
2210 FOR I=1 TO NR\ FOR J=1 TO NM\ PRINT TAB(J*8),FNR(B(I,J)),\ NEXT J\ PRINT\ N
EXT I
2220 PRINT TAB(10),"THE C MATRIX IS"
2230 FOR I=1 TO NC\ FOR J=1 TO NR\ PRINT TAB(J*8),FNR(C(I,J)),\ NEXT J\ PRINT\ N
```

SCALEM2 Computer Program.

```
10 REM ********************** SCALEM2.BAS **********************
20 REM *
30 REM *   WRITTEN BY RICK HOLDRIDGE  10 FEB 84
40 REM *   UPDATED ON 5 JUNE 84 FOR THE HOVER AUTOPILOTS
45 REM *   MODIFIED TO RUN ON THE VAX ON 8 JUN 84
50 REM *
60 REM *  THIS PROGRAM IS USED TO SCALE THE A B C N KX KXI  AND KXD MATRICES
70 REM *  FOR USE IN THE CH 47 HELICOPTER CONTROL SYSTEM WHICH USES
80 REM *  THE SPERRY 1819A FIXED POINT DIGITAL COMPUTER
90 REM *
100 REM *         Z(K+1)    A * Z(K)  + B * YM(K)
110 REM *         U(K+1)    C*Z(K+1)  + N * [YD(K+1)  + KX * DELX(K+1)
120 REM *                             + KXI * INTDELX(K+1) + KXD * XDOT(K+1)]
130 REM *                  WHERE   Z   COMPENSATOR STATES
140 REM *                          YM  MEASUREMENT VECTOR
150 REM *                          YD  DESIRED OUTPUT VECTOR
160 REM *                        DELX  POSITION ERROR VECTOR
170 REM *                     INTDELX  POSITION ERROR INTEGRAL VECTOR
175 REM *                        XDOT  INERTIAL VELOCITY
180 REM *                           A  COMPENSATOR DYNAMICS MATRIX
190 REM *                           B  COMPENSATOR OUTPUT DISTRIBUTION MATRIX
200 REM *                           C  COMPENSATOR OUTPUT DISTRIBUTION MATRIX
210 REM *                           N  FEEDFORWARD GAIN MATRIX TO ACHIEVE A
220 REM *                              DESIRED OUTPUT(INERTIAL VELOCITY)
230 REM *                          KX  PROPORTIONAL GAIN MATRIX ON POSITION
240 REM *                              ERROR (A DIAGONAL MATRIX)
250 REM *                         KXI  GAIN MATRIX ON THE INTEGRAL OF POSITION
260 REM *                              ERROR (A DIAGONAL MATRIX)
265 REM *                         KXD  GAIN MATRIX ON THE DERIVATIVE OF POSITION
267 REM *                              (INERTIAL VELOCITY) A DIAGONAL MATRIX
270 REM *
280 REM *  THE FOLLOWING DATA IS ENTERED INTO A FILE WHICH
290 REM *  THE PROGRAM WILL ASK THE NAME OF AND THEN READ THE
300 REM *  DATA FROM
310 REM *
320 REM *  NR NM NC TP        NR ORDER OF THE COMPENSATOR
330 REM *                     NM NUMBER OF MEASUREMENTS
340 REM *                     NC NUMBER OF CONTROLS AND DESIRED OUTPUTS
350 REM *                     TP CYCLE TIME IN SECONDS
360 REM *  A MATRIX(NR)       THE A MATRIX IS ENTERED AS A ROW CONTAINING
370 REM *                     THE MINIMAL NR NUMBER OF MATRIX ELEMENTS
380 REM *  B MATRIX(NR X NM)  MEASUREMENTS DISTRIBUTION MATRIX ENTERED
390 REM *                     BY ROW
400 REM *  C MATRIX(NC X NR)  COMPENSATOR STATE TO CONTROL DISTRIBUTION
410 REM *                     MATRIX ENTERED BY ROW
420 REM *  N MATRIX(NC X NC)  COMMAND DISTRIBUTION MATRIX ENTERED BY ROW
430 REM *  KX MATRIX(NC)      POSITION ERROR TO CONTROL GAIN MATRIX
435 REM *                     ENTER DIAGONAL ELEMENTS
440 REM *  KXI MATRIX(NC)     POSITION ERROR INTEGRAL TO CONTROL GAIN MATRIX
450 REM *                     ENTER DIAGONAL ELEMENTS
455 REM *  KXD MATRIX(NC)     INERTIAL VELOCITY TO CONTROL GAIN MATRIX.
456 REM *                     ENTER DIAGONAL ELEMENTS
460 REM *  BSCALE(NR)         THE SCALING FACTORS ON SPECIFIC COLUMNS OF B
470 REM *                     THIS ALLOWS FOR CONVERSION FROM DEGREES TO
480 REM *                     RADIANS OR VICE VERSA
490 REM *  CSCALE(NR)         THE SCALING FACTORS ON SPECIFIC COLUMNS OF C
500 REM *                     NORMALLY. THESE TERMS ARE 1
510 REM *  NSCALE(NC)         THE SCALING FACTORS ON SPECIFIC COLUMNS OF N
520 REM *                     NORMALLY. THESE TERMS ARE 1
530 REM *  YSCALE(NM)         THE SCALING ON EACH MEASUREMENT   FOR INSTANCE
540 REM *                     IF Y(1) IS THETA AND THETA IS SCALED AS 500 BITS
550 REM *                     PER DEGREE  THEN YSCALE(1) 500
560 REM *  CNTRLSCALE(NC)     THE COMPUTER SCALING ON EACH CONTROL   FOR INSTANCE

570 REM *                     CONTROL(1) IS LONG CYCLIC AND IS SCALED AS 1024 BIT
S
580 REM *                     PER INCH  THEN CSCALE(1)=1024
590 REM *  YDSCALE(NC)        THE COMPUTER SCALING ON EACH DESIRED OUTPUT
600 REM *  YMAX(NM)           THE VECTOR OF MAX VALUES OF THE MEASUREMENTS
610 REM *  YDMAX(NC)          THE VECTOR OF MAX VALUES OF THE DESIRED OUTPUTS
620 REM *
630 REM ***************************************************************
640 REM
650 REM  READ THE DATA FROM A FILE
660 REM
670 DEF FNR(S)  (1000000*S+.5)/1000000
680 PRINT "WELCOME TO SCALEM"
690 INPUT "PLEASE TYPE IN THE NAME OF THE FILE CONTAINING THE INPUT DATA" FILENA
ME$
700 OPEN FILENAME$ FOR INPUT AS #1
710 INPUT #1  TEMP$
720 INPUT #1  NR NM NC  TP
730 DIM A(NR) AFINAL(NR) B(NR NM) BCS(NR NM) BFINAL(NR NM) BTEMP(NR NM)
740 DIM C(NC NR) CCS(NC NR) CFINAL(NC NR) CTEMP(NC NR) N(NC NC) NCS(NC NC)
750 DIM NFINAL(NC NC) NTEMP(NC NC) KX(NC) KXFINAL(NC)
755 DIM KXI(NC) KXIFINAL(NC) KXD(NC) KXDFINAL(NC)
760 DIM KITEMP(NC NC) BSCALE(NM) CSCALE(NR) NSCALE(NC) YSCALE(NM)
770 DIM CNTRLSCALE(NC) YDSCALE(NC) YMAX(NM) YDMAX(NC) BVEC(NR)
775 DIM SCALEKX(NC) SCALEKXI(NC) SCALEKXD(NC)
780 INPUT #1 TEMP$
790 MAT INPUT #1 A
800 PRINT TAB(10) "THE A MATRIX IS"
810 FOR I=1 TO NR\ PRINT TAB(I*8) FNR(A(I)) \ NEXT I
820 INPUT #1 TEMP$
830 MAT INPUT #1 B
840 PRINT TAB(10) "THE B MATRIX IS"
850 FOR I 1 TO NR\ FOR J 1 TO NM\ PRINT TAB(J*8) FNR(B(I J)) \ NEXT J\ PRINT\ NE
XT I
860 INPUT #1 TEMP$
870 MAT INPUT #1 C
880 PRINT TAB(10) "THE C MATRIX IS"
890 FOR I 1 TO NC\ FOR J 1 TO NR\ PRINT TAB(J*8) FNR(C(I J)) \ NEXT J\ PRINT\ NE
XT I
900 INPUT #1 TEMP$
910 MAT INPUT #1 N
920 PRINT TAB(10) "THE N MATRIX IS"
930 FOR I 1 TO NC\ FOR J 1 TO NC\ PRINT TAB(J*8) FNR(N(I J)) \ NEXT J\ PRINT\ NE
XT I
940 INPUT #1 TEMP$
950 MAT INPUT #1 KX
960 PRINT TAB(10) "THE KX MATRIX IS"
970 FOR I 1 TO NC\ PRINT TAB(I*8) FNR(KX(I)) \ NEXT I
980 INPUT #1 TEMP$
990 MAT INPUT #1 KXI
1000 PRINT TAB(10) "THE KXI MATRIX IS"
1010 FOR I=1 TO NC\ PRINT TAB(I*8) FNR(KXI(I)) \ NEXT I
1012 INPUT #1 TEMP$
1014 MAT INPUT #1 KXD
1016 PRINT TAB(10) "THE KXD MATRIX IS"
1018 FOR I 1 TO NC\ PRINT TAB(I*8) FNR(KXD(I)) \ NEXT I
1020 INPUT #1 TEMP$
1030 MAT INPUT #1 BSCALE
1040 INPUT #1 TEMP$
1050 MAT INPUT #1 CSCALE
1060 INPUT #1 TEMP$
1070 MAT INPUT #1 NSCALE
```

SCALEM1 Computer Program. (contd)

```
1170 INPUT "PLEASE TYPE IN THE DESIRED SCALING AS POWER OF 2" ZSCALE2
1180 ZSCALE=2^ZSCALE2
1190 REM
1200 REM  NOW DO THE CALCULATION OF THE MATRICES IN COMPUTER SCALED
1210 REM  VARIABLES
1220 REM
1230 MAXB=0
1240 MAXC=0
1250 MAXN=0
1260 MAXKI=0
1270 FOR I=1 TO NR
1280 FOR J=1 TO NM
1290         BCS(I,J)=B(I,J)*BSCALE(J)*ZSCALE/YSCALE(I)
1300         IF ABS(BCS(I,J))>MAXB THEN MAXB=ABS(BCS(I,J))
1310 NEXT J\NEXT I
1320 FOR I=1 TO NC
1330 FOR J=1 TO NR
1340         CCS(I,J)=C(I,J)*CSCALE(J)*CNTRLSCALE(I)/ZSCALE
1350         IF ABS(CCS(I,J))>MAXC THEN MAXC=ABS(CCS(I,J))
1360 NEXT J\NEXT I
1370 FOR I=1 TO NC
1380 FOR J=1 TO NC
1390         NCS(I,J)=N(I,J)*NSCALE(J)*CNTRLSCALE(I)/YDSCALE(J)
1400         IF ABS(NCS(I,J))>MAXN THEN MAXN=ABS(NCS(I,J))
1403 REM MULTIPLY THE KI MATRIX BY THE CYCLE TIME FOR DISCRETIZATION
1406         KI(I,J)=TP*KI(I,J)
1410         KICS(I,J)=KI(I,J)*KISCALE(J)*CNTRLSCALE(I)/YDSCALE(I)
1420         IF ABS(KICS(I,J))>MAXKI THEN MAXKI=ABS(KICS(I,J))
1430 NEXT J\NEXT I
1440 MAXC2=LOG(MAXC)/LOG(2)
1450 MAXB2=LOG(MAXB)/LOG(2)
1460 MAXN2=LOG(MAXN)/LOG(2)
1470 REM THE "5" IS INCLUDED SINCE THE INTEGAL CONTROL IS A SUMMATION
1480 REM AND WE NEED A SAFETY FACTOR(OF 32) TO AVOID OVERFLOWS
1490 MAXKI2=LOG(MAXKI)/LOG(2)+5
1500 PRINT
1505 PRINT "THE A MATRIX SCALE FACTOR WILL BE 2^15 OR 32768"
1510 PRINT "POSSIBLE SCALING FOR MATRIX B BASED ON MAX ELEMENT OF COMPUTER SCALE
D B IS"
1520 PRINT "            2^17/2^" MAXB2
1530 PRINT "POSSIBLE SCALING FOR MATRIX C BASED ON MAX ELEMENT OF COMPUTER SCALE
D C IS"
1540 PRINT "            2^17/2^" MAXC2
1550 PRINT "POSSIBLE SCALING FOR MATRIX N BASED ON MAX ELEMENT OF COMPUTER SCALE
D N IS"
1560 PRINT "            2^17/2^" MAXN2
1570 PRINT "POSSIBLE SCALING FOR MATRIX TP*KI BASED ON MAX ELEMENT OF COMPUTER"
1580 PRINT "SCALED TP*KI INCLUDING A SAFETY FACTOR OF 2^5  IS"
1600 PRINT "            2^17/2^" MAXKI2
1610 INPUT "PLEASE TYPE IN THE DESIRED SCALE FACTORS FOR MATRICES B C N TP*KI" S
CALEB2,SCALEC2,SCALEN2,SCALEKI2
1630 REM
1640 REM  NOW DO THE FINAL SCALING OF THE MATRICES AND PRINT THEM
1650 REM
1660 FOR I=1 TO NR
1670          AFINAL(I)=A(I)*2^15
1680 NEXT I
1690 FOR I=1 TO NR
1700 FOR J=1 TO NM
1710          BFINAL(I,J)=BCS(I,J)*(2^SCALEB2)
1720 NEXT J\NEXT I
1730 FOR I=1 TO NC
1740 FOR J=1 TO NR
1750          CFINAL(I,J)=CCS(I,J)*(2^SCALEC2)
1760 NEXT J\NEXT I
1770 FOR I=1 TO NC
1780 FOR J=1 TO NC
1790          NFINAL(I,J)=NCS(I,J)*(2^SCALEN2)
1800          KIFINAL(I,J)=KICS(I,J)*(2^SCALEKI2)
1810 NEXT J\NEXT I
1820 PRINT
1830 PRINT
1840 PRINT TAB(10) "THE PHYSICAL VARIABLE MATRICES ARE"
1850 PRINT TAB(10) "THE A MATRIX IS"
1860 FOR I=1 TO NR\ PRINT TAB(I*8),FNR(A(I)) \ NEXT I
1870 PRINT TAB(10) "THE B MATRIX IS"
1880 FOR I=1 TO NR\ FOR J=1 TO NM\ PRINT TAB(J*8),FNR(B(I,J)) \ NEXT J\ PRINT\ N
EXT I
1890 PRINT TAB(10) "THE C MATRIX IS"
1900 FOR I=1 TO NC\ FOR J=1 TO NR\ PRINT TAB(J*8),FNR(C(I,J)) \ NEXT J\ PRINT\ N
EXT I
1910 PRINT TAB(10) "THE N MATRIX IS"
1920 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8),FNR(N(I,J)) \ NEXT J\ PRINT\ N
EXT I
1930 PRINT TAB(10) "THE TP*KI MATRIX IS"
1940 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8),FNR(KI(I,J)) \ NEXT J\ PRINT\
NEXT I
1950 PRINT
1960 PRINT TAB(10) "THE COMPUTER SCALED VARIABLE MATICES ARE"
1970 PRINT TAB(10) "THE COMPUTER SCALED B MATRIX IS"
1980 FOR I=1 TO NR\ FOR J=1 TO NM\ PRINT TAB(J*8),FNR(BCS(I,J)) \ NEXT J\ PRINT\
 NEXT I
1990 PRINT TAB(10) "THE COMPUTER SCALED C MATRIX IS"
2000 FOR I=1 TO NC\ FOR J=1 TO NR\ PRINT TAB(J*8),FNR(CCS(I,J)) \ NEXT J\ PRINT\
 NEXT I
2010 PRINT TAB(10) "THE COMPUTER SCALED N MATRIX IS"
2020 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8),FNR(NCS(I,J)) \ NEXT J\ PRINT\
 NEXT I
2030 PRINT TAB(10) "THE COMPUTER SCALED TP*KI MATRIX IS"
2040 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8),FNR(KICS(I,J)) \ NEXT J\ PRINT
\ NEXT I
2050 PRINT
2060 PRINT TAB(10) "THE COMPLETELY SCALED MATRICES ARE"
2070 PRINT TAB(10) "THE AFINAL MATRIX IS"
2080 FOR I=1 TO NR\ PRINT TAB(I*8),FNR(AFINAL(I)) \ NEXT I
2090 PRINT TAB(10) "THE BFINAL MATRIX IS"
2100 FOR I=1 TO NR\ FOR J=1 TO NM\ PRINT TAB(J*8),FNR(BFINAL(I,J)) \ NEXT J\ PRI
NT\ NEXT I
2110 PRINT TAB(10) "THE CFINAL MATRIX IS"
2120 FOR I=1 TO NC\ FOR J=1 TO NR\ PRINT TAB(J*8),FNR(CFINAL(I,J)) \ NEXT J\ PRI
NT\ NEXT I
2130 PRINT TAB(10) "THE NFINAL MATRIX IS"
2140 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8),FNR(NFINAL(I,J)) \ NEXT J\ PRI
NT\ NEXT I
2150 PRINT TAB(10) "THE (TP*KI)FINAL MATRIX IS"
2160 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8),FNR(KIFINAL(I,J)) \ NEXT J\ PR
INT\ NEXT I
2170 PRINT
2180 PRINT "THE A MATRIX REQUIRES A LRTA'3 THEN STRAU IN 1819 ASSEMBLY"
2190 PRINT "THE B MATRIX REQUIRES A LRTA'",18-SCALEB2,"THEN STRAU"
2200 PRINT "THE C MATRIX REQUIRES A LRTA'",18-SCALEC2,"THEN STRAU"
2210 PRINT "THE N MATRIX REQUIRES A LRTA'",18-SCALEN2,"THEN STRAU"
2220 PRINT "THE KI MATRIX REQUIRES A LRTA'",18-SCALEKI2,"THEN STRAU"
2230 END
```

SCALEM1 Computer Program.

```
10 REM ************************ SCALEM1 ***************************
15 REM *
20 REM *   WRITTEN BY RICK HOLDRIDGE. 10 FEB 84
30 REM *   MODIFIED TO RUN ON THE VAX. 8 JUN 84
40 REM *
50 REM *  THIS PROGRAM IS USED TO SCALE THE A,B,C,N MATRICES FOR
60 REM *  USE IN THE CH 47 HELICOPTER CONTROL SYSTEM WHICH USES
70 REM *  THE SPERRY 1819A FIXED POINT DIGITAL COMPUTER
80 REM *
90 REM *  THE FOLLOWING DATA IS ENTERED INTO A FILE WHICH
100 REM *  THE PROGRAM WILL ASK THE NAME OF AND THEN READ THE
110 REM *  DATA FROM
120 REM *
130 REM *  NR NM NC TP        NR ORDER OF THE COMPENSATOR
140 REM *                     NM NUMBER OF MEASUREMENTS
150 REM *                     NC NUMBER OF CONTROLS AND DESIRED OUTPUTS
160 REM *                     TP CYCLE TIME IN SECONDS
170 REM *  A MATRIX(NR)       THE A MATRIX IS ENTERED AS A ROW CONTAINING
180 REM *                     THE MINIMAL NR NUMBER OF MATRIX ELEMENTS
190 REM *  B MATRIX(NR X NM)  MEASUREMENTS DISTRIBUTION MATRIX ENTERED
200 REM *                     BY ROW
210 REM *  C MATRIX(NC X NR)  COMPENSATOR STATE TO CONTROL DISTRIBUTION
220 REM *                     MATRIX ENTERED BY ROW
230 REM *  N MATRIX(NC X NC)  COMMAND DISTRIBUTION MATRIX ENTERED BY ROW
240 REM *  KI MATRIX(NC X NC) INTEGRAL GAIN MATRIX
250 REM *  BSCALE(NR)         THE SCALING FACTORS ON SPECIFIC COLUMNS OF B
260 REM *                     THIS ALLOWS FOR CONVERSION FROM DEGREES TO
270 REM *                     RADIANS OR VICE VERSA
280 REM *  CSCALE(NR)         THE SCALING FACTORS ON SPECIFIC COLUMNS OF C
290 REM *                     NORMALLY, THESE TERMS ARE 1
300 REM *  NSCALE(NC)         THE SCALING FACTORS ON SPECIFIC COLUMNS OF N
310 REM *                     NORMALLY, THESE TERMS ARE 1
320 REM *  KISCALE(NC)        THE SCALING FACTORS ON SPECIFIC COLUMNS OF KI
330 REM *                     NORMALLY, THESE TERMS ARE 1
340 REM *  YSCALE(NM)         THE SCALING ON EACH MEASUREMENT.  FOR INSTANCE,
350 REM *                     IF Y(1) IS THETA AND THETA IS SCALED AS 500 BITS
360 REM *                     PER DEGREE, THEN YSCALE(1)=500
370 REM *  CNTRLSCALE(NC)     THE COMPUTER SCALING ON EACH CONTROL.  FOR INSTANCE

380 REM *                     CONTROL(1) IS LONG CYCLIC AND IS SCALED AS 1024 BIT
S
390 REM *                     PER INCH, THEN CSCALE(1)=1024
400 REM *  YDSCALE(NC)        THE COMPUTER SCALING ON EACH DESIRED OUTPUT
410 REM *  YMAX(NM)           THE VECTOR OF MAX VALUES OF THE MEASUREMENTS
420 REM *  YDMAX(NC)          THE VECTOR OF MAX VALUES OF THE DESIRED OUTPUTS
430 REM *
440 REM ******************************************************************
450 REM
460 REM  READ THE DATA FROM A FILE
470 REM
480 DEF FNR(S)=(1000000*S+.5)/1000000
490 PRINT "WELCOME TO SCALEM1"
500 INPUT "PLEASE TYPE IN THE NAME OF THE FILE CONTAINING THE INPUT DATA",FILENA
ME$
510 OPEN FILENAME$ FOR INPUT AS #1
520 INPUT #1, TEMP$
530 INPUT #1, NR,NM,NC,TP
540 DIM A(NR),AFINAL(NR),B(NR,NM),BCS(NR,NM),BFINAL(NR,NM),BTEMP(NR,NM)
550 DIM C(NC,NR),CCS(NC,NR),CFINAL(NC,NR),CTEMP(NC,NR),N(NC,NC),NCS(NC,NC)
560 DIM NFINAL(NC,NC),NTEMP(NC,NC),KI(NC,NC),KICS(NC,NC),KIFINAL(NC,NC)
570 DIM KITEMP(NC,NC),BSCALE(NM),CSCALE(NR),NSCALE(NC),KISCALE(NC),YSCALE(NM)
580 DIM CNTRLSCALE(NC),YDSCALE(NC),YMAX(NM),YDMAX(NC),BVEC(NR)
590 INPUT #1, TEMP$
600 MAT INPUT #1, A
610 PRINT TAB(10),"THE A MATRIX IS"
620 FOR I=1 TO NR\ PRINT TAB(I*8),FNR(A(I)) \ NEXT I
630 INPUT #1, TEMP$
640 MAT INPUT #1, B
650 PRINT TAB(10),"THE B MATRIX IS"
660 FOR I=1 TO NR\ FOR J=1 TO NM\ PRINT TAB(J*8),FNR(B(I,J)) \ NEXT J\ PRINT\ NE
XT I
670 INPUT #1, TEMP$
680 MAT INPUT #1, C
690 PRINT TAB(10),"THE C MATRIX IS"
700 FOR I=1 TO NC\ FOR J=1 TO NR\ PRINT TAB(J*8),FNR(C(I,J)) \ NEXT J\ PRINT\ NE
XT I
710 INPUT #1, TEMP$
720 MAT INPUT #1, N
730 PRINT TAB(10),"THE N MATRIX IS"
740 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8),FNR(N(I,J)) \ NEXT J\ PRINT\ NE
XT I
750 INPUT #1, TEMP$
760 MAT INPUT #1, KI
770 PRINT TAB(10),"THE KI MATRIX IS"
780 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8),FNR(KI(I,J)) \ NEXT J\ PRINT\ N
EXT I
790 INPUT #1, TEMP$
800 MAT INPUT #1, BSCALE
810 INPUT #1, TEMP$
820 MAT INPUT #1, CSCALE
830 INPUT #1, TEMP$
840 MAT INPUT #1, NSCALE
850 INPUT #1, TEMP$
860 MAT INPUT #1, KISCALE
870 INPUT #1, TEMP$
880 MAT INPUT #1, YSCALE
890 INPUT #1, TEMP$
900 MAT INPUT #1, CNTRLSCALE
910 INPUT #1, TEMP$
920 MAT INPUT #1, YDSCALE
930 INPUT #1, TEMP$
940 MAT INPUT #1, YMAX
950 INPUT #1, TEMP$
960 MAT INPUT #1, YDMAX
970 REM
980 REM  NOW FIND THE SCALING FOR THE COMPENSATOR STATES
990 REM
1000 MAXELE=0
1010 MAXVEC=0
1020 FOR I=1 TO NR
1030        BVEC(I)=0'
1040 FOR J=1 TO NM
1050        BELEMENT=B(I,J)*BSCALE(J)*YMAX(J)
1060        BVEC(I)=BVEC(I)+BELEMENT
1070        IF ABS(BELEMENT)>MAXELE THEN MAXELE=ABS(BELEMENT)\IE=I\JE=J
1080 NEXT J
1090        IF ABS(BVEC(I))>MAXVEC THEN MAXVEC=ABS(BVEC(I))\IV=I
1100 NEXT I
1110 MAXELE2=LOG(ABS(MAXELE))/LOG(2)
1120 MAXVEC2=LOG(ABS(MAXVEC))/LOG(2)
1130 PRINT "POSSIBLE SCALING FOR Z(K) AND Z(K+1) BASED ON MAXIMUM ELEMENT OF B*Y
 IS"
1140 PRINT "           2^17/2^",MAXELE2
1150 PRINT "POSSIBLE SCALING FOR Z(K) AND Z(K+1) BASED ON MAXIMUM VECTOR OF B*Y
IS"
1160 PRINT "           2^17/2^",MAXVEC2
```

Appendix N.

SCALEM1 and SCALEM2 Computer Programs

This appendix lists the computer programs for doing the fixed point scaling described in Appendix E. Also included are two example sets of data. These programs are written in VAX BASIC. The SCALEM1 computer program does the scaling for the longitudinal CAS controller. The SCALEM2 computer program does the scaling for the hover controller. The description of required data is at the beginning of each program. The SCALEM1 data is for the 6^{th} order compensator with integral control. The SCALEM2 data is for the final hover controller.

SIMPLOT Example Data File.

```
4,8,0,.1,15.0,0,0
18,22,20,21,16,17,18,22
'NAVION WITH FULL ORDER COMP HDOT COM = 10 FT/SEC  '
'FORWARD VEL(FT/SEC)   '
'CLIMB RATE(FT/SEC)    '
'  PITCH RATE(DEG/SEC) '
'  THETA  (DEG)        '
'  ELEVATOR(DEGREES)   '
'  THROTTLE(FT/SEC**2) '
'FORWARD VEL(FT/SEC)   '
'CLIMB RATE(FT/SEC)    '
0,0,0,0,0.0,10.0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
```

SIMPLOT Computer Program. (contd)

```
      DO 3100 I=1.NPNTS
            YARAY(I)=DAT(NCNT+1.I)
            IF (YARAY(I) GT YMAX) YMAX=YARAY(I)
            IF (YARAY(I) LT YMIN) YMIN=YARAY(I)
3100  CONTINUE
      CALL PHYSOR(X3ORG(NCRVE).Y3ORG(NCRVE))
      CALL AREA2D(6 0.2 7)
      CALL XNAME('TIME(sec)'.9)
      CALL YNAME(XREF(PLTIT(NCNT)).20)
      CALL CROSS
      CALL GRAF(0 .'SCALE'.TIME(NPNTS) YMIN.'SCALE' YMAX)
      CALL CURVE(TIME.YARAY.NPNTS.0)
      CALL ENDGR(NPCNT)
3400  CONTINUE
      CALL ENDPL(NPCNT)
3500  CONTINUE
      GO TO 5000

C THIS IS THE PART THAT DOES 4 PLOTS/PAGE

4000 DO 4500 NPCNT=1.NPAGE
      CALL PAGE(11 0.8 5)
      CALL PHYSOR(1 .1 )
      IF (NPLTR EQ 0) CALL HWROT('MOVIE')
      CALL NOBRDR
      CALL AREA2D(9 0.6 0)
      CALL HEADIN(XREF(GRTIT).50.2.1)
      CALL ENDGR(NPCNT)

C NOW START THE LOOP FOR PLOTTING THE 4 CURVES

      DO 4400 NCRVE=1.4

C NCNT IS THE COLUMN OF THE VECTOR IN DAT BEING PLOTTED

      NCNT=(4*NPCNT-4)+NCRVE
      YMAX=DAT(NCNT+1.1)
      YMIN=YMAX
      DO 4100 I=1.NPNTS
            YARAY(I)=DAT(NCNT+1.I)
            IF (YARAY(I) GT YMAX) YMAX=YARAY(I)
            IF (YARAY(I) LT YMIN) YMIN=YARAY(I)
4100  CONTINUE
      CALL PHYSOR(X4ORG(NCRVE).Y4ORG(NCRVE))
      CALL AREA2D(4 1.2 7)
      CALL XNAME('TIME(sec)'.9)
      CALL YNAME(XREF(PLTIT(NCNT)).20)
      CALL CROSS
      CALL GRAF(0..'SCALE'.TIME(NPNTS).YMIN.'SCALE' YMAX)
      CALL CURVE(TIME.YARAY.NPNTS.0)
      CALL ENDGR(NPCNT)
4400  CONTINUE
      CALL ENDPL(NPCNT)
4500  CONTINUE
      GO TO 5000
5000  CALL DONEPL
      RETURN
      END
```

SIMPLOT Computer Program. (contd)

```
C       NPLTR     =0  FOR OUTPUT TO VECTRI PLV WHICH CAN BE SENT TO
C                     THE VERSATEC FOR HARD COPIES
C                 =1  FOR THE PLOTS TO BE DISPLAYED ON A VT125
C
C       NPNTS THE TOTAL NUMBER OF DATA POINTS
C
C       CRTIT A CHARACTER*50 VARIABLE CONTAINING THE TITLE TO BE
C             ON ALL PAGES OF OUTPUT
C
C       PLTIT A CHARACTER*20 ARRAY OF 12 TITLES OF THE Y AXES OF
C             THE PLOTS
C
C
C
C**********************************************************************
        SUBROUTINE PLOTEM(DAT,NTYPE,NPLT,NPLTR,NPNTS,CRTIT,PLTIT)
        IMPLICIT REAL(A-H,O-Z)
        CHARACTER*50 CRTIT
        CHARACTER*20 PLTIT(12)
        DIMENSION DAT(13,5000),TIME(5000),YARAY(5000),X3ORG(3),Y3ORG(3)
        DIMENSION X4ORG(4),Y4ORG(4),NPARM(12)
        DATA X3ORG/1.25,1.25,1.25/
        DATA Y3ORG/7.1,4.0,.9/
        DATA X4ORG/1.25,6.25,1.25,6.25/
        DATA Y4ORG/4.25,4.25,1.0,1.0/
C
C STORE THE TIME POINT IN THE TIME ARRAY
C
        DO 10 I=1,NPNTS
                TIME(I)=DAT(1,I)
 10     CONTINUE
        NPAGE=NPLT/NTYPE
C
C SET UP VERSATEC PLOTTER OR USE VT125
C
        IF (NPLTR.EQ.0) GO TO 20
        CALL REGIS(1,0)
        GO TO 30
 20     CALL VRSTEC(0,0,0)
 30     CONTINUE
C
C NOW DETERMINE THE TYPE OF PAGE FORMAT
C
        IF (NTYPE.EQ.1) GO TO 1000
        IF (NTYPE.EQ.3) GO TO 3000
        IF (NTYPE.EQ.4) GO TO 4000
C       WRITE(6,100)
C 100   FORMAT(1X,'NTYPE WAS NOT 1,3, OR 4')
        GO TO 5000
C
C DO THE CASE OF ONLY ONE PLOT PER PAGE
C
 1000   DO 1500 NCNT=1,NPAGE
C
C LOAD THE YARAY WITH THE DATA TO BE PLOTTED AND
C ALSO FIND THE MAX VALUE OF Y
C
        YMAX=DAT(NCNT+1,1)
        YMIN=DAT(NCNT+1,1)
        DO 1100 I=1,NPNTS
                YARAY(I)=DAT(NCNT+1,I)
                IF (YARAY(I).GT.YMAX) YMAX=YARAY(I)
                IF (YARAY(I).LT.YMIN) YMIN=YARAY(I)
 1100   CONTINUE
        WRITE(6,*)YMAX
C
C USE HORIZONTAL PAGE FORMAT FOR VERSATEC
C OR VERTICLE FOR THE VT125
C
        CALL PAGE(11.,8.5)
        CALL PHYSOR(1.,1.)
        IF (NPLTR.EQ.0) CALL HWROT('MOVIE')
C
C SUPPRESS PAGE BORDER OUTLINE
C
        CALL NOBRDR
C
C SET UP PLOTTING AREA
C
        CALL AREA2D(9.0,6.0)
C
C PUT THE TITLE ON THE GRAPH
C
        CALL HEADIN(%REF(CRTIT),50,2,1)
C
C THE X AXIS WITH TIME IN SECONDS
C
        CALL XNAME('TIME(sec)',9)
C
C LABEL THE ORDINATE WITH THE VARIABLE NAME
C
        CALL YNAME(%REF(PLTIT(NPAGE)),20)
C
C SET UP THE GRAPH TYPE USING SELF SCALING
C AND PUT THE AXIS AT Y=0
C
        CALL CROSS
        CALL GRAF(0.,'SCALE',TIME(NPNTS),YMIN,'SCALE',YMAX)
C
C PLOT THE DATA
C
        CALL CURVE(TIME,YARAY,NPNTS,0)
C
C END ONE PAGE OF ONE PLOT
C
        CALL ENDPL(NCNT)
 1500   CONTINUE
        GO TO 5000
C
C THIS IS THE PART THAT DOES 3 PLOTS/PAGE
C
 3000 DO 3500 NPCNT=1,NPAGE
        CALL PAGE(8.5,11.)
        CALL PHYSOR(1.,1.)
        CALL NOBRDR
        CALL AREA2D(6.0,8.5)
        CALL HEADIN(%REF(CRTIT),50,2,1)
        CALL ENDGR(NPCNT)
C
C NOW START THE LOOP FOR PLOTTING THE 3 CURVES
C
        DO 3400 NCRVE=1,3
C
C NCNT IS THE COLUMN OF THE VECTOR IN DAT BEING PLOTTED
C
        NCNT=(3*NPCNT-3)+NCRVE
        YMAX=DAT(NCNT+1,1)
        YMIN=YMAX
```

SIMPLOT Computer Program. (contd)

```
15      continue
10      do 16 i 1 nc
        do 16 k 1 ns
        x y(k)
        y(ns+1) y(ns+1)+CFB(i k)*x
16      continue
        do 17 i=1 nc
        u(i)=y(ns+i)
17      continue
        do 18 i 1 no
        do 18 k 1 ns
        y(ns+nc+i) y(ns+nc+i)+hmat(i k)*y(k)
18      continue
        do 19 i=1 no
        do 19 k=1 nc
        y(ns+nc+i) y(ns+nc+i)+dmat(i k)*u(k)
19      continue
        if(nd eq 0)go to 25
        do 25 i=1 no
        do 25 k=1 nd
        y(ns+nc+i)=y(ns+nc+i)+dvmat(i k)*(w0(k)+dist(k))
25      continue
        do 300 i=1 no
        opt(i)=y(ns+nc+i)
        av(i k4) y(ns+nc+i)
300     continue
        do 301 i=1 nc
        opt(no+i)=u(i)
301     continue
        if(DABS(t (dt1*k4+t0)) GE  000001) GO TO 1201
C
C WRITE DATA TO THE DAT ARRAY
C
        DAT(1 K4)=T
        DO 1200 II=1 NPLT
                DAT(II+1 K4)=Y(NPARM(II))
1200    CONTINUE
1201    CONTINUE
        if(DABS(t (dt1*k4+t0)) lt  000001)k4 k4+1
139     t=t+dt
        if(idf  eq  0  and  t  gt  tmax)go to 20
        if(idf  eq  0)go to 10
        if(idf  ne  0  and  t  lt  tr)go to 10
        idf=0
        t=t0
        go to 139
20      continue
        IF(ID  NE  1)GO TO 705
        DATA (MDIST(I) I=1 10)/10*0 0/
        DATA ((CDIST(I J) J 1 10) I 1 10)/100*0 0/
        DO 702 I=1 ND
        DO 701 J=1 K4
        MDIST(I)=MDIST(I)+ADIST(I J)+WO(I)
701     CONTINUE
        MDIST(I)=MDIST(I)/K4
702     CONTINUE
        DO 704 I=1 ND
        DO 704 J=1 ND
        DO 703 K=1 K4
      CDIST(I J)=CDIST(I J)+(ADIST(I K) MDIST(I))*(ADIST(J K) MDIST(J))
703     CONTINUE
        CDIST(I J)=CDIST(I J)/K4
704     CONTINUE
        WRITE( 5 800)
800     FORMAT(/ 2X '     RANDOM DISTURBANCE MEAN VALUES ')
        WRITE( 5 802) (MDIST(I) I 1 ND)
        WRITE( 5 801)
801     FORMAT(/ 2X '     RANDOM DISTURBANCE COVARIANCE MATRIX ')
        DO 8000 I=1 ND
8000    WRITE( 5 802) (CDIST(I J) J=1 ND)
802     FORMAT(9(2X 1PD10 3))
        write( 5 775)
775     format(/ 2x 'SCALE FACTORS FOR RANDOM DISTURBANCES ')
        write( 5 802) (sf(i) i 1 nd)
        data (mav(i) i 1 10)/10*0 0/
        data ((cav(i j) j 1 10) i 1 10)/100*0 0/
        do 902 i 1 no
        do 901 j 1 k4
        mav(i) mav(i)+av(i j)
901     continue
        mav(i) mav(i)/k4
902     continue
        do 904 i 1 no
        do 904 j 1 no
        do 903 k 1 k4
        cav(i j) cav(i j)+(av(i k) mav(i))*(av(j k) mav(j))
903     continue
        cav(i j) cav(i j)/k4
        if(i  eq  j)rav(i) sqrt(cav(i i))
904     continue
        write(5 1000)
1000    format(/ 2x 'OUTPUT MEAN VALUES ')
        write(5 802) (mav(i) i=1 no)
        write(5 1001)
1001    format(/ 2x 'OUTPUT COVARIANCE MATRIX ')
        do 1002 i=1 no
1002    write(5 802) (cav(i j) j=1 no)
        write(5 905)
905     format(/ 2x 'RMS OUTPUT VALUES ')
        write(5 802) (rav(i) i=1 no)
C
C NOW CALL THE PLOTTING SUBROUTINE
C
705     NPNTS K4 1
        CALL PLOTEM(DAT NTYPE NPLT NPLTR NPNTS CRTIT PLTIT)
        STOP
        end


C*************************************************************
C
C SUBROUTINE PLOTEM(DAT NTYPE NPLT NPLTR NPNTS CRTIT PLTIT)
C
C THIS SUBROUTINE LOTS UP TO 12 VARIABLES VERSUS TIME
C WITH EITHER 1 3 OR 4 PLOTS PER PAGE
C
C       DAT AN ARRAY OF DIMENSION(13 5000) CONTAINING THE DATA TO
C           BE PLOTTED  THE FIRST COLUMN CONTAINS THE TIME(X AXIS)
C           FOR ALL 12 OF THE DATA SETS(LOCATED IN COLUMNS 2 13 OF
C           DAT
C
C       NTYPE      =1  FOR 1 PLOT PER PAGE
C                  =3  FOR 3 PLOTS PER PAGE
C                  =4  FOR 4 PLOTS PER PAGE
C
C       NPLT THE TOTAL NUMBER OF PLOTS  NPLT/NTYPE IS THE NUMBER
C            OF PAGES OF DATA AND MUST BE AN INTERCER
C
```

SIMPLOT Computer Program.

```
*************************************************************
******* PROGRAM DISCSM *************************************
******* A DISCRETE TIME SIMULATION OF A LINEAR SYSTEM ***************
******* WRITTEN BY BRUCE E  GARDNER  ****************************
******* LAST REVISED 11 FEB 83 BY RICK HOLDRIDGE    ****************
*************************************************************
        implicit real*8 (a h o z)

NOTE  DAT IS ONLY SINGLE PRECISION

        REAL DAT(13.5000)
        INTEGER*4 L1(10)
        CHARACTER*50 GRTIT
        CHARACTER*20 PLTIT(12)
        dimension y(75).yp(75).tswi(20).delfi(20).opt(75)
        dimension dist(20).sf(20).w0(20)
        dimension fmat(40.40).gmat(40.6) hmat(20.40).dmat(20 6)
        dimension cfb(6 40)
        dimension wmat(40.20).dwmat(20.20).cdist(20.20).adist(20,6000)
        dimension u(6).NPARM(12)
        real mdist(20) av(20.6000).rav(20).mav(20).cav(20.20)

READ THE PLOT DATA

        READ(30 *)NTYPE NPLT.NPLTR.DT1.TMAX.IDF.TR
        READ(30.*) (NPARM(I)).I=1.NPLT)
        READ(30 *)GRTIT (PLTIT(I).I=1 NPLT)
        read(01.*)ns.nc.nd.no dt
        read(01 *) ((fmat(i j)).j=1.ns).i=1.ns)
        if(no  eq  0)go to 1
        read(01.*) ((hmat(i j)).j=1 ns).i=1 no)
        read(01.*) ((dmat(i j)).j=1 nc).i=1.no)
        read(01.*) ((cfb(i.j)).j=1.ns).i=1.nc)
        if(nd  eq  0) go to 404
        read(01.*) ((wmat(i.j)).j=1.nd).i=1.ns)
        read(01 *) ((dwmat(i.j)).j=1.nd).i=1.no)
        read(01.*) (w0(i).i=1.nd)
        data (dist(i).i=1.20)/20*0 0/
590     write(5.600)
600     format(/.2x.'IF      DIST  IS RANDOM. TYPE 1. IF NOT. TYPE 0 ')
        read(5.*.end=590)id
        IF(ID  EQ  0)GO TO 404
601     WRITE(5.602)
602     FORMAT(/.2X 'INPUT SCALE FACTORS FOR      DISTURBANCES ')
        READ(5.*.END=601) (SF(I) I=1 ND)
603     WRITE(5 604)
604     FORMAT(/.2X.'IF DESIRE NEW SEEDS. TYPE ANY ODD INTEGER. IF NOT.
     *TYPE 0 ')
        READ(5.*.END=603)ISEED
C
C     INITIALIZE SEEDS
        DO 4 I=1.10
        L1(I)=10000+2*I-1
        IF(ISEED EQ 0)GO TO 4
        L1(I)=L1(I)+ISEED
4       CONTINUE
C
C READ IN THE INITIAL CONDITIONS FOR THE SIMULATIONS
C
404     read(30.*)(y(i).i=1.ns)
21       do 86 i=1.nc+no
        y(ns+i)=0 0
86      continue
        \4 l
        t tO
        if(idf  ne  0)go to 78
101     format(1x f11 4 14(f12 4))
139     CONTINUE
78      do 6 i 1 nc
        do 6 k 1 ns
        x y(k)
        y(ns+i)=y(ns+i)+CFB(i.k)*x
6       continue
        do 79 i=1 nc
        u(i)=y(ns+i)
79      continue
        if(idf  ne  0)go to 10
        do 7 i 1.no
        do 7 k=1.ns
        y(ns+nc+i) y(ns+nc+i)+hmat(i.k)*y(k)
7       continue
        do 8 i=1.no
        do 8 k=1.nc
        y(ns+nc+i)=y(ns+nc+i)+dmat(i.k)*u(k)
8       continue
        if(nd eq 0)go to 9
        do 9 i=1 no
        do 9 k=1.nd
        y(ns+nc+i)=y(ns+nc+i)+dwmat(i.k)*w0(k)
9       continue
        do 200 i=1.no
        opt(i)=y(ns+nc+i)
200     continue
        do 201 i=1.nc
        opt(no+i)=u(i)
201     continue
C
C WRITE DATA TO THE DAT ARRAY
C
        DAT(1.K4)=T
        DO 1100 II=1.NPLT
                DAT(II+1,K4)=Y(NPARM(II))
1100    CONTINUE
         t=t+dt
        K4=1
10      do 27 i=1.ns
        yp(i)=0 0
27      continue
        if(nd  le  0)go to 413
        if(id  eq  0)go to 22
        do 67 k=1.nd
        dist(k)=(RAN(L1(K))  5)/( 289102*SQRT(DT)*SF(K))
        if(idf  eq  0)adist(k.k4)=dist(k)
67      continue
22      do 30 i=1.ns
        do 30 k=1.nd
30      yp(i)=yp(i)+wmat(i.k)*(dist(k)+w0(k))
413     continue
        do 40 i=1.ns
        do 40 k=1.ns
40      yp(i)=yp(i)+fmat(i.k)*y(k)
70      do 71 i=1.ns
71      y(i)=yp(i)
        if(idf  ne  0)go to 133
        do 87 i=1.nc+no
        y(ns+i)=0 0
```

m- Number of controls.

p'' - Number of performance variables.

Item 3

GRTIT,PLTIT(NPLT)

where:

GRTIT- A 50 character variable containing the title which will be put on all *NPLT/NTYPE* pages of plots.

PLTIT- An array of *NPLT* 20 character variables containing the y-axis labels for the plots. The x-axis is always time.

Note: These character variables must be exactly 50 and 20 characters long.

Item 4

XC0(n + r + ns)

XC0 is an array containing $n + r + ns$ initial conditions on the simulation states in the following order:

State	Parameter
x_1	
$\downarrow$	plant states
x_n	
z_1	
$\downarrow$	compensator states
z_r	
w_1	
$\downarrow$	noise filter states
w_{ns}	

Description of "Plotdata" File inputs

Item 1

NTYPE,NPLT,NPLTR,DT1,TMAX,IDF,TR

where:

NTYPE- "1" for 1 plot per page, horizontal. "3" for 3 plots per page, vertical. "4" for 4 plots per page, horizontal.

NPLT- The total number of plots to be made $NPLT/NTYPE$ must be an integer less than 13.

NPLTR- "1" for immediate results on a VT125 screen. "0" to create plot files, VECTR1.PLV and PARM.PLV.

DT1- The data point interval, $DT1/DT$(from RSANDY) must be an integer.

TMAX- Final time of the simulation, $TMAX/DT1$ must be less than 5000.

IDF- "1" to run the simulation TR seconds prior to recording data for plotting. This is used to allow filtered noise to reach a steady covariance. "0" to start taking plot data at time= 0.

TR- The number of seconds to wait prior to recording and plotting data.

Item 2

Plot parameter ID's, the array *NPARM*

NPARM is an array containing *NPLT* identification numbers of the variables to be plotted. The parameters are identified in the following sequence:

ID number	Parameter
1	x_1
↓	↓ plant states
n	x_n
$n+1$	z_1
↓	↓ compensator states
$n+r$	z_r
$n+r+1$	w_1
↓	↓ noise filter states
$n+r+ns$	w_{ns}
$n+r+ns+1$	u_1
↓	↓ controls
$n+r+ns+m$	u_m
$n+r+ns+m+1$	y_1
↓	↓ performance variables(from RSANDY)
$n+r+ns+m+p''$	$y_{p''}$

where:

n- Order of the plant.

r- Order of the compensator.

ns- Number of states in all the noise filters.

Running SIMPLOT

@SIMPLOT Plotdata Simfile

where:

SIMPLOT– A VMS command file which runs the SIMPLOT.EXE file with *Plotdata* and *Simfile* as data files.

Plotdata– A users created file containing data used by SIMPLOT. The input item descriptions are shown on following pages.

Simfile– The simulation model file previously created by an RSANDY run.

The SIMPLOT program will ask 3 questions:

1. "Are the disturbances random?"

Type "1" for yes or "0" for no. If no noise was modeled in the RSANDY run which created the *Simfile*, you must type "0". If you had noise in the RSANDY run but want a clean time response, you can type "0" and no noise will show up in the time responses. If you answered "0" to this question, the simulation will be run. If you answered "1", the program will ask:

2. "Input new random number generator seed?"

Type in any odd integer for a new seed or type in zero for the default seed.

3. "Input scale factors for disturbances"

To force the simulation to be driven by noise having the same RMS as the RSANDY data, type "1,1,1...1" where there are as many 1's as there were random inputs in the RSANDY data, i.e. m'. If you want to scale the RMS of the noise, change the "1's" accordingly. For example, typing "2,.5" will make the first noise source twice the RMS of the RSANDY data and will make the second source half as large.

Appendix M.

SIMPLOT Computer Program

This appendix is the user's guide for the SIMPLOT computer program. The simulation part of the code was written by Bruce Gardner. It uses models created by the RSANDY program to run simulations of the closed loop designs. The program has the option of including the random disturbances used in the RSANDY design. Up to 12 variables can be plotted versus time and displayed on a VT125 screen or sent to a file for later plotting. The listing of the program and an example data set (Navion with full-order compensator from Chapter 2) are shown at the end of the appendix. The user's guide begins on the next page.

SCALEM2 Computer Program. (contd)

```
EXT I
2240 PRINT TAB(10),"THE N MATRIX IS"
2250 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8),FNR(N(I,J)),\ NEXT J\ PRINT\ N
EXT I
2260 PRINT
2270 PRINT TAB(10),"THE COMPUTER SCALED VARIABLE MATICES ARE"
2280 PRINT TAB(10),"THE COMPUTER SCALED B MATRIX IS"
2290 FOR I=1 TO NR\ FOR J=1 TO NM\ PRINT TAB(J*8),FNR(BCS(I,J)) \ NEXT J\ PRINT\
 NEXT I
2300 PRINT TAB(10),"THE COMPUTER SCALED C MATRIX IS"
2310 FOR I=1 TO NC\ FOR J=1 TO NR\ PRINT TAB(J*8),FNR(CCS(I,J)),\ NEXT J\ PRINT\
 NEXT I
2320 PRINT TAB(10),"THE COMPUTER SCALED N MATRIX IS"
2330 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8),FNR(NCS(I,J)),\ NEXT J\ PRINT\
 NEXT I
2340 PRINT
2350 PRINT TAB(10),"THE COMPLETELY SCALED MATRICES ARE"
2360 PRINT TAB(10),"THE AFINAL MATRIX IS"
2370 FOR I=1 TO NR\ PRINT TAB(I*8),FNR(AFINAL(I)),\ NEXT I
2380 PRINT TAB(10),"THE BFINAL MATRIX IS"
2390 FOR I=1 TO NR\ FOR J=1 TO NM\ PRINT TAB(J*8),FNR(BFINAL(I,J)),\ NEXT J\ PRI
NT\ NEXT I
2400 PRINT TAB(10),"THE CFINAL MATRIX IS"
2410 FOR I=1 TO NC\ FOR J=1 TO NR\ PRINT TAB(J*8);FNR(CFINAL(I,J)),\ NEXT J\ PRI
NT\ NEXT I
2420 PRINT TAB(10),"THE NFINAL MATRIX IS"
2430 FOR I=1 TO NC\ FOR J=1 TO NC\ PRINT TAB(J*8);FNR(NFINAL(I,J)),\ NEXT J\ PRI
NT\ NEXT I
2440 PRINT TAB(10),"THE KXFINAL MATRIX IS"
2450 FOR I=1 TO NC\ PRINT TAB(I*8),FNR(KXFINAL(I));\ NEXT I
2460 PRINT TAB(10),"THE KXIFINAL MATRIX IS"
2470 FOR I=1 TO NC\ PRINT TAB(I*8),FNR(KXIFINAL(I));\ NEXT I
2472 PRINT TAB(10),"THE KXDFINAL MATRIX IS"
2474 FOR I=1 TO NC\ PRINT TAB(I*8),FNR(KXDFINAL(I));\ NEXT I
2480 PRINT
2490 PRINT "THE A MATRIX REQUIRES A LRTA'3 THEN STRAU IN 1819 ASSEMBLY"
2500 PRINT "THE B MATRIX REQUIRES A LRTA'";18-SCALEB2;"THEN STRAU"
2510 PRINT "THE C MATRIX REQUIRES A LRTA'",18-SCALEC2,"THEN STRAU"
2520 PRINT "THE N MATRIX REQUIRES A LRTA'",18-SCALEN2;"THEN STRAU"
2530 PRINT "THE KX(1) ELEMENT REQUIRES A LRTA'",18-SCALEKX(1),"THEN STRAU"
2540 PRINT "THE KX(2) ELEMENT REQUIRES A LRTA'",18-SCALEKX(2);"THEN STRAU"
2550 PRINT "THE KX(3) ELEMENT REQUIRES A LRTA'",18-SCALEKX(3),"THEN STRAU"
2560 PRINT "THE KXI(1) ELEMENT REQUIRES A LRTA'",18-SCALEKXI(1),"THEN STRAU"
2570 PRINT "THE KXI(2) ELEMENT REQUIRES A LRTA'",18-SCALEKXI(2),"THEN STRAU"
2580 PRINT "THE KXI(3) ELEMENT REQUIRES A LRTA'";18-SCALEKXI(3),"THEN STRAU"
2582 PRINT "THE KXD(1) ELEMENT REQUIRES A LRTA'",18-SCALEKXD(1),"THEN STRAU"
2584 PRINT "THE KXD(2) ELEMENT REQUIRES A LRTA'";18-SCALEKXD(2),"THEN STRAU"
2586 PRINT "THE KXD(3) ELEMENT REQUIRES A LRTA'",18-SCALEKXD(3),"THEN STRAU"
2590 END
```

SCALEM1 Computer Program Example Data.

```
"NR,NM,NC,TP"
6,4,2,.05
"A MATRIX(NR)"
-.23081,.89831,-.23642,1.17826,.43492,.88649
"B MATRIX(NR X NM) MEASUREMENTS DISTRIBUTION MATRIX "
-16.358,-456.87,-.2653,.0545&
-8.274,-230.9,-.15366,.01224&
10.224,195.99,.02073,-.00518&
2.39548,49.65,.00599,.00061&
2.749,160.16,.17429,.0093&
1.04027,-.01363,-.00002,.00428
"C MATRIX(NC X NR) COMPENSATOR STATE TO CONTROL DISTRIBUTION MATRIX "
0.0,1.0,0.0,1.0,1.0,.68818&
-.91396,2.70164,-.90986,4.64211,.56013,1.0
"N MATRIX(NC X NC) COMMAND DISTRIBUTION MATRIX"
-.08369,-.03789&
-.164,.07336
"KI MATRIX(NC X NC) INTEGRAL GAIN MATRIX"
-.0042511,-.04904&
-.0040024,-.042269
"BSCALE(NM)------- THE SCALING FACTORS ON SPECIFIC COLUMNS OF B."
.017452,.017452,1,1
"CSCALE(NR)------- THE SCALING FACTORS ON SPECIFIC COLUMNS OF C."
1,1,1,1,1,1
"NSCALE(NC)------- THE SCALING FACTORS ON SPECIFIC COLUMNS OF N."
1,1
"KISCALE(NC)------ THE SCALING FACTORS ON SPECIFIC COLUMNS OF KI "
1,1
"YSCALE(NM)------- THE SCALING ON EACH MEASUREMENT."
500,500,32,8
"CNTRLSCALE(NC)--- THE COMPUTER SCALING ON EACH CONTROL."
1024,1024
"YDSCALE(NC)------ THE COMPUTER SCALING ON EACH DESIRED OUTPUT."
8,32
"YMAX(NM)--------- THE VECTOR OF MAX VALUES OF THE MEASUREMENTS."
20,20,20,30
"YDMAX(NC)-------- THE VECTOR OF MAX VALUES OF THE DESIRED OUTPUTS."
30,20
```

SCALEM2 Computer Program Example Data.

```
"NR,NM,NC,TP"
5 8.3. 05
"THE MINIMAL DISCRETE COMPENSATOR DYNAMICS MATRIX, PHI, IS:"
-0 78263,1 74302,0.90592,0.96006,0.72946
"THE MINIMAL DISCRETE COMPENSATOR INPUT MATRIX, GAMMAMIN, IS:"
-0 00068,0.00024,-0.00074,-0.01160,0.04977,0.01823,0.10458,-1.91023&
-0 00076,-0 00083,-0.00088,-0.01252,0.04972,0.00800,0.08074,-1.75084&
0 00214,-0 00052,0.00084,-0.00071,-0.10784,-0.05930,-0.00479,0.37056&
-0 00048,0.00001,0.00156,0.00007,0.00701,0.00129,0.00276,0.00769&
-0 00356,0.00115,0.00006,0.00581,-0.67143,0.13067,-2.77471,-1.64643
"THE MINIMAL COMPENSATOR OUTPUT MATRIX, HMIN, IS:"
-1 79786,1.82597 1.00000,-0 16434,1.00000&
0 10394,-0 03719,0 36894,1.00000,0.11184&
0.00000,1 00000,0.79317,0.03578,0.09061
"N MATRIX(NC X NC) COMMAND DISTRIBUTION MATRIX"
-4 829E-02,-9 785E-03,-2 378E-03&
7 004E-03,-7 883E-02,2 098E-03&
-1 175E-02,-3 420E-03,5.886E-02
"THE KX MATRIX"
- 26522,- 19939,-1 2212
"THE KXI MATRIX"
- 0000864,- 0001028,- 17365
"THE KXD MATRIX"
- 094118,-.72424,-3 0
"BSCALE(NM)------- THE SCALING FACTORS ON SPECIFIC COLUMNS OF B."
1,1,1, 017452,.017452,.017452,.017452,.017452
"CSCALE(NR)------- THE SCALING FACTORS ON SPECIFIC COLUMNS OF C."
1 1.1.1,1
"NSCALE(NC)------- THE SCALING FACTORS ON SPECIFIC COLUMNS OF N."
1,1,1
"YSCALE(NM)------- THE SCALING ON EACH MEASUREMENT."
32,32,32,500,500,500,500,500
"CNTRLSCALE(NC)--- THE COMPUTER SCALING ON EACH CONTROL."
1024,1024,1024
"YDSCALE(NC)------ THE COMPUTER SCALING ON EACH DESIRED OUTPUT."
32,32,32
"YMAX(NM)--------- THE VECTOR OF MAX VALUES OF THE MEASUREMENTS."
50,50,30,10,10,30,20,30
"YDMAX(NC)-------- THE VECTOR OF MAX VALUES OF THE DESIRED OUTPUTS."
20,20,20
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END

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