NASA Contractor Report 179428

Aircraft Flight Test Trajectory Control

P.K.A. Menon and R.A. Walker

(NASA-CR-179428) AIRCRAFT FLIGHT TEST TRAJECTORY CONTROL Final Contractor Report (Integrated Systems) 197 p CSCL 01C

N88-16707

Unclas

G3/08 0123312

January 1988

NASA

National Aeronautics and
Space Administration

NASA Contractor Report 179428

Aircraft Flight Test Trajectory Control

P.K.A. Menon and R.A. Walker
Integrated Systems, Inc., 101 University Avenue, Palo Alto, California 94301

Prepared for
Ames Research Center
Dryden Flight Research Facility
Edwards, California
Under contract NAS 2-11877

1988

National Aeronautics and
Space Administration
Ames Research Center
Dryden Flight Research Facility
Edwards, California 93523-5000

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SECTION 1
INTRODUCTION

1.1 BACKGROUND

Flight Test Trajectory Control (FTTC) is an emerging, pilot-aiding technology valuable for improving flight test results and applicable to maneuver control and guidance in a number of contexts. This technique has provided the means for flying maneuvers consistently, precisely, and repeatably from flight to flight. Two versions of these controllers have been used: a closed-loop automatic system and an open-loop system providing manual piloting information. A closed-loop system used to collect performance, pressures, and loads data from the highly maneuverable aircraft technology (HiMAT) vehicle is described in [1]. The application of the open-loop system on the NASA F-111 transonic aircraft technology (TACT), F-15 airframe/propulsion system interaction studies, and F-15 shuttle tiles test programs are given in [2].

Originally, the open-loop flight-test-trajectory guidance algorithms were developed on-line, in a piloted simulation using cut-and-try techniques that were not only man power intensive, but often produced less than optimal controllers. A closed-loop system designed using one-loop-at-a-time classical design approach is documented in [3]. Full-state feedback approach for closed-loop system design using linear quadratic synthesis is described in [4]. Both these approaches have limitations in terms of design methodology and controller complexity.

The work reported in reference [2] and more recent ongoing work have included detailed modeling of all the piloted aircraft subsystems for suitable control law development. This research has identified the maneuver modeling as a significant technology needing further clarification and development. The maneuver modeling aspect of trajectory guidance and control law design will be emphasized here in describing this developing technology.

In the present work, closed loop mechanization is carried out with the pilot in a supervisory role. The thrust here is in four areas

1. Maneuver modeling,

2. Application of modern linear multivariable synthesis,

3. Techniques for the development of reference command and gain-scheduled perturbation controllers, and

4. Exploratory investigation of the emerging nonlinear system design techniques via prelinearizing transforms.

1.2 SUMMARY OF RESEARCH ACCOMPLISHED

Maneuver modeling for all the given flight test trajectories were successfully carried out. In the present work 64 straight and level trims, 51 level turn trims at a load factor of 2, and 30 level turn trims at a load factor of 4 were employed. A 3-D linear interpolation was employed. Thus a flight condition is characterized by altitude, Mach number and load factor. Linearized aerodynamic coefficients were also stored. This data in conjunction with kinematic and some dynamic equations are then used to generate state and control histories for all the flight test maneuvers.

Two multivariable synthesis techniques were used to obtain output feedback linear perturbation controllers viz.

1) Constrained eigenstructure assignment (Shapiro & Andry, 1982)

2) Minimum error excitation technique (Kosut, 1970)

Out of these two, the constrained eigenstructure assignment technique was found to be the hardest one to iterate on primarily due to the current lack of understanding of the explicit relationship between eigenvectors and the desired time response. This difficulty, while not crucial in full state feedback design can become an extremely important element in output feedback design. Due to its high sensitivity to the input eigenvectors, it was discarded after the initial research phase. A paper outlining these issues was presented at the 1985 American Control Conference (see Appendix A). The minimum error excitation suboptimal design was successful and is advocated as the main design approach.

Exploratory research on nonlinear maneuver autopilot synthesis brought out the feasibility of generating the maneuver autopilots by employing singular perturbation theory in conjunction with prelinearizing transforms. The methodology is outlined, though the controllers have not been worked out. A simple example problem to serve as an illustrative example is given in Appendix B. This technique appears to hold considerable promise and will be further pursued in future research.

The designs obtained were scheduled as functions of Mach number and load factor and were tested on a linear simulation. The performance has been found satisfactory within the validity of the linear model assumptions. In the next phase these designs will be tested on a nonlinear simulation of the F-15 aircraft.

1.3 STUDY RESULTS

Results from this work fall into four categories, (1) control design technique evaluations, (2) specific control analysis and design, (3) software developments for control law mechanization, and (4) specific control law validations. The various deliverables in these areas are:

1) For control design technique evaluations

   a) A paper evaluating the eigenstructure assignment technique [6]

   b) An assessment and extension of the nonlinear prelinearizing control technique [7], and demonstration on a simple example. (See Appendix B)

2) For control analysis and design

   a) Development and clarification of maneuver modeling equations beyond the analysis in references [4, 10].

   b) Condensation of the F-15 aircraft nonlinear characteristics to a table of reference states and controls via nonlinear simulation trim values at approximately 145 conditions on the flight envelope.

   c) Decomposition of the 8 maneuvers over the flight envelope into 30 linear perturbation models (15 with fixed throttle and 15 with variable thrust).

   d) Solution of 30 output feedback gains which can be used with the 30 linear perturbation models to simulate maneuvers throughout the envelope.

3) For software developments

   a) Extensions to Integrated Systems, Inc. (ISI's) MATRIX_x^{TM} SYSTEM_BUILD^{TM} package including a linear time varying FORTRAN block to give a generic linear time varying simulation capability (such a capability can be easily mechanized to model linear time-varying simulations of engine and aircraft dynamics, for example).

   b) Development of a three-dimensional interpolation program which converts table look-ups in altitude, Mach, and load factor to a one-dimensional table look-up with respect to time for a specific maneuver,

   c) Documented command files Aircraft-CAS model building and Maneuver Auto Pilot (MAP) design in the MATRIX_x language for the model generation, control law design, and simulation validation process, and

4) Demonstration of the maneuver autopilot validations in a linear simulation.

The linear control laws developed in this work are now ready for validation on a nonlinear batch simulation. With suitable algebraic equation manipulation, the nonlinear control laws can also be mechanized on a nonlinear simulation.

1.4 REPORT ORGANIZATION

Section 2 describes the aircraft and command augmentation system (CAS) models, the choice of outputs useful for feedback and the procedure for obtaining linear models. Section 3 specifies the flight test maneuvers analyzed in terms of the maneuver objective and how that objective can be reduced to a set of equations which constrain a required set of outputs. Section 4 outlines the linear techniques evaluated and used for the design of perturbation feedback controllers as well as the nonlinear tracking feedback controller. Section 5 reviews the linear simulation mechanization and discusses the demonstration results for the eight required maneuvers. Conclusions are given in Section 6. The appendices describe in detail the issues in linear time-varying simulation, the evaluation of constrained eigenstructure assignment and the output error feedback controller designs, and nonlinear tracking control via prelinearizing transformations.

SECTION 2

AIRCRAFT AND COMMAND AUGMENTATION SYSTEM (CAS) MODELS

This section reviews the overall linear system model used to both develop and validate the linear perturbation control laws. Figure 2-1 below shows the design process used.

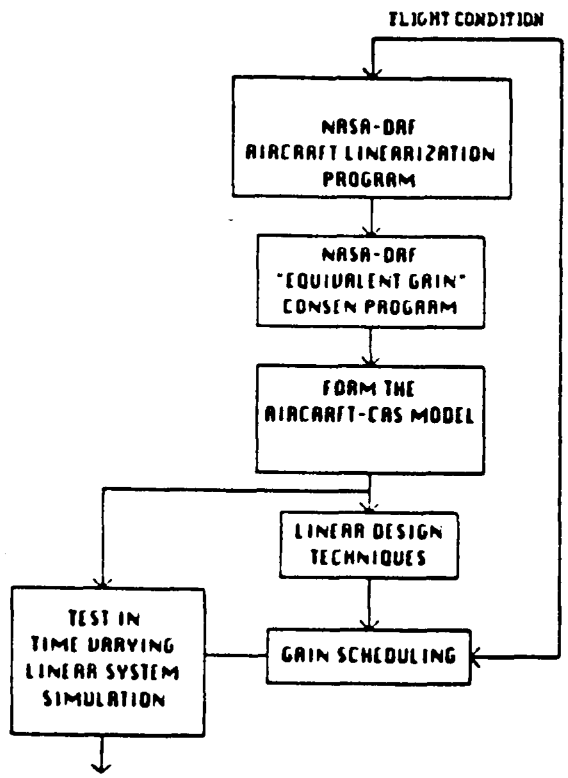

Figure 2-1. Use of Linear System Flight Test Trajectory Model

The rest of the section describes the airframe, engine, and command augmentation (CAS) models and how they are integrated into the overall linear design and evaluation model.

2.1 AIRCRAFT MODEL

As shown in Figure 2-1, the airframe model was obtained from the NASA Ames Dryden Flight Research Facility (ADFRF) LINEAR Program [11], yielding the aircraft model in the standard form

$$\dot{x} = Ax + Bu,$$

$$y = Hx + Fu$$

where

$$x^T: \ [\delta V, \delta\alpha, \delta q, \delta\theta, \delta\beta, \delta p, \delta r, \delta\phi, \delta h],$$

$$y^T: \ [\delta\dot{p}, \delta A_n, \delta q, \delta\dot{q}, \delta p, \delta A_{ny,i}, \delta\dot{r}, \delta r, \delta M, \delta\alpha, \delta\gamma, \delta\phi, \delta\beta].$$

The first nine outputs are required in the linearized CAS model.

2.2 ENGINE MODEL

An engine model of the form

$$\frac{0.2}{s + 0.2}$$

was assumed. However, since this lag can be compensated for with a simple lead-lag compensator, the problem of a slow engine time constant was not included in the overall design, assuming exact cancellation. The actual residual due to mismodeling can best be addressed with the nonlinear simulation. Figure 2-2 below shows the overall mechanization including the CAS states described next.

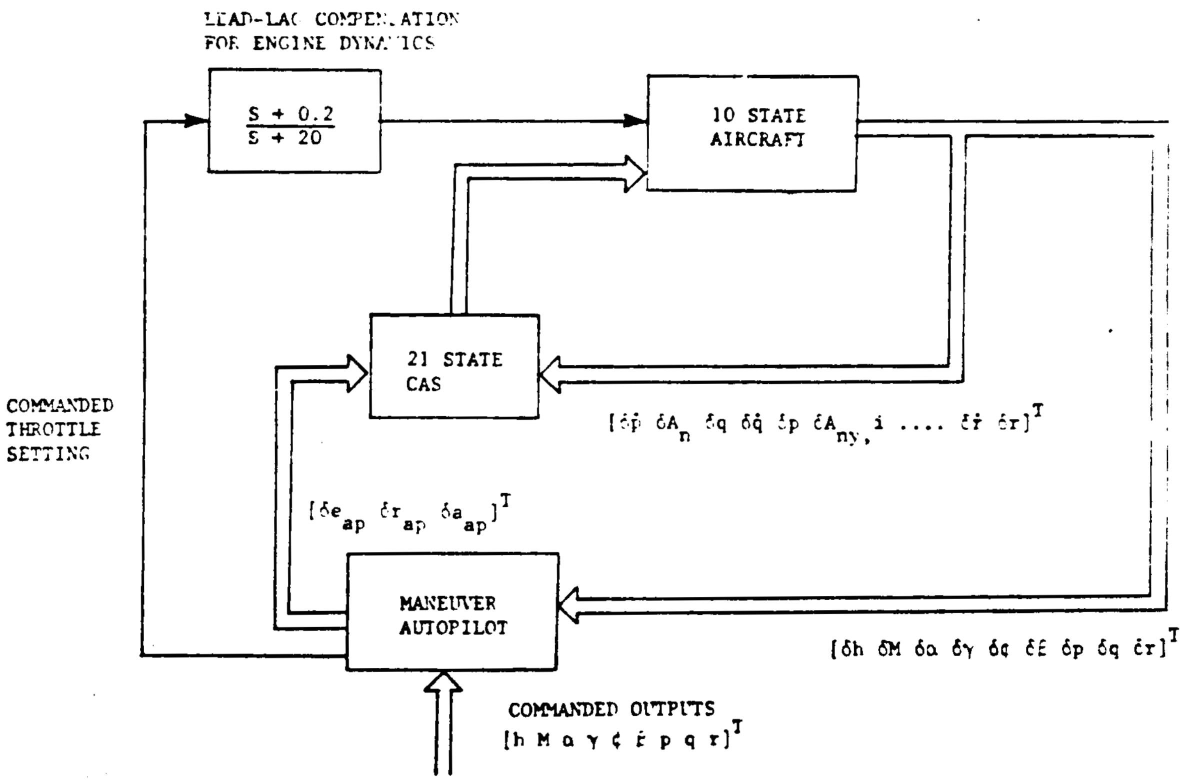

Figure 2-2. Linear Perturbation Flight Test Trajectory Control System

2.3 COMMAND AUGMENTATION SYSTEM (CAS) MODEL

The CAS model is highly nonlinear with gain schedules and multiplicative and saturation nonlinearities. This was linearized with a gross linearization and an "equivalent gain" for the multiplicative nonlinearities determined by the NASA ADFRF CONSEN program. The CONSEN program simulates the actual CAS for several time steps at a given flight condition. When all the transients have decayed, the ratio of inputs and outputs are then used to compute the equivalent gains.

The CAS system has no access to ailerons in the aircraft under consideration and hence, all the flight test maneuvers will be accomplished using throttle, elevator, rudder and differential tail. The maneuver autopilot outputs will be connected to the existing autopilot interface in the CAS, as shown in Figures 2-3 through 2-5.

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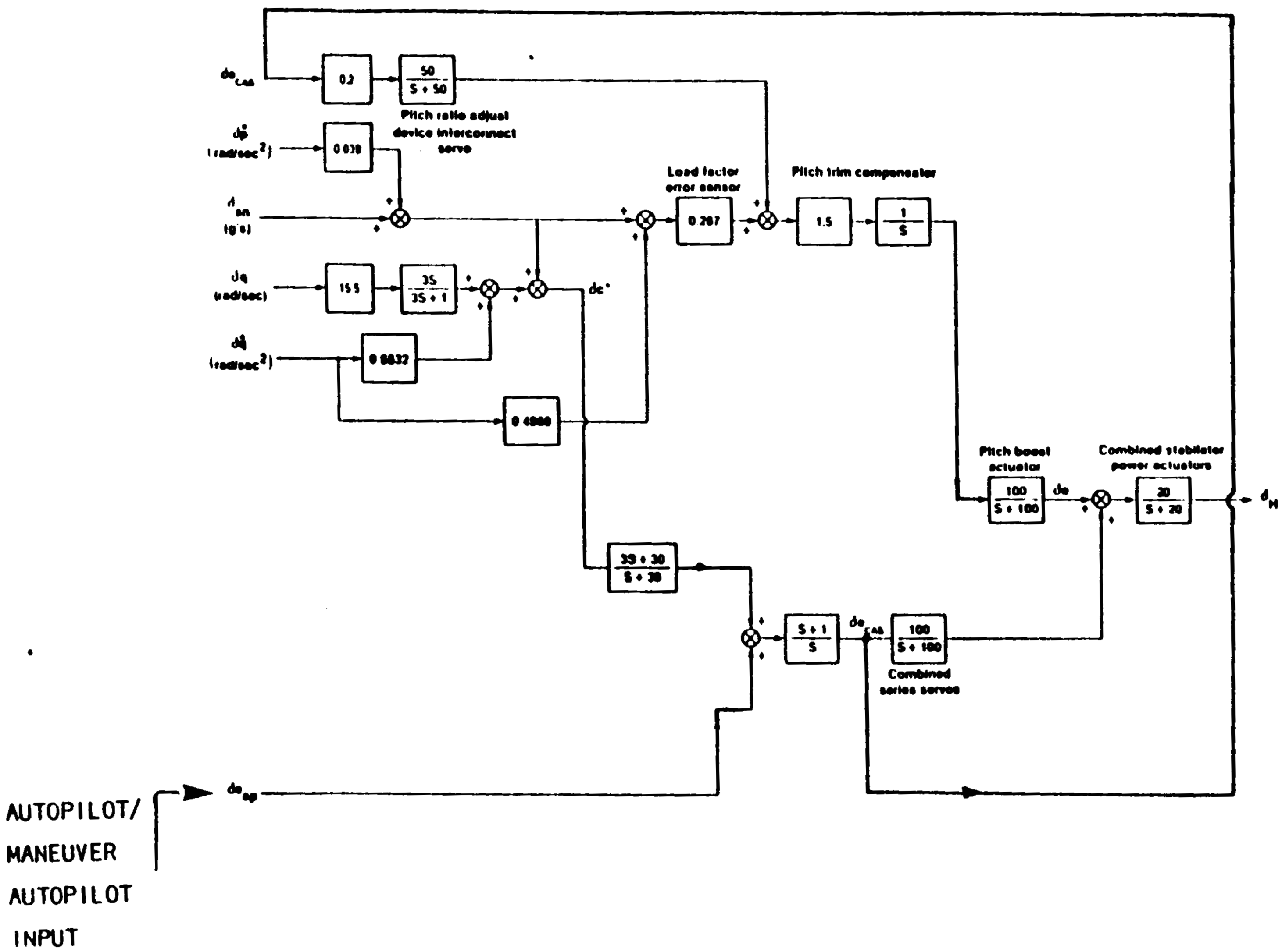

Figure 2-3. Pitch CAS - Gross Linearized System
(Pilot Inputs and Trim Loops Eliminated)

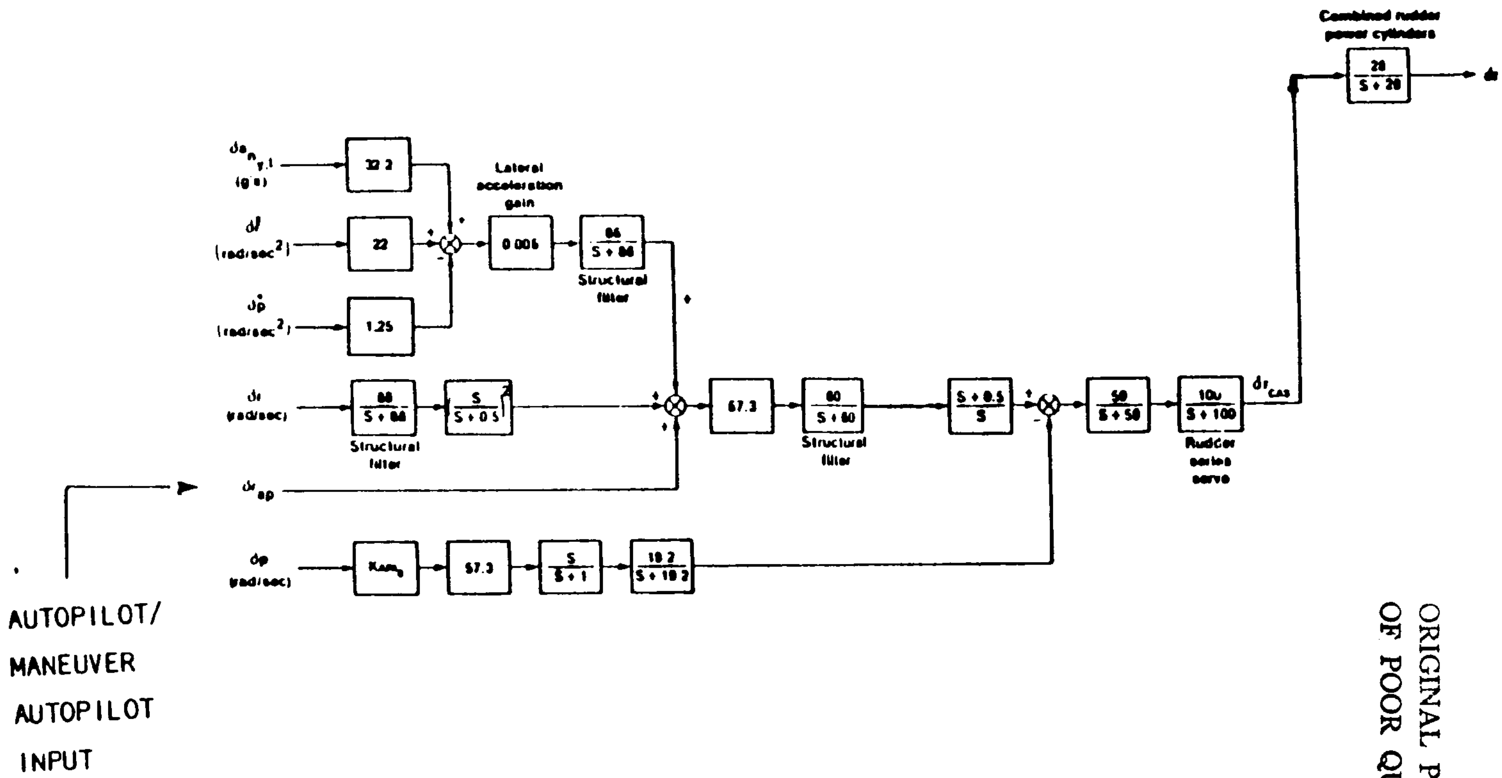

Figure 2-4. Yaw CAS Gross Linearized System
(Pilot Inputs and Trim Loops Eliminated Gain
$Kari_s$ determined from "CONSEN" Program)

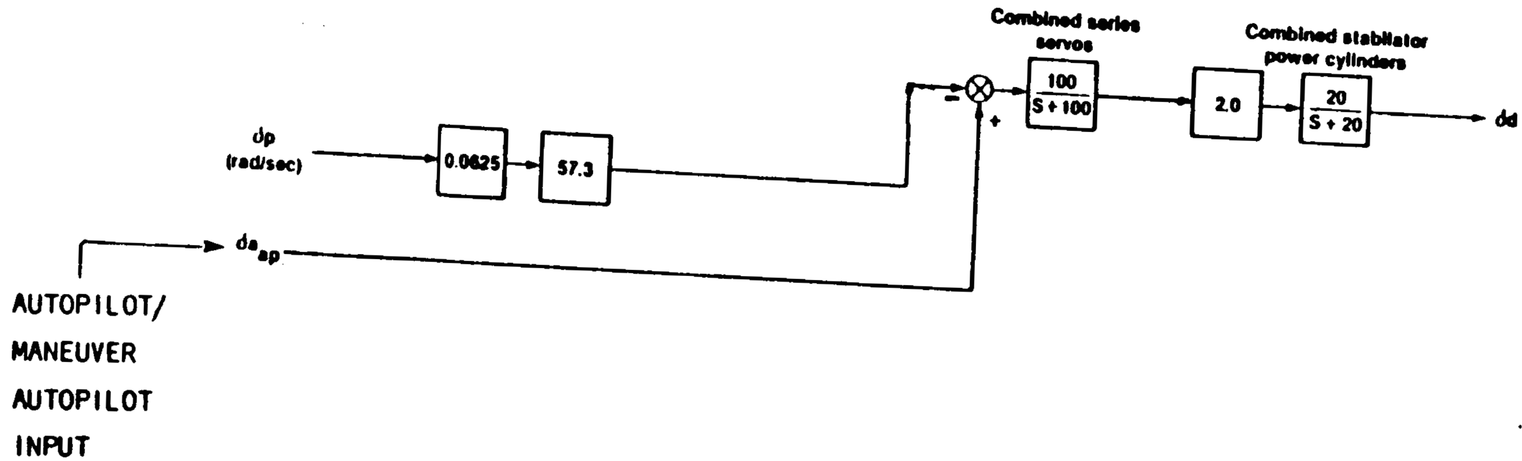

Figure 2-5. Roll CAS Gross Linearized System
(Pilot Inputs and Trim Loops Eliminated)

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2.4 LINEAR MODEL SUMMARY

The overall linear model has nine aircraft states, one engine state, and twenty-one CAS states. The outputs to be used in the maneuver autopilot, for all maneuvers, are

$$y^T = [\delta h, \delta M, \delta\alpha, \delta\gamma, \delta\phi, \delta\beta, \delta p, \delta q, \delta r].$$

Selection of these quantities for feedback are primarily dictated by the various flight test maneuvers to be executed. Thus, the altitude, Mach number and the angle of attack are to be either regulated about reference values or should be made to follow desired command histories. The choice of roll attitude feedback arises from a requirement to maintain wings level along symmetric flight test trajectories. In nonsymmetric flight test maneuvers, desired load factors can be sustained by an appropriate roll attitude command. For all flight test maneuvers, the angle of sideslip needs to be regulated about zero; this prompts the use of β feedback. An output feedback controller is envisaged in the present development. Since most output feedback synthesis approaches do not guarantee stability, it is decided to incorporate derivative feedbacks for as many output variables as feasible. This led to the selection of the body rates p, q, r to serve as derivative feedbacks for angle of attack, angle of sideslip and the roll attitude. The Mach number and the flight path angle serve as derivative feedbacks for altitude. Since most flight test maneuvers require angle of attack tracking, an integral feedback is incorporated in the angle of attack channel. While executing nonsymmetric flight test maneuvers, the roll attitude can sometimes be very close to 90°. At these conditions, small perturbations in the roll attitude can induce major changes in altitude and other states. Hence in order to provide a tight roll attitude control, two integral feedbacks are introduced for the roll attitude ϕ.

SECTION 3
MANEUVER MODELING

The desired trajectory or maneuver to be modeled governs the subsequent control law development in two ways. First, the maneuver prescribes the equations of motion of the vehicle on the reference trajectory and secondly the maneuver regimes determine the linear perturbation equations about the commanded trajectory from which the linear control law is developed.

Aircraft flight test trajectories could be based on inertial reference (e.g., level-turn or 3-D guidance) or reference with respect to another vehicle or vehicles (e.g., in air-to-air combat). To place the flight test trajectory control design problem in a proper framework, the constraints which determine the equations of motion for various large classes of trajectories are described below.

The subsections which follow give a general overview of maneuver modeling and the descriptions of the specified maneuvers analyzed in this work.

3.1 MANEUVER MODELING OVERVIEW

We divide single vehicle flight paths into those which require continuous control along the trajectory and those that specify a final flight condition. In either case the flight test trajectory could be specified in terms of one of the following:

1. Constraints on position components,
2. Constraints on velocity components and altitude,
3. Constraints on combinations of load, speed and altitude.

Combinations of these constraints could also be considered. The flight test maneuvers discussed in this report belong to the second and third categories. Reference [4] gives some early results in flight test trajectory modeling.

3.1.1 Constraints on Position Components

Examples of trajectories which involve position constraints along the flight path are

1. 4-D guidance (x(t), y(t), h(t) are given functions of time).

2. 3-D guidance (x, y, h are related to each other, e.g., fly along a hypothetical wire in space). Examples of 3-D guidance are approach to landing, terminal area flight paths and threat evasion for reconnaissance aircraft and bombers. This also includes straight and level flight and flights along predetermined paths.

Examples of trajectories which specify position constraints at the final trajectory point are:

1. 4-D specification (arrive at a certain point, at a certain time, e.g., touchdown on the runway at a specified point).

2. 3-D specification (fly-to-VOR, terrain following).

Note that each of these trajectories requires position measurement. The 4-D guidance trajectory indirectly specifies velocity and acceleration components. Thus, specification of position components is the most comprehensive constraint on the trajectory. Such a rigid constraint may be unnecessary for most test maneuvers.

3.1.2 Constraints on Velocity Components and Altitude

While the horizontal position components do not, in general, affect aerodynamic variables, the altitude determines density and by itself affects dynamic pressure. Thus, it must always be considered as a possible variable to be constrained. In fact, the altitude and dynamic pressure are so important that a majority of flight test trajectories will define the altitude profile (this includes maintaining constant altitude).

Examples of this class of trajectories are:

1. $u(t)$, $v(t)$, $w(t)$ and $h(t)$ [in other words, Mach number, dynamic pressure, $\beta(t)$ and $\alpha(t)$.] $\beta(t)$ may be zero.

2. Mach number, angle-of-attack and dynamic pressure (as in shuttle tile tests).

Various other combinations of velocity components and altitudes could also be specified.

Mach number, angle-of-attack and altitude constraints could also be desired at one point on the trajectory. For example, the zoom-and-pushover is a trajectory where angle-of-attack, Mach number and altitude are specified at one point on the trajectory.

3.1.3 Constraints on Combinations of Load, Speed and Altitude

The trajectory specifications could involve components of loads along the three axes, velocity components and altitude. The typical load specification will consist of desired vertical acceleration. The desired value of the lateral acceleration is usually zero. The total speed is often specified in lieu of the fore-and-aft acceleration.

Many combinations of load, speed and altitude specifications are possible. Some examples are as follows:

1. A constant load, constant Mach number level turn,

2. A constant Mach number, constant altitude windup turn.

Often, the desired flight trajectory for an aircraft depends upon the position and flight test trajectory of other vehicles. Typical examples are collision avoidance, air combat, or avoidance of air-to-air missiles. The specification is typically based on the position of a target aircraft with respect to the aircraft whose trajectory is being controlled.

The next section gives a specific objectives and their analytical development for each of the maneuvers for which autopilots were designed.

3.2 MANEUVER MODELING

To summarize, the objective of maneuver modeling is to generate a consistent set-of state and control histories to serve as commands and open loop controls for the maneuver autopilot using a data base consisting of trim conditions. Two sets of trims have been found adequate for all the maneuvers discussed here, viz, straight and level trims and level turn trims. To the extent feasible, kinematic relationships are employed to generate the state-control histories. Whenever this is not possible, linearized aerodynamics and engine models are used. Note that the following development is not restricted a particular aircraft.

The commands and the open loop controls consist of:

Commands: Altitude, Mach number, angle-of-attack, flight path angle, roll attitude, angle of side slip, roll-pitch-yaw body rates.

Openloop Controls: Throttle, elevator, rudder and differential tail.

In the following, the maneuver modeling for individual flight test trajectories will be discussed in detail. It is important to note that all these maneuvers assume zero sideslip.

3.2.1 Transient Trajectory

The objective of this maneuver is to transfer an aircraft flying straight and level at a Mach-altitude pair to another Mach-altitude pair at a desired flight path angle. This maneuver is normally employed as the initial-terminal transient to other flight test maneuvers and hence the name.

The simplest way to mechanize this maneuver to assume a cubic polynomial in time for the altitude. Thus,

$$h = h_o + a_1 t + a_2 t^2 + a_3 t^3; \; t_o \leq t \leq t_f \tag{3.1}$$

from which

$$\dot{h} = a_1 + 2a_2 t + 3a_3 t^2 \tag{3.2}$$

The requirement for a cubic polynomial arises from the constraints that one wishes to place at the two ends, i.e., initial and final altitudes are specified along with altitude rates at the two boundaries. To simplify the development, constant acceleration along the flight path is assumed next, viz,

$$V = V_o + \dot{V}t, \tag{3.3}$$

where

$\dot{V} = \dfrac{V_f - V_o}{t_f}$, V_f is the specified final speed and t_f, the final time.

The flight path angle is readily computed from

$$\gamma = \sin^{-1} \left(\frac{\dot{h}}{V}\right)$$

As noted elsewhere, a data base consisting of straight and level trims at several Mach-altitude pairs are available.

Assuming that the path angle is small, such that

$$\text{Lift} \simeq \text{weight}$$

along this maneuver, the angle of attack history can be generated by linearly interpolating between stored straight and level trim data at the Mach number - altitude given by the equations (3.1) and (3.3). Since the angle of attack will be close to the straight and level trim values, the aerodynamic surface setting at these trims can be used to generate approximate open loop control settings. Assuming next that under these conditions, the actual drag is close to the trim values, the required thrust may be computed as follows.

Assuming that the aircraft thrust is aligned with the vehicle longitudinal axis, the acceleration along the flight path for symmetric flight is given by

$$\dot{V} = \frac{T\cos\alpha_{trim} - D}{m} - g\sin\gamma \qquad (3.4)$$

In the expression (3.4), T is the thrust, γ flight path angle, α the angle of attack, D the aerodynamic drag, m the aircraft mass and V the velocity along the flight path. In order to compute the required thrust, the equation (3.4) can be manipulated to the form given below

$$T = \frac{(\dot{V} + g\sin\gamma)m + D}{\cos\alpha_{trim}} \qquad (3.5)$$

To compute the throttle setting, a linear thrust-throttle characteristic will be assumed. Thus,

$$T_{max} = \frac{T_{trim}}{\eta_{trim}} , \tag{3.6}$$

η_{trim} is the straight and level throttle setting and T_{max} is the thrust corresponding to maximum throttle setting.

$$\therefore \quad \eta_{actual} = T/T_{max} \tag{3.7}$$

During this maneuver, one expects the body rates to be small. Consequently, the commanded values of these quantities are zero.

If the throttle setting emerging from this analysis is greater than the maximum or less than the minimum, it indicates that the assumed time of flight for the maneuver is unrealistic or that the model is inadequate or both. This quantity has then to be changed appropriately to make the maneuver feasible.

3.2.2 Level Acceleration/Deceleration

This is a wings level, constant altitude maneuver with Mach number constant or changing at a specified rate. The maneuver modeling for this trajectory is essentially a subset of the trajectory 3.2.1. Putting $a_1=a_2=a_3=0$ in (3.1) results in

$$\begin{aligned} h &= h_0, \text{ constant} \\ \gamma &= 0, \text{ constant} \end{aligned} \tag{3.8}$$

and $V = V_0 + \dot{V}t$, with $\dot{V}$ specified.

The required thrust and the corresponding throttle can be computed as in 3.2.1. The open loop control surface settings and the other commands are linearly interpolated from the straight and level trim data base.

3.2.3 Pushover, Pullup

This is a wings level, constant Mach number maneuver in which the angle of attack is varied a specified increment about the trim value at some specified rate. The maneuver is shown in Fig. 3.1. The corresponding angle of attack history is given in Fig. 3.2.

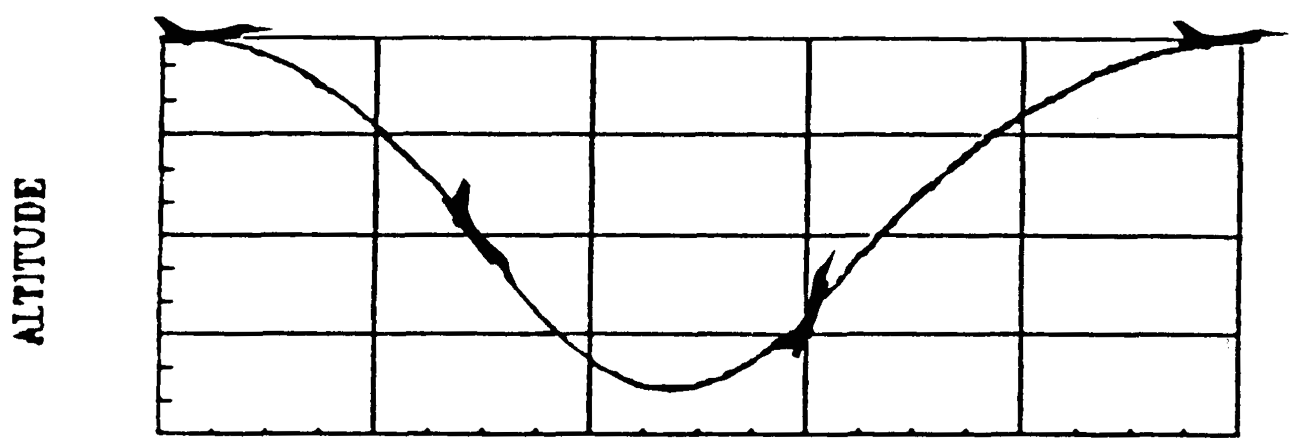

Figure 3.1. Pushover - Pullup Flight Test Trajectory.

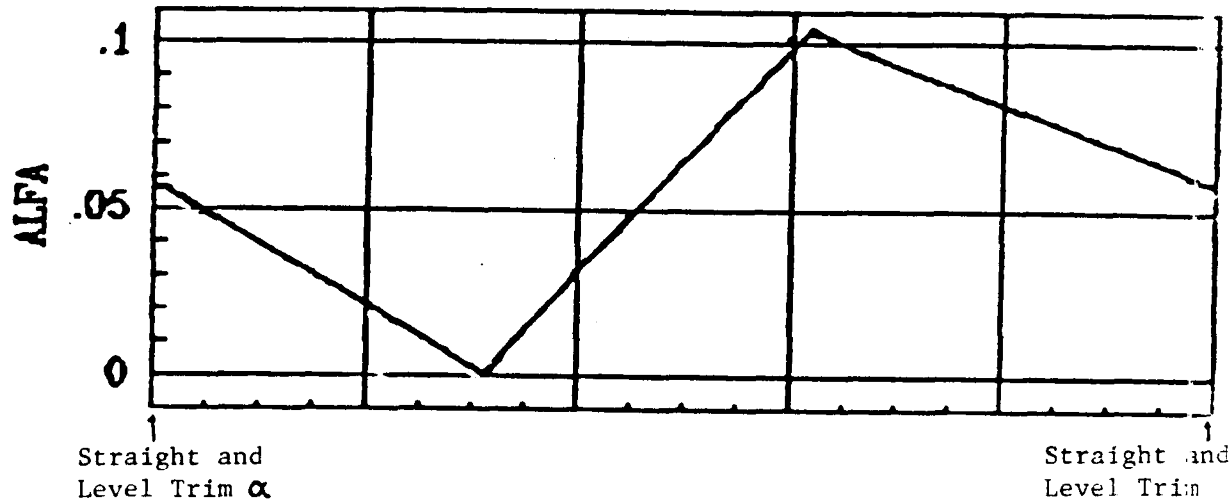

Figure 3.2. Angle of Attack History Along the Pushover - Pullup Flight Test Trajectory.

The maneuver modeling for this flight test trajectory uses the assumption that pitch rate is close to zero. Since the aircraft is in symmetric flight, the flight path angle γ can be calculated as the difference between the pitch attitude and θ and the angle of attack α. Thus

$$\gamma = \theta - \alpha, \tag{3.9}$$

and α is specified as a function of time, the flight path angle can be computed. Now,

$$\dot{h} = V\sin\gamma = MC\ \mathrm{Sin}\gamma \tag{3.10}$$

where C is the speed of sound specified as a function of altitude h and M is the desired Mach number. Equation (3.10) can be analytically or numerically integrated to yield the altitude history. The throttle setting may be computed from the following equations.

Since Mach number is to remain constant throughout the maneuver, one can differentiate the expression for Mach number ($M = \frac{V}{C}$) with respect to time and equate to zero to obtain

$$\frac{\dot{V}}{C} - \frac{V}{C^2}\frac{\partial c}{\partial h}\dot{h} = 0 \tag{3.11}$$

substituting for $\dot{h}$ from (3.10), one has

$$\dot{V} = \frac{V^2}{C}\frac{\partial c}{\partial h}\sin\gamma \tag{3.12}$$

Equating expressions (3.12) and (3.4), one has

$$\frac{V^2}{C}\frac{\partial c}{\partial h}\sin\gamma = \frac{T\cos\alpha - D}{m} - g\sin\gamma \tag{3.13}$$

From which

$$T = [\frac{V^2}{C}\frac{\partial c}{\partial h} + g]\frac{m\sin\gamma}{\cos\alpha} + \frac{D}{\cos\alpha} \tag{3.14}$$

The drag at the commanded angle of attack can be computed from linearized drag coefficient specified as a function of α, the dynamic pressure and the reference area. As before, the linear throttle assumption is invoked to compute the throttle setting.

$$\eta_{actual} = T \cdot \frac{\eta_{trim}}{T_{trim}} \tag{3.15}$$

3.2.4 Zoom and Pushover

The zoom and pushover is a wings-level, thrust stabilized less than 'g maneuver. The flight trajectory is a parabolic path with the target Mach/altitude/angle of attack point at the apex. An illustration of the zoom and pushover flight test trajectory is given in Fig. 3.3. The maneuver begins at O with straight and level flight conditions. A transient-maneuver is performed to transfer the aircraft to the point A with all controls active. At the point A, the throttle is fixed at a predetermined value and the aircraft executes the zoom and pushover trajectory. At the point B, the thrust control is reinstated and a transient trajectory transfers the aircraft back to straight and level flight conditions at point C.

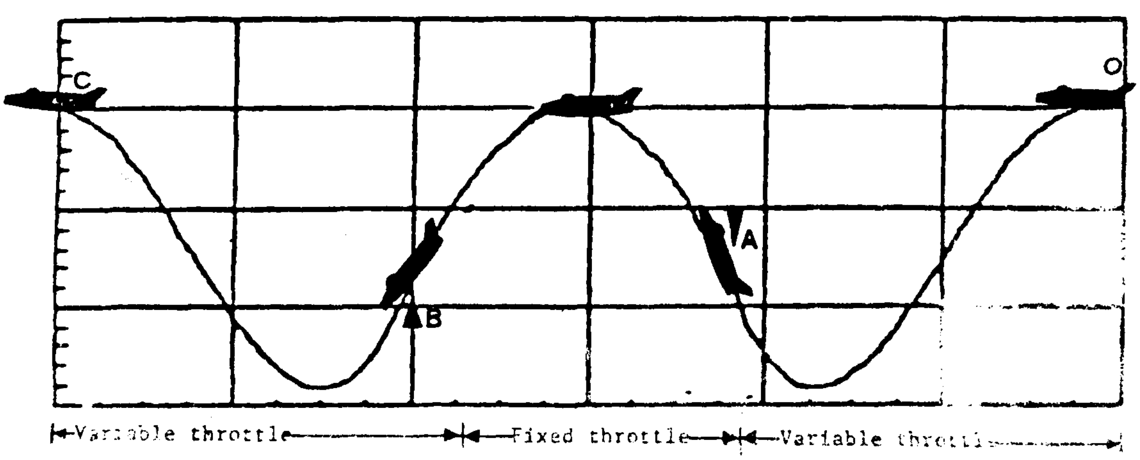

Figure 3.3 Zoom and Pushover Flight Test Trajectory

This is perhaps the most complicated of all the symmetric flight test maneuvers. This flight test trajectory consists of three phases. In the first phase, the aircraft is transferred from its straight and level flight condition to the beginning of the parabolic flight path. The second phase is the required zoom and pushover maneuver followed by the third phase which brings the aircraft back to its original straight and level flight conditions. The first and third phase maneuvers are essentially transients and the maneuver modeling discussed in 3.2.1 is directly applicable. The second phase will be analyzed in this section.

A parabolic flight path has the following properties

1. Horizontal acceleration is zero
2. Vertical acceleration is constant
3. Total energy is constant.

Since the apex speed is specified, say V_T, one has

$$\dot{x} = V\cos\gamma = \text{constant} = V_T$$

Here, x is the down range. Note that since the aircraft is in symmetric flight, the cross range is zero. Thus,

$$\gamma = \pm \cos^{-1}\left[\frac{V_T}{V}\right] \tag{3.16}$$

a positive or negative sign has to be chosen based on whether the aircraft is flying towards the apex or away from it.

From the given apex speed, angle of attack and altitude, the lift and drag can be computed using the straight and level trims data base using linearized aerodynamic coefficients. From constant energy property, one has, at the apex of the parabola,

$$T\cos\alpha_T = D \tag{3.17}$$

From which, the throttle setting at the apex can be computed as follows

$$\eta_{actual} = T \cdot \frac{\eta_{trim}}{T_{trim}} \tag{3.18}$$

with lift and thrust, the vertical acceleration at the apex can be computed. Thus

$$\frac{T\sin\alpha_T + L}{m} - g = g_a \tag{3.19}$$

Note that g_a should be a negative quantity, numerically less than the acceleration due to gravity g. The acceleration g_a has to remain constant through the parabolic path. To summarize, the aircraft trajectory approximates the path of a projectile in a uniform conservative force field. The total energy of the aircraft in this field is given by

$$E = h + \frac{V^2}{-2g_a} = \text{constant} \tag{3.20}$$

Expression (3.20) can be used to compute the speed along the parabolic path, given the altitude.

Next, given the altitude at which the parabola is to begin, and perhaps end, one can write

$$h = h_o + \dot{h}_o t + \frac{g_a}{2}t^2 \tag{3.21}$$

with $\dot{h}_o$ computed using the following relations.

$$V_o = \sqrt{-2g_a(E-h_o)}$$

$$\gamma_o = \cos^{-1}\left[\frac{V_T}{V_0}\right]$$

and

$$\dot{h}_o = V_o \sin\gamma_o \tag{3.22}$$

The time of flight on this parabola is easily computed with equation (3.21) in the general case or with the following equation if the zoom and pushover parabola is symmetric about its axis.

$$t_f = \frac{2}{-g_a}\sqrt{(V_o^2-V_T^2)} \tag{3.23}$$

Note that the throttle is to remain fixed at the value given by the equation (3.18). The angle of attack throughout the parabolic path is computed from

$$\frac{T\cdot\alpha + L_o + L_\alpha \alpha}{m} - g\cos\gamma = g_a \tag{3.24}$$

with $T = T_{max} \cdot n_{actual}$ and small angle approximation for α has been used.

The open loop control surface settings are assumed to be the interpolated values from the straight and level trim data base.

3.2.5 Excess Thrust Windup Turn

This is a maneuver with angle of attack linearly increasing from the wings-level trim condition to some specified final value at a specified rate. The maneuver is performed at constant altitude and constant Mach number. A schematic figure of this maneuver is shown in Fig. 3.4.

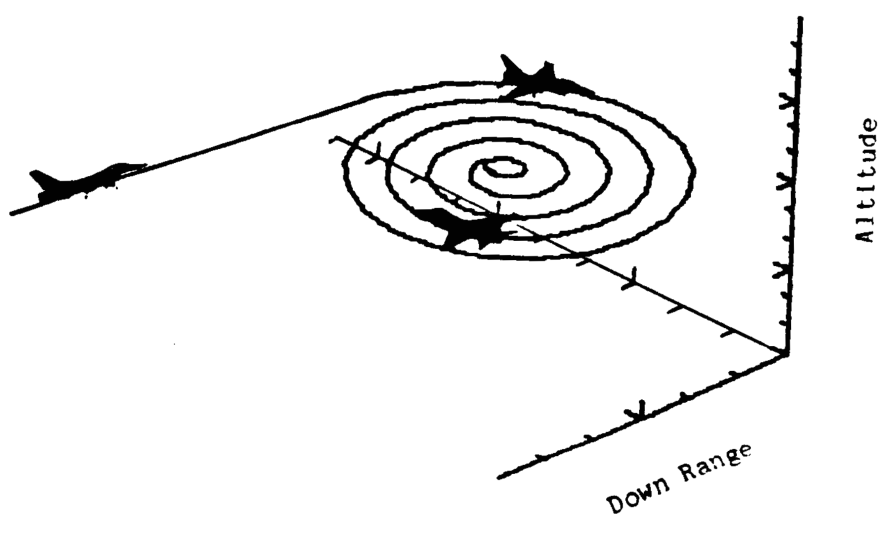

Figure 3.4. Excess Thrust Windup Turn Flight Test Trajectory.

As mentioned elsewhere in this report, the trim data base consists of straight and level trims at several Mach-altitude pairs along with level turns at several Mach-altitude-load factor conditions. Since excess thrust windup turn can be considered to consist of several level turn trim conditions appropriately pieced together, this maneuver model is merely a 3-Dimensional interpolation using the trim data base.

3.2.6 Constant Throttle Windup Turn

This is a maneuver with angle of attack increasing linearly at a specified rate from trim to some specified final value. The maneuver is performed at a predetermined, constant thrust level. Mach number is maintained by trading potential for kinetic energy via an appropriate altitude rate.

Since Mach number is constant, one can write as in equation (3.12)

$$\dot{V} = \frac{V^2}{C} \frac{\partial C}{\partial h} \sin\gamma \tag{3.25}$$

Further, since the altitude, Mach number and angle of attack at the initial point are known, one can compute

$$T_{max} = T_{trim}/\eta_{trim} \tag{3.26}$$

from the trim data base. Let the throttle be fixed at a value η_R. Thus, the actual thrust

$$T_R = T_{max} \cdot \eta_R \tag{3.27}$$

If the actual thrust T_R is greater than that required for level turn at the given Mach-altitude-angle of attack condition, the Mach number can be maintained constant only by a positive altitude rate. The reverse applies whenever T_R is less than T_{trim}. Let the excess thrust over the level turn trim be

$$\Delta T = T_R - T_{trim} \tag{3.28}$$

Now, one has

$$\frac{V^2}{C} \frac{\partial c}{\partial h} \sin\gamma = \frac{\Delta T \cdot \text{Cos}\alpha}{m} - g\sin\gamma \tag{3.29}$$

from which,

$$\gamma = \sin^{-1}\left[\frac{\Delta T \text{Cos}\alpha}{m(\frac{V^2}{C} \frac{\partial c}{\partial h} + g)}\right] \tag{3.30}$$

Also,

$$\dot{h} = V\sin\gamma \tag{3.31}$$

The expression (3.31) can be numerically integrated over one step to obtain the new altitude. The calculations may be repeated as many times as one wishes to obtain the trajectory.

It is important to begin this trajectory at a high-g turn, since fixing the throttle at a straight and level condition can result in an initial acceleration or a high path angle climb/descent. Hence, in order to avoid confusion, this maneuver requires an initial and terminal maneuver. Thus three phases are required to execute this maneuver.

1. A trajectory beginning at straight and level flight at the desired Mach-altitude pair and ending at a high-g level turn with all control surfaces and throttle active.

2. Constant thrust windup trajectory.

3. Terminal maneuver at constant altitude transferring the vehicle from the level turn at constant thrust conditions to straight and level flight.

A typical constant thrust windup turn trajectory is given in Fig. 3.5.

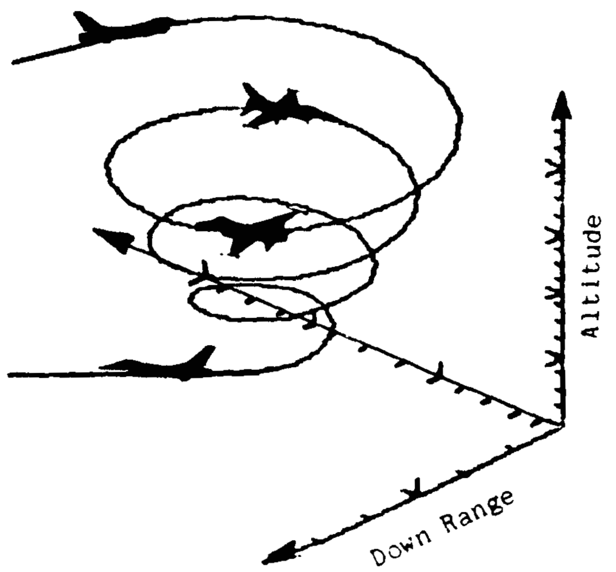

Figure 3.5. Constant Thrust Windup Turn Trajectory Descending Flight.

3.2.7 Constant Dynamic Pressure and Constant Load Factor Trajectory

This maneuver is initiated at a predetermined load factor, Mach number, and dynamic pressure. Thus, the initiation of this maneuver is not necessarily the wings-level condition. This maneuver can be either an ascending or descending at a specified Mach number rate. Dynamic pressure and load factor are held constant throughout the maneuver. Altitude is gained or lost to maintain dynamic pressure with changing Mach number.

As in the maneuver 3.2.6, this trajectory also requires three phases. The first is a level turn to achieve the required load factor from straight and level flight at the desired Mach-altitude pair. The third phase restores the aircraft to straight and level flight at the final Mach-altitude condition. Both these maneuvers can be constructed by interpolating between the stored trim data points at the current Mach-altitude-load factor conditions. In the following we shall discuss the constant dynamic pressure-constant load factor trajectory modeling. Note that this development does not depend explicitly on the load factor. Thus, this model is valid for all load factors including a constant unity load factor, wings level, constant dynamic pressure trajectory.

The dynamic pressure, Q is given by

$$Q = \frac{1}{2}\rho(h) \cdot V^2 \tag{3.32}$$

Differentiating the expression (3.32) with respect to time and using the altitude rate equation, with $\dot{Q} = 0$, one has

$$\frac{1}{2}\frac{\partial\rho}{\partial h} V^3 \sin\gamma + \rho(h)\dot{V} = 0$$

or

$$\dot{V} = -\frac{1}{2\rho}\frac{\partial\rho}{\partial h}V^2\sin\gamma \tag{3.33}$$

Since the Mach number is given by

$$M = V/C(h),$$

in order to maintain a desired Mach rate, one must have

$$\dot{M} = \frac{\dot{V}}{C} - \frac{V^2}{C^2}\frac{\partial c}{\partial h}\sin\gamma$$

from which

$$\dot{V} = \dot{M}C + \frac{V^2}{C}\frac{\partial c}{\partial h}\sin\gamma \tag{3.34}$$

Equating the expressions (3.33) and (3.34), one has

$$\gamma = \operatorname{Sin}^{-1}\left[\frac{-\dot{M}\,C}{\left(\frac{1}{2\rho}\frac{\partial\rho}{\partial h} + \frac{1}{c}\frac{\partial c}{\partial h}\right)V^2}\right] \tag{3.35}$$

There are two important conclusions that can be drawn from the expression (3.35)

1. Since $\frac{\partial\rho}{\partial h}$ and $\frac{\partial c}{\partial h}$ are negative (density and speed of sound decrease with increasing altitude), a positive $\dot{M}$ will result in a climbing trajectory while a negative $\dot{M}$ will yield a descending path.

2. This maneuver cannot be flown at altitudes where $\frac{\partial\rho}{\partial h}$ and $\frac{\partial c}{\partial h}$ are nearly zero unless the desired Mach rate is also zero.

As before, the altitude rate equation

$$\dot{h} = V\sin\gamma \tag{3.36}$$

may be numerically integrated over a small time step to obtain the new altitude. The actual throttle setting is again computed from the level turn trim thrust and throttle setting at the current Mach-altitude-load factor as follows.

$$T_{max} = T_{trim}/\eta_{trim} \tag{3.37}$$

$$T = [g - \frac{1}{2\rho}\frac{\partial\rho}{\partial h}V^2]\frac{m\sin\gamma}{\cos\alpha} + \frac{D}{\cos\alpha} \tag{3.38}$$

$$\eta_{actual} = T/T_{max} \tag{3.39}$$

The angle of attack and drag in the expression (3.38) are the interpolated values from the trim data base at the current Mach-altitude-load factor. The Mach number as a function of time is obtained from

$$M = M_o + \dot{M}t \tag{3.40}$$

The command body rates and open loop control surface deflections are again the interpolated values from the trim data base.

3.2.8 Constant Reynolds Number and Constant Load Factor Trajectory

This maneuver is initiated at a predetermined load factor, Mach number and Reynolds number. Thus, the initiation of this maneuver is not necessarily the wings-level condition. This maneuver can be either ascending or descending at a specified Mach number rate. Reynolds number and load factor are held constant throughout the maneuver. Altitude is gained or lost to maintain Reynolds number with changing Mach number.

This maneuver model is different from 3.2.7 only in the way that one computes the flight path angle and the throttle setting. Hence only these two aspects will be discussed in the following. As in maneuver 3.2.7, the modeling does not depend explicitly on the load factor. Consequently, the following development is valid for all load factors including a wings level, unity load factor - Constant Reynold's number trajectory.

The Reynold's number, Re is given by

$$Re = \frac{VD\rho(h)}{\mu(h)}\text{, where } \mu \text{ is the Viscosity of atmosphere} \tag{3.41}$$

Differentiating the expression (3.41) with respect to time and using the altitude rate equation, with $\dot{R}e = 0$; one has

$$\dot{V} = \left(\frac{1}{\mu}\frac{\partial\mu}{\partial h} - \frac{1}{\rho}\frac{\partial\rho}{\partial h}\right)V^2 \sin\gamma \tag{3.42}$$

Equating the expression (3.42) to equation (3.34),

$$\gamma = \sin^{-1}\left[\frac{\dot{M}C}{\left(\frac{1}{\mu}\frac{\partial\mu}{\partial h} - \frac{1}{\rho}\frac{\partial\rho}{\partial h} - \frac{1}{C}\frac{\partial c}{\partial h}\right)V^2}\right] \tag{3.43}$$

As in the constant dynamic pressure, constant load factor flight test trajectory, we note that this maneuver cannot be flown at altitudes where $\frac{\partial\mu}{\partial h}$, $\frac{\partial\rho}{\partial h}$ and $\frac{\partial c}{\partial h}$ are nearly zero unless the desired Mach rate is also zero. The actual throttle setting can be computed from the level turn trim thrust and throttle setting at the current Mach-altitude-load factor as follows.

$$T = \left[\left(\frac{1}{\mu}\frac{\partial\mu}{\partial h} - \frac{1}{\rho}\frac{\partial\rho}{\partial h}\right)V^2 + g\right]\frac{m\sin\gamma}{\mathrm{Cos}\alpha} + \frac{D}{\mathrm{Cos}\alpha} \tag{3.44}$$

$$\eta_{actual} = T\,\frac{\eta_{trim}}{\eta_{trim}} \tag{3.45}$$

To facilitate easier computations, a FORTRAN program has been written to generate the required commands and open loop control settings given the appropriate data. A listing of this code is given in Appendix C.

SECTION 4

MANEUVER AUTOPILOT DESIGN

The previous section described the required maneuver modeling, whereby for eight chosen maneuvers, a subset of the outputs are constrained to prespecified time histories. For the control analysis and design done in this study to have any value when applied to the F-15 nonlinear simulation or the actual aircraft, consistent values for all of the dynamic states and corresponding control values along the trajectory must be found. There are at least two straightforward ways to generate the required reference states and controls. First, one could iteratively simulate with the nonlinear model until an open loop law approximates the desired output time histories. This could be done systematically with numerical nonlinear optimization, using a parameterization of the control surface and thrust time histories. Or secondly, one can trim the nonlinear simulation at a number of conditions close to the desired trajectory and approximate the dynamic reference trajectory from these trim values. The latter approach was chosen both because of the completeness and flexibility of this tabular representation of the nonlinear aircraft characteristics, and because of the connection with the perturbation trim controllers designed to work along with the reference trajectory commands. It should also be pointed out that this "static" approach eliminated the need for any nonlinear simulation during the control design stage, apart from execution of a linearizing program [11] which contains the nonlinear F-15 aircraft equations.

The next subsection shows how a table of trim values can be used to develop a "linear model" of the entire F-15 flight test system for design and evaluation of the aircraft dynamic response in specified nonlinear maneuvers. A second subsection outlines two different linear control design techniques, evaluating their strengths and weaknesses, giving perturbation controller designs using these two techniques. A final subsection presents an assessment and extension of the nonlinear prelinearizing control technique [12], the application of which will be demonstrated in the next study phase, along with linear gain scheduled controllers, on the full nonlinear dynamic simulation.

4.1 THE F-15 FLIGHT TEST SYSTEM "LINEAR" MODEL

It must be emphasized that while the control design approaches demonstrated in this work are based on linear models, the maneuvers desired are highly nonlinear. As discussed above, the nonlinear characteristics of the F-15 are condensed into a table of trim values, which when properly used with linear perturbation controllers gives a linear time varying simulation which accurately represents the nonlinear aircraft response through the nonlinear maneuvers. Adequate control through the nonlinear maneuvers requires not only consistent open loop reference commands but linear perturbation gain-scheduled controllers as well. The gain-scheduled perturbation controllers are designed efficiently by decomposing the desired eight maneuvers into 15 linear design points for both the fixed and variable throttle cases.

4.1.1 The F-15 Nonlinear Tabular Model

The nonlinear dynamics of the F-15 can be represented over the envelope with a sufficient number of trim values $\bar{X}$ and $\bar{U}$: 145 points were stored, distributed as shown on the altitude-Mach plane in Figure 4-1.

A much coarser grid of flight conditions, than shown in this figure for the reference trajectory, was used for the linear perturbation models about the trajectory, and consequently in the linear control design stage. Table 4-1 shows the coarse discretization considered. Since it becomes increasingly difficult to trim the aircraft, particularly at high load factors, in the off-diagonal points in the altitude-Mach plane, only five conditions, the diagonal ones indicated in Table 4-1, were used with the three different load factors -- 1g, 3g, and 4g. The eight maneuvers were initiated at different conditions (see Section 3) to exercise controllers at various points on the flight envelope.

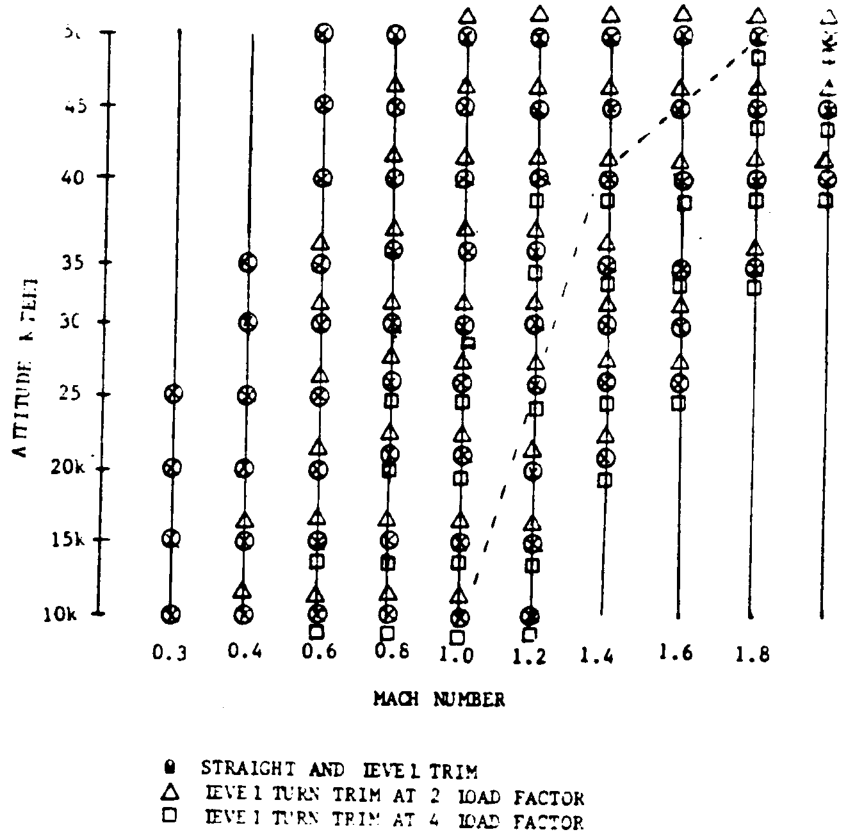

Figure 4-1. F-15 Nonlinear Tabular Model Trim Points

TABLE 4-1. F-15 LINEAR PERTURBATION MODEL AND DESIGN CONDITIONS

h/M	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
50k							X	
40k					X			
30k				X				
20k			X					
10k		X						

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The trim conditions used in this work are those with $\dot{\underline{x}} = 0$, namely the net forces and moments are zero. Since altitude rate is zero, a load factor greater than one automatically pulls the aircraft into a level turn trim.

The static nature of the trim points is overcome in constructing a dynamic reference trajectory by assuming a ramp in velocity for a specified time of transition between two trim points. This constant dV/dt yields the thrust adjustment necessary to add to the trimmed thrust for a "dynamic" reference thrust and $\underline{V}$ command. Conceptually, one could solve for an adjusted $\underline{x}$ command in all the states; however, the required computation and storage is large. Therefore, only the feedforward thrust (or throttle) command is adjusted as described here, and the linear perturbation controller generates the extra transient control commands necessary for all the states to transition between the trim points. This mechanization is discussed more fully in the next subsection.

In summary, the nonlinear F-15 model required for eight nonlinear maneuvers has been represented by a tabular description of trim values of the nonlinear simulation at discrete points on the flight envelope. The number of points used to represent the reference command is much finer than for the linear models because the reference command effectively contains the nonlinear behavior in it. Load factors greater than one, level turn trims, have been used to generate the asymmetric models.

By keeping the linear perturbation model grid coarse, only a few perturbation controllers need be designed, reducing both linear model scheduling and gain scheduling requirements in the linear time-varying simulation validations. Nonlinear simulations in the next research phase will confirm whether or not the number of design points is sufficient. Accurately speaking, the "controller", is not merely the linear perturbation gains, but the way they are mechanized along with the reference commands.

4.1.2 Linear Perturbation Controllers

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Currently, control systems for nonlinear plants are synthesized using perturbation models or the so called linearized plant models in conjunction with the powerful linear system design approaches. The controllers so obtained may be termed Linear Perturbation Controllers to denote the linear nature of the controllers and to indicate their function, viz, controlling perturbations about the reference condition. If the system is required to track a given command, the perturbation models need to be generated at several operating points along the command history and controllers designed. In highly nonlinear systems such as aircraft, these controllers can display significant variations, often requiring these to be scheduled as a function of the independent variable.

The objective of the controller is to ensure that a given nonlinear system

$$\dot{X} = f(X,U) \tag{4.1}$$

follows a given trajectory $\underline{X}(t)$. Here $X \in \mathbb{R}^n$, $U \in \mathbb{R}^m$. To obtain the perturbation models or the linearized models, some points along the desired trajectory $\underline{X}(t)$ are selected, say $\underline{X}_1$, $\underline{X}_2$, $\underline{X}_3$ . . . . A set of controls corresponding to these points, $\underline{U}_1$, $\underline{U}_2$, $\underline{U}_3$ . . . . are next computed such that

$$f(\underline{X}, \underline{U}) = 0 \tag{4.2}$$

Note that this is not the only possible approach. If the desired trajectory satisfies $\dot{\underline{X}} = f(\underline{X},\underline{U})$ for nonzero $\dot{\underline{X}}$, then it can be used in the subsequent development.

To derive the perturbation model with state perturbations δX and control perturbations δU, let

$$
\begin{aligned}
X &= \underline{X} + \delta X \\
U &= \underline{U} + \delta U
\end{aligned}
\tag{4.3}
$$

Expanding the nonlinear system (4.1) about $\underline{X}$, $\underline{U}$ and retaining only the first order terms (this implies that the perturbation are small), one has

$$\delta \dot{X} = f_X \delta X + f_U \delta U \tag{4.4}$$

The subscripts denote partial derivative matrices. Note that f_X and f_U depend on $\underline{X}$, $\underline{U}$. The expression (4.4) describes a linear dynamic system for which a controller of the form

$$\delta U = K \delta X \tag{4.5}$$

can be designed at the operating points $\underline{X}_1$, $\underline{X}_2$, ...

Next, to ensure that the system transits through these operating points, the following procedure is setup.

Assume that a linear interpolation scheme between $\underline{X}_1$, $\underline{X}_2$, ... $\underline{X}_n$ adequately describes the desired trajectory. Further, assume that at any interpolated reference flight conditions $\underline{X}_j$, in between $\underline{X}_i$, $\underline{X}_{i+1}$; $f(\underline{X}_j, \underline{u}_j) \simeq 0$. In this case, the perturbation model (4.4) is given by

$$\delta\dot{X} = f_X\delta X + f_U\delta U - \dot{\underline{X}}(t) \tag{4.6}$$

Note that $\dot{\underline{X}}$ is a piecewise constant function and appears as a disturbance in the perturbation model.

As noted earlier, the perturbation controller is designed with $\dot{\underline{X}} = 0$. Recalling that

$$\begin{aligned} X &= \delta X + \underline{X} \\ U &= \delta U + \underline{U} \\ \dot{X} &= \delta\dot{X} + \dot{\underline{X}} \end{aligned} \tag{4.7}$$

Using (4.7) in (4.6), the linearized equations can be put in the form

$$\dot{X} = f_X(X-\underline{X}) + f_U(U-\underline{U})$$

or

$$\dot{X} = f_X X + f_U U - Z(t) \tag{4.8}$$

where

$$Z(t) = f_X\underline{X} + f_U\underline{U}$$

Similarly, the perturbation controller (4.5) becomes

$$U - \underline{U} = K(X-\underline{X})$$

or

$$U = K(X-\underline{X}) + \underline{U} \tag{4.9}$$

Expression (4.9) indicates the implementation of the linear perturbation controller, given in Figure 4-2. for clarity.

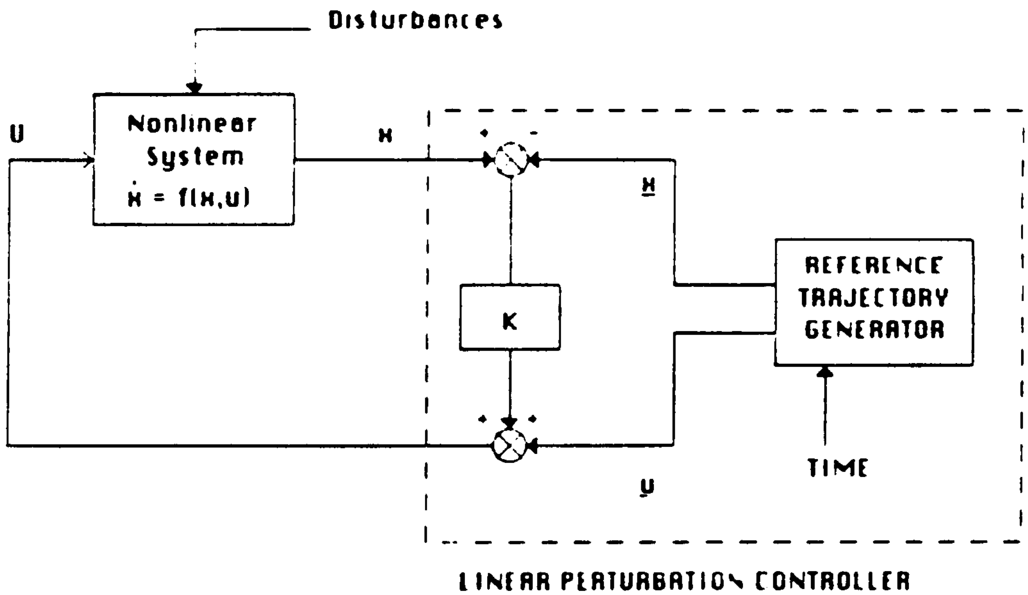

Figure 4-2. Implementation of the Linear Perturbation Controller

Note that the gain matrix K varies as a function of some scheduled variable. Expression (4.8) has an interesting interpretation, viz, when the perturbations about the desired path are small, it describes the nonlinear system dynamics with a high degree of fidelity. Hence, under closed loop control, the dynamics given by (4.8) will be very close to that of the original nonlinear system (4.1). This fact means that linear, time varying simulations can be mechanized in a straightforward way from the relationships and models discussed here. While section five reviews the concept of linear time-varying simulation before giving the validation results, it is convenient to continue our line of thought and go over the mechanization here in the maneuver autopilot design section.

4.1.3 Linear Time Varying Simulation

As noted elsewhere, for highly nonlinear systems such as aircraft, the gain matrix K in (4.9) would display large variations as a function of the flight condition. And hence, some type of scheduling strategy will be essential for the satisfactory operation of the control system. To evolve the scheduling strategy, it is desirable to have a simulation of the system which has lesser complexity than the original nonlinear system.

Examining expression (4.8) in view of the above, one finds that the partial derivative matrices f_X and f_U as functions of $\underline{X}$, $\underline{U}$ have already been computed at the controller design stage. The reference trajectory $\underline{X}$, $\underline{U}$ is also known. Since this expression describes the nonlinear system dynamics adequately for small perturbations, it may be used to develop a linear time varying simulation to evaluate the controller scheduling. Figure 4-3 gives the formal structure of the linear time varying simulation. This block diagram is structurally similar to the linear perturbation controller implementation given in Figure 4.2. The essential difference between them is that the nonlinear aircraft model has been replaced by a linear time-varying model with disturbance inputs. As mentioned in Section 4.1.2, $\underline{X}$ and $\underline{U}$ are linearly interpolated between time points. In order to simplify the mechanization, the partial derivative matrices f_X and f_U are stored at the same time points and linearly interpolated. Thus, along a contemplated maneuver, three or four $\underline{X}$, $\underline{U}$, points are chosen and the corresponding f_X, f_U, matrices are stored. Note that in the present analysis the $\underline{X}$, $\underline{U}$, points are chosen such that at an intermediate point $f(\underline{X}_j, \underline{U}_j) \simeq 0$. In the course of simulations, if it turns out that in order to track the required $\underline{X}$ history, the total control required is greater than that available, it is indicative that either the assumed maneuver time is unrealistic or that the model is inadequate or both.

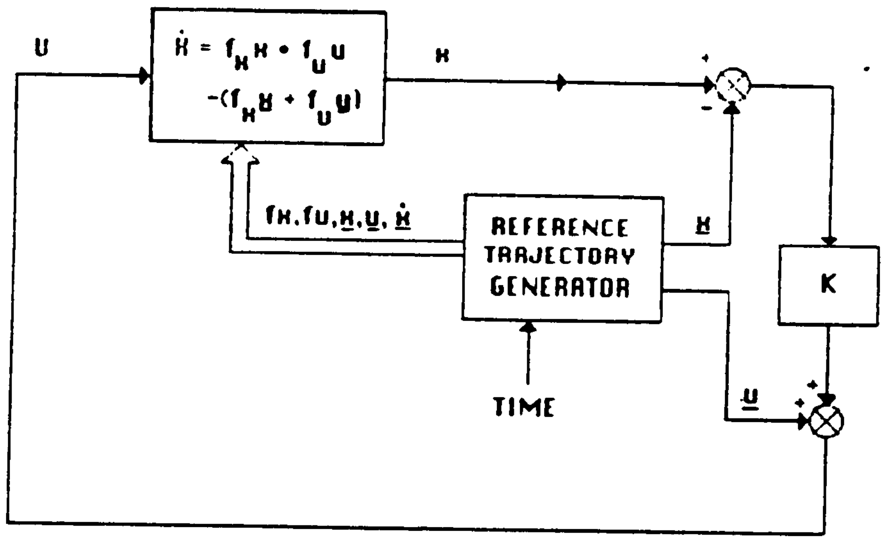

Figure 4-3. Linear Time Varying Simulation

A description of how a generic time varying simulation can be implemented in the MATRIX^{TM} SYSTEM_BUILD^{TM} model building and simulation program is given in Appendix D.

4.2 LINEAR DESIGN TECHNIQUES

Given a small set of linear trim conditions, linear perturbation controllers can be designed to track desired reference commands. The simplest practical controllers, once the outputs are augmented with appropriate integrators for desirable steady state tracking, are output feedback controllers. Two different output feedback approaches were evaluated, viz, eigenstructure assignment and the minimum error excitation technique.

4.2.1 Eigenstructure Assignment Design

As described in Section 2, the model through which the desired maneuver autopilots (MAP) must work includes the fully augmented aircraft: This actually makes the control design task more difficult than dealing only with the bare airframe. The combination of CAS states and integral error states give a considerable number of eigenvalues that are slow, and therefore must be moved, and also exhibit a reasonable degree of state coupling. This coupling results in some sensitivity of results to the choice of eigenspace requested. The model used and specific results are given in Appendix A. Complete details of this eigenassignment approach can be found in [13]. It is perhaps of interest to note that in addition to the capability to handle controller structure constraints, this technique can be modified to accept partial specification of eigenvectors. This feature can be valuable in high order systems. In summary, to employ this synthesis approach, the following are required.

(i) Based on the practical aspects of the problem, choose a minimal set of measurements which will permit the designer to achieve the desired performance. Introduce dynamic compensators such as integral feedbacks, lead-lag networks, etc., based on experience.

(ii) Choose a set of desired eigenvalues and eigenvectors equal to the number of outputs.

While the selection of desired eigenvalues is often apparent in a given problem, the desired eigenvectors are difficult to select. Three approaches were developed to help guide this choice, viz, minimally restructured eigenassignment, decoupling eigenassignment and dominant mode eigenassignment.

4.2.1.1 Minimally Restructured Eigenassignment

Since it is known that the closed loop eigenvectors lie in a subspace spanned by the columns of $(\lambda_i I-A)\ B^{-1}$, $i = 1, \ldots n$, linear combinations of these vectors were used as desired eigenvectors. The weights to be used in generating these linear combinations were constructed from the additional information that unassigned eigenvectors should be close to their open loop values in a least square sense.

4.2.1.2 Decoupling Eigenassignment

Since we are interested in having the least cross axis coupling in the controller as possible, the desired eigenvectors in the longitudinal channel may be chosen so that the responses from lateral channels are blocked, i.e., select eigenvectors as

$$\begin{bmatrix} (\lambda_i I-A) & B \\ C_{LAT} & 0 \end{bmatrix} \begin{bmatrix} v_i \\ w_i \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$v_d = \sum_{i=1}^{n} \alpha_i v_i$$

V_d are the desired eigenvectors. α_i are selected using the same criteria as in the minimally structure case. Though these two approaches could be made to work at each flight condition by iterating on the desired eigenvalues, they failed to easily produce a set of acceptable eigenvectors which could be used at other flight conditions. Next, partial specification of desired eigenvectors was attempted using the dominant mode approach.

4.2.1.3. Dominant Mode Eigenassignment

According to ref [13], complete specification of desired eigenvectors are neither necessary nor desirable. Depending on the states that should or should not participate in a given mode, appropriate entries in the eigenvectors are made ones or zeros, leaving other entries free. With these eigenvectors, the desired eigenvalues are moved as far left from the imaginary axis as possible with least change in the location of unplaced eigenvalues. The desired eigenvectors so obtained appeared to work over most flight conditions. Note, however, that extensive iterations on the desired eigenvalues may often be required to produce a satisfactory design.

4.2.1.4 Conclusions on Output Eigenstructure Assignment

Specific maneuver autopilot design results are discussed in Appendix A, along with the more complete description and evaluation of output eigenstructure assignment for application to flight test trajectory control, including difficulties in selecting desirable eigenvalues and eigenvectors. This approach demands several iterations to converge to a satisfactory design and does not appear to easily give suitable insight for output feedback design of high order multivariable systems which will be used at other operating points. If a rational method to generate an achievable set of eigenvectors is devised, this technique will be made more attractive. One possibility might be to generate gradients of the eigensystem between flight conditions and include this information in the single point design technique. The next two subsections describe two other techniques of output feedback gain solution.

4.2.2 Minimum Error Excitation Output Feedback Design

Following Kosut's [8] notation in describing his development of the minimum error excitation output feedback design method, for the linear system

$$\dot{x} = Ax + Bu,$$

$$y = Hx,$$

one first designs a full state LQ regulator

$$J = \frac{1}{2} \int_{o}^{\infty} (xH^T Q_y Hx + u^T Ru)dt,$$

with the optimal feedback control law $u^* = F^*x$.

Both because algebraic output feedback methods do not guarantee stability and because of the presence of slow closed loop full-state feedback modes (either neutrally stable unobservable modes or other sluggish phugoid like, spiral or integral error modes), it is desirable to design with a guaranteed stability margin [14, 15]. Specifying a stability margin of α ensures that the real parts of all closed loop roots are less than $-\alpha$. This is equivalent to optimizing the performance index

$$J = \frac{1}{2} \int_{o}^{\infty} e^{-2\alpha t}(xH^T Q_y Hx + u^T Ru)dt,$$

and can be accomplished by destabilizing the open loop plant by $\bar{A} = A + \alpha I$; solving for the corresponding optimal gains in the standard LQ problem, and using them with the original open loop dynamics matrix A. Costs were chosen according to Bryson's rule [15], the inverse of the squared deviation desired on inputs and outputs, with a scalar factor between Q and R to regulate the extent of high gain solution achieved.

A minimum norm output error feedback law can be determined from

$$u = C_y y, \quad \text{with}$$

$$C_y = H^+ F^*,$$

where H^+ is the pseudoinverse of H. This is merely a least squares projection of the full state gains onto the output subspace.

The sensitivity of the projection described above can be minimized by doing a weighted least squares, where the weight is the closed loop state covariance excited by a unit error density. One merely solves the Lyapunov equation

$$(A + BF^*)P + p(A + BF^*)^T + I = 0,$$

to obtain the constrained gain

$$F_y = F^*PH^T\,(HPH^T)^{-1}H, \text{ or}$$

$$C_y = F^*PH^T(HPH^T)^{-1}$$

The destabilized open loop plant $\bar{A}$ was used instead of A in the Lyapunov equation solution to retain as much of the full-state law guaranteed stability margin as possible.

Maneuver autopilots were designed at all flight conditions within two iterations using the above output feedback design procedure. The design criterion were

$Re(\lambda_i) < -.2 \Rightarrow$ a 5 second maximum time constant in tracking, and

$\xi > .7 \Rightarrow$ low overshoot.

With the integral error states and general low frequency oscillatory poles pairs due to lateral/longitudinal coupling, the plant is not a simple one to control. Since Mach and load factor were chosen as the scheduling variables, 15 designs were generated - five designs at three load factors shown in Table 4-2. The state and control weighting matrices used in this synthesis is listed in Appendix E. The corresponding output feedback gains are also given in this appendix.

Since the zoom-and-push-over and excess thrust windup turn require fixed throttle, 15 more designs were generated without this control, also shown in Table 4-2.

Typical initial condition responses in a straight and level flight condition at 40K feet and Mach of 1.4 are shown in Figure 4-4.

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TABLE 4-2. SLOWEST MODE BEHAVIOR AT ALL DESIGN CONDITIONS (Subscript 1 corresponds to the design with all controls, subscript 2 corresponds to the design without throttle control)

h,m LOAD FACTOR	h = 10000' M = 0.8	h = 20000' M = 1.0	h = 30000' M = 1.2	h = 40000' M = 1.4	h = 50000' M = 1.6
1	λ_1 = -0.277 ξ_1 = 0.996 λ_2 = -0.28 ξ_2 = 1	λ_1 = -0.289 ξ_1 = 0.97 λ_2 = -0.257 ξ = 1	λ_1 = -0.3 ξ_1 = 0.95 λ_2 = -0.234 ξ_2 = 1	λ_1 = -0.308 ξ_1 = 0.945 ξ_2 = -0.2276 ξ_2 = 1	λ_1 = -0.292 ξ_1 = 0.94 λ_2 = -0.219 ξ_2 = 1
2	λ_1 = -0.28 ξ_1 = 0.99 λ_2 = -0.288 ξ_2 = 0.99	λ_1 = -0.26 ξ_1 = 0.94 λ_2 = -0.268 ξ_2 = 0.947	λ_1 = -0.23 ξ_1 = 0.9 λ_2 = -0.254 ξ_2 = 0.947	λ_1 = -0.2274 ξ_1 = 0.2 λ_2 = -0.276 ξ_2 = 0.958	λ_1 = -0.225 λ_1 = -0.858 λ_2 = -0.242 ξ_2 = 0.88
4	λ_1 = -0.267 ξ_1 = 0.99 λ_2 = -0.28 ξ_2 = 0.99	λ_1 = -0.23 ξ_1 = 0.92 λ_2 = -0.23 ξ_2 = 1	λ_1 = -0.209 ξ_1 = 0.866 λ_2 = 0.243 ξ_2 = 0.95	λ_1 = 0.17 ξ_1 = 0.98 λ_2 = -0.2405 ξ_2 = 1	λ_1 = -0.116 ξ_1 = 0.95 λ_2 = -0.209 ξ_2 = 0.895

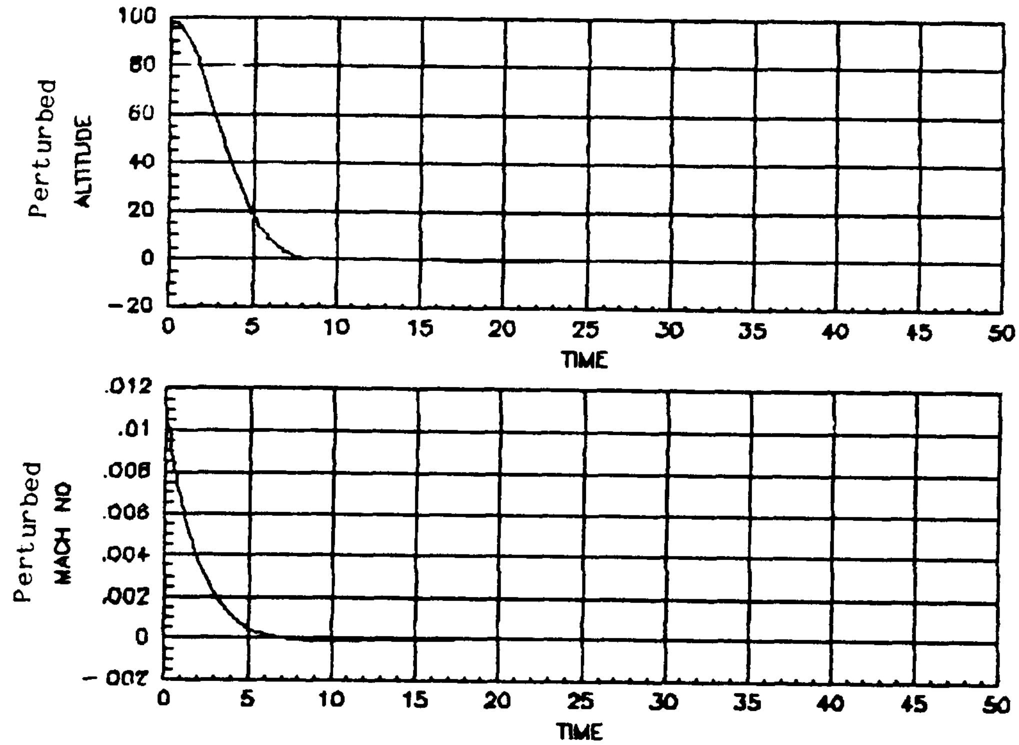

Figure 4-4. Initial Condition Response for the Output Feedback Minimum Error Excitation Perturbation Controller (Reference Condition H = 40k', Mach = 1.4, Straight and Level Flight)

Section 5 gives the tracking behavior of the output feedback minimum norm controllers in the eight maneuvers of interest.

4.3 NONLINEAR FLIGHT TEST TRAJECTORY CONTROLLERS

Research on nonlinear flight test trajectory control (FTTC) design was conducted with the goal of completely eliminating the need for gain scheduling. A brief literature review is given below, outlining how recent theoretical work can be applied to the FTTC problem before a demonstration problem is given to illustrate the approach.

This research deals with the synthesis of nonlinear flight test trajectory controllers using the recent results in prelinearizing transforms due to Meyer [17-33] and singular perturbation theory [34-36]. The use of singular perturbation theory in this problem simplifies the command generation scheme in addition to providing a consistant approach for eliminating ignorable state variables. The prelinearizing transformations are more transparent in this formulation. The slow-fast computations are clearly separated and can be carried out at different rates on the flight control computer. It is interesting to note that in Ref. 21, even though the controller development did not make use of singular perturbation theory, the time-scale separation formed a basis for implementation on the flight control computer. A schematic block diagram of the slow-fast flight test trajectory controller is given in Figure 4-5.

Flight test controller synthesis will be developed for the F-15 fighter aircraft in the next contract phase. For the F-15 and most fighter aircraft, it can be assumed that the aircraft under consideration has the four usual controls: throttle, aileron, rudder and elevator. The objective of the flight test controller is to track the given commands in airspeed, angle of attack, angle of sideslip and altitude in presence of disturbances and modeling imperfections. It is clear that the commanded trajectory has to be executable by the aircraft under consideration. Note that the flight test control problem discussed here is distinct from those described by Meyer, et. al. [20-22] since, in their work, the trajectory to be followed consisted of the three position components specified as functions of time.

Modeling and time-scale separation can be exploited to a considerable degree in this approach. The mechanization details of prelinearization and the slow-fast controller synthesis for general flight test maneuvers will be given in the next project phase based on the problem formulation developed here.

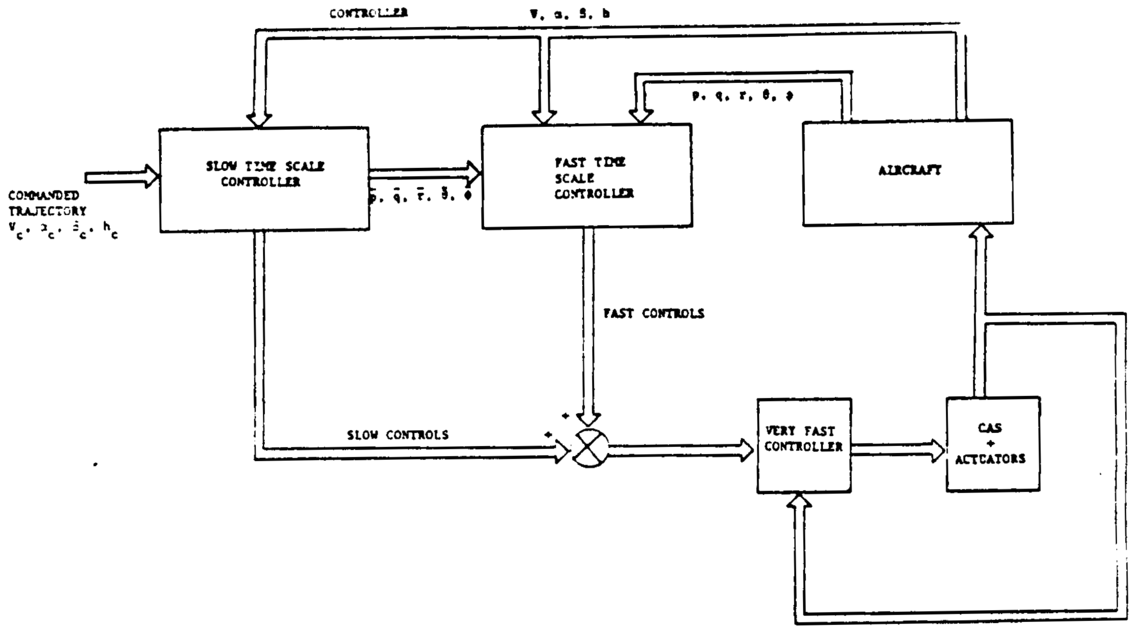

Figure 4-5. Singular Perturbation Nonlinear Flight Test Trajectory Controller.
Slow states: V, α, β, h
Fast states: p, q, r, θ, ϕ
Very fast states: CAS and Actuator states

An illustrative example of this nonlinear controller approach is given in Appendix B.

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SECTION 5

SIMULATION AND EVALUATION

The performance of perturbation controllers for initial condition errors was verified during the design phase. Some techniques for evaluating their tracking performance will be discussed in this section. Though it is clear that the actual performance of these controllers can only be assessed with the full nonlinear aircraft model, it is desirable to introduce an intermediate validation phase to ensure a smooth transition from perturbation controller design to full nonlinear simulation. It should be emphasized at the outset that the simulations discussed here are approximate and consequently the tracking performance will differ in the nonlinear simulation validation in the next study phase.

5.1 MANEUVER SIMULATION

Originally, it was decided to carry out a linear time varying simulation of the systems using linearized aircraft models along the desired flight-test trajectory as discussed in Appendix D. For a two state variable model analyzed in Appendix B, the computing time was small. However, the aircraft and CAS system has 31 states and continuous interpolation was found to be extremely time consuming. In view of the excessive computational effort required, and the limited value of the information obtained, it was then decided to switch models and controller gains along a desired flight test trajectory. This approach introduced artificial gain switching transients and also led to misleading conclusions. Hence whenever feasible, the simulations discussed here used one interpolated model, and gains based on the flight condition halfway through the maneuver. With this approach, the modeling inaccuracies will be almost equally distributed throughout the maneuver.

It should be emphasized that the simulations with linearized models will test only the feedback controller portion of the maneuver autopilot. The open loop control histories generated from maneuver modeling can be tested only during the full nonlinear simulation of aircraft and CAS.

5.2 MANEUVER SIMULATION MECHANIZATION

The linear perturbation equations used for design have been discussed in Section 4. In this section, these will be modified to generate linear simulations. The linearized aircraft with CAS is of the form

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

$$\delta y = H\delta x$$

The output feedback perturbation controller is of the form

$$\delta u = C_y \delta y.$$

Expanding the perturbation equations back out gives

$$\dot{x} - \dot{\underline{x}} = F(x-\underline{x}) - GC_yH(x-\underline{x})$$

$$\dot{x} = (F - GC_yH)x - [(F-GC_yH)\underline{x} - \dot{\underline{x}}],$$

from which the maneuver simulations can be mechanized. Note that $\dot{\underline{x}}$ can be viewed as a disturbance (and neglected) or as a part of the external reference command. For the high speed maneuvers simulated here $\dot{\underline{x}}$ clearly cannot be ignored, but were computed numerically with a forward differencing of $\underline{x}$.

5.3 MANEUVER SIMULATION RESULTS

As discussed earlier, $\dot{\underline{x}}$ was computed numerically from $\underline{x}$ and used as part of the reference command. Since $\underline{x}$ has corners, there are jumps, or spurious step inputs due to the discontinuities in $\dot{\underline{x}}$. Using a smooth $\underline{x}$ from quadratic or cubic spline fits to the trim points $\underline{x}_i$ will remedy this problem; however, the effects of the discontinuities can clearly be seen in the tracking trajectories in this subsection.

In the following, typical simulation results for each flight test trajectory will be presented. The flight conditions in these simulations are chosen so that the maneuver autopilot is exercised over nearly the entire aircraft envelope. Except where indicated, in the plots that follow, the dotted lines denote the commanded variables generated from the maneuver modeling program while the solid line represents the trajectory evolution from the linear simulation.

5.3.1 Transient Trajectory

In this simulation, a transient trajectory is setup to transfer the aircraft from straight and level flight conditions at 20000' altitude and Mach 0.8 to straight and level flight conditions at 30000' altitude and Mach 1.2 in 60 seconds. The simulation results are presented in Figs. 5-1 through 5-3. The altitude tracking is very good. However, the throttle history in Fig. 5-3 indicates that during the first five seconds, the controller commanded a negative throttle. This is caused by the nonminimum phase behavior of the aircraft, clearly discernable in the Mach number and angle of attack histories. In the actual implementation, the commanded altitude can be modified to include an initial descend leg in order to compensate for the nonminimum phase behavior. Alternately, the commanded Mach number can be modified to have an initial decreasing segment. In any case, mere command modification would fix the initial negative throttle difficulty.

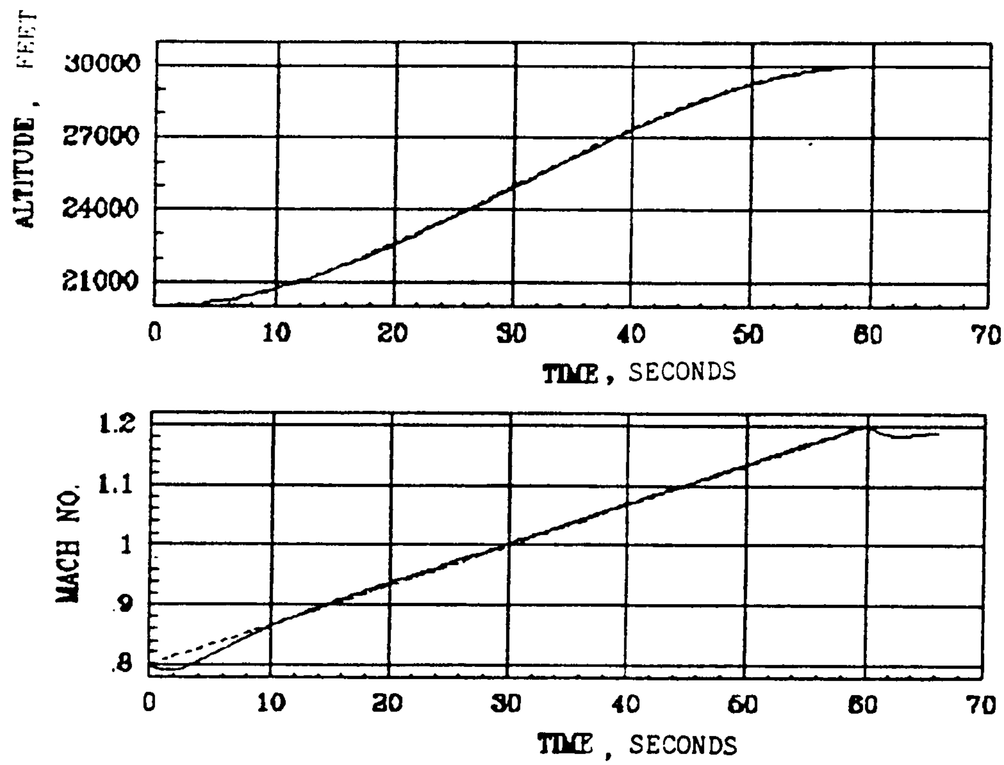

Figure 5-1. Altitude and Mach Number Evolution Along the Transient Trajectory

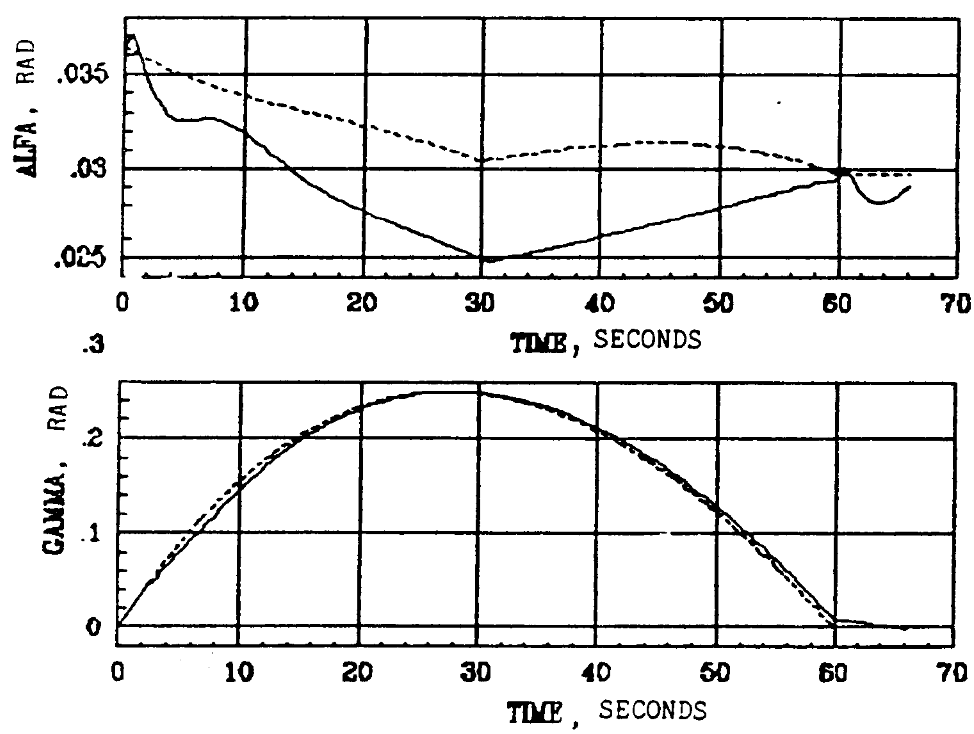

Figure 5-2. Angle of Attack and Flight Path Angle Evolution Along the Transient Trajectory

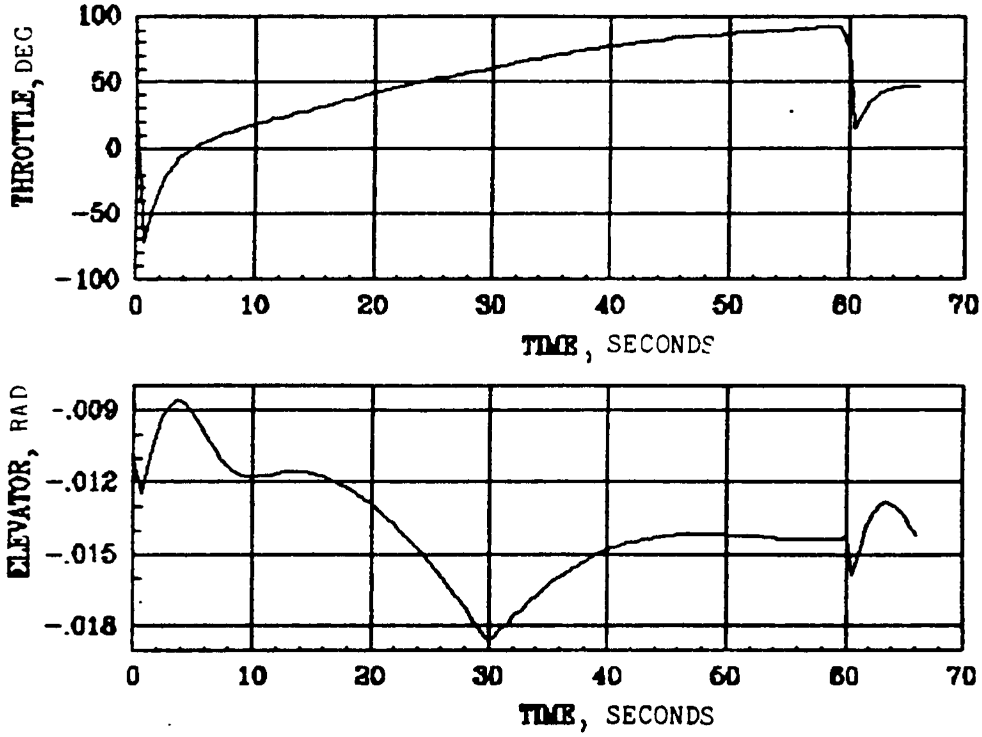

Figure 5-3. Throttle and Elevator Deflection Along the Transient Trajectory.

5.3.2 Level Acceleration

A level acceleration flight test trajectory at 30000' altitude is considered here. The aircraft is required to accelerate from Mach 0.9 to Mach 1.2 in 60 seconds. The tolerence on altitude is $\pm$ 50' while Mach number error should be within $\pm$0.01. The simulation results for this maneuver are presented in Figs. 5-4 through 5-6. The Controller was able to maintain the altitude within $\pm$0.1 feet while tracking the Mach number within the given specifications. The throttle and elevator deflections given in Fig. 5-6 are well within the saturation levels. From the maximum throttle requirment in this maneuver, it appears that the maneuver time could be decreased by about 20 seconds.

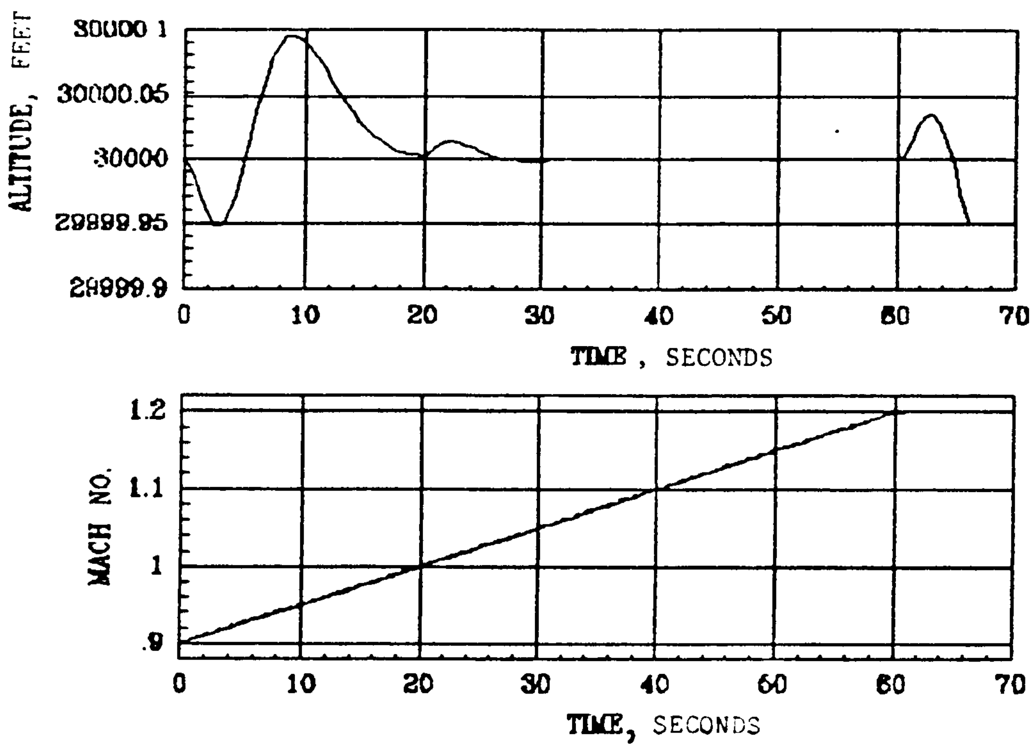

Figure 5-4. Altitude and Mach Number Evolution Along the Level Acceleration Flight Test Trajectory.

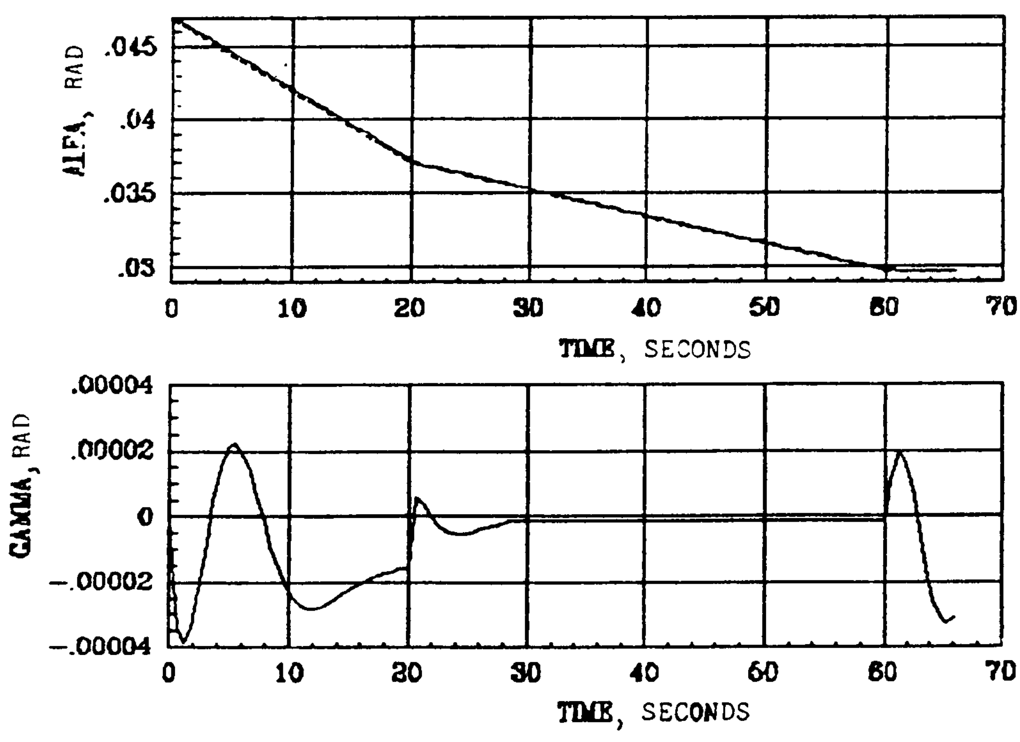

Figure 5-5. Angle of Attack and Flight Path Angle Evolution Along the Level Acceleration Flight Test Trajectory.

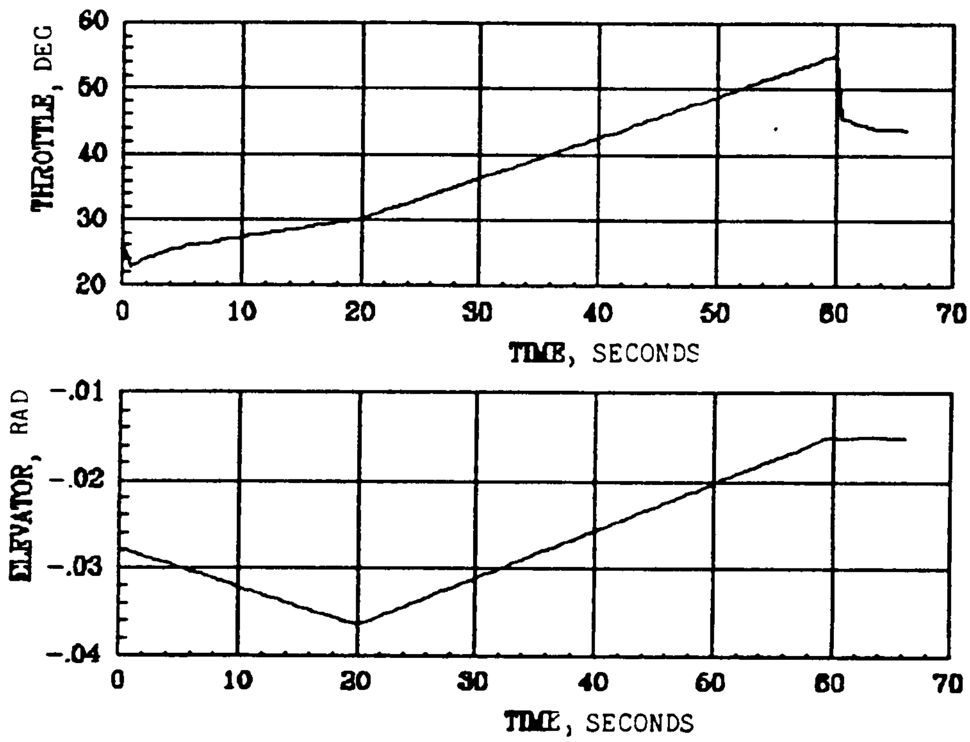

Figure 5-6. Throttle and Elevator Deflection Along the Level Acceleration Flight Test Trajectory.

5.3.3 Pushover, Pullup

This maneuver was initiated at 30000' altitude and 0.8 Mach straight and level flight condition. The objective is to track a piewise linear angle of attack history given in Fig. 5-8 while maintaining the Mach number constant at the initial value. The results of the maneuver simulation are given in Figs. 5-7 through 5-9. From Fig. 5-7, it can be seen that the Mach number error is within 0.001 of the commanded value. The angle of attack tracking error is less than 0.2° throughout the maneuver. The throttle history given in Fig. 5-9 shows a small negative region at the imitation of pullup at 30 seconds and is primarily due to the corner in the angle of attack command. Smoothing this corner in the final mechanization would eliminate this negative throttle region.

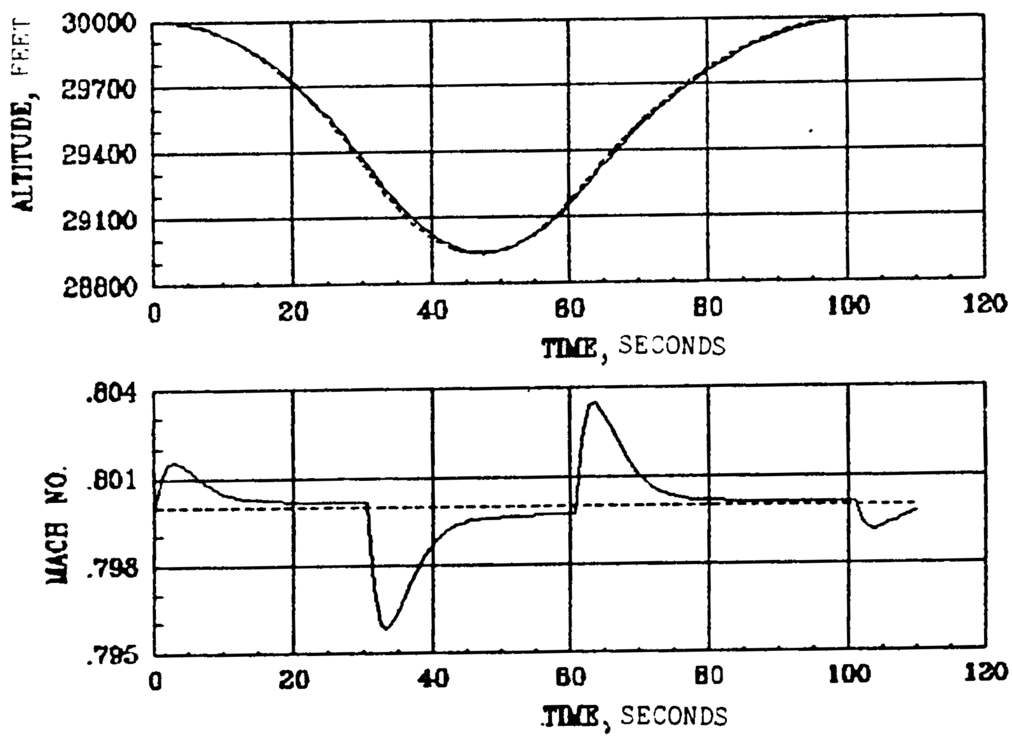

Figure 5-7. Altitude and Mach Number Evolution Along the Pushover/Pullup Flight Test Trajectory

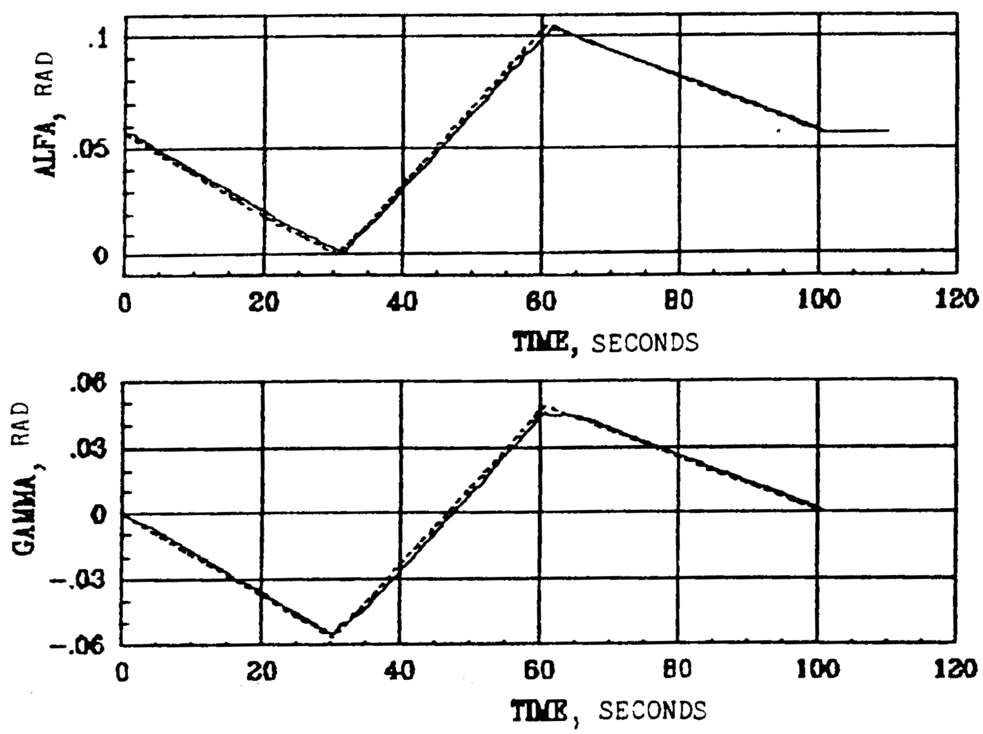

Figure 5-8. Angle of Attack and Flight Path Angle Evolution along the Pushover/Pullup Flight Test Trajectory

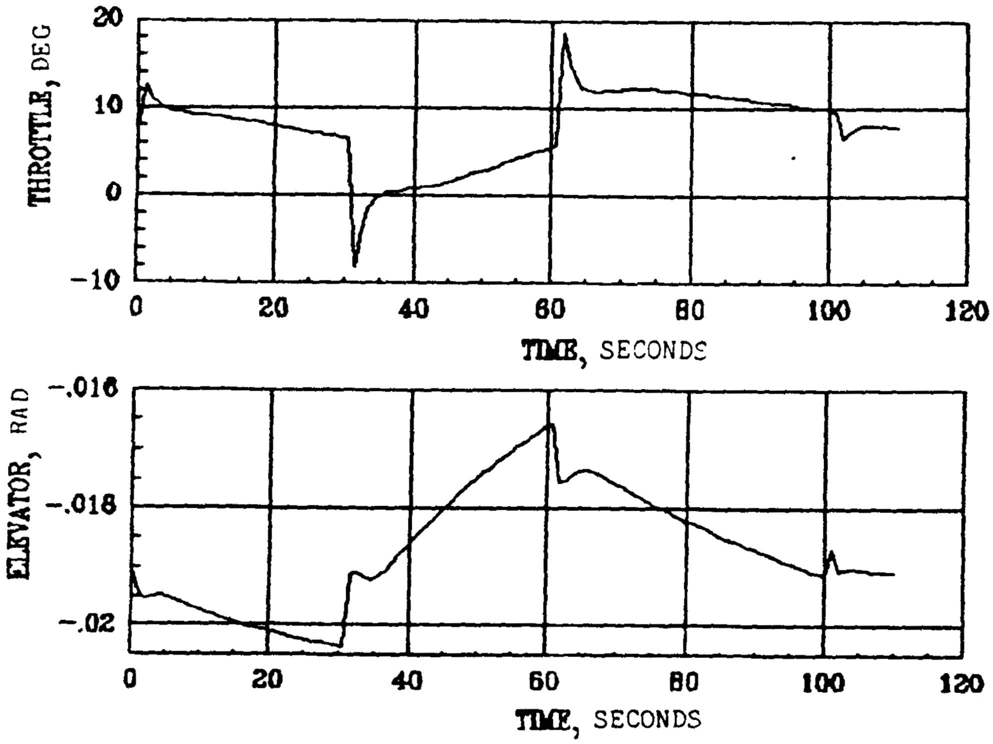

Figure 5-9. Throttle and Elevator Deflection along the Pushover/Pullup Flight Test Trajectory.

5.3.4 Zoom and Pushover

As noted in the maneuver modeling, this flight test trajectory is executed in three phases. In the first phase the aircraft is transferred from straight and level flight conditions to the beginning of the zoom and pushover parabolic trajectory. The second phase consists of the zoom and pushover trajectory while the third phase restores the aircraft to the original straight and level flight condition. During the first and third phases all the controls are active, but the throttle is fixed during the zoom and pushover trajectory.

In the present case, the aircraft is first trimmed to fly straight and level at 30000' altitude and Mach 0.4. An initial transient trajectory is then executed with all controls active until the point marked A in Fig. 5-10. At this point, the throttle is fixed and the aircraft executes the parabolic zoom and pushover trajectory until the point B in this figure. The throttle is released at point B and the aircraft performs another transient maneuver to restore it to the original conditions.

Since the controller performance along the transient trajectory has already been investigated in Section 5.3.1, the tracking performance along the zoom and pushover trajectory will only be demonstrated here. The aircraft begins the zoom and pushover maneuver at about 28000' and Mach 0.45 and completes the maneuver at about the same conditions. The controller performance is illustrated in Figs. 5-10 through 5-12. The conditions at the apex of the parabola is of particular interest in this maneuver. From Fig 5-11, it can be observed that the angle of attack at the apex is within 0.005 radian of the required value. The altitude error is within 50' at the apex and the Mach number is within 0.05 of the required value. Initial transients in altitude and Mach number can be seen at point A in Fig. 5-10. These are essentially due to the availability of just one control variable, the elevator, to track three state variables: altitude, Mach number and angle of attack. Thus, an initial condition error on altitude would propagate to Mach number and angle of attack channels and vice versa.

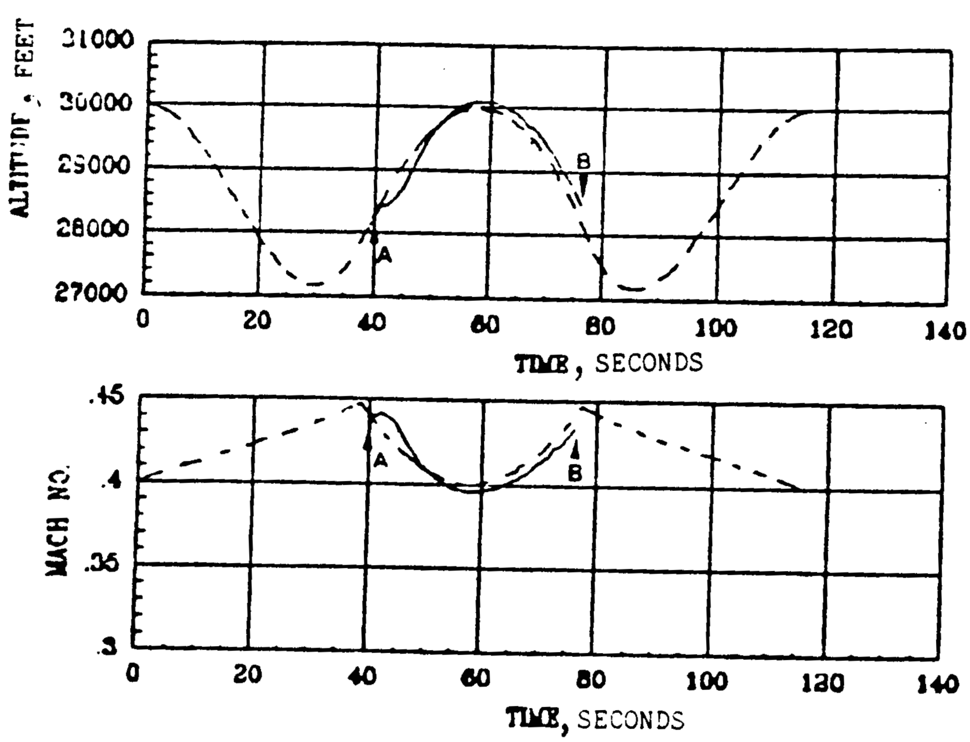

Figure 5-10. Altitude and Mach Number Evolution along the Zoom and Pushover Flight Test Trajectory.
A: Throttle Fixed
B: Throttle Released

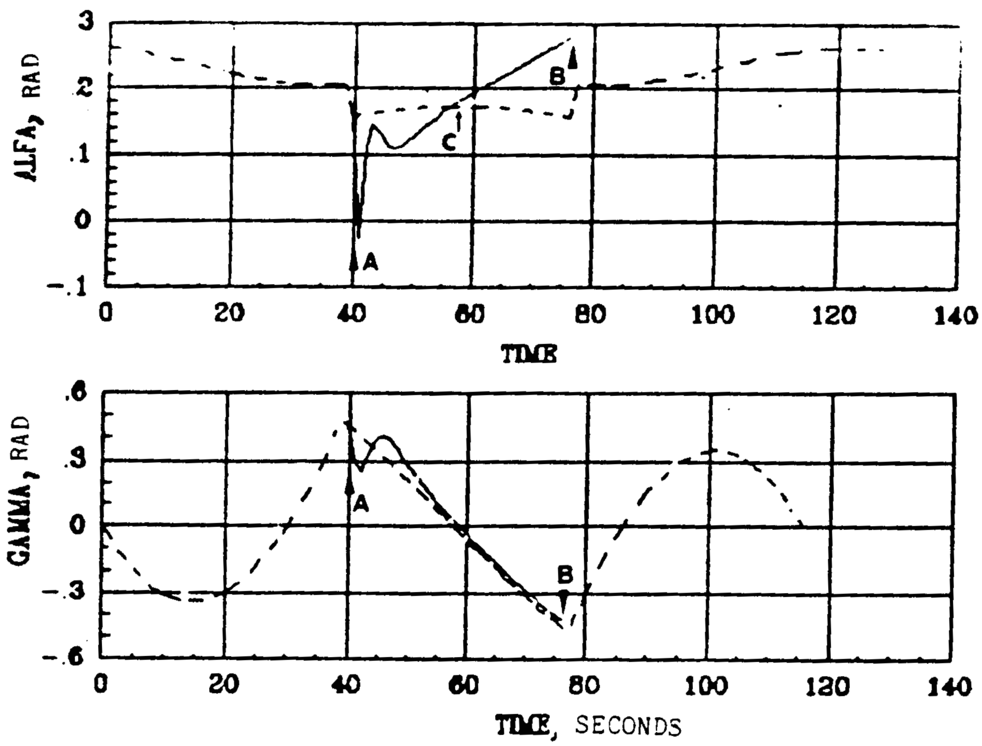

Figure 5-11. Angle of Attack and Flight Data Angle along the Zoom and Pushover Flight Test Trajectory.
A: Throttle Fixed
B: Throttle Released
C: Apex of the Parabola

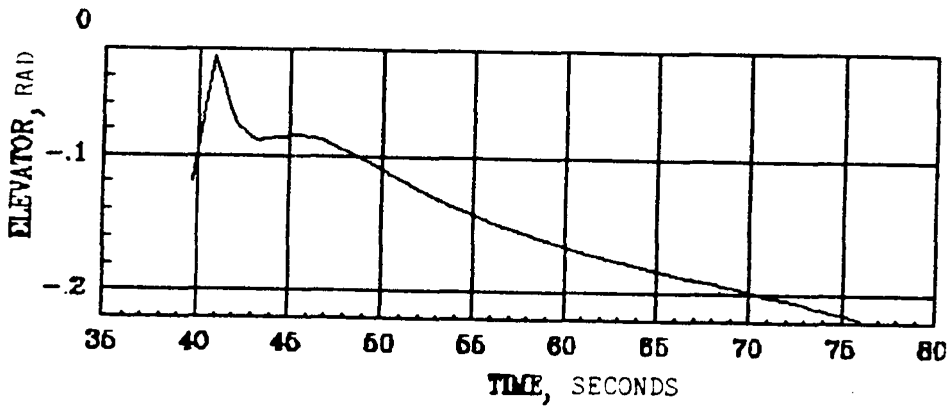

Figure 5-12. Elevator Deflection along the Zoom and Pushover Flight Test Trajectory.

5.3.5 Excess Thrust Windup turn

The results for an excess thrust windup turn trajectory at 40000' altitude and Mach 1.4 are given in Figs. 5-13 through 5-19. The altitude and Mach number were required to be constant throughout the windup turn trajectory, while tracking an angle of attack command as shown in Fig. 5-14. The aircraft roll altitude in this maneuver is close to 70° and results in a highly coupled model to be controlled by the maneuver autopilot. It can be observed that the maneuver autopilot maintained the altitude within $\pm 5'$ and the Mach number error is within ± 0.002. Except at the beginning and the end of the maneuver, the angle of attack error is within 0.005 radian of the commanded value. For about 10 seconds during the beginning and end of the maneuver, the rudder deflection is close to 12° while in the high roll attitude region, an elevator deflection of nearly 17° was demanded. This indicates that at the present flight conditions, a less stringent maneuver should be attempted.

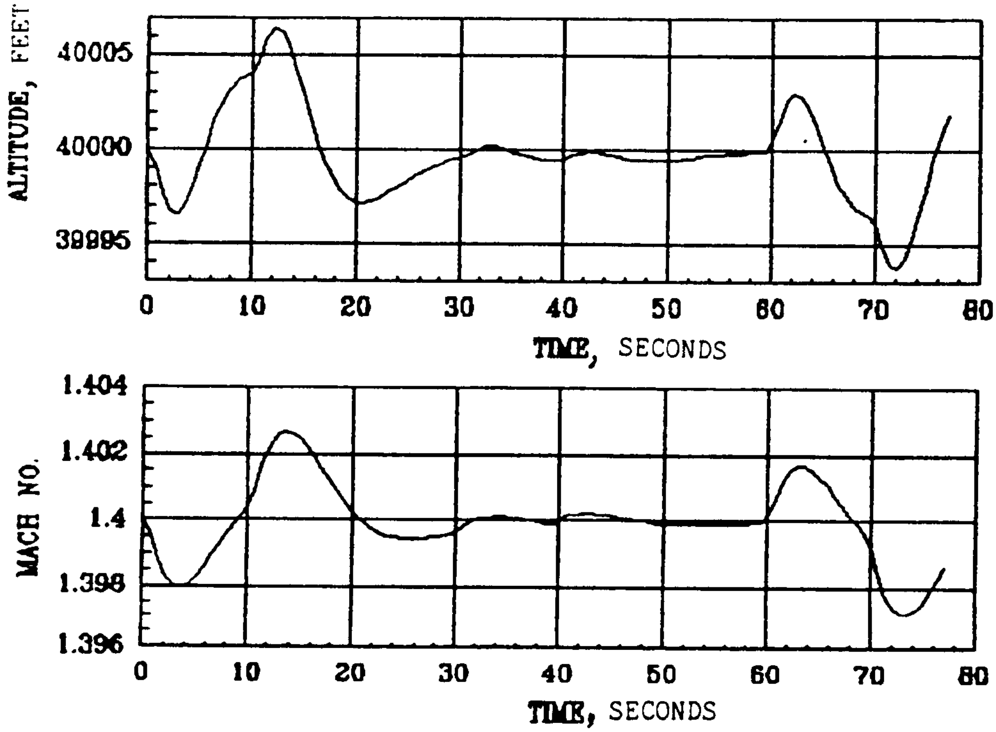

Figure 5-13. Altitude and Mach Number Evolution along the Excess Thrust Windup Turn Flight Test Trajectory

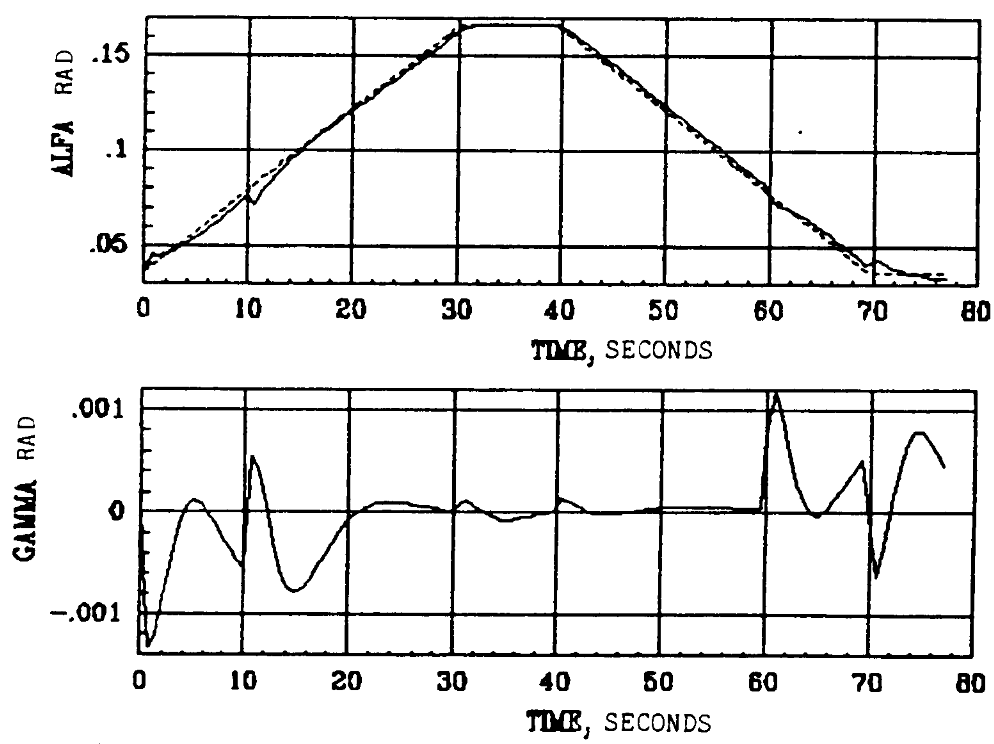

Figure 5-14 Angle of Attack and Flight Path Angle Evolution along the Excess Thrust Windup Turn Flight Test Trajectory

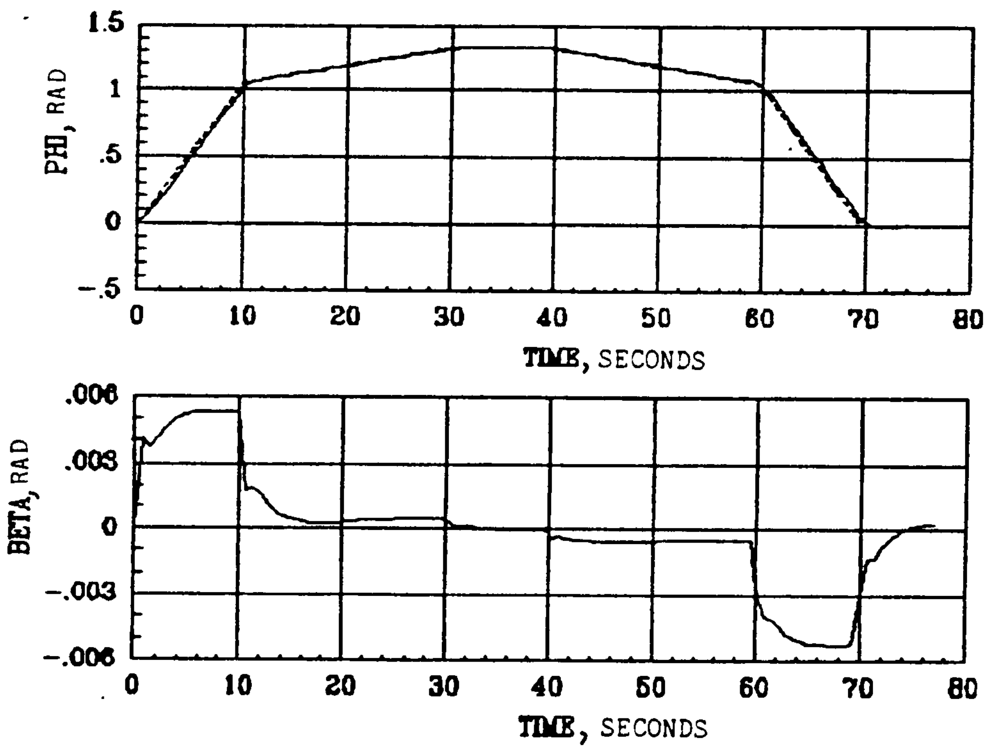

Figure 5-15. Roll Attitude and Angle of Side Slip Along the Excess Thrust Windup Turn Flight Test Trajectory

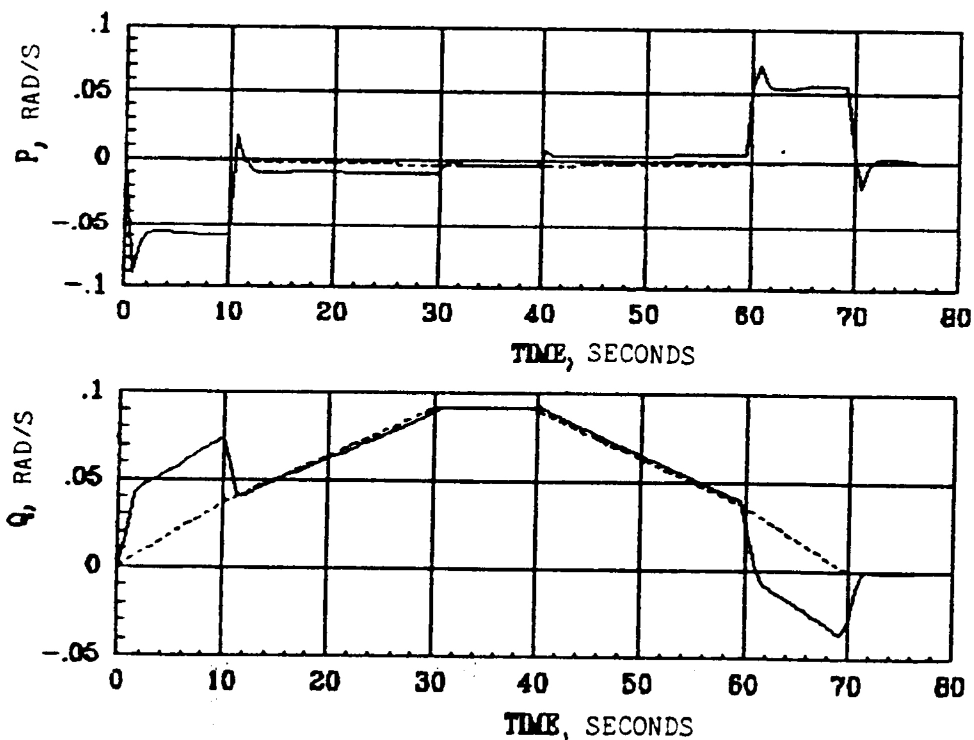

Figure 5-16. Roll and Pitch Body Rate Evolution Along the Excess Thrust Windup Turn Flight Test Trajectory

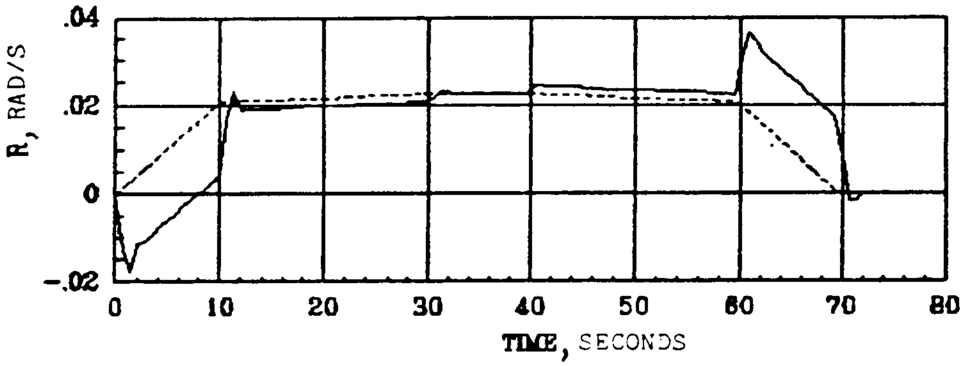

Figure 5-17. Yaw Body Rate Evolution along the Excess Thrust Windup Turn Flight Test Trajectory

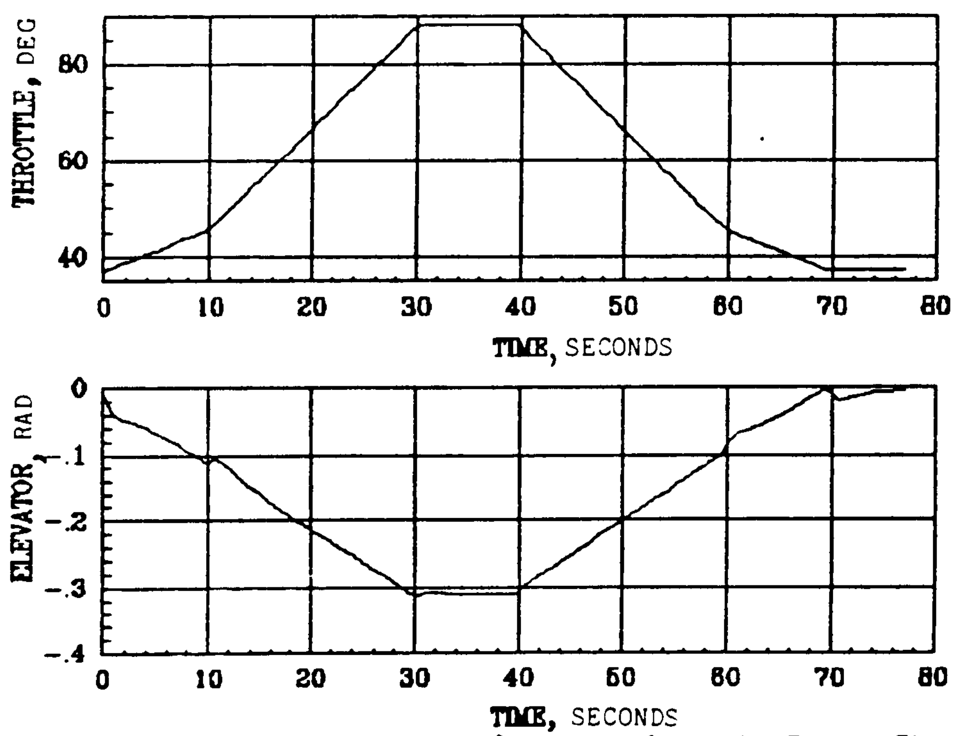

Figure 5-18. Throttle and Elevator Deflection along the Excess Thrust Windup Turn Flight Test Trajectory

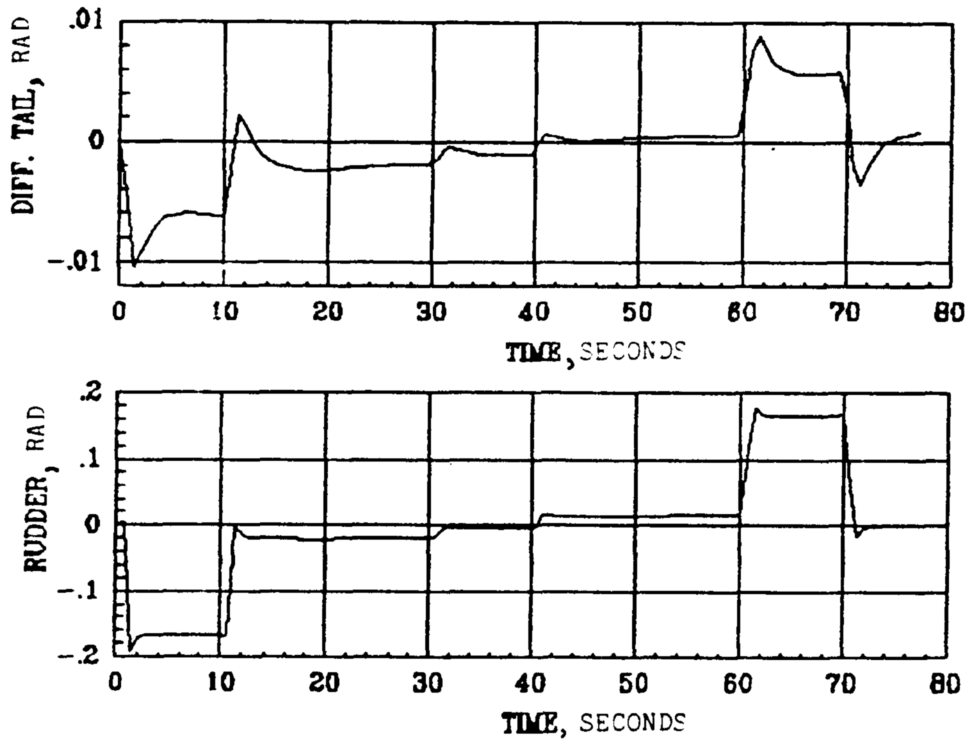

Figure 5-19. Differential Tail and Rudder Deflection along the Excess Thrust Windup Turn Flight Test Trajectory.

5.3.6 Constant thrust windup turn

A descending constant thrust windup trajectory will be illustrated in the following. The aircraft starting at straight and level flight condition enters a level turn with linearly increasing angle of attack, upto 30 seconds in Fig. 5-21. At this point, the throttle is fixed and the constant thrust windup trajectory begins. At the end of the maneuver, the Angle of attack is gradually decreased to the straight and level trim values. During the constant throttle windup turn trajectory, the Mach number is to remain constant. The simulation results for this maneuver are given in Figs. 5-20 through 5-26. From Fig. 5-20, it can be seen that the Mach number was maintained within ± 0.0075 while the angle of attack tracking error was within 0.01 radians. The control surface deflections were within the saturation limits except at the point where the constant throttle windup trajectory began. This is due to the corner present in the altitude and angle of attack command histories. By smoothing these corners in the commands, the control surface limit violation can be avoided.

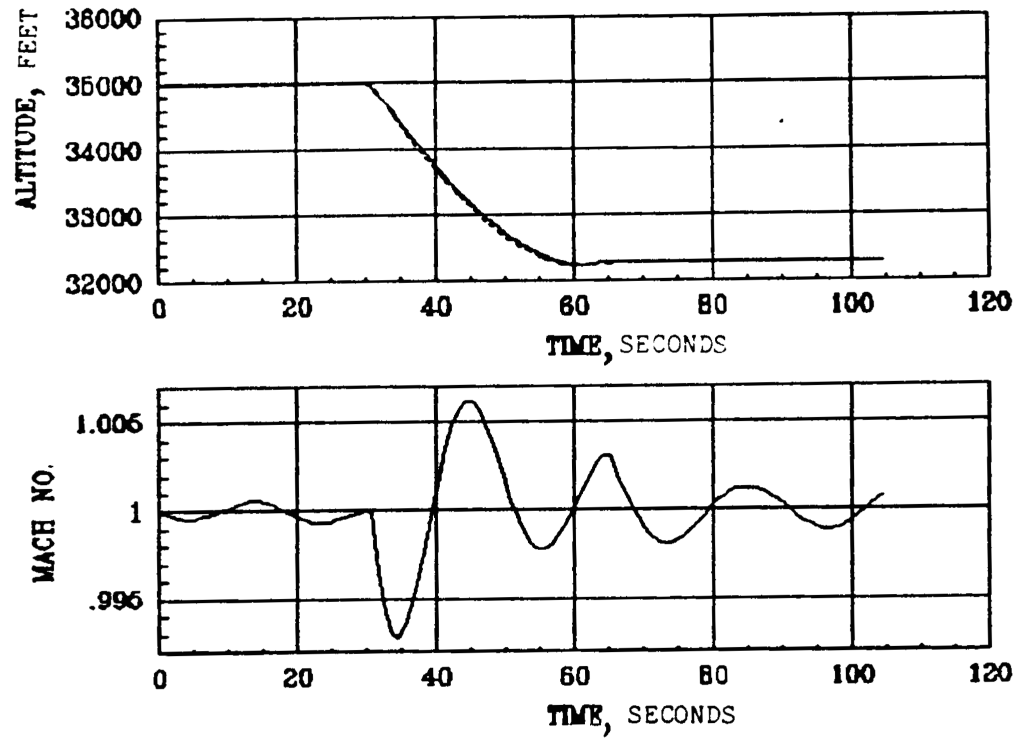

Figure 5-20. Altitude and Mach Number Evolution Along the Constant Throttle Windup Turn Flight Test Trajectory.

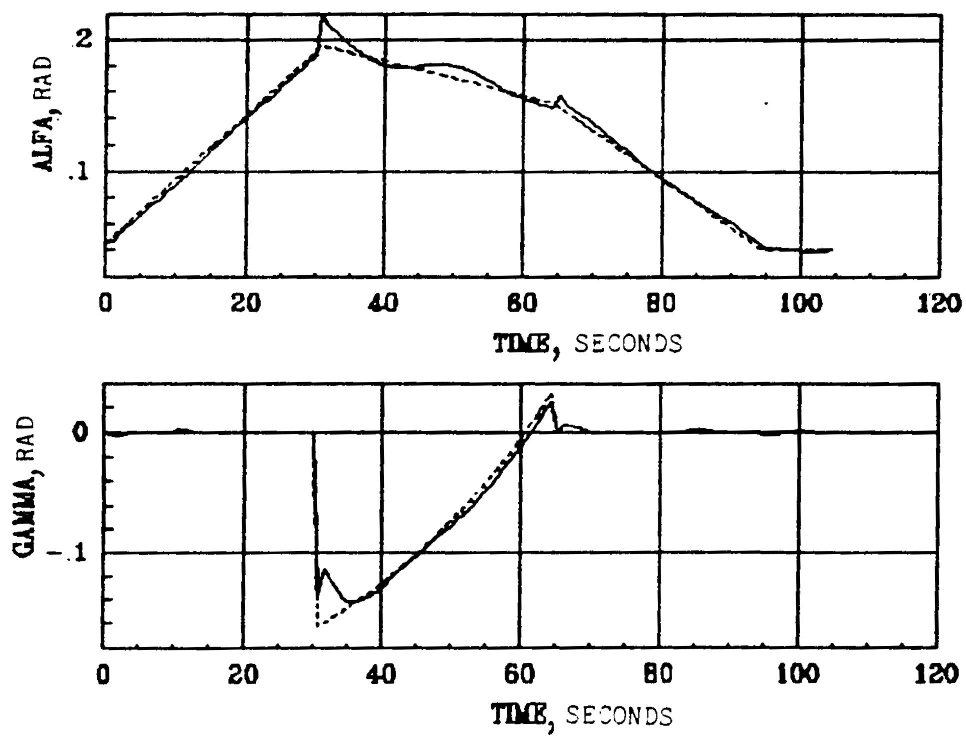

Figure 5-21. Angle of Attack and Flight Path Angle Evolution Along the Constant Throttle Windup Turn Flight Test Trajectory.

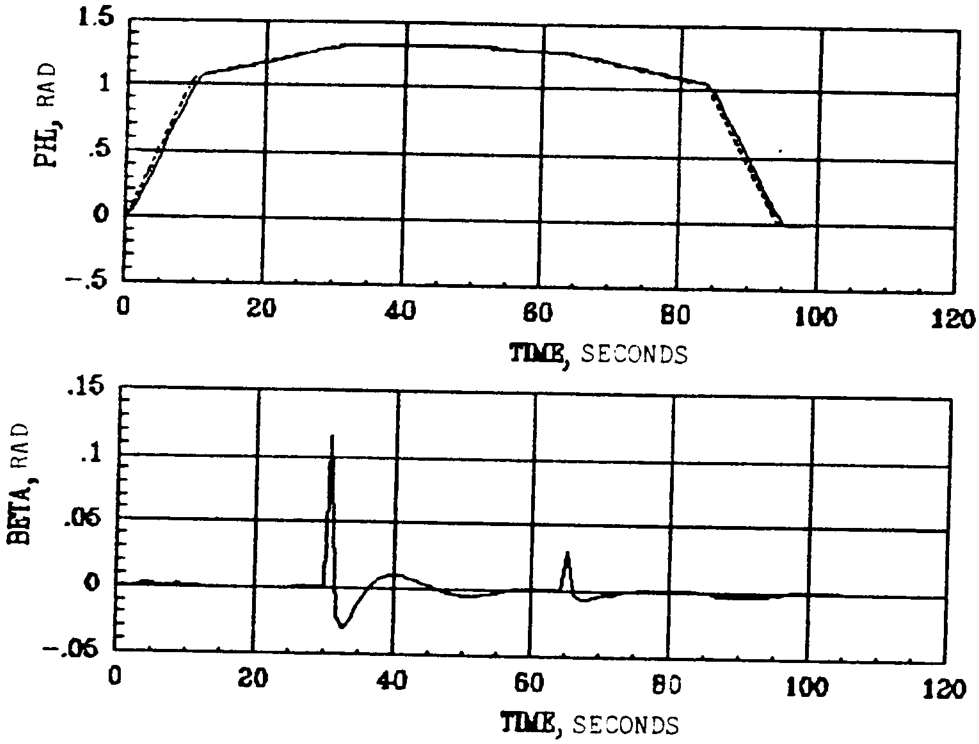

Figure 5-22. Roll Altitude and Angle of Side Slip Evolution Along the Constant Throttle Windup Turn Flight Test Trajectory.

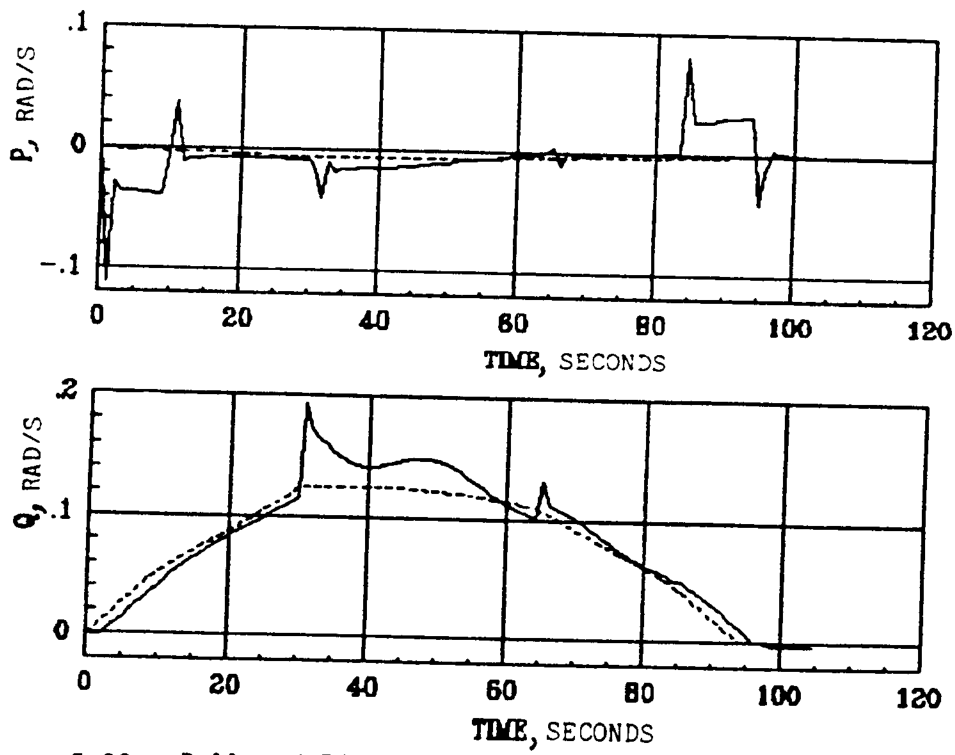

Figure 5-23. Roll and Pitch Body Rate Evolution Along the Constant Throttle Windup Turn Flight Test Trajectory.

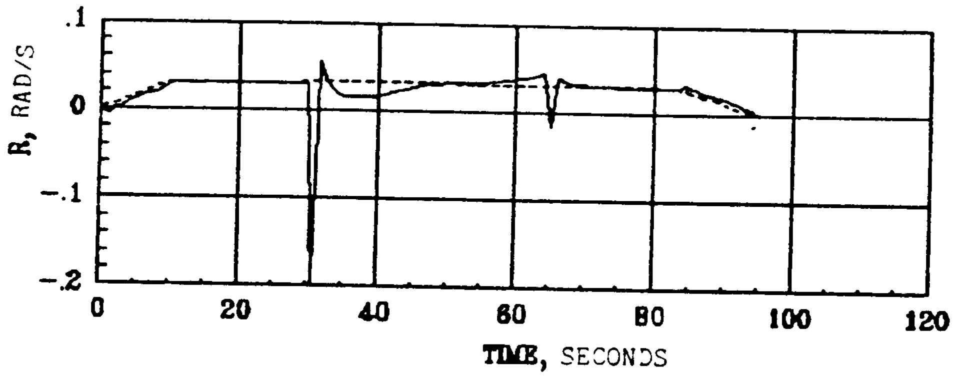

Figure 5-24. Yaw Body Rate Evolution along the Constant Throttle Windup Turn Flight Test Trajectory.

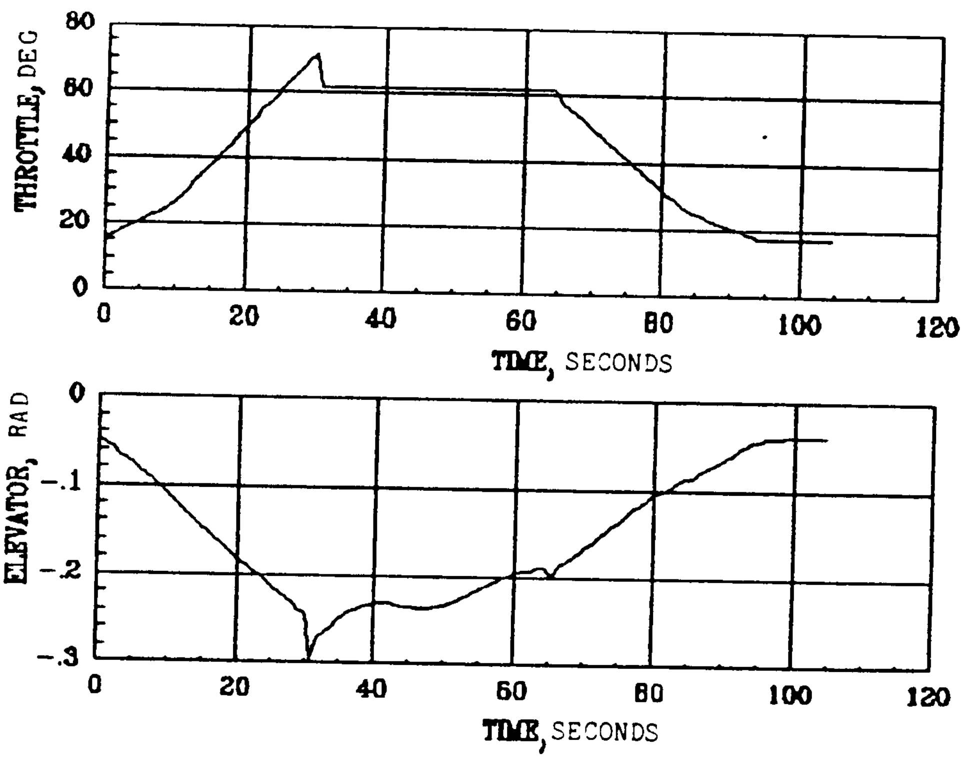

Figure 5-25. Throttle and Elevator Deflection along the Constant Throttle Windup Turn Flight Test Trajectory.

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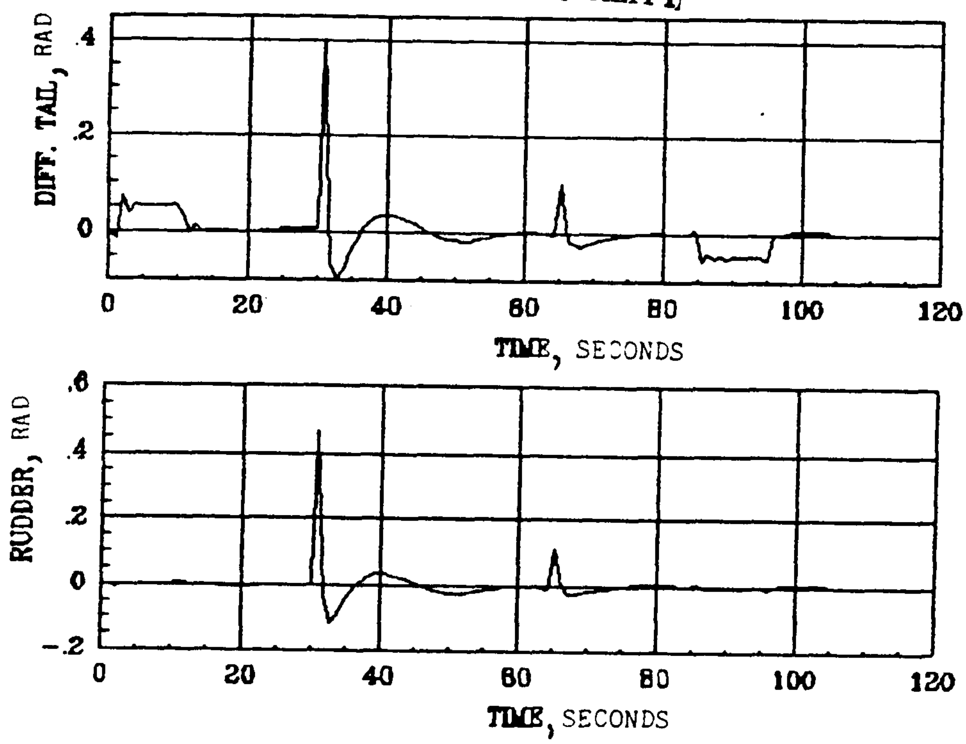

Figure 5-26. Differential Tail and Rudder Deflection along the Constant Throttle Windup Turn Flight Test Trajectory.

5.3.7 Constant Dynamic Pressure - Constant Load Factor Maneuver

As noted in the maneuver modeling section, this maneuver can be ascending or descending based on the required Mach rate. The controller performance along an ascending constant dynamic pressure-constant load factor trajectory is given in Figs. 5-27 through 5-34. This trajectory consists of three phases. The first phase begins with initial conditions chosen to obtain the desired dynamic pressure. Next the aircraft is placed in a turn to generate the required load factor. In the present case, a load factor of 4 was employed. Next, the desired Mach rate is initiated and the constant dynamic pressure-constant load factor trajectory is executed. In the present case, in order to achieve a Mach rate of 0.0067/second, the aircraft had to climb from 35000' altitude to 43000'altitude in 30 seconds. These histories are given in Fig. 5-27. The control surface deflections are well within the saturation limits except at the points where the altitude and Mach number commands contains corners. The dynamic pressure history given in Fig. 5-34 was maintained within 4% of the required value.

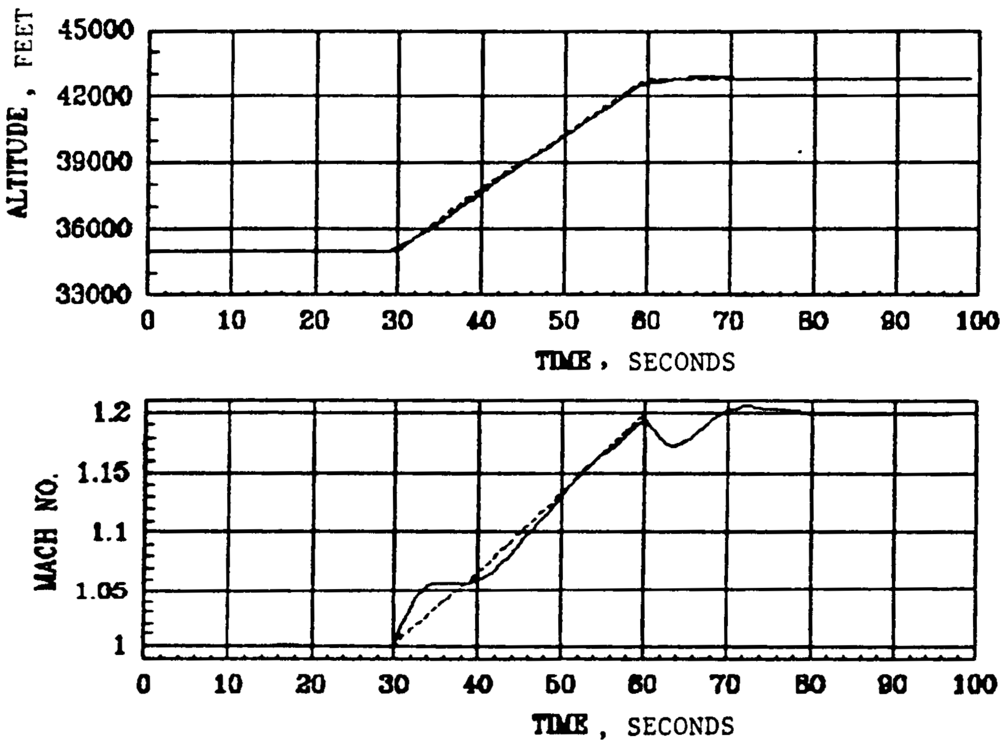

Figure 5-27. Altitude and Mach Number Evolution Along the Constant Dynamic Pressure Constant Load Factor Flight Test Trajectory

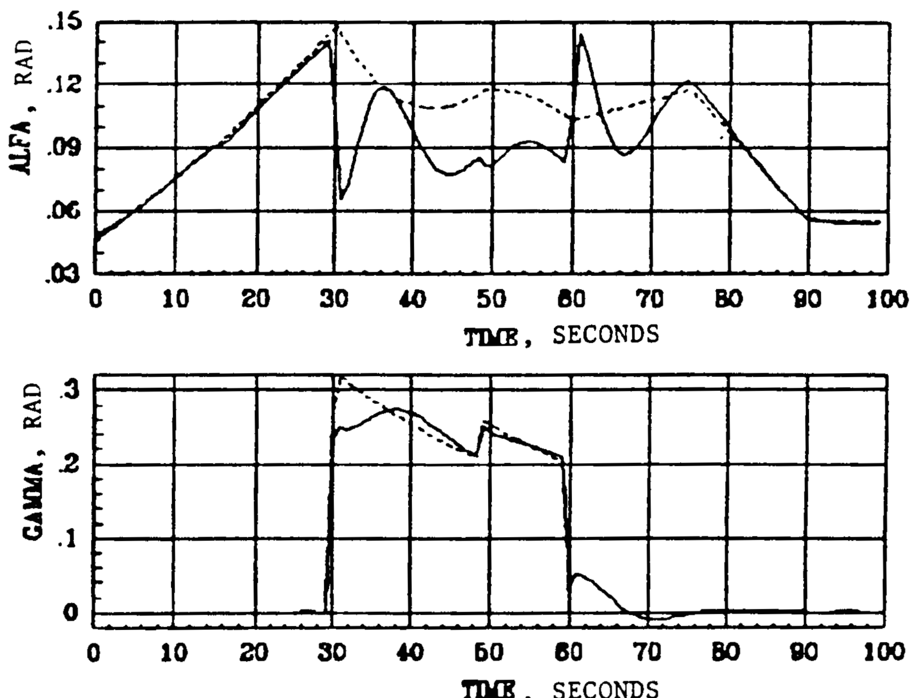

Figure 5-28. Angle of Attack and Flight Path Angle Evolution along the Constant Dynamic Pressure Constant Load Factor Flight Test Trajectory

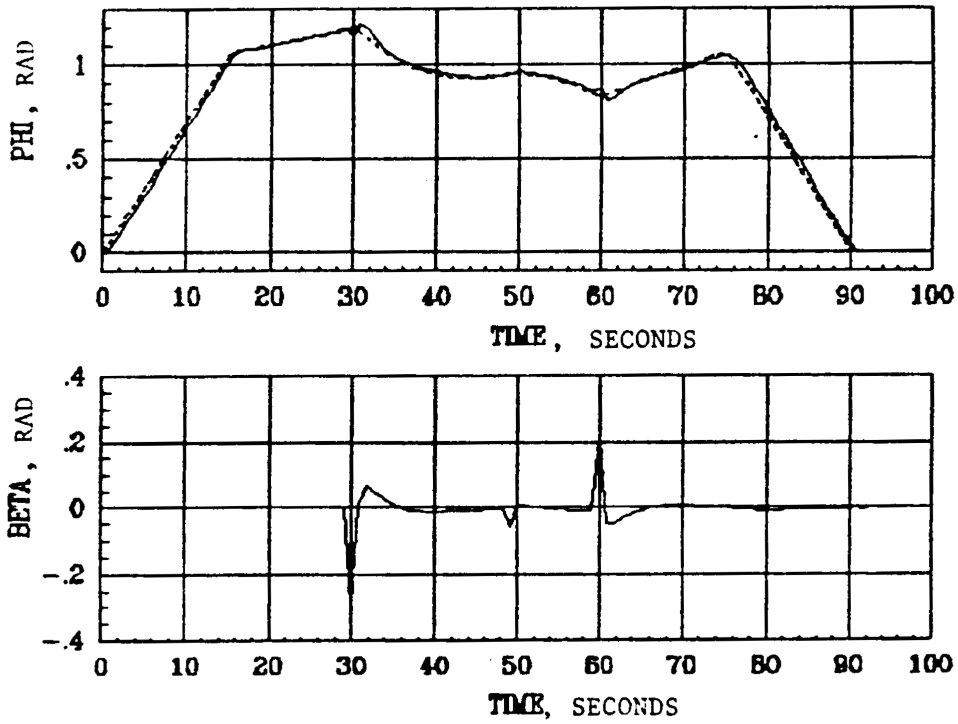

Figure 5-29. Roll Attitude and Angle of Side Slip Evolution along the Constant Dynamic Pressure Constant Load Factor Flight Test Trajectory

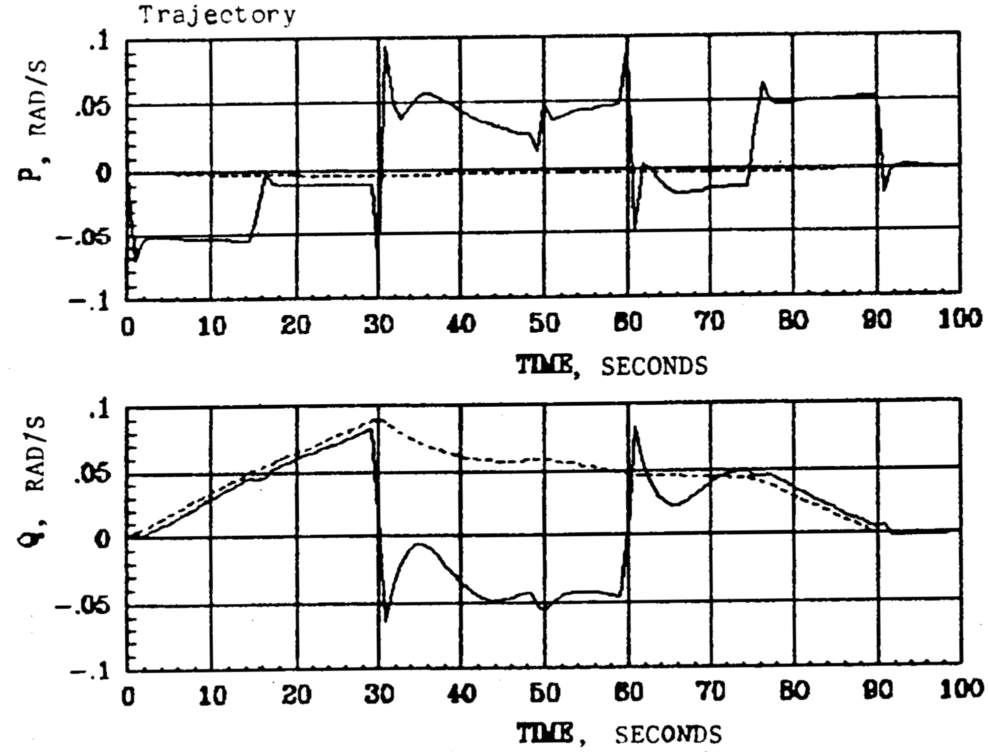

Figure 5-30. Roll and Pitch Body Rates along the Constant Dynamic Pressure Constant Load Factor Flight Test Trajectory

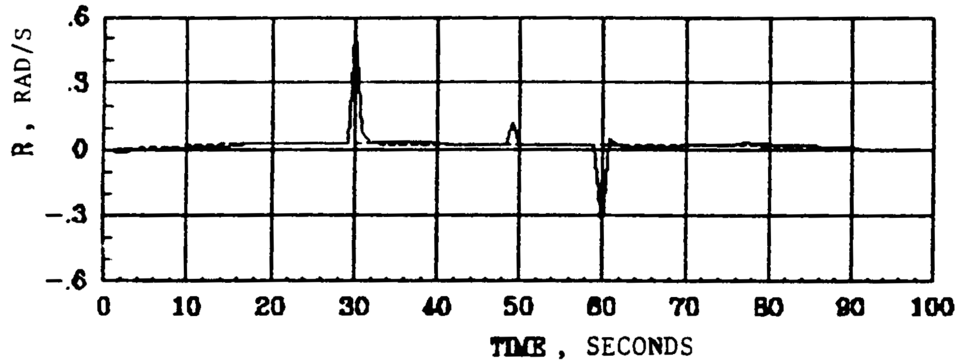

Figure 5-31. Yaw Body Rate along the Constant Dynamic Pressure Constant Load Factor Flight Test Trajectory.

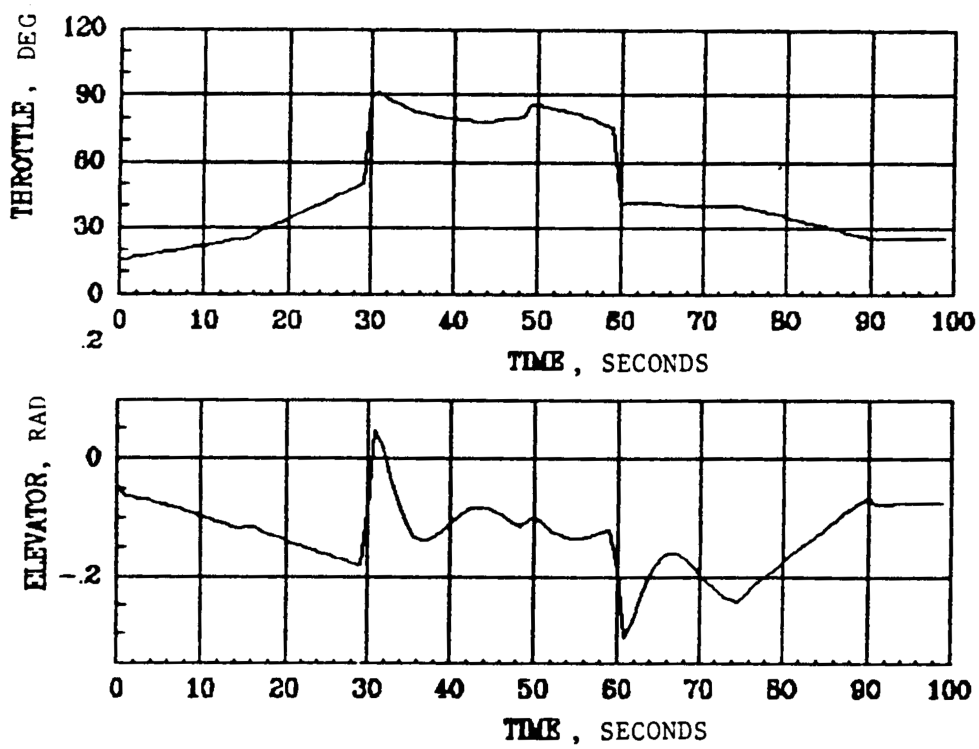

Figure 5-32. Throttle and Elevator Deflection Along the Constant Dynamic Pressure Constant Load Factor Flight Test Trajectory.

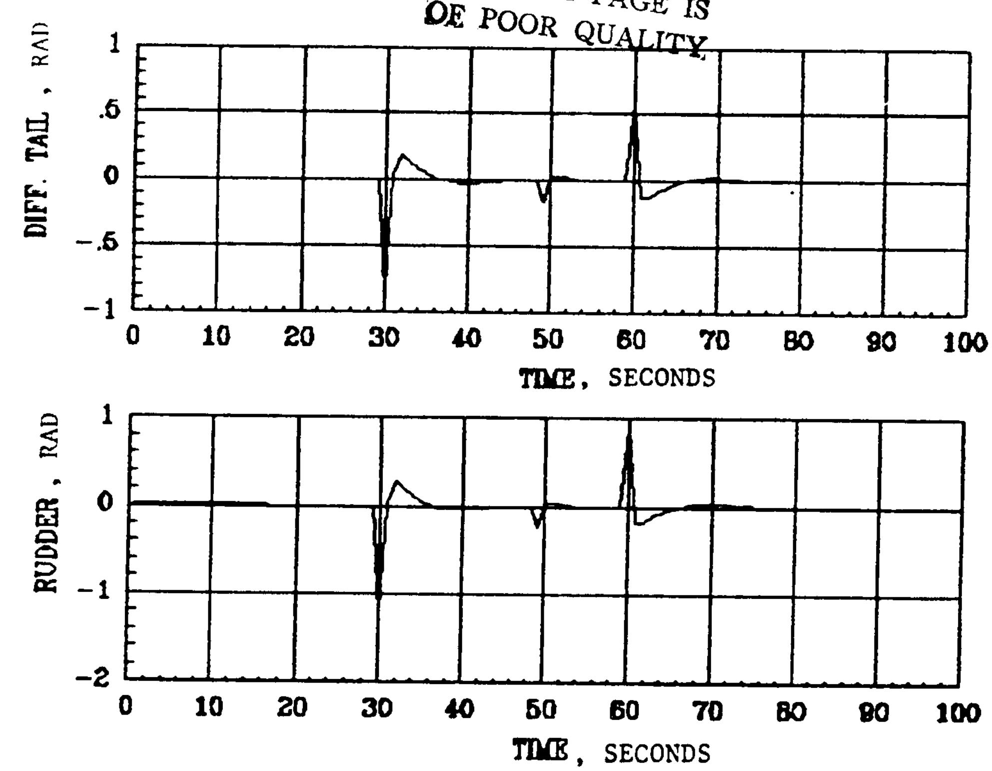

Figure 5-33. Differential Tail and Rudder Deflection along the Constant Dynamic Pressure Constant Load Factor Flight Test Trajectory

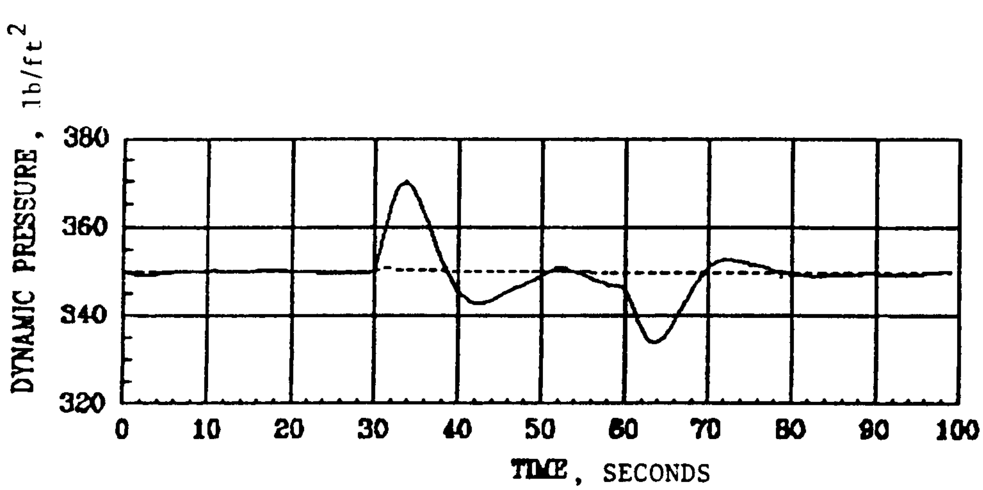

Figure 5-34. Dynamic Pressure along the Constant Dynamic Pressure Constant Load Factor Flight Test Trajectory

5.3.8 Constant Reynold's Number - Constant Load Factor Maneuver

This maneuver sequence is identical to the constant dynamic pressure-constant load factor trajectory. The controller performance for a negative Mach rate - Constant Reynolds' number-constant load factor trajectory is given in Figs. 5-35 through 5-42. Note that the Reynold's number given in Fig. 5-42 should be multiplied by the characteristic diameter to obtain the actual Reynold's number. From the performance results given in Fig. 5-40 and 5-41, it can be seen that the control surface deflections momentarily violate the saturation limits at the points corresponding to the corners in the commanded values. Throughout the trajectory, Reynold's number is within 1.5% of the required value.

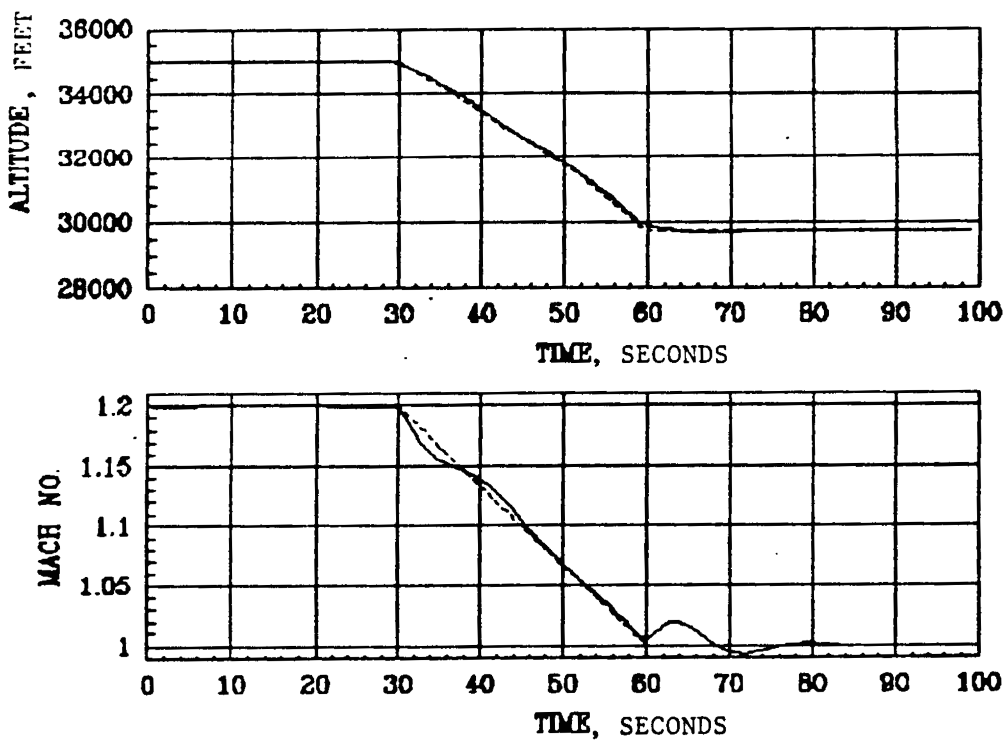

Figure 5-35. Altitude and Mach Number Evolution Along the Constant Reynold's Number Constant Load Factor Flight Test Trajectory.

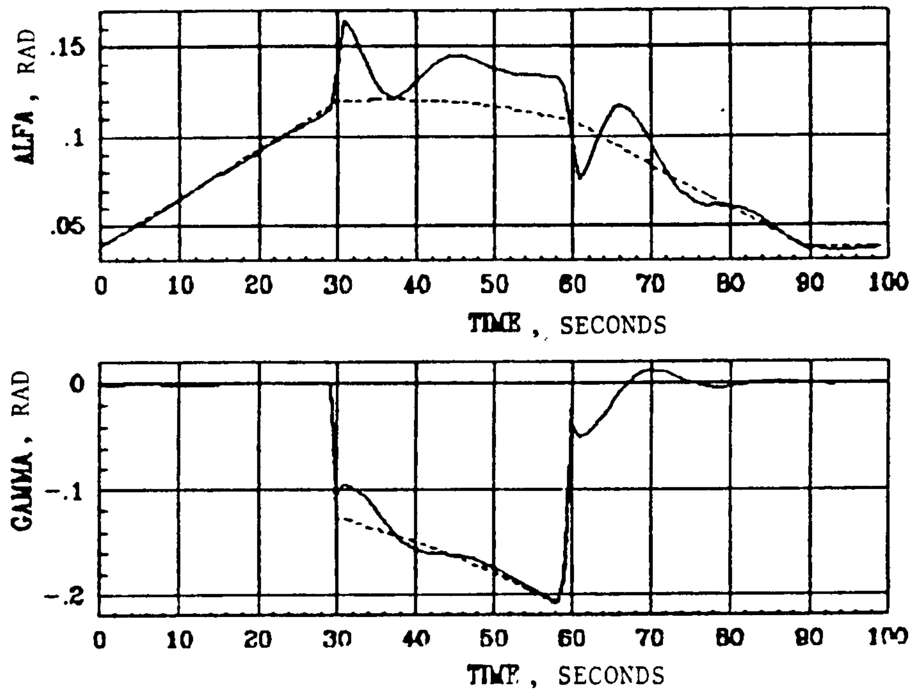

Figure 5-36. Angle of Attack and Flight Path Angle Evolution along the Constant Reynold's Number Constant Load Factor Flight Test Trajectory

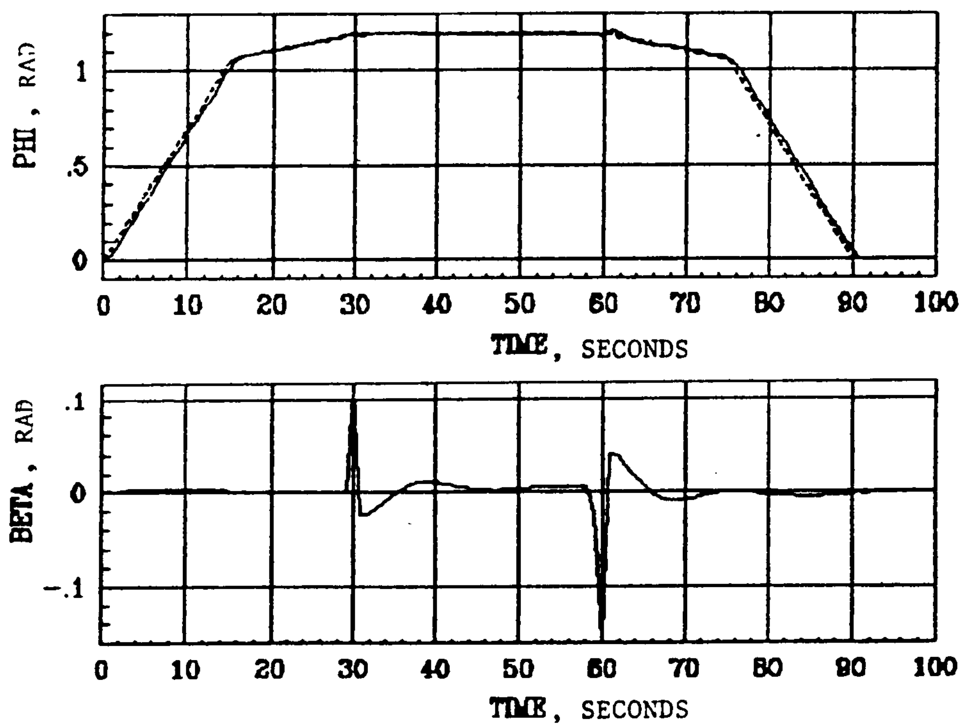

Figure 5-37. Roll Attitude and Angle of Side Slip Evolution Along the Constant Reynold's Number Constant Load Factor Flight Test Trajectory.

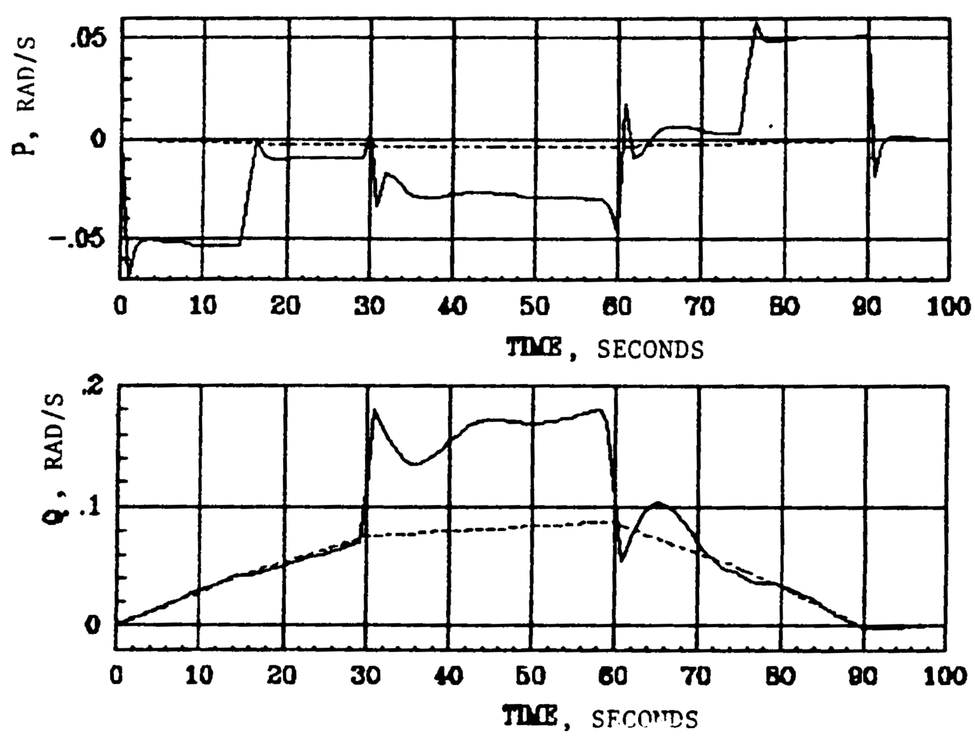

Figure 5-38. Roll and Pitch Body Rates along the Constant Reynold's Number Constant Load Factor Flight Test Trajectory.

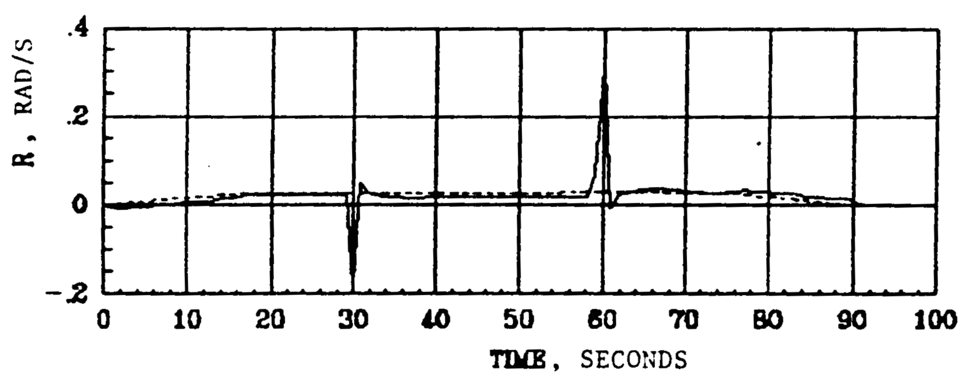

Figure 5-39. Yaw Body Rate along the Constant Reynold's Number Constant Load Factor Flight Test Trajectory.

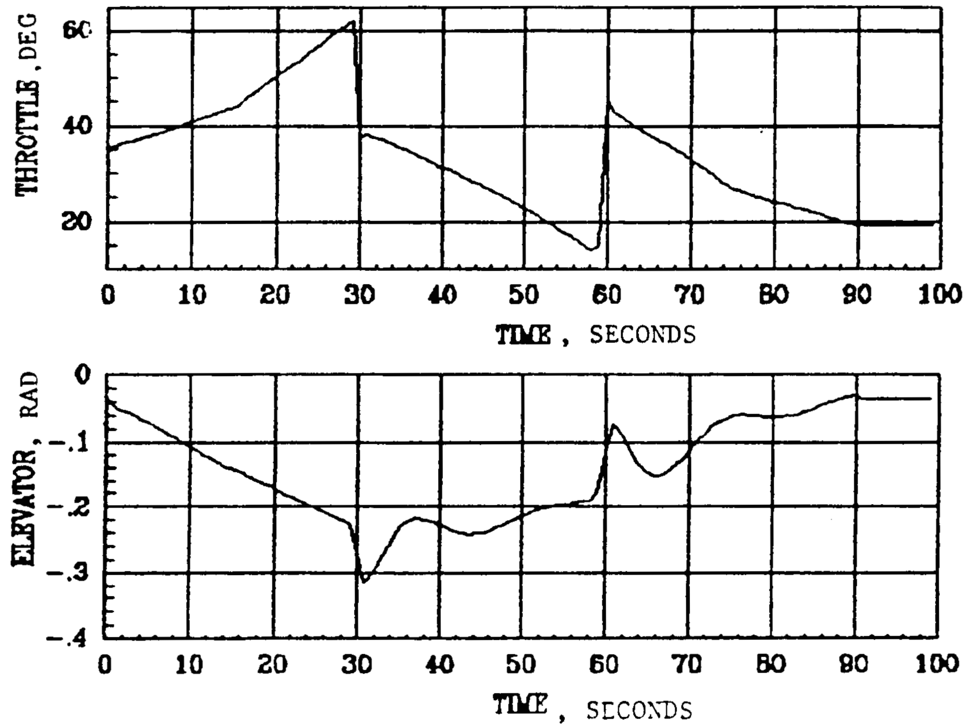

Figure 5-40. Throttle and Elevator Deflection along the Constant Reynold's Number Constant Load Factor Flight Test Trajectory

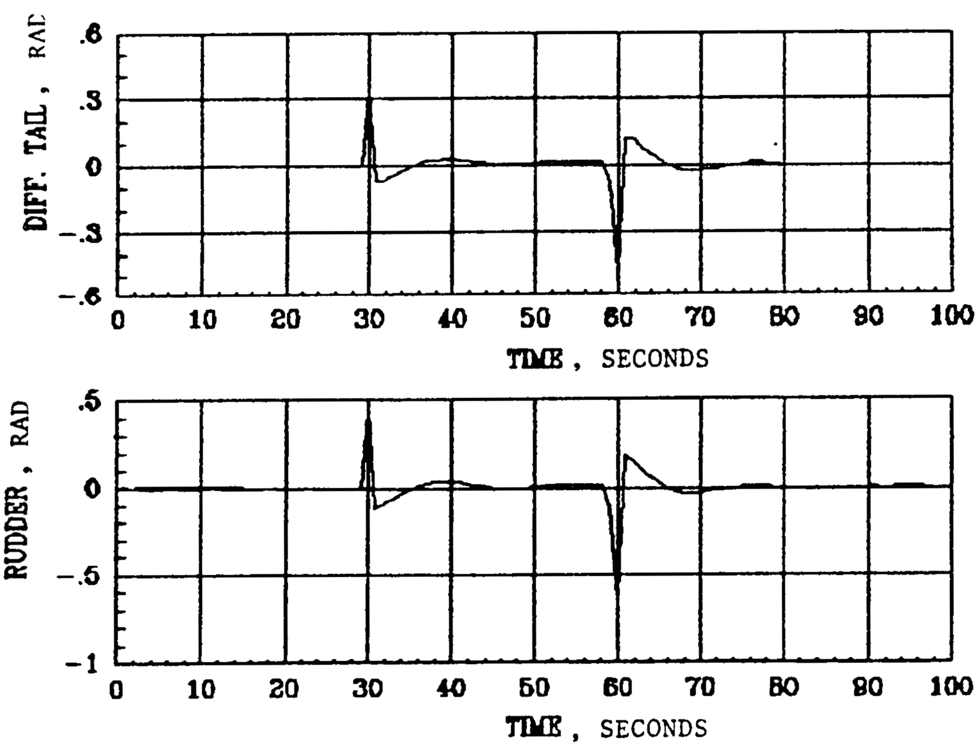

Figure 5-41. Differential Tail and Rudder Deflection Along the Constant Reynold's Number Load Factor Flight Test Trajectory.

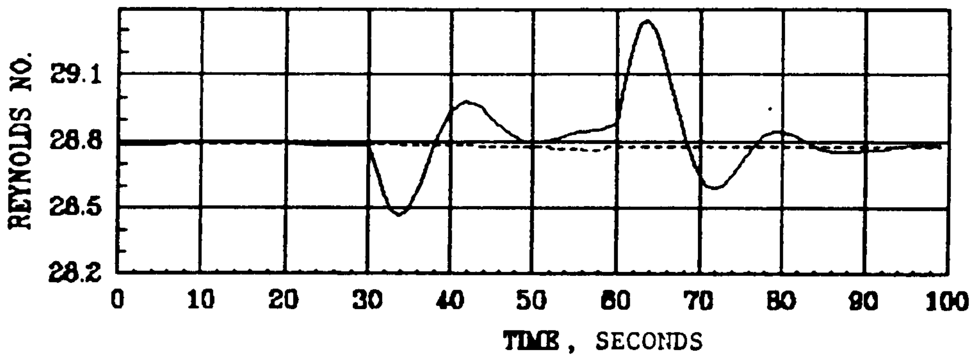

Figure 5-42. Reynold's Number Along the Constant Reynold's Number Constant Load Factor Flight Test Trajectory.

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SECTION 6
SUMMARY AND FUTURE WORK

This report summarizes the analysis done in the first phase of a study for developing and validating a flight test trajectory controller for eight maneuvers. System modeling, control design results, control design technique evaluation, validation and software deliverable results and conclusions are summarized here. This final section describes future work which will build upon this study in the further validation and flight testing of these flight test trajectory controllers.

6.1 SYSTEM MODELING

With newly developed linearization tools by NASA Ames Dryden Flight Research Facility, the linear airframe models are straight forwared to obtain. Command augmentation system CAS models are important and although they complicate the maneuver autopilot designs, they are essential since the maneuver autopilot must work through the CAS in the manned simulation or in the F-15 itself.

The output analytical constrained relations developed in section 3 which discusses maneuver modeling were found to be fundamental in achieving a consistent maneuver autopilot. The nonlinear aerodynamics can be effectively reduced to a reference command table by appropriate linearizations throughout the flight envelope. A small number of linear perturbation models can be used to decompose the eight desired maneuvers into a few sets of linear perturbation equations.

6.2 CONTROL DESIGN RESULTS

Output feedback controllers with appropriate integral aerostates were found to be the simplest form of feedback controllers. Integral aerostates must be chosen carefully to avoid controllability problems which are problematic in the design stage. The use of a guaranteed stability margin in the control design technique was found to be a powerful method when working with the high order augmented and coupled models. It was found that a five second response time with a minimal amount of overshoot was straightforward to achieve at all design points.

6.3 CONTROL DESIGN TECHNIQUE EVALUATIONS

The eigenstructure assignment technique was found to work well on a bare airframe but with a complex augmented model was not useful as a design technique because there is no procedure to perform a converging iterative design approach.

The minimum error excitation output feedback method with a preliminary guaranteed stability margin full state design worked well at all flight conditions.

6.4 MANEUVER AUTOPILOT VALIDATION

The maneuver autopilots were validated in a linear simulation. The tracking response for reasonably high performance maneuvers were found to be quite acceptable, and except for exceeding the control authority at isolated points, is ready for further testing in a full nonlinear simulation.

6.5 SOFTWARE DELIVERABLES

The tools used in model development control design evaluation and design throughout the envelope as well as validation were made available to NASA Ames Dryden Flight Research Facility. These included a time varying simulation mechanized in ISI's MATRIX_X SYSTEM_BUILD (see Appendix A). In addition a stand alone program which performs a three dimensional interpolation in state variables and converts this through the interpolation into a 1D table as a function of time for a specific maneuvers was developed and also delivered to NASA. The 1-D interpolation in time can then be used in SYSTEM_BUILD to mechanize a time varying simulation. Documented command files were delivered for the model generation, control law design, and construction of linear simulation using a single model throughout the flight maneuver. Command files for building, loading the data and executing a time varying simulation model were also provided.

6.6 FUTURE WORK

The next phase of this study will involve validation of flight test trajectory control laws in a batch nonlinear simulation. The gain scheduled linear perturbation controllers developed in this study Are currently ready for validation in such a simulation. The fineness of the discretization both of the reference commands and linear perturbation models may need to be revised in the next phase. An open-loop simulation of the reference control values will give an initial check of the accuracy of our nonlinear tabular model. The nonlinear simulation provided by NASA Ames Dryden Flight Research Facility will include both the CAS model as well as the airframe dynamics and Sensor models. The structure of the nonlinear control law, while only outlined here, was developed to a point where with some symbolic or algebraic manipulation by hand, it can be mechanized on the nonlinear simulation. The advantage of this control law is that a single set of gains will work for all maneuvers throughout the envelope. Such a transformed linear system can be easily controlled and the resulting gains back transformed with the nonlinear equations to give a nonlinear control law.

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APPENDIX A

FLIGHT TEST TRAJECTORY CONTROLLER SYNTHESIS WITH CONSTRAINED EIGENSTRUCTURE ASSIGNMENT

INTRODUCTION:

This Appendix gives the details of research conducted on the eigenstructure assignment. The material in the Appendix A-I was presented as a paper in the 1985 American Control Conference at Boston. Appendix A-II and A-III give the aircraft - CAS models and the constrained eigenstructure designs at two flight conditions. Appendix A-IV gives the desired eigenvalues and eigenvectors used in the synthesis.

The aircraft - CAS model used here is of the form

$$\dot{x} = Fx + Gu$$
$$y = Hx$$

where:

the state variables x are the perturbed values of

- V, total airspeed
- α, Angle of attack
- q, pitch body rate
- θ, pitch attitude
- β, angle of sideslip
- p, roll body rate
- γ, yaw body rate
- ϕ, roll attitude
- h, altitude
- engine actuator state and 21 CAS states

U: the control vector consists of perturbed values of throttle, elevator, differential tail and rudder.

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y: the measurement vector and consists of the perturbed values of

$\dot{p}$: roll angular acceleration

A_n: normal acceleration

q: pitch rate

$\dot{q}$: pitch angular acceleration

p: roll rate

$A_{y,i}$: y-body acceleration, not at the vehicle center of gravity

$\dot{r}$: yaw angular acceleration

r: yaw rate

h: altitude

M: mach number

α: angle of attack

n: load factor

ϕ: roll attitude

θ: pitch attitude

$\dot{h}$: altitude rate

UB: x-body axis velocity

A_{nx}: x-body axis acceleration at vehicle C.G.

CONCLUSIONS:

The constrained eigenstructure assignment design procedure in its present form demands several iterations to converge to a satisfactory design and does not appear to easily yield suitable insight for output feedback design of high order multivariable systems. If a rational method to generate an achievable set of desired eigenvectors is devised, this technique will be made more attractive.

APPENDIX A-I

PAPER PRESENTED AT 1985 ACC, JUNE 19-21

BOSTON, M.A.

FLIGHT TEST TRAJECTORY CONTROLLER SYNTHESIS WITH CONSTRAINED EIGENSTRUCTURE ASSIGNMENT+

by

P.K.A. Menon, H.A. Saberi, R.A. Walker
Integrated Systems, Inc.
101 University Avenue
Palo Alto, CA 94301

and

E.L. Duke
NASA Ames
Dryden Flight Research Facility/OFDC
Edwards, CA 93523

ABSTRACT

Flight test trajectory controller synthesis using constrained eigenvalue/eigenvector assignment procedure is presented. Associated modeling problems and the difficulties encountered in employing this synthesis technique are highlighted.

+Research supported by NASA-Ames-Dryden Flight Research Facility under Contract NAS2-11877.

1. INTRODUCTION:

Flight test trajectory control is a technique designed to aid in the collection of large quantities of high quality data. This technique has provided the means for flying maneuvers consistantly, precisely, and repeatably from flight to flight. Two versions of these controllers have been used: a closed-loop automatic system and an open-loop system providing manual piloting information. A closed-loop system used to collect performance, pressures, and loads data from the highly maneuverable aircraft technology (HiMAT) vehicle is described in [1]. The application of the open-loop system on the NASA F-111 transonic aircraft technology (TACT), F-15 airframe/propulsion system interaction studies, and F-15 shuttle tiles test programs are given in [2].

Originally, the open-loop flight-test-trajectory guidance algorithms were developed on-line, in a piloted simulation using cut-and-try techniques that was not only man power intensive, but often produced less than desirable controllers. A closed-loop system designed using one-loop-at-a-time classical design approach is documented in [3]. Full-state feedback approach for closed-loop system design using Linear quadratic synthesis is described in [4]. Both these approaches have limitations in terms of design methodology and controller complexity.

The research currently underway includes an exploration of various multivariable synthesis techniques for this problem. The first approach considered is that of constrained eigen value/eigen vector assignment [5]. A primary goal is to develop controllers based on output feedback so as to decrease controller complexity and to enhance robustness. The objective of this paper is to point out strengths and weakness of this technique when used in a, realistic, relatively a large problem such as required for flight test trajectory controllers.

2. THE FLIGHT TEST TRAJECTORY CONTROL PROBLEM:

Flight test trajectories are flown to evaluate an aircraft within its known operational envelope and to explore the boundaries of its capabilities. This makes the flight test trajectory control a very demanding task. Control systems designed for this purpose must not only operate satisfactorily in terms of keeping the flight test variables within acceptable tolerance but should also be reasonably insensitive to model parameter variations.

An approach to closed-loop flight test trajectory controller synthesis consists of linearizing the aircraft model at several flight conditions about the flight test trajectory and designing multivariable controllers, which in some sense minimizes the deviations from the reference path. Time varying nature of the linearized aircraft model along the reference path brings about the need for scheduling gains as a function of time or as functions of some important flight variables such as dynamic pressure, Mach number etc. The gain scheduling aspects will not be pursued any further in this paper, and in all that follows, discussions will center around a linear-time-invariant aircraft model. Further, though the flight test trajectory controller is discrete, in this preliminary stage it will be assumed that the sampling rate is sufficiently high, permitting the application of continuous control design techniques.

The aircraft under consideration is a high performance fighter with command augmentation system (CAS) engaged in all the three axes. The CAS is a highly nonlinear system with saturations, multiplicative nonlinearities and gain schedules. At a particular flight condition, this system can be approximated by a linear system with "equivalent" gains derived from nonlinear simulations. The aircraft model at the same flight condition is obtained from a generic aircraft linearization code developed at NASA-Dryden Flight Research Facility [6]. The state variables used are total speed, angle of attack and angle of sideslip, pitch rate, yaw rate, roll rate, pitch attitude, roll altitude and altitude. Throttle, rudder, elevator and differential tail constitute the control variables. The engine dynamics are modeled as a first order lag. Thus, the aircraft together with CAS at a particular flight condition is a coupled 31-st order system with four controls, the aircraft model having 10 states. A block diagram of the system with flight test trajectory controller (called the Maneuver AutoPilot here) included in the loop is shown in Figure 1. Note that MAP controls the aircraft through CAS. Due to this, even if the aircraft model is decoupled in longitudinal and lateral axes at a particular flight condition, the CAS introduces a strong coupling into the system. In concise terms, the chief objective of the present study is to synthesize the maneuver autopilot so as to effect satisfactory transient response. Six maneuvers have been analyzed, which are sketched below.

2.1 Level Acceleration/Deceleration

This is a wings-level, constant altitude maneuver with Mach number constant or changing at a specified rate.

2.2 Pushover, Pullup

This is a wings-level, constant Mach number maneuver in which angle of attack is varied a specified increment about the trim value at some specified rate.

2.3 Zoom and Pushover

The zoom and pushover is a wings-level, thrust stabilized less than 1g maneuver. The flight trajectory is a parabolic path with the target Mach/altitude/angle of attack point at the apex.

2.4 Excess Thrust Windup Turn

This is a maneuver with angle of attack linearly increasing from the wings-level trim condition to some specified final value at a specified rate. The maneuver is performed at constant altitude and constant Mach number.

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2.5 Constant Throttle Windup Turn

This is a maneuver with angle of attack increasing linearly at a specified rate from trim to some specified final value. The maneuver is performed at a predetermined, constant thrust level. Mach number is maintained by trading potential for kinetic energy via an appropriate altitude rate.

2.6 Constant Reynolds Number and Constant Load Factor Trajectory

This maneuver is initiated at a predetermined load factor, Mach number, and dynamic pressure. Thus, the initiation of this maneuver is not necessarily the wings-level condition. This maneuver can be either an ascending or descending maneuver at a specified Mach number rate. Reynolds number and load factor are held constant throughout the maneuver. Altitude is gained or lost to maintain Reynolds number with changing Mach number.

The simplest of these is the level acceleration/deceleration trajectory and the MAP design for this maneuver will be used as the illustrative example in this paper.

3. OUTPUT FEEDBACK DESIGN:

As indicated earlier, output feedback is attractive because of simplicity. Further, gain scheduling will be essential in this situation and in order to minimize the amount of stored data, it is desirable to have a capability to impose control structural constraints.

Currently, several approaches are available for output feedback design, see Refs [5, 7-10] for example. It is not the purpose of this paper to compare and contrast these, but to evaluate a specific technique from an application point of view. Constrained eigen value/eigen vector assignment technique of [5] was used in this particular application with the hope that it would permit the generation of designs based on the classical notions of poles, zeros and their relative location in the complex plane. Additionally, the selection of this technique was motivated by the example in [5], viz, the lateral axis stability Augmentation System for the L1011 airplane. Salient features of this approach are outlined in the following for clarity of the subsequent discussions.

3.1 Constrained Eigen Value Vector Assignment [5]:

Consider the linear time invariant system

$$\dot{x} = Ax + BU$$

$$y = Cx$$

with $X \epsilon R^n$, $U \epsilon R^m$, $y \epsilon R^r$ and A, B, C are real constant matrices of compatible dimensions.

It is desired to design a feedback controller of the form

$$U = Fy$$

with a structural constraint that some specified elements of F satisfy

$$f_{ij} = 0$$

It is assumed that the system can be stabilized with given outputs y, and that any dynamic compensators required have been appended to the original system.

The design problem is: given a self conjugate set of scalars $\{\lambda_i^d\}$ $i = 1, 2 \ldots r$, and a corresponding self conjugate set of n vectors $\{v_i^d\}$ $i = 1, 2 \ldots r$, and a given controller structural constraint, find a real $m \times r$ matrix F such that r of the eigen values of A + BFC are "close" to the set $\{\lambda_i^d\}$ and the corresponding eigen vectors of A + BFC are "close" to the respective member of $\{v_i^d\}$.

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Note that if there are no constraints on the feedback matrix, it is feasible to place r desired eigen values exactly.

However, one is not at liberty to place $v_1, v_2 \ldots v_r$ by an arbitrary set of desired closed loop eigen vectors $\{v_i^d\}$ $i = 1, 2 \ldots r$ since this set might not belong to the set of assignable closed loop eigenvectors. It then becomes necessary to find some approximation to the set $\{v_i^d\}$ which is assignable, yet "close" in some sense to the original $\{v_i^d\}$. It will be seen subsequently that this is the main difficulty in the application of this technique to a complex problem such as flight test trajectory controller design.

Complete details of this approach can be found in [5]. It is perhaps of interest to note that in addition to the capability to handle controller structure constraints, this technique can be modified to accept partial specification of eigen vectors. This feature can be valuable in high order systems. In summary, to employ this synthesis approach, the following are required.

(i) Based on the practical aspects of the problem, choose a minimal set of measurements which will permit the designer to achieve the desired performance. Introduce dynamic compensators such as integral feedbacks, lead-lag networks, etc., based on experience.

(ii) Choose a set of desired eigenvalues and eigenvectors equal to the number of outputs.

While the selection of desired eigenvalues is often apparent in a given problem, the desired eigenvectors are difficult to select. A piece of information which might serve as a guide in this selection is the fact the closed loop eigenvectors v_i corresponding to the closed loop eigenvalues λ_i must lie in the subspace spanned by the columns of the matrix $(\lambda_i I-A)^{-1}B$. Further, the matrix $C\,V$, $V = \{v_1, v_2 \ldots v_r\}$ should be invertible. If the complete specification of desired eigenvectors are not feasible, a rough rule is to pick the entries in these eigenvectors as zeros or ones based on whether a particular measurement needs to contribute to a particular mode or not. In any case, constructing a set of desired eigenvectors that are assignable constitutes the most difficult part of this design technique.

4. FLIGHT TEST TRAJECTORY CONTROLLER SYNTHESIS:

As an illustrative example, constrained eigenstructure assignment technique is next used in the design of level acceleration/deceleration flight test trajectory. Alternate design approaches have been used for this maneuver and hence comparative evaluation was feasible. The level acceleration/deceleration maneuver requires the roll attitude to be maintained zero and the altitude to be held constant. The mach number should be maintained constant or should change at a specified rate. To ensure zero steady state errors, integral feedbacks are first introduced in the altitude and mach number channels. Since the mach number command can be a ramp, an additional integrator is required in this channel to decrease tracking errors. This, however, was not done because the tracking errors with a single integral feedback has been found to be within acceptable values.

The desired eigenvalues to be used in the design are clear at the outset, based on the four modes for aircraft model, viz, the phugoid, short period, dutch roll and roll convergence. The controller structure constraint in this flight maneuver is that the errors in lateral channel will be corrected using rudder and differential tail, while the errors in longitudinal channel will be corrected using elevator and throttle. In view of the time varying nature of the model, one would like to pick a set of eigenvalues and eigenvectors at a particular flight condition through extensive design iterations and then attempt to use these at other flight conditions.

The choice of desired eigenvectors is not clear at this point. Three approaches were tried with varying degrees of success. These are sketched in the following.

4.1 Minimally Restructered Eigenassignment

Since it is known that the closed loop eigenvectors lie in a subspace spanned by the columns of $(\lambda_i I-A)^{-1}\bar{B}$, $i = 1, \ldots n$, linear combinations of these vectors were used as desired eigen vectors. The weights to be used in generating these linear combinations were constructed from the additional information that unassigned eigenvectors should be close to their open loop values in a least square sense.

4.2 Decoupling Eigenassignment

A variation to the above was attempted next. Since we are interested in having the least cross axis coupling in the controller as possible, the desired eigenvectors in the longitudinal channel may be chosen to that the responses from lateral channels are blocked, i.e. select eigenvectors as

$$\left[\begin{array}{c|c} (\lambda_i I-A) & B \\ \hline C_{LAT} & 0 \end{array}\right] \left[\begin{array}{c} v_i \\ \hline w_i \end{array}\right] = \left[\begin{array}{c} 0 \\ \hline 0 \end{array}\right]$$

$$V_d = \sum_{i=1}^{n} \alpha_i v_i$$

V_d are the desired eigenvectors. α_i are selected using the same criteria as 4.1. Though these two approaches could be made to work at each flight condition by iterating on the desired eigen values, they failed to easily produce a set of acceptable eigen vectors which could be used at other flight conditions. Next, partial specification of desired eigenvectors was attempted as follows:

4.3 Dominant Mode Eigenassignment

According to ref [5], complete specification of desired eigenvectors are neither necessary nor desirable. Depending on the states should or should not participate in a given mode, appropriate entries in the eigenvectors are made ones or zeros, leaving other entries free. With these eigenvectors, the desired eigenvalues are moved as far left from the imaginary axis as possible with least change in the location of unplaced eigenvalues. The desired eigenvectors so obtained appeared to work over most flight conditions. Note, however, that extensive iterations on the desired eigenvalues may often be required to produce a satisfactory design.

The open-loop eigenvalues for the aircraft-CAS linearized model at Mach 1.2 and 10000' altitude is given in table 1. The system has a pole on the right half of s plane. Partial specification of the desired eigenvectors are constructed next, based on the states that should or should not participate in a given measurement. The desired eigenvectors used in the present example are given in table 2. It can be seen from this table that no restriction has been placed on states associated with CAS. A manual iteration is now undertaken to determine the desired eigenvalues. Since the designer is interested in producing a stable system with as high a speed of response as possible, the eigenvalues to be moved are the ones closest to the imaginary axis. Hence, these are moved as far to the left of the imaginary axis as possible with least change in the location of other eigenvalues. Table 3 shows a set of desired eigenvectors obtained from this exercise. The output feedback gains obtained from the constrained eigenvalue/eigenvector design technique is given in table 4. Table 5 gives the closed loop eigenvalues. Comparing this with table 3 shows that the achieved eigen values are close to the desired ones.

In Figures 2 and 3, the time response of the system for a ramp mach number command are shown. A question that occurs naturally at this point is whether the design can be improved by further adjustment of desired eigen values and eigen vectors. Examination of the constrained eigen value/eigen vector approach yields no answer to this question.

5. CONCLUSIONS

Design of a maneuver autopilot for flight test trajectory control using constrained eigenvalue/eigenvector assignment was discussed. Difficulties encountered in the generation of desired eigenvalues and eigenvectors were outlined. This approach demands several iterations to converge to a satisfactory design and does not appear to easily give suitable insight for output feedback design of high order multivariable systems which will be used at other operating points. If a rational method to generate an achievable set of eigenvectors is devised, this technique will be made more attractive. One possibility might be to generate gradients of the eigensystem between flight conditions and include this information in the single point design technique.

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TABLE 1. OPEN-LOOP EIGEN VALUES FOR AIRCRAFT-CAS LINEARIZED MODEL AT MACH 1.2 AND 1000's ALTITUDE

-5.9456D+01 +2.0293D+01i	-1.2176D+01 +1.0192D+01i
-5.9456D+01 -2.0293D+01i	-1.2176D+01 -1.0192D+01i
-1.3674D+02 -3.2629D-15i	-2.9438D+00 +5.3113D+00i
-4.8879D+01 +3.0434D-17i	-2.9438D+00 -5.3113D+00i
-8.7758D+01 +5.8218D+01i	-2.3186D-01 +1.8504D-01i
-8.7758D+01 -5.8218D+01i	-2.3186D-01 -1.8504D-01i
-1.0180D+02 +5.1723D-15i	-3.4734D-01 -7.4748D-19i
-1.0000D+02 +4.2144D-15i	-6.5704D-02 -8.2699D-18i
-8.8198D+01 +3.5469D-16i	3.1435D-04 +4.3959D-03i
-2.3286D+01 +8.2436D-17i	3.1435D-04 -4.3959D-03i
-7.4117D+00 +3.3574D+01i	-5.4174D-01 +0.0000D+00i
-7.4117D+00 -3.3574D+01i	-5.0000D-01 +0.0000D+00i
-7.9725D+00 +8.2655D+00i	1.4997D-03 +0.0000D+00i
-7.9725D+00 -8.2655D+00i	-2.7600D-01 +0.0000D+00i
	-2.0000D-01 +0.0000D+00i
	-1.0000D+00 +0.0000D+00i
	-1.9200D+01 +0.0000D+00i

TABLE 2. DESIRED EIGEN VECTORS AND THEIR INTERPRETATION "99" STANDS FOR UNSPECIFIED COMPONENTS

Measurements									
ϕ	p	h	h	a_x	M	$\int M$	$\int h$		
0.	0.	0.	0.	99.	99.	99.	0.	v	
0.	0.	99.	99.	1.	99.	0.	99.	α	
0.	0.	99.	99.	0.	0.	0.	99.	q	
0.	0.	0.	1.	99.	0.	99.	0.	θ	
0.	0.	0.	0.	0.	0.	0.	0.	β	
99.	1.	0.	99.	0.	0.	0.	0.	p	
0.	0.	0.	0.	0.	0.	0.	0.	r	
1.	99.	99.	99.	0.	0.	0.	0.	ϕ	
0.	0.	1.	99.	99.	0.	99.	99.	h	
0.	0.	0.	0.	99.	1.	0.	0.	Thrust Actuator	
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		States
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.	CAS States	
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	99.	99.	99.	99.	99.	99.		
99.	99.	0.	0.	99.	99.	1.	0.	$\int M$	
99.	99.	99.	99.	0.	0.	0.	1.	$\int h$	

TABLE 3. DESIRED EIGEN VALUES

-2.0000D-01	+2.0000D-01i
-2.0000D-01	-2.0000D-01i
-1.5000D-01	+1.0000D-01i
-1.5000D-01	-1.0000D-01i
-1.4000D-01	+1.4000D-01i
-2.5000D-01	+0.0000D+00i
-1.4000D-01	-1.4000D-01i
-2.7000D-01	+0.0000D+00i

TABLE 4. OUTPUT FEEDBACK CONTROLLER

$$
\begin{bmatrix} \delta T \\ \delta e \\ \delta a \\ \delta r \end{bmatrix}
= \begin{bmatrix}
-2.6554D{-}02 & -6.7021D{-}02 & -4.2989D{-}02 & -1.1488D{+}02 & -1.0926D{+}02 & -1.3532D{+}03 & -1.3895D{+}02 & -2.7503D{-}03 \\
1.3255D{-}01 & 4.1906D{-}01 & 5.9632D{-}02 & 2.9394D{+}02 & -6.4494D{+}00 & -4.9372D{+}01 & -7.9314D{+}00 & 5.8963D{-}03 \\
-6.0067D{+}00 & -5.1092D{+}01 & 0 & 0 & 0 & 0 & 0 & 0 \\
2.6041D{-}01 & -2.3116D{+}00 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} \delta \phi \\ \delta p \\ \delta h \\ \delta \dot{h} \\ \delta a_x \\ \delta M \\ \int \delta M \\ \int \delta h \end{bmatrix}
$$

TABLE 5. CLOSED LOOP EIGEN VALUES

-1.3612D+02	+7.9936D-15i	-4.1391D+00	-1.4054D+01i
-1.1955D+02	+2.4338D-15i	-4.1391D+00	+1.4054D+01i
-1.0000D+02	+6.1189D-16i	-3.2028D+00	+4.0631D+00i
-8.8194D+01	+4.5058D-15i	-3.2028D+00	-4.0631D+00i
-8.8004D+01	-5.7886D+01i	-1.0000D+00	+0.0000D+00i
-8.8004D+01	+5.7886D+01i	-6.9439D-01	+6.7315D-01i
-6.1080D+01	+2.1706D+01i	-6.9439D-01	-6.7315D-01i
-6.1080D+01	-2.1706D+01i	-5.0000D-01	+0.0000D+00i
-4.9065D+01	+1.0959D-16i	-4.7765D-01	+0.0000D+00i
-2.6024D+01	+6.4031D-15i	-3.4069D-01	+1.1513D-17i
-1.9200D+01	+0.0000D+00i	-2.7000D-01	+1.3002D-17i
-5.4187D+00	+3.3073D+01i	-2.5000D-01	+1.3092D-17i
-5.4187D+00	-3.3073D+01i	-2.0045D-01	-2.0037D-01i
-5.0713D+00	-4.4306D+01i	-2.0045D-01	+2.0037D-01i
-5.0713D+00	+4.4306D+01i	-1.5000D-01	-1.0000D-01i
		-1.5000D-01	+1.0000D-01i
		-1.4000D-01	-1.4000D-01i
		-1.4000D-01	+1.4000D-01i

desired eigenvalues

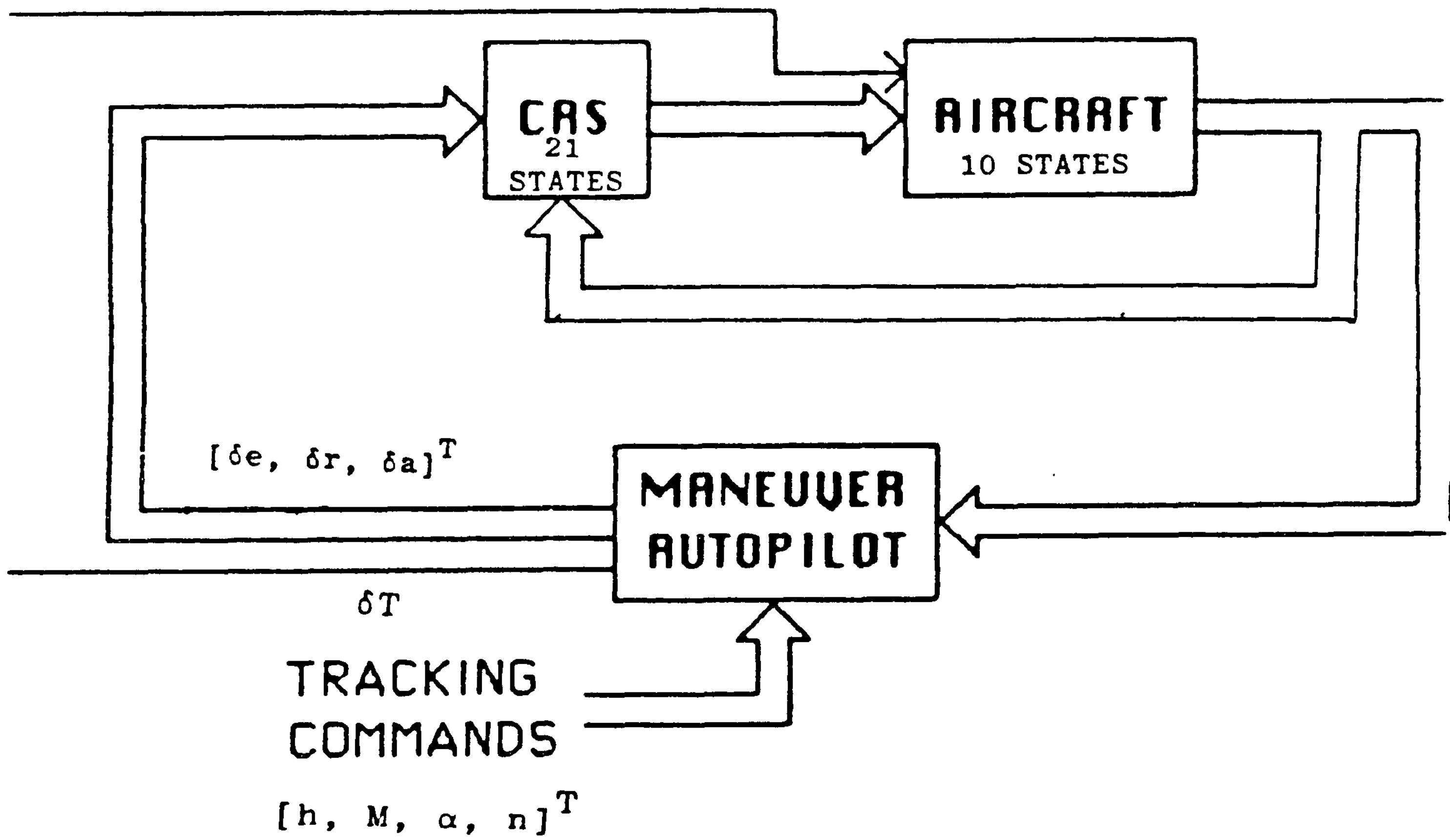

Figure 1. Flight Test Trajectory Control System

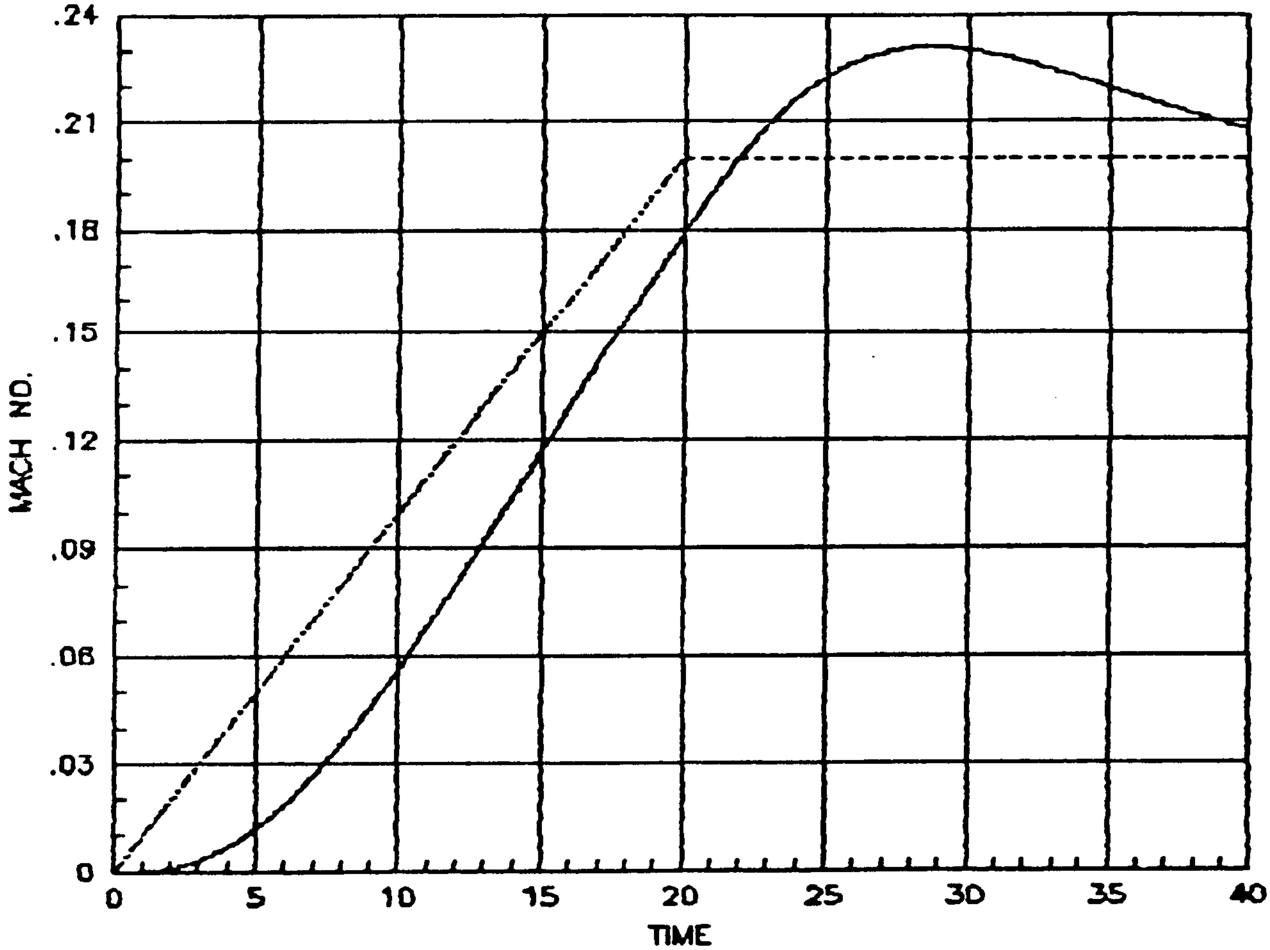

Figure 2. Mach No. vs Time Response for a Ramp Mach No. Command

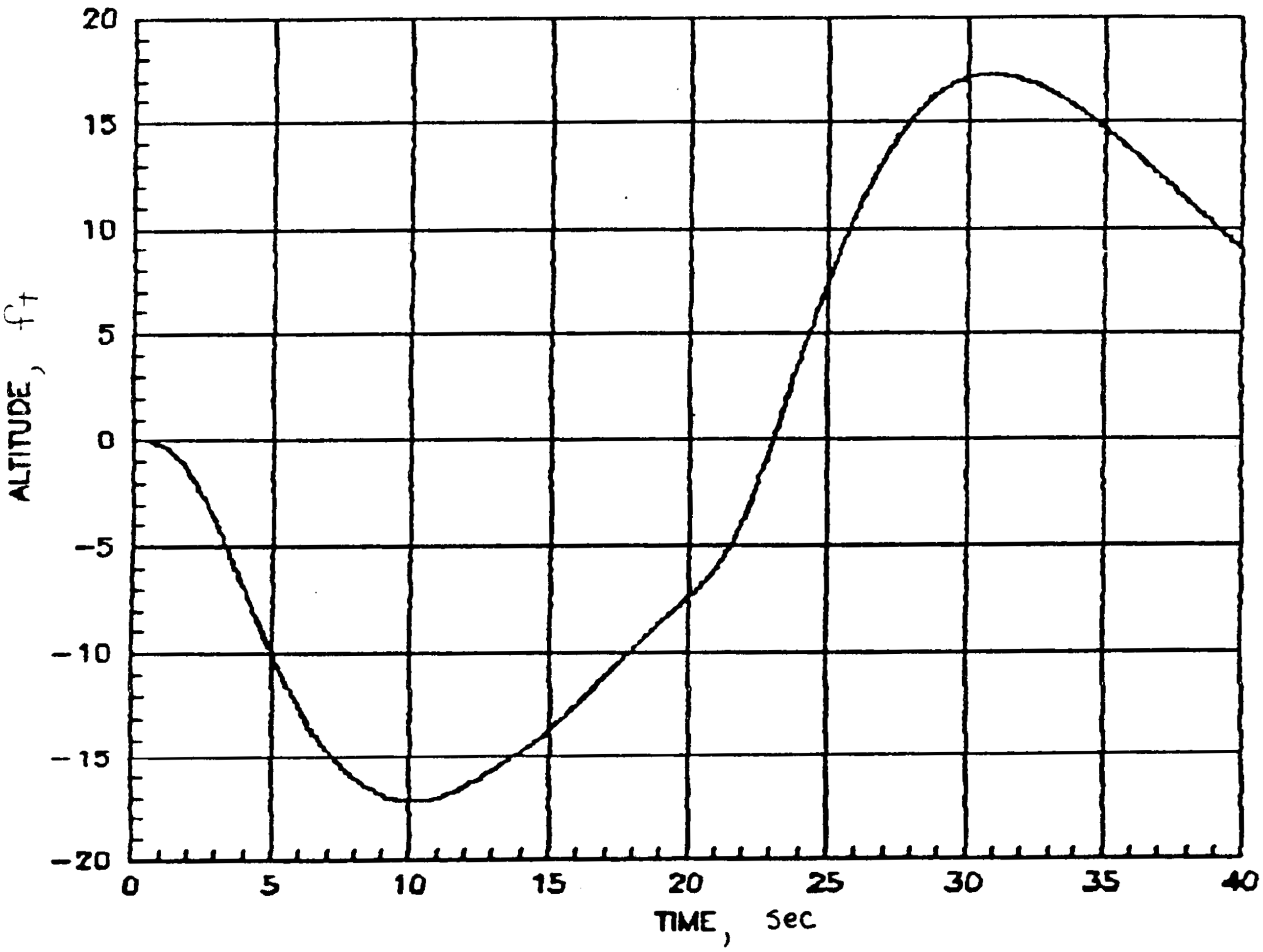

Figure 3. Altitude vs. Time Response for a Ramp Mach No. Command

APPENDIX A-II

AIRCRAFT - CAS LINEARIZED MODEL AND FTTC DESIGN USING EIGENSTRUCTURE ASSIGNMENT AT 1.2 MACH, 10000 ALTITUDE

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1. F Matrix (31 x 31)

COLUMNS 1 THRU 6

7.3178D-02	-5.5611D+01	-1.7893D-17	-3.2144D+01	0.0000D+00	0.0000D+00
-2.9558D-05	-2.3342D+00	1.0000D+00	-1.1679D-06	0.0000D+00	0.0000D+00
7.3543D-03	-1.0458D+02	-5.1574D+00	1.0534D-03	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-5.0793D-01	1.1914D-02
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.1327D+02	-5.0653D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	3.0049D+01	-6.0755D-03
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	1.0000D+00
0.0000D+00	-1.2929D+03	0.0000D+00	1.2929D+03	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.8719D-01	6.7079D+02	3.5929D+02	2.0658D-02	-1.3253D+02	-5.9264D+00
0.0000D+00	0.0000D+00	-5.1667D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-3.7437D-01	-1.3416D+03	-7.1859D+02	-4.1316D-02	2.6505D+02	1.1853D+01
1.8719D-02	6.7079D+01	3.5929D+01	2.0658D-03	-1.3253D+01	-5.9264D-01
1.8719D+00	6.7079D+03	3.5929D+03	2.0658D-01	-1.3253D+03	-5.9264D+01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-3.5813D+02
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	6.2544D+01	2.6651D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	1.5440D-03	3.7962D-01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-3.4866D-06	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	-5.0352D-08	2.9138D-06	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-9.9953D-01	2.4860D-02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
9.9565D-01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-1.0568D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.1915D-02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-2.0000D-01	0.0000D+00	0.0000D+00
1.1649D+00	0.0000D+00	-1.0320D-06	-5.3667D-05	-5.0000D+01	3.0000D+01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-3.3333D-01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	1.5000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-2.3296D+00	0.0000D+00	2.0640D-06	1.0733D-04	0.0000D+00	-6.0000D+01
1.1649D-01	0.0000D+00	-1.0320D-07	-5.3667D-06	0.0000D+00	3.0000D+00
1.1649D+01	0.0000D+00	-1.0320D-05	-5.3667D-04	0.0000D+00	3.0000D+02
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-1.0533D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
8.8000D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

F Matrix (Cont'd)

COLUMNS 13 THRU 18

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-9.0184D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-2.3830D-01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-4.5153D+01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	1.0000D-01	1.0000D+01	0.0000D+00	-6.3810D+02
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.0000D+02	-1.0000D+02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	-3.0000D+01	0.0000D+00	0.0000D+00	1.2762D+03
0.0000D+00	0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00	-6.3810D+01
0.0000D+00	0.0000D+00	1.0000D+02	1.0000D+02	-1.0000D+02	-6.3810D+03
0.0000D+00	3.4904D-01	0.0000D+00	0.0000D+00	3.4904D-01	-2.0000D+01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

COLUMNS 19 THRU 24

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	-2.0888D-02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	5.6458D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	3.7345D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	6.6056D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	-1.3211D+02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	6.6056D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	6.6056D+02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-1.0000D+02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
6.9808D-01	-2.0000D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	-6.6399D+00	-8.6000D+01	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-8.8000D+01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-5.0000D-01	-5.0000D-01	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-5.0000D-01	-5.0000D-01	-5.0000D-01
0.0000D+00	0.0000D+00	3.4380D+03	3.4380D+03	3.4380D+03	3.4380D+03
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

F Matrix (Cont'd)

ORIGINAL PAGE IS
OF POOR QUALITY

COLUMNS 25 THRU 30						COLUMN 31
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-3.8962D-02	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-3.9064D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.1634D+01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-4.5705D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	9.1410D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-4.5705D-01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-4.5705D+01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.2963D+02	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-6.0000D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
5.0000D-01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
5.9000D+01	5.9000D+01	-5.9000D+01	0.0000D+00	0.0000D+00	0.0000D+00	-5.9000D+01
0.0000D+00	0.0000D+00	1.0000D+02	-1.0000D+02	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	4.8866D-01	-2.8000D+01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	1.9200D+01	-1.9200D+01

2. G-Matrix (31 x 4).

ORIGINAL PAGE IS
OF POOR QUALITY

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
2.0000D-01	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	1.0000D+01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	1.0000D+02	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	1.0000D+02	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	3.4380D+03
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

ORIGINAL PAGE IS
OF POOR QUALITY

3. H-Matrix (17 x 31)

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.1327D+02	-5.0653D+00
1.2151D-03	9.3810D+01	0.0000D+00	-3.1062D-05	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
7.3543D-03	-1.0458D+02	-5.1574D+00	1.0534D-03	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	1.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-2.0410D+01	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	3.0049D+01	-6.0755D-03
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
9.2815D-04	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.1892D-03	9.2813D+01	0.0000D+00	-1.2611D-06	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	-1.2929D+03	0.0000D+00	1.2929D+03	0.0000D+00	0.0000D+00
9.9994D-01	-1.5381D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-2.2601D-03	-6.1083D-01	0.0000D+00	8.8325D-06	0.0000D+00	0.0000D+00

COLUMNS 7 THRU 12

9.9565D-01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-3.7795D-06	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	-5.0353D-08	2.9137D-06	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-1.0568D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	9.7656D-01	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-3.7834D-06	0.0000D+00	0.0000D+00
0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	4.7963D-05	1.1805D-02	0.0000D+00	0.0000D+00

H-Matrix (Cont'd)

COLUMNS 13 THRU 18

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	9.5783D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-4.5153D+01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	9.5847D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.6616D-01

COLUMNS 19 THRU 24

0.0000D+00	5.6458D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	-8.3936D-01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	3.7345D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

H-Matrix (Cont'd)

ORIGINAL PAGE IS OF POOR QUALITY

COLUMNS 25 THRU 30

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-3.9064D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.5656D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.1634D+01	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

COLUMN 31

0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00

Controller Design

$$U = GAIN * z$$

where

z are perturbed values of

$$[\phi \ p \ h \ \dot{h} \ ax \ M \ \int M \ \int h]^T$$

and

$$u = [\delta T \ \delta e_{ap} \ \delta a_{ap} \ \delta\gamma_{ap}]^T$$

GAIN =

COLUMNS 1 THRU 6

-2.6554D-02	-6.7021D-02	-4.2989D-02	-1.1488D+02	-1.0926D+02	-1.3532D+03
1.3259D-01	4.1906D-01	5.9632D-02	2.9394D+02	-6.4494D+00	-4.9372D+01
-6.0067D+00	-5.1092D+01	3.7164D-12	1.7632D-08	-7.0812D-12	6.1661D-10
2.6041D-01	-2.3116D+00	4.0677D-13	1.9321D-09	-4.5292D-13	7.2911D-11

COLUMNS 7 THRU 8

-1.3895D+02	-2.7503D-03
-7.9314D+00	5.8963D-03
-1.8390D-11	3.6752D-13
-1.0162D-12	4.1311D-14

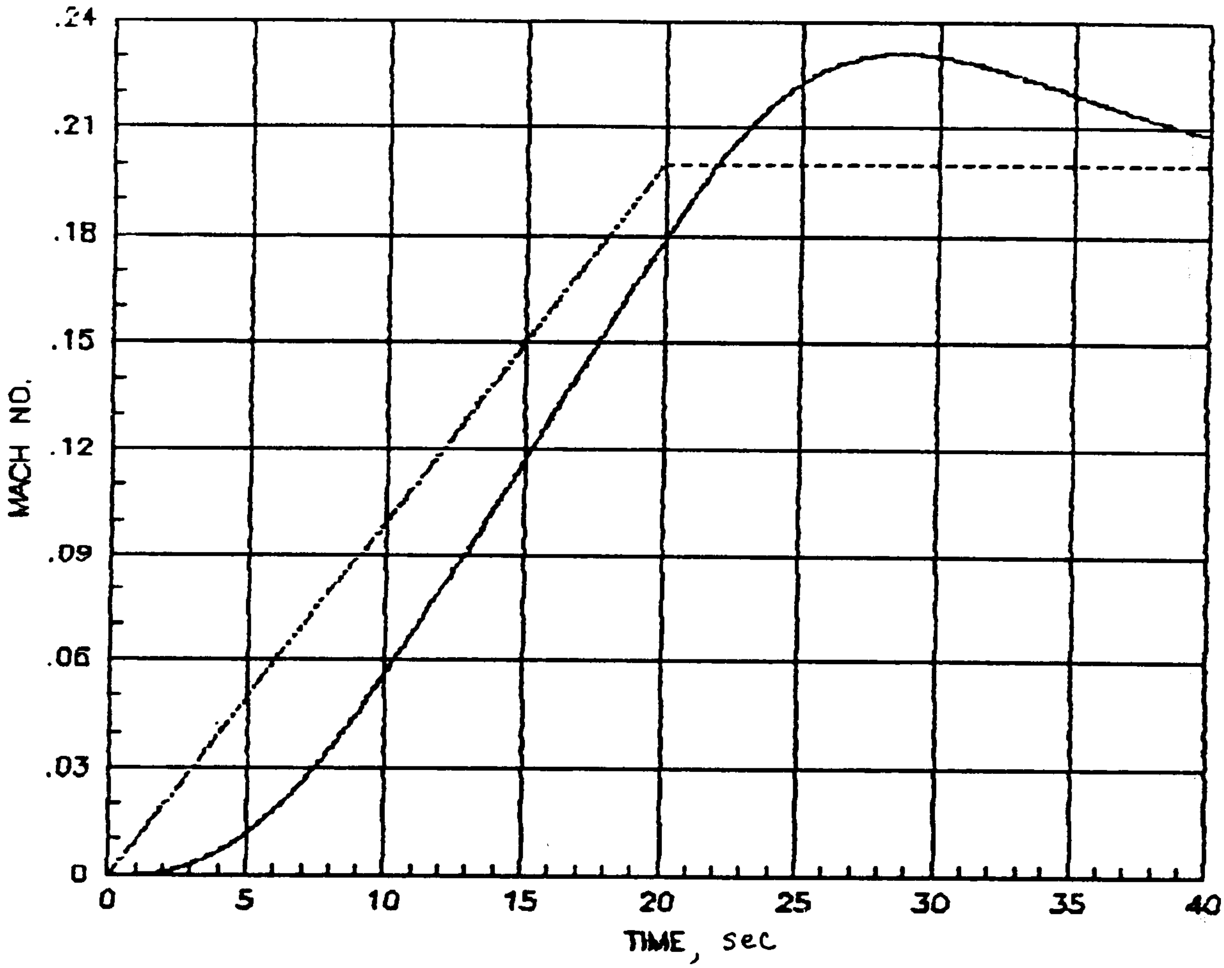
Open-loop eigenvalues:

ORIGINAL PAGE IS
OF POOR QUALITY

-5.9456D+01	+2.0293D+01i
-5.9456D+01	-2.0293D+01i
-1.3674D+02	-3.7679D-15i
-4.8679D+01	+3.0434D-17i
-8.7758D+01	+5.8218D+01i
-8.7758D+01	-5.8218D+01i
-1.0180D+02	+5.1723D-15i
-1.0000D+02	+4.2144D-15i
-8.8196D+01	+3.5469D-16i
-2.3286D+01	+8.2436D-17i
-7.4117D+00	+3.3574D+01i
-7.4117D+00	-3.3574D+01i
-7.9725D+00	+8.2655D+00i
-7.9725D+00	-8.2655D+00i
-1.2176D+01	+1.0192D+01i
-1.2176D+01	-1.0192D+01i
-2.9438D+00	+5.3113D+00i
-2.9438D+00	-5.3113D+00i
-2.3186D-01	+1.8504D-01i
-2.3186D-01	-1.8504D-01i
-3.4734D-01	-7.4748D-15i
-6.5704D-02	-8.2699D-18i
3.1435D-04	+4.3959D-03i
3.1435D-04	-4.3959D-03i
-5.4174D-01	+0.0000D+00i
-5.0000D-01	+0.0000D+00i
1.4997D-03	+0.0000D+00i
-2.7600D-01	+0.0000D+00i
-2.0000D-01	+0.0000D+00i
-1.0000D+00	+0.0000D+00i
-1.9200D+01	+0.0000D+00i

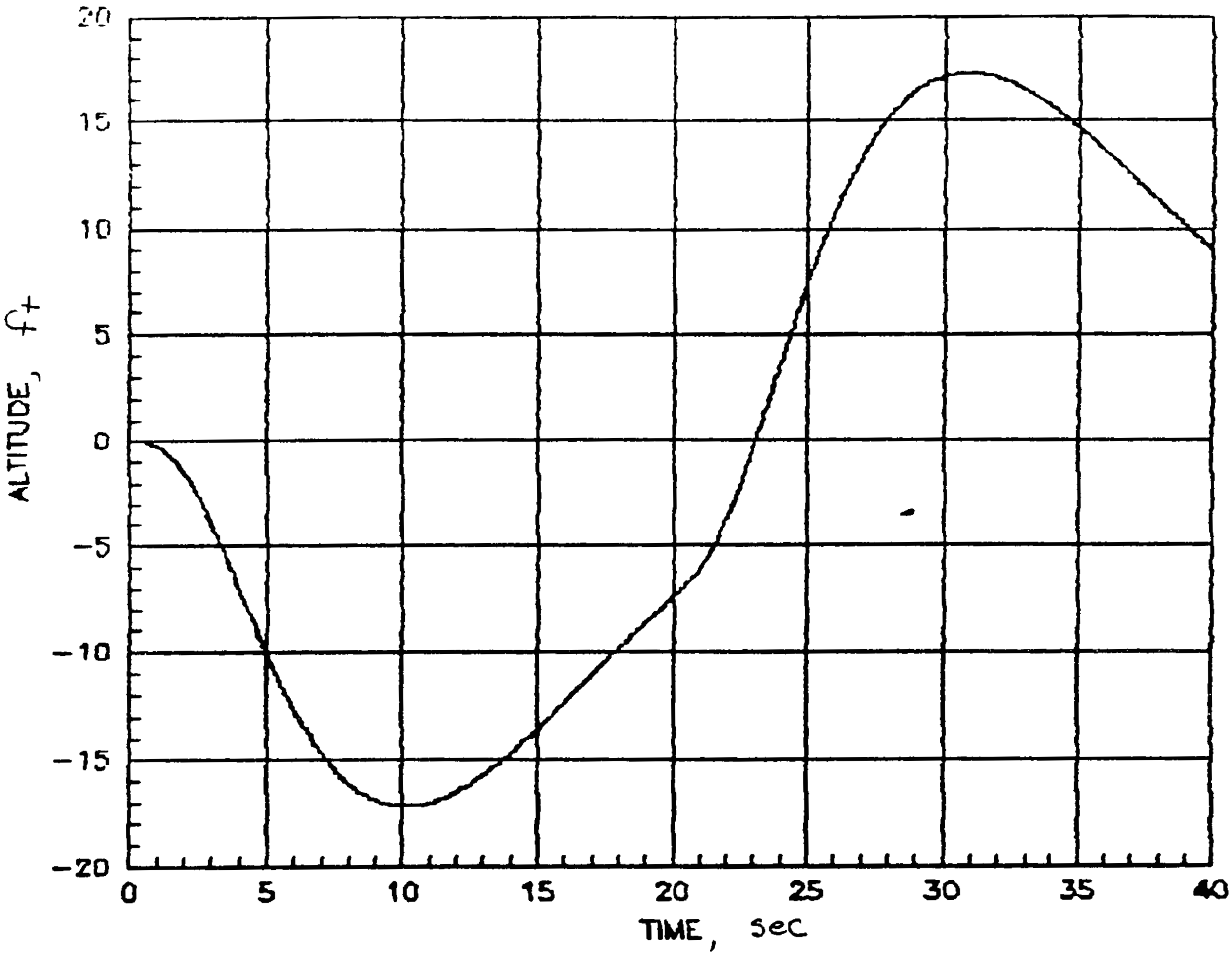
Closed-loop eigenvalues:

-1.3612D+02	+7.9936D-15i
-1.1955D+02	+2.4338D-15i
-1.0000D+02	+6.1189D-16i
-8.8194D+01	+4.5056D-15i
-8.8004D+01	-5.7886D+01i
-8.8004D+01	+5.7886D+01i
-6.1080D+01	+2.1706D+01i
-6.1080D+01	-2.1706D+01i
-4.9065D+01	+1.0959D-16i
-2.6024D+01	+6.4031D-15i
-1.9200D+01	+0.0000D+00i
-5.4187D+00	+3.3073D+01i
-5.4187D+00	-3.3073D+01i
-5.0713D+00	-4.4306D+01i
-5.0713D+00	+4.4306D+01i
-4.1391D+00	-1.4054D+01i
-4.1391D+00	+1.4054D+01i
-3.2028D+00	+4.0631D+00i
-3.2028D+00	-4.0631D+00i
-1.0000D+00	+0.0000D+00i
-6.9439D-01	+6.7315D-01i
-6.9439D-01	-6.7315D-01i
-5.0000D-01	+0.0000D+00i
-4.7765D-01	+0.0000D+00i
-3.4069D-01	+1.1513D-17i
-2.7000D-01	+1.3002D-17i
-2.5000D-01	+1.3092D-17i
-2.0045D-01	-2.0037D-01i
-2.0045D-01	+2.0037D-01i
-1.5000D-01	-1.0000D-01i
-1.5000D-01	+1.0000D-01i
-1.4000D-01	-1.4000D-01i
-1.4000D-01	+1.4000D-01i



CLOSED-LOOP TIME RESPONSE

MACH NO VS TIME FOR A RAMP MACH NO COMMAND



CLOSED-LOOP TIME RESPONSE

ALTITUDE VS TIME FOR A RAMP MACH NO COMMAND

APPENDIX A-III

AIRCRAFT - CAS LINEARIZED AND
FTTC DESIGN USING EIGENSTRUCTURE ASSIGNMENT
AT 0.7 MACH, 10000 ALTITUDE

ORIGINAL PAGE IS
OF POOR QUALITY

1. F MATRIX (31 x 31)

COLUMNS 1 THRU 6

-1.1778D-02	2.2125D+01	0.0000D+00	-3.2144D+01	0.0000D+00	0.0000D+00
-1.2492D-04	-1.3292D+00	1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
7.6271D-04	-6.6234D+00	-3.1248D+00	1.0976D-03	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
5.3481D-13	-2.7167D-10	0.0000D+00	0.0000D+00	-2.8898D-01	3.3443D-02
-3.4792D-09	8.9156D-10	0.0000D+00	0.0000D+00	-4.3656D+01	-2.8255D+00
-1.3023D-10	-4.9208D-08	0.0000D+00	0.0000D+00	1.0573D+01	-4.8592D-02
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	1.0000D+00
0.0000D+00	-7.5418D+02	0.0000D+00	7.5418D+02	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.0380D-01	7.9775D+02	4.0096D+02	2.2495D-02	-5.1078D+01	-3.3058D+00
0.0000D+00	0.0000D+00	-5.1667D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-2.0759D-01	-1.5955D+03	-8.0191D+02	-4.4991D-02	1.0216D+02	6.6116D+00
1.0380D-02	7.9775D+01	4.0096D+01	2.2495D-03	-5.1078D+00	-3.3058D-01
1.0380D+00	7.9775D+03	4.0096D+03	2.2495D-01	-5.1078D+02	-3.3058D+01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-3.5813D+02
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.1261D-09	-5.5416D-07	0.0000D+00	0.0000D+00	2.9700D+01	1.0590D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	3.7924D-01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-1.6157D-05	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	6.0962D-06	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-9.9944D-01	4.2597D-02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.5447D+00	-2.5849D-23	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-7.5853D-01	3.2312D-24	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
3.3462D-02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-2.0000D-01	0.0000D+00	0.0000D+00
1.8073D+00	2.5849D-23	0.0000D+00	-3.0426D-05	-5.0000D+01	3.0000D+01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-3.3333D-01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	1.5000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-3.6146D+00	-5.1699D-23	0.0000D+00	6.0853D-05	0.0000D+00	-6.0000D+01
1.8073D-01	0.0000D+00	0.0000D+00	-3.0426D-06	0.0000D+00	3.0000D+00
1.8073D+01	-2.0680D-22	0.0000D+00	-3.0426D-04	0.0000D+00	3.0000D+02
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-8.0059D+00	-8.0594D-07	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
8.8000D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

F Matrix (Cont'd)

COLUMNS 13 THRU 18

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.4052D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.8849D-01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.9473D-01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	1.0000D+01	1.0000D+01	0.0000D+00	-2.6660D+02
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.0000D+02	-1.0000D+02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	-3.0000D+01	0.0000D+00	0.0000D+00	5.3319D+02
0.0000D+00	0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00	-2.6660D+01
0.0000D+00	0.0000D+00	1.0000D+02	1.0000D+02	-1.0000D+02	-2.6660D+03
0.0000D+00	3.4904D-01	0.0000D+00	0.0000D+00	3.4904D-01	-2.0000D-01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

COLUMNS 19 THRU 24

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	-2.3627D-02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	1.9029D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	2.1105D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	2.2263D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	-4.4527D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	2.2263D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	2.2263D+02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-1.0000D+02	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
6.9808D-01	-2.0000D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	2.0690D+00	-8.6000D+01	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-8.8000D+01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-5.0000D-01	-5.0000D-01	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-5.0000D-01	-5.0000D-01	-5.0000D-01
0.0000D+00	0.0000D+00	3.4380D+03	3.4380D+03	3.4380D+03	3.4380D+03
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

ORIGINAL PAGE IS
OF POOR QUALITY

F Matrix (Cont'd)

COLUMNS 25 THRU 30						COLUMN 31
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-5.1077D-02	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-2.1310D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-5.1451D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-2.4933D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	4.9866D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-2.4933D-01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-2.4933D+01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-6.4105D+01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-6.0000D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
5.0000D-01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
5.9000D+01	5.9000D+01	-5.9000D+01	0.0000D+00	0.0000D+00	0.0000D+00	-5.9000D+01
0.0000D+00	0.0000D+00	1.0000D+02	-1.0000D+02	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	4.8866D-01	-2.8000D+01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	1.9200D+01	-1.9200D+01

2. G-Matrix (31 x 4)

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
2.0000D-01	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	1.0000D+01	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	1.0000D+02	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	1.0000D+02	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	3.4380D+03
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

3. H-Matrix (17 x 31)

COLUMNS 1 THRU 6

-3.4792D-09	9.0949D-10	0.0000D+00	0.0000D+00	-4.3656D+01	-2.8255D+00
2.9388D-03	3.1117D+01	5.8949D-05	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
7.6271D-04	-6.6234D+00	-3.1248D+00	1.0976D-03	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	1.0000D+00
3.5246D-11	-6.3682D-09	0.0000D+00	0.0000D+00	-6.7738D+00	0.0000D+00
-1.3023D-10	-4.9207D-08	0.0000D+00	0.0000D+00	1.0573D+01	-4.8592D-02
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
9.2815D-04	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
2.9309D-03	3.1042D+01	2.9147D-05	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	-7.5418D+02	0.0000D+00	7.5418D+02	0.0000D+00	0.0000D+00
9.9943D-01	-2.5208D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-2.6793D-04	1.7293D+00	-2.1420D-08	5.5879D-06	0.0000D+00	0.0000D+00

COLUMNS 7 THRU 12

1.5447D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-5.1791D-06	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	6.0962D-06	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	-5.8208D-08	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-7.5853D-01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	9.7656D-01	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	-5.1863D-06	0.0000D+00	0.0000D+00
0.0000D+00	1.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	1.1792D-02	0.0000D+00	0.0000D+00

H-Matrix (Cont'd)

COLUMNS 13 THRU 18

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	4.4173D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.9473D+01
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	4.4225D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	1.0411D-01

COLUMNS 19 THRU 24

0.0000D+00	1.9029D+01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	-5.5384D-01	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	2.1105D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

H-Matrix (Cont'd)

COLUMNS 25 THRU 30

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-2.1310D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-1.1973D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	-5.1451D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00

COLUMN 31

0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00
0.0000D+00

Controller Design

$$U = \text{Gain}*z$$

where

z are perturbed values of

$$[\phi \ p \ h \ \dot{h} \ a_x \ M \ \int M \ \int h]^T$$

and

$$u = [\delta T \ \delta e_{ap} \ \delta a_{ap} \ \delta \gamma_{ap}]^T$$

```
GAIN      =

  COLUMNS    1 THRU    6
 -1.4777D-02  -7.3096D-02  -9.2850D-02  -1.7141D-01  -1.3559D+02  -1.5352D+03
  1.1924D-02   3.2934D-02   1.0155D-02   3.9151D-02  -2.0442D+00  -1.9619D+01
 -2.5437D+00  -1.2855D+01   2.9255D-11   4.3619D-11   7.2545D-08  -5.4697D-06
  1.4103D-01  -8.3187D-02  -5.8683D-12   2.9327D-11  -5.9810D-08  -7.4338D-07

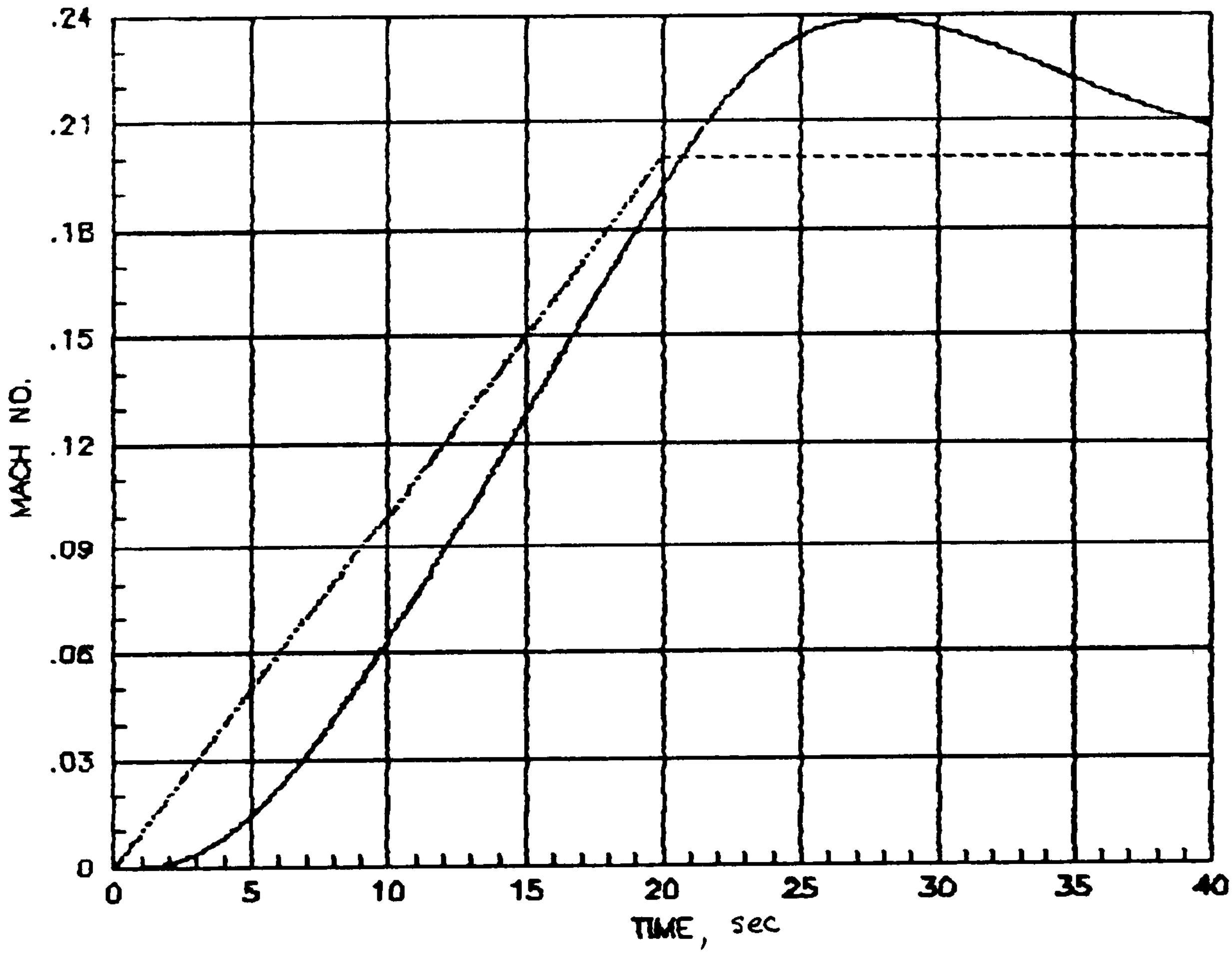
  COLUMNS    7 THRU    8
 -1.3916D+02  -7.2697D-03
 -2.4791D+00   1.0732D-03
 -1.3702D-06   3.7197D-12
 -2.3738D-08  -1.1493D-13
```

Open-loop eigenvalues

```
-1.2884D+02 -8.8818D-16i
-8.5428D+01 -4.9351D+01i
-8.5426D+01 +4.9351D+01i
-8.8039D+01 +5.9819D-17i
-1.0060D+02 +1.1917D-16i
-5.0262D+01 -1.1145D-15i
-8.8175D+01 +1.8853D-16i
-1.0000D+02 +2.8730D-15i
-2.8867D+01 -3.6097D+00i
-2.8867D+01 +3.6097D+00i
-1.4689D+01 -2.7807D+01i
-1.4689D+01 +2.7807D+01i
-1.5371D+01 -4.0164D-16i
-3.8389D+00 -2.4781D+00i
-3.8389D+00 +2.4781D+00i
-7.8327D+00 +1.0559D-16i
-1.7710D+00 +3.1453D+00i
-1.7710D+00 -3.1453D+00i
-4.8829D-01 +7.9997D-16i
-6.1246D-01 +1.7102D-17i
-2.7438D-01 +7.6776D-02i
-2.7438D-01 -7.6776D-02i
-5.0000D-01 -2.3109D-17i
-1.2194D-02 +1.4478D-16i
-5.2200D-11 +5.6029D-15i
 1.6208D-03 -5.8158D-15i
 7.6579D-03 +1.4094D-17i
-1.7139D-01 -5.1627D-18i
-2.0000D-01 +0.0000D+00i
-1.0000D+00 +0.0000D+00i
-1.9200D+01 +0.0000D+00i
```

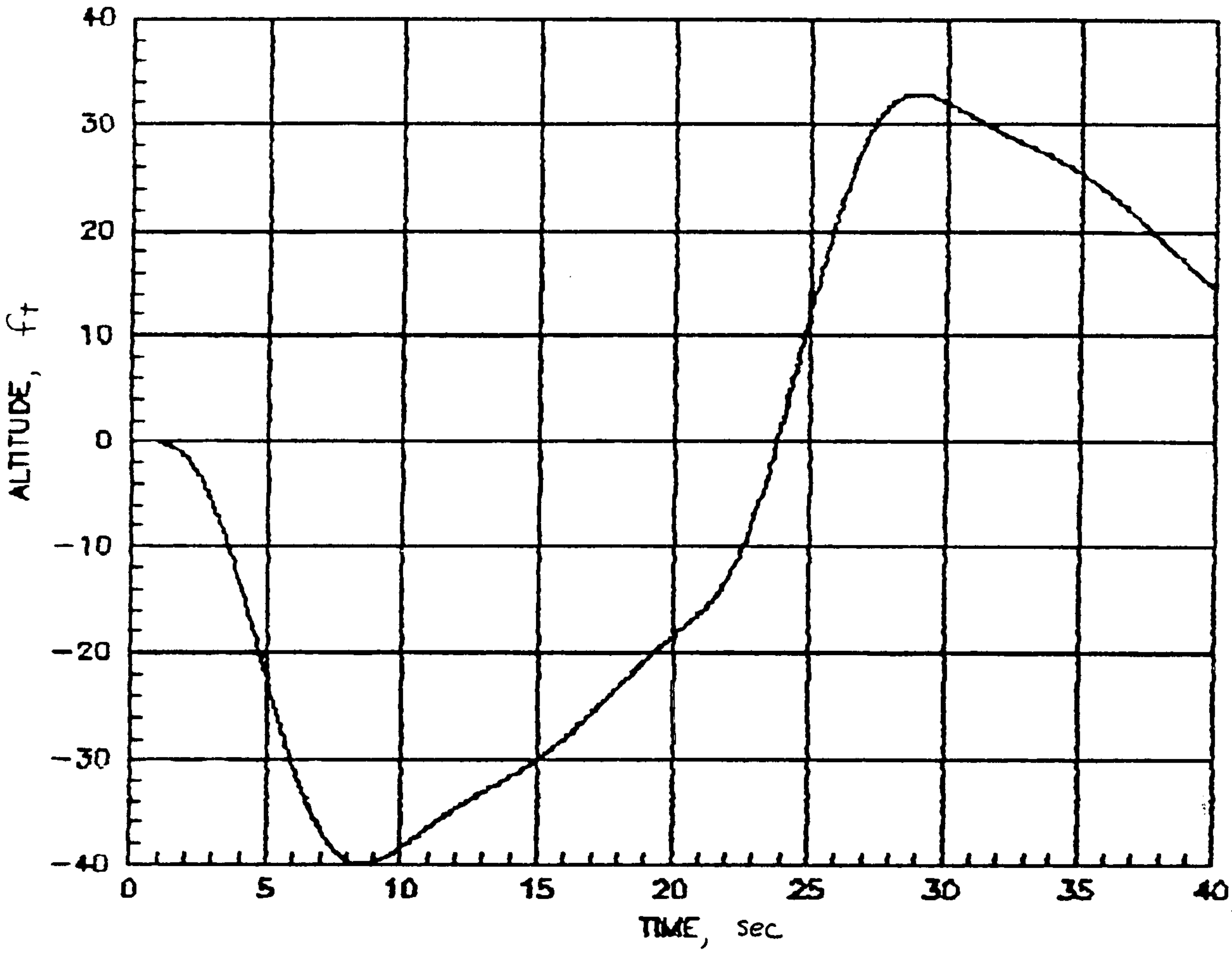
Closed-loop eigenvalues

```
-1.2863D+02 +0.0000D+00i
-1.0264D+02 -1.6401D-15i
-1.0000D+02 -4.2141D-16i
-8.8174D+01 -2.6184D-15i
-6.7871D+01 -2.8902D-15i
-8.5441D+01 +4.9337D+01i
-8.5441D+01 -4.9337D+01i
-5.0270D+01 +6.0993D-16i
-2.8984D+01 -3.6460D+00i
-2.8984D+01 +3.6460D+00i
-1.9200D+01 +0.0000D+00i
-1.4759D+01 -2.7853D+01i
-1.4759D+01 +2.7853D+01i
-1.0067D+01 +1.2750D+01i
-1.0067D+01 -1.2750D+01i
-3.6721D+00 +1.6772D+00i
-3.6721D+00 -1.6772D+00i
-2.1011D+00 +3.1638D+00i
-2.1011D+00 -3.1638D+00i
-1.0000D+00 +0.0000D+00i
-5.5401D-01 +0.0000D+00i
-5.0000D-01 +0.0000D+00i
-3.8063D-01 -1.9930D-17i
-2.7000D-01 -1.1628D-17i
-2.5000D-01 +1.8920D-17i
-2.0023D-01 -2.0010D-01i
-2.0023D-01 +2.0010D-01i
-1.9303D-01 -7.2059D-01i
-1.9303D-01 +7.2059D-01i
-1.5000D-01 -1.0000D-01i
-1.5000D-01 +1.0000D-01i
-1.4000D-01 +1.4000D-01i
-1.4000D-01 -1.4000D-01i
```



CLOSED-LOOP TIME RESPONSE

MACH NO VS TIME FOR A RAMP MACH NO COMMAND



CLOSED-LOOP TIME RESPONSE

ALTITUDE VS TIME FOR A RAMP MACH NO COMMAND

APPENDIX A-IV

DESIRED EIGENVALUES AND EIGENVECTORS USED IN THE SYNTHESIS

DESIRED EIGENVALUES:

```
-2.0000D-01 +2.0000D-01i
-2.0000D-01 -2.0000D-01i
-1.5000D-01 +1.0000D-01i
-1.5000D-01 -1.0000D-01i
-1.4000D-01 +1.4000D-01i
-2.5000D-01 +0.0000D+00i
-1.4000D-01 -1.4000D-01i
-2.7000D-01 +0.0000D+00i
```

DESIRED EIGENVECTORS:

MEASUREMENTS

φ	p	h	h	a_x	M	∫M	∫h	States
0.	0.	0.	0.	99.	99.	99.	0.	v
0.	0.	99.	99.	1.	99.	0.	99.	α
0.	0.	99.	99.	0.	0.	0.	99.	q
0.	0.	0.	1.	99.	0.	99.	0.	θ
0.	0.	0.	0.	0.	0.	0.	0.	β
99.	1.	0.	99.	0.	0.	0.	0.	p
0.	0.	0.	0.	0.	0.	0.	0.	r
1.	99.	99.	99.	0.	0.	0.	0.	φ
0.	0.	1.	99.	99.	0.	99.	99.	h
0.	0.	0.	0.	99.	1.	0.	0.	Thrust Actuator
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	CAS States
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	99.	99.	99.	99.	99.	99.	
99.	99.	0.	0.	99.	99.	1.	0.	∫M
99.	99.	99.	99.	0.	0.	0.	1.	∫h

APPENDIX B

A DEMONSTRATION EXAMPLE FOR EXACT NONLINEAR CONTROLLER DESIGN WITH PRELINEARIZING TRANSFORMATION

INTRODUCTION

The theory of prelinearizing transformations for a class of nonlinear feedback system design has already achieved maturity. Pioneering work on these transformations for flight control problems was carried out at NASA Ames research center by G. Meyer and others [1-14]. Though several papers are currently available, they deal with large dimension problems and consequently do not contain sufficient detail to serve as introductory example.

The objective of this technical memo is to illustrate the application of these transformations with a simple but realistic example. The theory is excluded completely from the discussions since the transformation scheme for this example turns out to be direct. The performance of the exact nonlinear controller is compared with a gain scheduled linear perturbation controller to bring out the advantages of the former in clear detail.

ILLUSTRATIVE EXAMPLE:

Consider a two state variable model of a transport aircraft landing in the presence of winds as follows

$$\dot{V} = \frac{\eta T - D}{mV\cos\gamma} - \frac{g}{V}\tan\gamma \qquad (1)$$

$$\dot{h} = \tan\gamma \qquad (2)$$

here, V is airspeed, h altitude, T maximum thrust, D aerodynamic drag, γ flight-path angle, and η is the throttle setting. γ and η are the control variables in this model and down range is the independent variable. Now, a hypothetical thrust and drag characteristics are assumed as

$$T = T_o(V + V_w)$$

$$D = e^{-\beta h} D_o(V + V_w)^2$$

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and $V_w = V_w(h)$, V_w is the wind speed specified along flight path.

Note that the engine model is grossly incorrect at low speeds.

It is required that the aircraft follow a given trajectory $V_R(t)$, $h_R(t)$.

Since there are two state variables and two control variables in this problem, consider a transformation of the form

$$x_1 = V,\ x_2 = h$$

$$u_1 = \frac{nT-D}{mV\cos\gamma} - \frac{g}{V}\tan\gamma;\ u_2 = \tan\gamma$$

such that the transformed system is the form

$$\dot{x}_1 = u_1 \tag{3}$$

$$\dot{x}_2 = u_2 \tag{4}$$

This model is in Brunovsky's canonical form according to Meyer [10]. If the number controls are less than the number of states, a simple transformation such as the one given above is no longer possible. A transformation is still feasible under certain weak conditions but will involve additional algebra.

To consider the regulator problem first, a controller of the form

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{bmatrix} V \\ h \end{bmatrix}$$

can be designed for the system (3), (4) using any of the available techniques for linear system design. Note, however that the designed controller should satisfy physical constraints on u_1 and u_2.

Real controls can then be computed as

$$\gamma = \tan^{-1}(k_{21}V + k_{22}h) \tag{5}$$

$$\eta = [k_{11}V + k_{12}h + \frac{g}{V}\tan\gamma]\,\frac{mV\cos\gamma}{T} + \frac{D}{T} \tag{6}$$

Expressions (5) and (6) give the nonlinear regulator for the aircraft problem. A block diagram of the plant with regulator is given in Fig. 1.

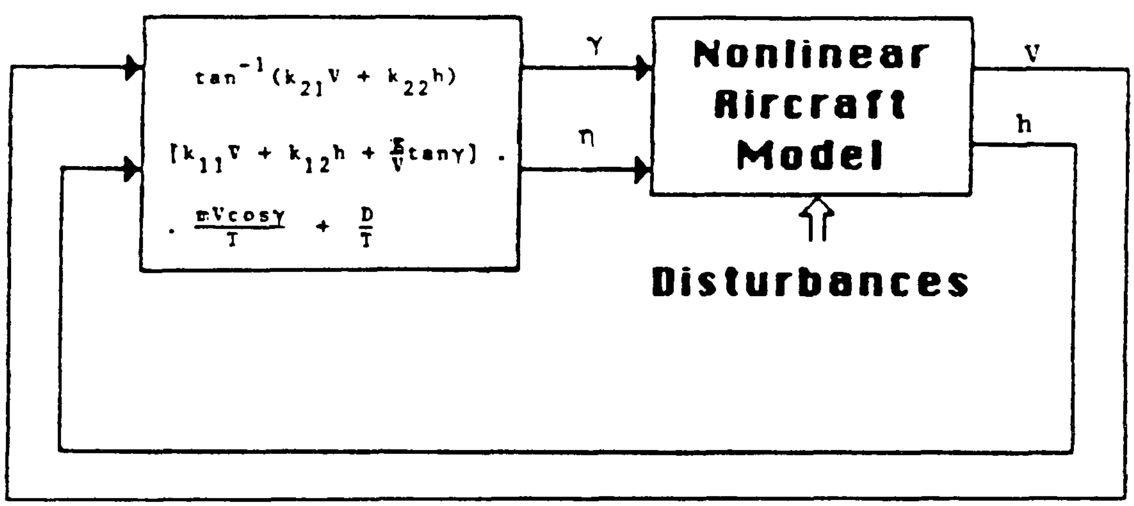

Figure 1. Nonlinear Regulator with Aircraft

The tracking problem is addressed next. Define the new state variables

$$x = V - V_R$$
$$y = h - h_R$$

$$\dot{x} = \frac{nT-D}{mV\cos\gamma} - \frac{g}{V}\tan\gamma - C_1$$

$$\dot{y} = \tan\gamma - C_2$$

where

$$\dot{V}_R = C_1,\ \dot{h}_R = C_2$$

using the transformations

$$x_1 = x,\ x_2 = y$$

$$u_1 = \frac{nT-D}{mV\cos\gamma} - \frac{g}{V}\tan\gamma - C_1$$

$$u_2 = \tan\gamma - C_2$$

one has the following

$$\dot{x}_1 = u_1 \tag{7}$$

$$\dot{x}_2 = u_2 \tag{8}$$

which is in the Brunovsky's canonical form.

As before, a feedback regulator can be synthesized for (7), (8) as shown below using linear design approaches.

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{bmatrix} V-V_R \\ h-h_R \end{bmatrix}$$

This controller can be transformed to original coordinates to give:

$$\gamma = \tan^{-1}\left[k_{21}(V-V_R) + k_{22}(h-h_R) + C_2\right] \tag{9}$$

$$\eta = [k_{11}(V-V_R) + k_{12}(h-h_R) + C_1 + \frac{g}{V}\tan\gamma]\frac{mV\cos\gamma}{T} + \frac{D}{T} \qquad (10)$$

Expressions (9) and (10) give the nonlinear controller for tracking the commands $V_R(t)$ and $h_R(t)$. If a tighter control is desired, additional integral feedbacks can be incorporated with very little difficulty.

NONLINEAR CONTROLLER EVALUATION

To evaluate the nonlinear controller (9) and (10), a feedback gain matrix was computed first using linear quadratic regulator theory with the following state and control weighting matrices.

$$R_{xx} = \begin{bmatrix} 1 & 0 \\ 0 & 100 \end{bmatrix}, \qquad R_{uu} = \begin{bmatrix} 5000 & 0 \\ 0 & 10^8 \end{bmatrix}.$$

These computations were carried out with the hypothetical data

$$\frac{T_o}{m} = 0.04025, \quad \frac{D_o}{m} = 0.0136238 \times 10^{-2}.$$

To serve as a standard for comparison, a gain scheduled linear perturbation controller was designed with the same data. Four design conditions were used which are given in Table 1.

TABLE 1. LINEARIZATION POINTS FOR THE ILLUSTRATIVE EXAMPLE

Range feet	h_R, $\underline{h}$ feet	V_R, $\underline{V}$ feet/s	C_2, $\underline{\dot{h}}$	C_1, $\underline{\dot{V}}$
0	10000	350	-0.04667	-0.000467
150000	3000	280	-0.06	-0.0016
200000	0.0	200	0.0	-0.02
205000	0.0	60	0.0	0.0

Note that the linearization points were on the commanded trajectory.

Two simulations are next setup. The first one implementing the nonlinear controller (9) and (10) and the second one using the gain scheduled linear perturbation controller. A disturbance in the form a wind shear was introduced in the simulations for additional realism, (fig. 2).

Figures 2-4 give the results. Note that the nonlinear controller has a slightly superior tracking performance. The real advantage of using this controller, however, is that it performs well using one set of gains throughout the operating region while the linear perturbation controller requires a gain schedule to achieve acomparable performance.

CONCLUSIONS

A simple illustrative example was discussed in this technical memo to demonstrate the power of the prelinearization transformations in synthesizing exact nonlinear controllers. Comparisons were made against a gain scheduled linear perturbation controllers to show relative advantages.

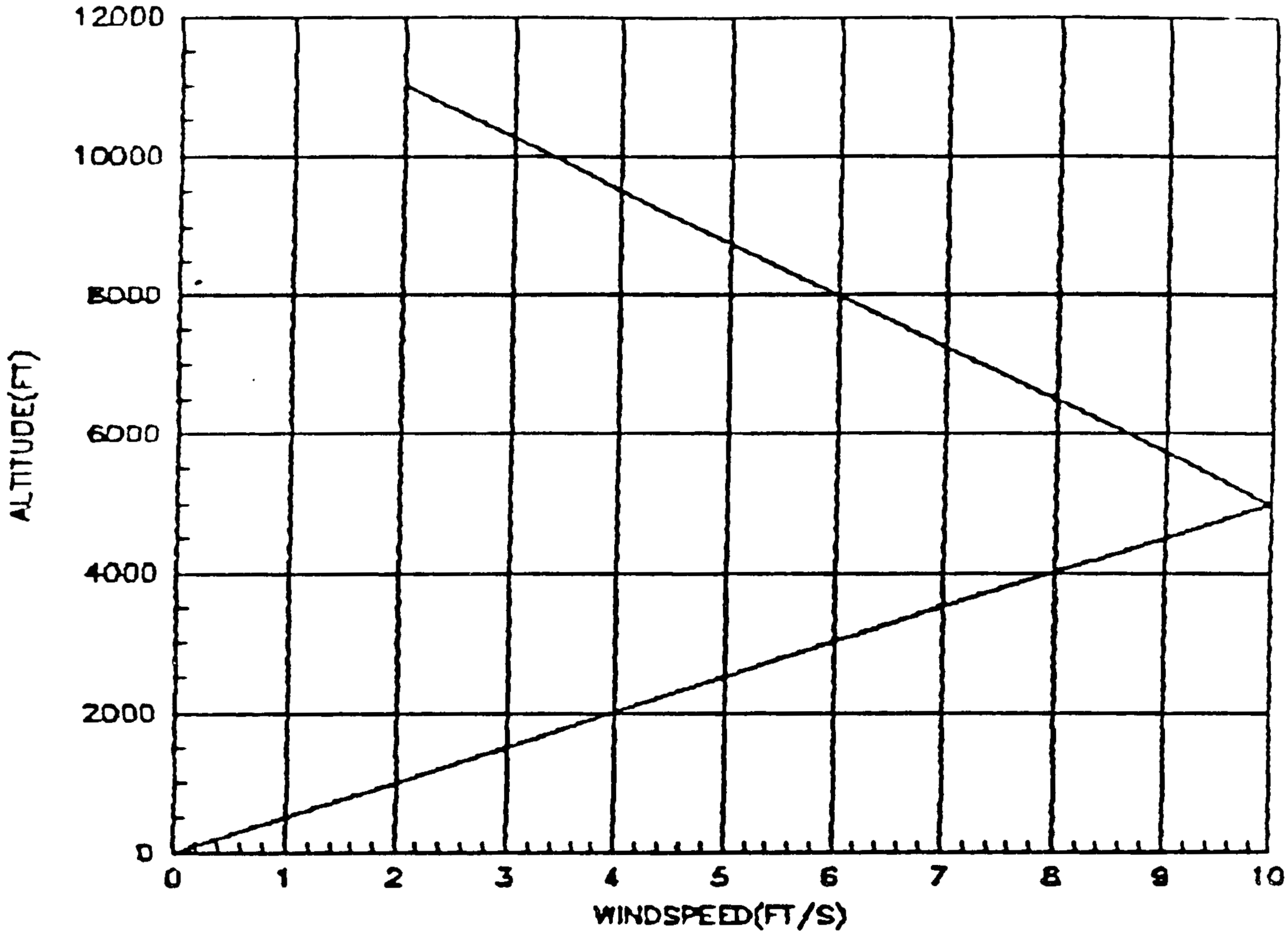

Figure 2. Wind Shear Used in Simulations

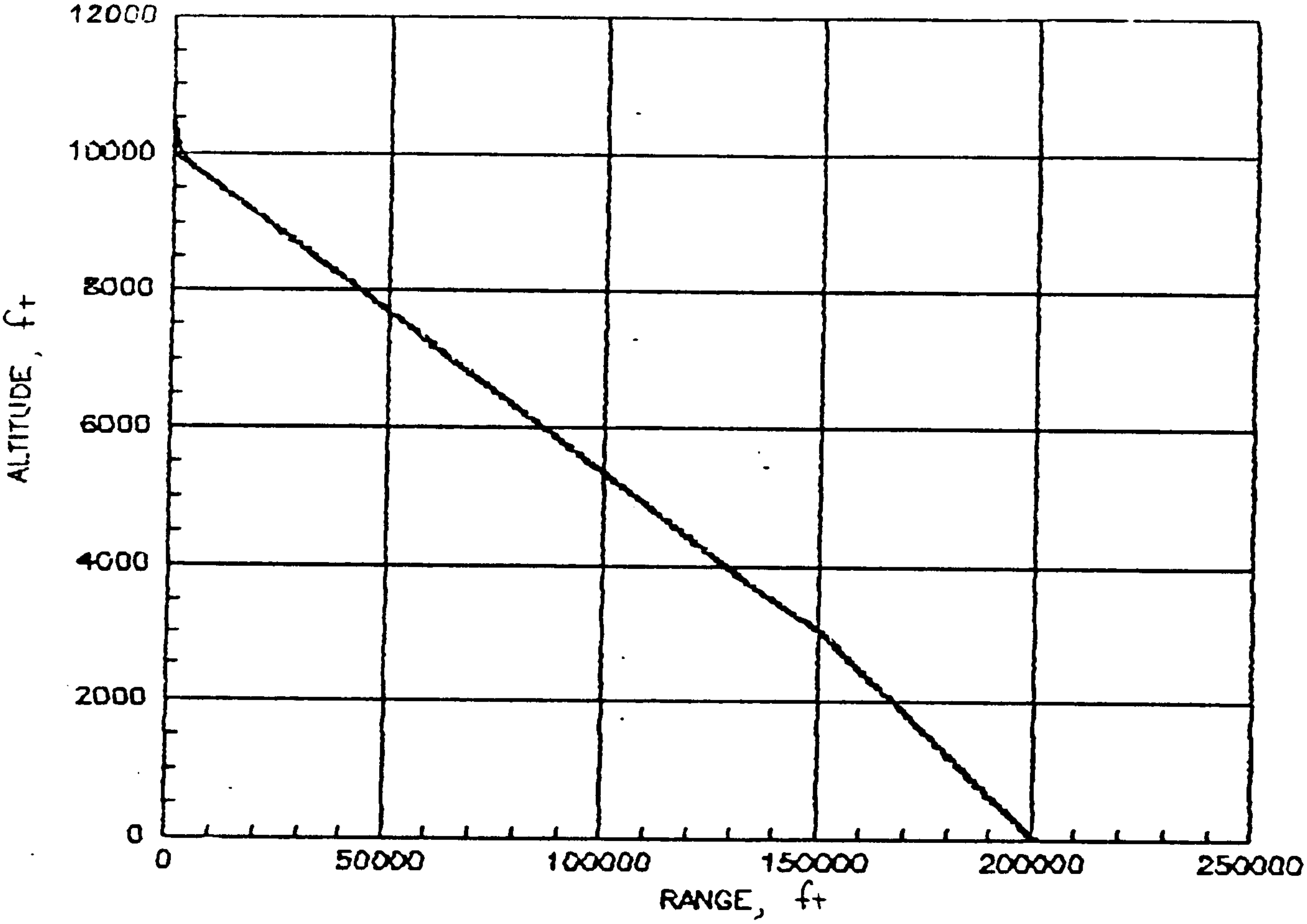

Figure 3. Comparison of the Performance of Linear and Nonlinear Controllers: Altitude vs. Range

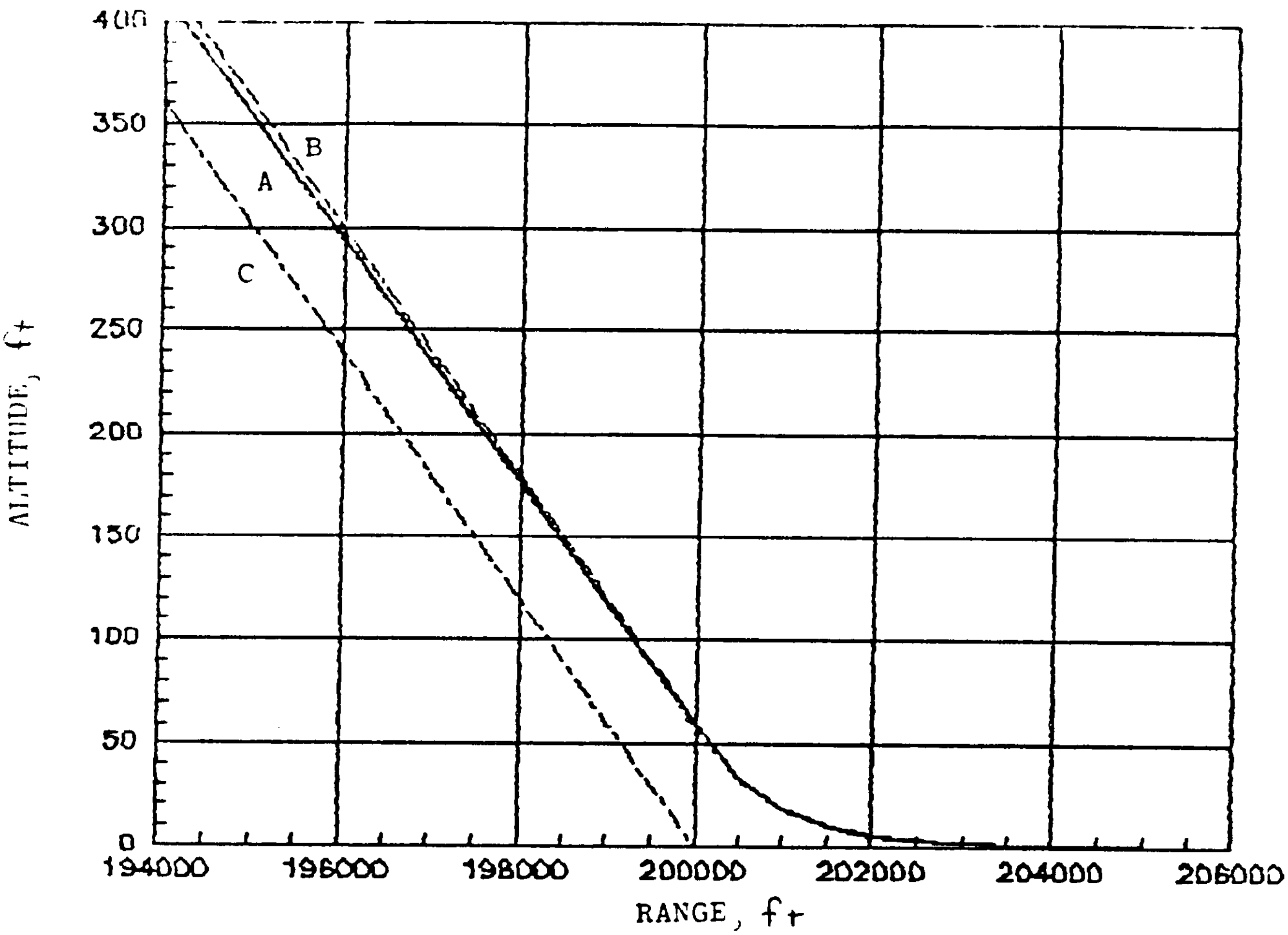

Figure 4. Comparison of the Performance of Linear and Nonlinear Controllers in the Vicinity of Touchdown: Altitude vs. Range

A: Nonlinear Controller

B: Linear Perturbation Controller

C: Commanded Trajectory

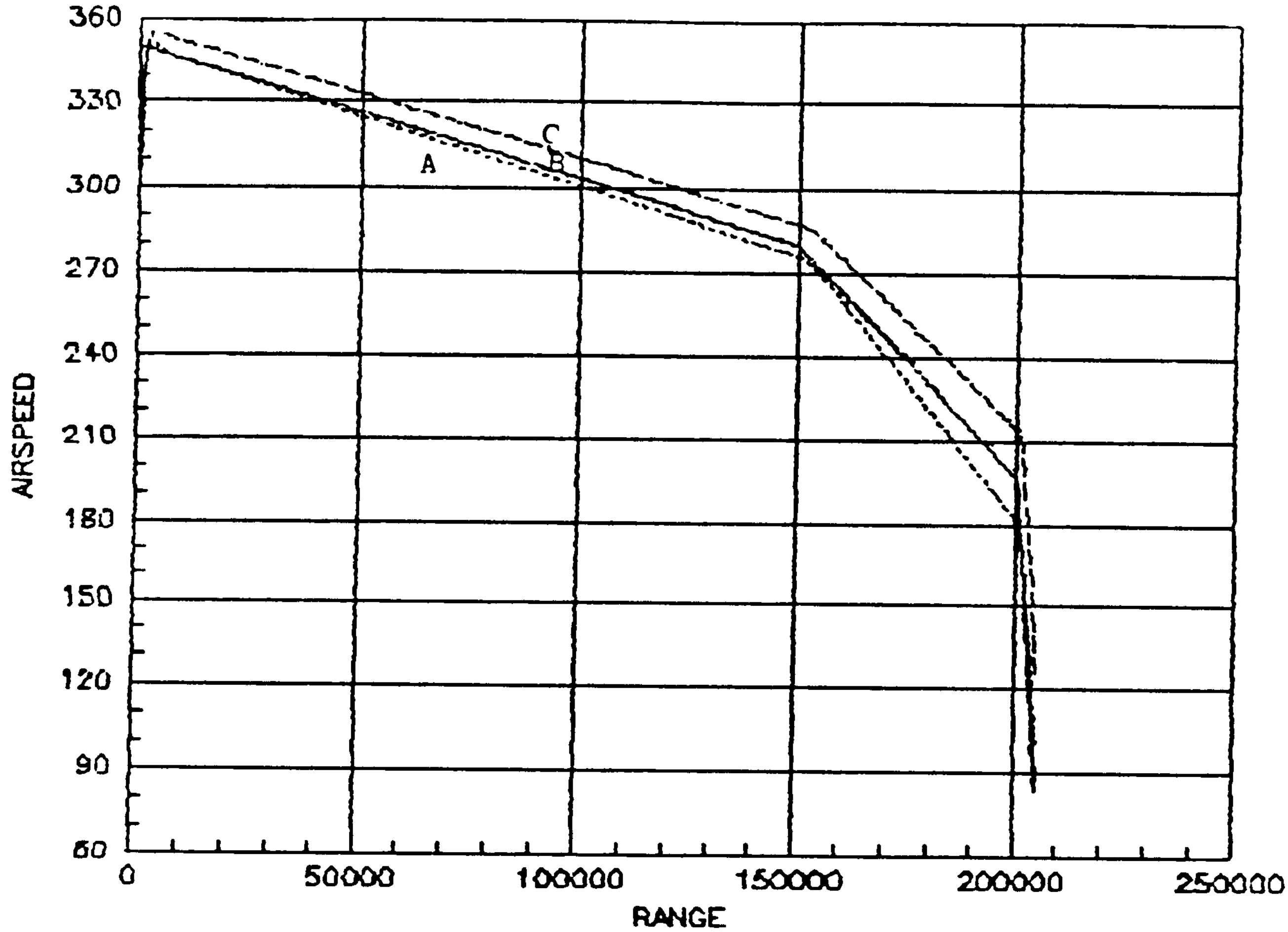

Figure 5. Comparison of the Performance of Linear and Nonlinear Controllers: Airspeed vs. Range

A: Nonlinear Controller

B: Commanded Trajectory

C: Linear Perturbation Controller

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APPENDIX C

FORTRAN PROGRAM FOR MANEUVER MODELING

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```
C     COMMAND AND REFERENCE TRAJECTORY GENERATION
C     ROUTINE FOR FLIGHT TEST TRAJECTORIES
C
C     COMMANDS FOR ALL FLIGHT TEST TRAJECTORIES ARE:
C
C                   1.  MACH NUMBER
C                   2.  ALTITUDE
C                   3.  ANGLE OF ATTACK
C                   4.  FLIGHT PATH ANGLE
C                   5.  ROLL ATTITUDE
C
C     REFERENCE TRAJECTORY CONSISTS OF
C
C                   1.  PITCH RATE q
C                   2.  YAW RATE r
C                   3.  ROLL RATE p
C                   4.  ANGLE OF SIDESLIP - BETA
C                   5.  THROTTLE
C                   6.  ELEVATOR
C                   7.  DIFFERENTIAL TAIL
C                   8.  RUDDER
C                   9.  AILERON
C
C     IN THE SYMMETRIC FLIGHT TEST TRAJECTORIES, q IS
C     ASSUMED ZERO, CONSEQUENTLY, THETA IS A FAST VARIABLE,
C     ALL OUTPUT ANGLES ARE IN RADIANS.
C
C     IOPT SPECIFIES THE MANEUVER
C     OPTIONS :
C      IOPT
C       0    :  GENERATES TRANSIENTS FROM A GIVEN
C               ALTITUDE-MACH PAIR TO ANOTHER
C               ALTITUDE-MACH PAIR ; TIME OF FLIGHT
C               SHOULD BE GIVEN
C                 INITIAL ALTITUDE=XI1
C                 INITIAL MACH    =XI2
C                 FINAL ALTITUDE  =XI3
C                 FINAL MACH      =XI4
C                 TIME OF FLIGHT  =XI5
C
C       1    :  GENERATES LEVEL ACCELERATION/DECELERATION
C               TRAJECTORY GIVEN INITIAL H,M;INTERMEDIATE M
C               AND TIMES T1 AND TF
C                 INITIAL ALTITUDE=XI1
C                 INITIAL MACH    =XI2
C                 FINAL MACH      =XI3
C                 FINAL TIME      =XI4
C
C       2    :  GENERATES PUSH OVER/PULLUP TRAJECTORY GIVEN
C               INITIAL H,M ;MINIMUM ALFA  ;MAXIMUM
C               ALFA AND TIMES T1 , T2 AND TF
C                  INITIAL ALTITUDE  =XI1
C                  INITIAL MACH      =XI2
C                  MINIMUM ALFA      =XI3
C                  MAXIMUM ALFA      =XI4
C                  TIME FOR MIN. MACH=XI5
C                  TIME FOR MAX. MACH=XI6
C                  FINAL TIME        =XI7
C
C       3    :  GENERATES ZOOM AND PUSHOVER TRAJECTORY GIVEN
C               APEX MACH NUMBER, ALTITUDE,ANGLE OF ATTACK
C               AND THE MINIMUM H.  ASSUMED HERE THAT THE
C               TRAJECTORY BEGINS AND ENDS AT THE APEX SPEED
C               AND MACH NUMBER.  NOTE THAT THE APEX ALFA SHOULD
C               BE LESS THAN THE STRAIGHT AND LEVEL ALFA AT THE
C               APEX ALTITUDE AND MACH NUMBER.
C                  APEX ALTITUDE      =XI1
C                  APEX MACH          =XI2
C                  APEX ALFA          =XI3
C                  INITIAL ALTITUDE   =XI4
C
C       4    :  GENERATES THE EXCESS THRUST WINDUP TURN
C               TRAJECTORY GIVEN THE INITIAL H,M,FINAL ALFA,
C               AND THE TIME OF FLIGHT, ASSUMED THAT THE
C               TIME TO RETURN THE AIRCRAFT FROM FINAL TURN
C               TO LEVEL FLIGHT IS THE SAME AS TIME OF FLIGHT
C                  INITIAL ALTITUDE  =XI1
C                  INITIAL MACH      =XI2
C                  FINAL ALFA        =XI3
C                  TIME OF FLIGHT    =XI4
C                  DWELL TIME        =XI5
C
C       5    :  GENERATES THE CONSTANT THROTTLE WINDUP TURN
C               TRAJECTORY GIVEN THE INITIAL H,M;FINAL ALFA,
C               THE THROTTLE SETTING ,MANEUVER TIME AND THE
C               FINAL STABILIZATION TIME.
C                  INITIAL ALTITUDE  =XI1
C                  INITIAL MACH      =XI2
C                  INITIAL ALFA      =XI3
C                  FINAL ALFA        =XI4
C                  MANEUVER TIME     =XI5
C                  FINAL/INITIAL
C                  STABILIZATION TIME=XI6
C                  THROTTLE SETTING  =XI7
C
C       6    :  GENERATES THE CONSTANT DYNAMIC PRESSURE AND
C               CONSTANT LOAD FACTOR TRAJECTORY, GIVEN
C               THE INITIAL H,M, FINAL MACH NUMBER, TIME OF
C               FLIGHT AND THE REQUIRED DYNAMIC PRESSURE
C               AND LOAD FACTOR.  ASSUMED THAT THE FINAL
C               TRANSIENT TIME IS THE SAME AS THE INITIAL
C               TRANSIENT TIME, ALSO DESIRED DYNAMIC PRESSURE
C               IS ASSUMED TO BE THE INITIAL DYNAMIC PRESSURE.
C                  INITIAL ALTITUTE  =XI1
C                  INITIAL MACH      =XI2
C                  FINAL MACH        =XI3
C                  LOAD FACTOR       =XI4
C                  TIME OF FLIGHT    =XI5
C                  INITIAL TRANSIENT
C                  TIME              =XI6
C
C       7    :  GENERATES THE CONSTANT REYNOLD'S NUMBER AND
C               CONSTANT LOAD FACTOR TRAJECTORY, GIVEN
C               THE INITIAL H,M, FINAL MACH NUMBER,TIME OF
C               FLIGHT AND THE REQUIRED REYNOLD'S NUMBER
C               AND LOAD FACTOR.  ASSUMED THAT THE DESIRED
C               REYNOLD'S NUMBER IS THE INITIAL VALUE
C                  INITIAL ALTITUDE  =XI1
C                  INITIAL MACH      =XI2
C                  FINAL MACH        =XI3
C                  LOAD FACTOR       =XI4
C                  TIME OF FLIGHT    =XI5
C                  INITIAL TRANSIENT
C                  TIME              =XI6
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION TIME(1000),XMC(1000),HC(1000),ALPC(1000)
      DIMENSION GAMC(1000),PSI(1000),CRANGE(1000)
```

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```
      DIMENSION PHIC(1000),PREF(1000),QREF(1000),RREF(1000)
      DIMENSION BETREF(1000),THROR(1000),ELVR(1000)
      DIMENSION DTAILR(1000),RUDR(1000),AILR(1000)
      DIMENSION DPRES(1000),FACL(1000),REYNO(1000),DRANGE(1000)
      INTEGER ID1(10),ID2(10),ID3(10),ID4(10),ID5(10),ID6(10)
      INTEGER ID7(10),ID8(10),ID9(10),ID10(10),ID11(10)
      INTEGER ID12(10),ID13(10),ID14(10),ID15(10),ID16(10)
      INTEGER ID17(10),ID18(10),ID19(10),ID20(10),ID21(10)
      CHARACTER*80 INFIL,MATFIL
C
C     F-15 AIRCRAFT WEIGHT AND ACCELERATION DUE TO GRAVITY
C
      DATA W,G,PAI/40700.D0,32.14352D0,3.1415927D0/
      XMASS=W/G
      HPAI=PAI/2.D0
C
C     STRAIGHT AND LEVEL FLIGHT LOAD FACTOR
      XSALF=1.D0
      DR=PAI/180.D0
C
C     READIN DATA
C
C     VVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVV
C     OPEN(UNIT=8,FILE='JUNK.OUT',STATUS='NEW')
C
      WRITE(6,*) 'ENTER INPUT DATA FILENAME:'
      READ(5,'(A80)')INFIL
      WRITE(6,*) 'ENTER OUTPUT DATA FILENAME:'
      READ(5,'(A80)') MATFIL
      OPEN(UNIT=5,FILE=INFIL,STATUS='OLD')
      OPEN(UNIT=7,FILE=MATFIL,STATUS='NEW')
      READ(5,*) IOPT,NPTS
      READ(5,*)XI1,XI2,XI3,XI4,XI5,XI6,XI7
C
C
C
      NTS=0.9D0*NPTS
      IF(IOPT.GT.0)GO TO 1000
C     TOTAL # OF COMMAND POINTS=NPTS
C     THE LAST 10% POINTS ARE USED
C     FOR STABILIZATION
C
C     COMMAND GENERATION FOR TRANSIENT TRAJECTORIES
C
      H=XI1
      H0=H
      XM=XI2
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      VEL1=XM*ASP
      HF=XI3
      XMF=XI4
      CALL ATMO(HF,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      VEL=XMF*ASP
      TF=XI5
      VDOT=(VEL-VEL1)/TF
C
C     COMPUTE THE COEFFICIENTS OF THE ALTITUDE POLYNOMIAL
C
      A2=3.D0*(HF-H)/(TF*TF)
      A3=(H-HF)/(0.5D0*TF*TF*TF)
      GAMMA=0.D0
      XMDOT1=(XMF-XM)/TF
      DT=TF/NTS
      TIM=0.D0
```

```
      DO 1 I=1,NPTS
      CALL TRIMS(H,XM,XSALF,ALF,BET,XLIFT,THRST,DRG,PHI,
     1          THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      TIME(I)=TIM
      FACL(I)=1.D0
      XMC(I)=XM
      HC(I)=H
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      DPRES(I)=0.5D0*RHO*XM*XM*ASP*ASP
      ALPC(I)=ALF*DR
      GAMC(I)=GAMMA
      PHIC(I)=0.D0
      PREF(I)=0.D0
      QREF(I)=0.D0
      RREF(I)=0.D0
      BETREF(I)=0.D0
C
C     THROTTLE COMPUTATION
C     LINEAR THROTTLE ASSUMPTION
C
      TMAX=THRST*100.D0/THRO
      TR=((VDOT+G*DSIN(GAMC(I)))*XMASS+DRG)/DCOS(ALPC(I))
      ETA=TR*100.D0/TMAX
      IF(ETA.LT.0.D0)ETA=0.D0
      IF(ETA.GT.100.D0)ETA=100.D0
      THROR(I)=ETA
      ELVR(I)=ELV
      DTAILR(I)=DTL
      RUDR(I)=RUD
      AILR(I)=AIL
C
      XMDOT=XMDOT1
      TIM=TIM+DT
      H=H0+A2*TIM*TIM+A3*TIM*TIM*TIM
      HDOT=2.D0*A2*TIM+3.D0*A3*TIM*TIM
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      XM=XM+XMDOT*DT
      VEL=XM*ASP
      IF(TIM.LE.TF)GO TO 2
      HDOT=0.D0
      XMDOT=0.D0
      VDOT=0.D0
      XM=XMF
      H=HF
      GAMMA=0.D0
2     CONTINUE
      GAMMA=DASIN(HDOT/VEL)
1     CONTINUE
      GO TO 8000
1000  IF(IOPT.GT.1)GO TO 2000
C
C     COMMAND GENERATION FOR LEVEL ACCELERATION/DECELERATION
C     TRAJECTORY
C
      H=XI1
      XM=XI2
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      VEL1=XM*ASP
      XMMAX=XI3
      VEL=XMMAX*ASP
      TF=XI4
      XMDOT1=(XMMAX-XM)/TF
      VDOT=(VEL-VEL1)/TF
      DT=TF/NTS
```

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```
      TIM=0.D0
      DO 3 I=1,NPTS
      XMDOT=XMDOT1
      CALL TRIMS(H,XM,XSALF,ALF,BET,XLIFT,THRST,DRG,PHI,
     1           THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      TIME(I)=TIM
      FACL(I)=1.D0
      XMC(I)=XM
      HC(I)=H
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      DPRES(I)=0.5D0*RHO*XM*XM*ASP*ASP
      ALPC(I)=ALF*DR
      GAMC(I)=0.D0
      PHIC(I)=0.D0
      PREF(I)=0.D0
      QREF(I)=0.D0
      RREF(I)=0.D0
      BETREF(I)=0.D0
C
C     THROTTLE COMPUTATION
C
      TR=(VDOT*XMASS+DRG)/DCOS(ALPC(I))
      TMAX=THRST*100.D0/THRO
      ETA=TR*100.D0/TMAX
      IF(ETA.LT.0.D0)ETA=0.D0
      IF(ETA.GT.100.D0)ETA=100.D0
      THROR(I)=ETA
      ELVR(I)=ELV
      DTAILR(I)=DTL
      RUDR(I)=RUD
      AILR(I)=AIL
      IF(TIM.LE.TF)GO TO 8
      XMDOT=0.D0
      VDOT=0.D0
8     CONTINUE
      XM=XM+XMDOT*DT
      TIM=TIM+DT
      IF(TIM.GT.TF)XM=XMMAX
3     CONTINUE
      GO TO 8000
2000  IF(IOPT.GT.2)GO TO 3000
C
C     COMMAND GENERATION FOR PUSHOVER/PULLUP TRAJECTORY
C
      H=XI1
      HI=H
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      XM=XI2
      VEL=XM*ASP
      ALPMIN=XI3*DR
      ALPMAX=XI4*DR
      TAMIN=XI5
      TAMAX=XI6
      TF=XI7
      CALL TRIMS(H,XM,XSALF,ALF,BET,XLIFT,THRST,DRG,PHI,
     1           THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      THET=THETA*DR
      ALFA=ALF*DR
      ALP0=ALFA
      ALDOT1=(ALPMIN-ALP0)/TAMIN
      ALDOT2=(ALPMAX-ALPMIN)/(TAMAX-TAMIN)
      ALDOT3=(ALP0-ALPMAX)/(TF-TAMAX)
      DT1=TAMIN/(0.3D0*NTS)
      DT2=(TAMAX-TAMIN)/(0.3D0*NTS)
      DT3=(TF-TAMAX)/(0.4D0*NTS)
      DO 4 I=1,NPTS
      ALDOT=ALDOT1
      DT=DT1
      CALL TRIMS(H,XM,XSALF,ALF,BET,XLIFT,THRST,DRG,PHI,
     1           THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      TIME(I)=TIM
      FACL(I)=1.D0
      XMC(I)=XM
      HC(I)=H
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      DPRES(I)=0.5D0*RHO*XM*XM*ASP*ASP
      ALPC(I)=ALFA
      GAMC(I)=-(THET-ALPC(I))
      PHIC(I)=0.D0
      PREF(I)=0.D0
      QREF(I)=0.D0
      RREF(I)=0.D0
      BETREF(I)=0.D0
C
C     THROTTLE COMPUTATION
C
C     LINEAR THROTTLE ASSUMPTION
C
      TMAX=THRST*100.D0/THRO
      TR=(G*DSIN(GAMC(I))*XMASS+DRG)/DCOS(ALPC(I))
      ETA=TR*100.D0/TMAX
      IF(ETA.LT.0.D0)ETA=0.D0
      IF(ETA.GT.100.D0)ETA=100.D0
      THROR(I)=ETA
      ELVR(I)=ELV
      DTAILR(I)=DTL
      RUDR(I)=RUD
      AILR(I)=AIL
      IF(TIM.GT.TAMIN)ALDOT=ALDOT2
      IF(TIM.GT.TAMIN)DT=DT2
      IF(TIM.GT.TAMAX)ALDOT=ALDOT3
      IF(TIM.GT.TAMAX)DT=DT3
      IF(TIM.GT.TF)ALDOT=0.D0
      ALFA=ALFA+ALDOT*DT
      HDOT=VEL*DSIN(GAMC(I))
      H=H+HDOT*DT
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      VEL=XM*ASP
      IF(TIM.LE.TF)GO TO 9
      ALFA=ALP0
      H=HI
9     CONTINUE
      TIM=TIM+DT
4     CONTINUE
      GO TO 8000
3000  IF(IOPT.GT.3)GO TO 4000
C
C     COMMAND GENERATION FOR ZOOM AND PUSHOVER
C     TRAJECTORY
C
C     APEX QUANTITIES
      HT=XI1
      XMT=XI2
      HF=HT
      XMF=XMT
      CALL ATMO(HT,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      VT=XMT*ASP
      CALL TRIMS(HT,XMT,XSALF,ALF,BET,XLIFT,THRST,DRG,PHI,
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     1                THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      ALPF=ALF*DR
      ALPT=XI3*DR
C
C      CDALFA AND CLALFA HAVE TO BE USED IN THE COMPUTATION OF TT
C      AND VERTIFICAL ACCELERATION IN THE FINAL VERSION.
C      TO BE CORRECTED
C      IN THE INITIAL PHASE, LIFT AT ZERO ANGLE OF ATTACK IS
C      ASSUMED TO BE ZERO.
C      DRAG IS ASSUMED TO BE THE LEVEL FLIGHT VALUE
      TT=DRG/DCOS(ALPT)
      TMAX=THRST*100.D0/THRO
      TOT=TT*100.D0/TMAX
      XLALFA=XLIFT/ALPF
      ALIFT=XLALFA*ALPT
C
C     VERTICAL ACCELERATION-ARTIFICIAL GRAVITY
C
      GA=G-((TT*DSIN(ALPT)+ALIFT)/XMASS)
      E=HT+(VT*VT/(2.D0*GA))
C
C     QUANTITIES AT THE BEGINNING OF THE TEST PARABOLA
C
      HI=XI4
      VI=DSQRT(2.D0*GA*(E-HI))
      GAMI=DACOS(VT/VI)
      HDOTI=VI*DSIN(GAMI)
C     TIME OF FLIGHT FROM VI TO VT
      DVT=DABS(VI*VI-VT*VT)
      T1=DSQRT(DVT)/GA
      TF1=2.D0*T1
C
C     INITIAL TRANSIENT PARABOLA
C
      IPHASE=1
C
C     COMPUTE THE COEFFICIENTS OF THE ALTITUDE-TIME
C     POLYNOMIAL.  TIME OF FLIGHT ASSUMED TO BE TF1
C     THIS CUBIC POLYNOMIAL IS USED TO GENERATE BOTH
C     INITIAL AND TERMINAL TRANSIENTS
C
      A2=(HDOTI*TF1-2.D0*(HI-HT))/(TF1*TF1*TF1)
      A1=(HDOTI-3.D0*A2*TF1*TF1)/(2.D0*TF1)
C
C     VDOT COMPUTATION ; VDOT=CONSTANT IN THE INITIAL
C     AND TERMINAL TRANSIENTS
C
      VDOT=(VI-VT)/TF1
      VDOT1=VDOT
C
      H=HT
      XM=XMT
      V=VT
      GAMMA=0.D0
      TIM=0.D0
C
C     TOTAL TIME OF FLIGHT AND STEP SIZE
C
      TF=3.D0*TF1
      TTF=2.D0*TF1
      DT=TF/NTS
      INDEXM=1
      DO 5 I=1,NPTS
      TIME(I)=TIM
      FACL(I)=1.D0
      XMC(I)=XM
      HC(I)=H
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      DPRES(I)=0.5D0*RHO*XM*XM*ASP*ASP
      CALL TRIMS(H,XM,XSALF,ALF,BET,XLIFT,THRST,DRG,PHI,
     1           THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      ALA=ALF*DR
      TMAX=THRST*100.D0/THRO
      IF(IPHASE.EQ.2)GO TO 16
C
C     THROTTLE COMPUTATION FOR INITIAL AND TERMINAL
C     TRANSIENTS
C
      TR=((VDOT1+G*DSIN(GAMC(I)))*XMASS+DRG)/DCOS(ALPC(I))
      ETA=TR*100.D0/TMAX
      IF(ETA.LT.0.D0)ETA=0.D0
      IF(ETA.GT.100.D0)ETA=100.D0
      GO TO 17
   16 CONTINUE
C
C     THROTTLE IS FIXED; COMPUTE ACTUAL THRUST
C
      ETA=TOT
      ACT=TMAX*TOT/100.D0
C     COMPUTE DLIFT/DALFA WITH THE ASSUMPTION THAT LIFT=0
C     AT ALFA=0.
      XLALFA=XLIFT/ALA
      ALA=(G-GA)*XMASS/((ACT+XLALFA)*DCOS(GAMMA))
   17 CONTINUE
      ALPC(I)=ALA
      GAMC(I)=GAMMA
      PHIC(I)=0.D0
      PREF(I)=0.D0
      QREF(I)=0.D0
      RREF(I)=0.D0
      BETREF(I)=0.D0
      THROR(I)=ETA
      ELVR(I)=ELV
      DTAILR(I)=DTL
      RUDR(I)=RUD
      AILR(I)=AIL
      TIM=TIM+DT
      IF(TIM.GT.TF1)IPHASE=2
      IF(TIM.GE.TTF)IPHASE=3
C
C     INITIAL TRANSIENT
C
      IF(IPHASE.EQ.2.OR.IPHASE.EQ.3)GO TO 11
      H=HT+A1*TIM*TIM+A2*TIM*TIM*TIM
      HDOT=2.D0*A1*TIM+3.D0*A2*TIM*TIM
      VDOT1=VDOT
      V=V+VDOT1*DT
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      XM=V/ASP
      GAMMA=DASIN(HDOT/V)
      INDEXM=INDEXM+1
      GO TO 15
   11 IF(IPHASE.EQ.3)GO TO 13
C
C     PARABOLIC TEST TRAJECTORY
      DEL=TIM-TF1
      IF(DEL.LT.0.D0)DEL=0.D0
      H=HI+HDOTI*DEL-0.5D0*GA*DEL*DEL
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      HDOT=HDOTI-GA*DEL
      V=DSQRT(2.D0*GA*(E-H))
      ANGL=HDOT/V
      IF(ANGL.GT.1.D0)ANGL=1.D0
      IF(ANGL.LT.-1.D0)ANGL=-1.D0
      GAMMA=DASIN(ANGL)
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      XM=V/ASP
      GO TO 15
13    IF(TIM.GT.TF)GO TO 14
C
C     TERMINAL TRANSIENT
C
      H=HC(INDEXM)
      GAMMA=-GAMC(INDEXM)
      XM=XMC(INDEXM)
      VDOT1=-VDOT
      INDEXM=INDEXM-1
      IF(INDEXM.LT.1)INDEXM=1
      GO TO 15
C
C     TERMINAL STABILIZATION
C
14    H=HF
      XM=XMT
      ALFA=ALPF
      VDOT1=0.D0
      GAMMA=0.D0
15    CONTINUE
5     CONTINUE
      GO TO 8000
4000  IF(IOPT.GT.4)GO TO 5000
C
C     COMMAND GENERATION FOR EXCESS THRUST WINDUP TURN
C     TRAJECTORY
C
      H=XI1
      XM=XI2
      CALL TRIMS(H,XM,XSALF,ALF,BET,XLIFT,THRST,DRG,PHI,
     1           THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      ALP=ALF
      ALP0=ALF
      ALPT=XI3
C     ALFA IS COMPUTED IN DEGREES AND SUBSEQUENTLY CONVERTED
C     TO RADIANS
      TF=XI4
      TD=XI5
      T1=TF
      T2=TF+TD
      T3=T2+TF
      ALDOT=(ALPT-ALP)/TF
      DT=(2.D0*TF+TD)/NTS
      TIM=0.D0
      DO 18 I=1,NPTS
C
      XLC=-1.D0
      TIME(I)=TIM
      XMC(I)=XM
      HC(I)=H
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      DPRES(I)=0.5D0*RHO*XM*XM*ASP*ASP
      ALPC(I)=ALP*DR
      CALL TRIMS(H,XM,XLC,ALP,BET,XLIFT,THRST,DRG,PHI,
     1           THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
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      FACL(I)=XLC
      GAMC(I)=0.D0
      PHIC(I)=PHI*DR
      PREF(I)=P*DR
      QREF(I)=Q*DR
      RREF(I)=R*DR
      BETREF(I)=0.D0
      THROR(I)=THRO
      ELVR(I)=ELV
      DTAILR(I)=DTL
      RUDR(I)=RUD
      AILR(I)=AIL
      TIM=TIM+DT
      IF(TIM.LE.T1)ALP=ALP+ALDOT*DT
      IF(TIM.GT.T1.AND.TIM.LE.T2)ALP=ALPT
      IF(TIM.GT.T2.AND.TIM.LT.T3)ALP=ALP-ALDOT*DT
      IF(TIM.GT.T3)ALP=ALP0
      IF(ALP.LT.ALP0)ALP=ALP0
18    CONTINUE
      GO TO 8000
5000  IF(IOPT.GT.5)GO TO 6000
C
C     COMMAND GENERATION FOR CONSTANT THROTTLE WINDUP TURN
C     TRAJECTORY
C
      H=XI1
      XM=XI2
      CALL TRIMS(H,XM,XSALF,ALF,BET,XLIFT,THRST,DRG,PHI,
     1           THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      ALP0=XI3
      ALPF=XI4
      TF=XI5
      TS=XI6
      TOT=XI7
C     ALFA IS COMPUTED IN DEGREES AND SUBSEQUENTLY CONVERTED
C     TO RADIANS
      ALD0=(ALP0-ALF)/TS
      ALD1=(ALPF-ALP0)/TF
      T1=TS
      T2=TS+TF
      T3=T2+TS
      ALP=ALF
      DT=T3/NTS
      TIM=0.D0
      ISW=0
      DO 19 I=1,NPTS
C
      XLC=-1.D0
      TIME(I)=TIM
      XMC(I)=XM
      HC(I)=H
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      VEL=XM*ASP
      DPRES(I)=0.5D0*RHO*VEL*VEL
      ALPC(I)=ALP*DR
      CALL TRIMS(H,XM,XLC,ALP,BET,XLIFT,THRST,DRG,PHI,
     1           THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      PHIC(I)=PHI*DR
      ETA=THRO
      GAMMA=0.D0
C
C     ACTUAL THRUST AND FLIGHT PATH ANGLE COMPUTATIONS
C
      IF(TIM.LT.T1.OR.TIM.GE.T2)GO TO 20
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      ETA=TOT
      ALDOT=ALD1
      TMAX=THRST*100.D0/THRO
C
C     THROTTLE IS FIXED; COMPUTE ACTUAL THRUST
C
      ACT=TMAX*TOT/100.D0
C     EXCESS THRUST OVER AND ABOVE TRIM
      DTHRST=ACT-THRST
C
      CA=DCOS(ALPC(I))
      D=XM*VEL*DASPDH
      E=DTHRST*CA/XMASS
C
      GAMMA=DASIN(E/(D+G))
      HDOT=VEL*DSIN(GAMMA)
20    CONTINUE
      FACL(I)=XLC
      GAMC(I)=GAMMA
      PREF(I)=P*DR
      QREF(I)=Q*DR
      RREF(I)=R*DR
      BETREF(I)=0.D0
      THROR(I)=ETA
      ELVR(I)=ELV
      DTAILR(I)=DTL
      RUDR(I)=RUD
      AILR(I)=AIL
      TIM=TIM+DT
      IF(TIM.LT.T1)ALDOT=ALD0
      IF(TIM.LT.T2)GO TO 21
      IF(ISW.EQ.1)GO TO 21
      ISW=1
      CALL TRIMS(H,XM,XSALF,ALTF,BET,XLIFT,THRST,DRG,PHI,
     1          THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      ALDOT=(ALTF-ALP)/TS
      HDOT=0.D0
21    CONTINUE
      ALP=ALP+ALDOT*DT
      H=H+HDOT*DT
      IF(TIM.GE.T3)ALP=ALTF
19    CONTINUE
      GO TO 8000
6000  IF(IOPT.GT.6)GO TO 7000
C
C     COMMAND GENERATION FOR CONSTANT LOAD FACTOR AND
C     CONSTANT DYNAMIC PRESSURE TRAJECTORY
C
      H=XI1
      XM=XI2
      XMF=XI3
      XNSPEC=XI4
      TF=XI5
      TT=XI6
      XMDOT1=(XMF-XM)/TF
      DFACR=(XNSPEC-1.D0)/TT
      T1=TT
      T2=TT+TF
      T3=T2+TT
      DT1=T3/NTS
      TIM=0.D0
      XLC=1.D0
      DO 24 I=1,NPTS
C
      DT=DT1
      TIME(I)=TIM
      XMC(I)=XM
      HC(I)=H
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      VEL=XM*ASP
      DPRES(I)=0.5D0*RHO*VEL*VEL
      CALL TRIMS(H,XM,XLC,ALP,BET,XLIFT,THRST,DRG,PHI,
     1          THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      ALPC(I)=ALP*DR
      PHIC(I)=PHI*DR
      ETA=THRO
      GAMMA=0.D0
      XMDOT=0.D0
      XNDOT=DFACR
      IF(TIM.GE.T2)XNDOT=-DFACR
      IF(TIM.GE.T3)XNDOT=0.D0
C
C     ACTUAL THROTTLE AND FLIGHT PATH ANGLE COMPUTATIONS
C
      IF(TIM.LE.T1.OR.TIM.GE.T2)GO TO 25
      XNDOT=0.D0
C
C     FLIGHT PATH ANGLE COMPUTATION
C
      VSQ=VEL*VEL
      DENOM=(DRODH*VSQ/(2.D0*RHO))+(XM*VEL*DASPDH)
      XNUM=-XMDOT1*ASP
      IF(DABS(DENOM).LE.1.D-08)GO TO 26
      SINGAM=XNUM/DENOM
      IF(SINGAM.LE.-1.D0)SINGAM=-1.D0
      IF(SINGAM.GE.1.D0)SINGAM=1.D0
      GAMMA=DASIN(SINGAM)
      XMDOT=XMDOT1
26    CONTINUE
      SINGAM=DSIN(GAMMA)
      COSGAM=DCOS(GAMMA)
C
C     THROTTLE COMPUTATION
C
      TMAX=THRST*100.D0/THRO
      VDOT=-DRODH*VSQ*SINGAM/(2.D0*RHO)
C
      ADP=ALPC(I)
      CA=DCOS(ADP)
C
      DTHRST=(VDOT+G*SINGAM)*XMASS/CA
      ACT=DTHRST+THRST
      ETA=ACT*100.D0/TMAX
      IF(ETA.LT.0.D0)ETA=0.D0
      IF(ETA.GT.100.D0)ETA=100.D0
C
25    CONTINUE
      FACL(I)=XLC
      GAMC(I)=GAMMA
      PREF(I)=P*DR
      QREF(I)=Q*DR
      RREF(I)=R*DR
      BETREF(I)=0.D0
      THROR(I)=ETA
      ELVR(I)=ELV
      DTAILR(I)=DTL
      RUDR(I)=RUD
      AILR(I)=AIL
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      TIM=TIM+DT
      HDOT=VEL*DSIN(GAMMA)
      H=H+HDOT*DT
      XLC=XLC+XNDOT*DT
      IF(XLC.LE.1.D0)XLC=1.D0
      XM=XM+XMDOT*DT
      IF(TIM.GT.T3)XLC=1.D0
24    CONTINUE
      GO TO 8000
7000  IF(IOPT.GT.7)GO TO 8000
C
C     COMMAND GENERATION FOR CONSTANT LOAD FACTOR AND
C     CONSTANT REYNOLD'S NUMBER TRAJECTORY
C
      H=XI1
      XM=XI2
      XMF=XI3
      XNSPEC=XI4
      TF=XI5
      TT=XI6
      XMDOT1=(XMF-XM)/TF
      DFACR=(XNSPEC-1.D0)/TT
      T1=TT
      T2=TT+TF
      T3=T2+TT
      DT=T3/NTS
      TIM=0.D0
      XLC=1.D0
      DO 27 I=1,NPTS
C
      TIME(I)=TIM
      XMC(I)=XM
      HC(I)=H
      CALL ATMO(H,ASP,RHO,XMU,DASPDH,DRODH,DMUDH)
      VEL=XM*ASP
C
C     TO GET THE ACTUAL RE XMU HAS TO BE IN THE RIGHT
C     UNITS AND THE CHARACTERISTIC LENGTH HAS TO BE
C     MULTIPLIED
C
      REYNO(I)=VEL*RHO/XMU
      DPRES(I)=0.5D0*RHO*VEL*VEL
      CALL TRIMS(H,XM,XLC,ALP,BET,XLIFT,THRST,DRG,PHI,
     1           THETA,P,Q,R,THRO,ELV,AIL,RUD,DTL,IER)
      ALPC(I)=ALP*DR
      PHIC(I)=PHI*DR
      ETA=THRO
      GAMMA=0.D0
      XMDOT=0.D0
      XNDOT=DFACR
      IF(TIM.GE.T2)XNDOT=-DFACR
      IF(TIM.GE.T3)XNDOT=0.D0
C
C     ACTUAL THROTTLE AND FLIGHT PATH ANGLE COMPUTATIONS
C
      IF(TIM.LE.T1.OR.TIM.GE.T2)GO TO 28
      XNDOT=0.D0
C
C     FLIGHT PATH ANGLE COMPUTATION
C
      VSQ=VEL*VEL
      XNUM=XMDOT1*ASP
      DENOM=VSQ*((DMUDH/XMU)-(DRODH/RHO)-(DASPDH/ASP))
      IF(DABS(DENOM).LE.1.D-08)GO TO 29
      SINGAM=XNUM/DENOM
      IF(SINGAM.LE.-1.D0)SINGAM=-1.D0
      IF(SINGAM.GE.1.D0)SINGAM=1.D0
      GAMMA=DASIN(SINGAM)
      XMDOT=XMDOT1
29    CONTINUE
      SINGAM=DSIN(GAMMA)
      COSGAM=DCOS(GAMMA)
C
C     THROTTLE COMPUTATION
C
      TMAX=THRST*100.D0/THRO
      VDOT=VSQ*SINGAM*((DMUDH/XMU)-(DRODH/RHO))
C
      ADP=ALPC(I)
      CA=DCOS(ADP)
C
      DTHRST=(VDOT+G*SINGAM)*XMASS/CA
      ACT=DTHRST+THRST
      ETA=ACT*100.D0/TMAX
      IF(ETA.LT.0.D0)ETA=0.D0
      IF(ETA.GT.100.D0)ETA=100.D0
C
28    CONTINUE
      FACL(I)=XLC
      GAMC(I)=GAMMA
      PREF(I)=P*DR
      QREF(I)=Q*DR
      RREF(I)=R*DR
      BETREF(I)=0.D0
      THROR(I)=ETA
      ELVR(I)=ELV
      DTAILR(I)=DTL
      RUDR(I)=RUD
      AILR(I)=AIL
      TIM=TIM+DT
      HDOT=VEL*DSIN(GAMMA)
      H=H+HDOT*DT
      XLC=XLC+XNDOT*DT
      IF(XLC.LE.1.D0)XLC=1.D0
      XM=XM+XMDOT*DT
      IF(TIM.GT.T3)XLC=1.D0
27    CONTINUE
8000  CONTINUE
C
      I=I-1
C
C     SAVING DATA FOR MATRIXX
C
      DATA ID1/'T','I','M','E',' ',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID1,NPTS,I,1,0,0,TIME,)
      DATA ID2/'M','A','C','H',' ',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID2,NPTS,I,1,0,0,XMC,)
      DATA ID3/'A','L','T',' ',' ',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID3,NPTS,I,1,0,0,HC,)
      DATA ID4/'A','L','F','A',' ',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID4,NPTS,I,1,0,0,ALPC,)
      DATA ID5/'G','A','M','M','A',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID5,NPTS,I,1,0,0,GAMC,)
      DATA ID6/'P','H','I',' ',' ',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID6,NPTS,I,1,0,0,PHIC,)
      DATA ID7/'P',' ',' ',' ',' ',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID7,NPTS,I,1,0,0,PREF,)
      DATA ID8/'Q',' ',' ',' ',' ',' ',' ',' ',' ',' ',' ',' '/
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      CALL SAVLOD(7,ID8,NPTS,I,1,0,0,QREF,)
      DATA ID9/'R',' ',' ',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID9,NPTS,I,1,0,0,RREF,)
      DATA ID10/'B','E','T','A',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID10,NPTS,I,1,0,0,BETREF,)
      DATA ID11/'E','T','A',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID11,NPTS,I,1,0,0,THROR,)
      DATA ID12/'E','L','V',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID12,NPTS,I,1,0,0,ELVR,)
      DATA ID13/'D','T','A','I','L',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID13,NPTS,I,1,0,0,DTAILR,)
      DATA ID14/'R','U','D',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID14,NPTS,I,1,0,0,RUDR,)
      DATA ID15/'A','I','L',' ',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID15,NPTS,I,1,0,0,AILR,)
      DATA ID16/'L','D','F','A','C',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID16,NPTS,I,1,0,0,FACL,)
      DATA ID17/'D','Y','N','P',' ',' ',' ',' ',' ',' '/
      CALL SAVLOD(7,ID17,NPTS,I,1,0,0,DPRES,)
      DATA ID18/'R','E','Y','N','O','L','D',' ',' ',' '/
      CALL SAVLOD(7,ID18,NPTS,I,1,0,0,REYNO,)
C
      STOP
      END
C
C
C
      SUBROUTINE SAVLOD(LUNIT,ID,MA,M,N,IMG,JOB,XREAL,XIMAG)
C
C     ---------- SUBROUTINE SAVLOAD ---------------------------
C
      INTEGER LUNIT,ID(10),M,N,IMG,JOB
      DOUBLE PRECISION XREAL(1),XIMAG(1)
C
C     IMPLEMENT SAVE AND LOAD
C     LUNIT = LOGICAL UNIT NUMBER
C     ID = NAME, FORMAT 4A1
C     M, N = DIMENSIONS
C     IMG = NONZERO IF XIMAG IS NONZERO
C     JOB = 0      FOR SAVE
C         = SPACE AVAILABLE FOR LOAD
C     XREAL, XIMAG = REAL AND OPTIONAL IMAGINARY PARTS
C
C     SYSTEM DEPENDENT FORMATS
  101 FORMAT(10A1,3I4)
  102 FORMAT(4Z18)
      IF (JOB .GT. 0) GO TO 20
C
C     SAVE
C
   10 WRITE(LUNIT,101) ID,M,N,IMG
      DO 15 J = 1, N
        K = (J-1)*MA + 1
        L = K + M - 1
        WRITE(LUNIT,102)  (XREAL(I),I=K,L)
        IF (IMG .NE. 0) WRITE(LUNIT,102)  (XIMAG(I),I=K,L)
   15 CONTINUE
      RETURN
C
C     LOAD
C
   20 READ(LUNIT,101,END=30,ERR=29)  ID,M,N,IMG
      MA=M
      IF (M*N .GT. JOB) GO TO 30
      DO 25 J = 1, N
         K = (J-1)*MA+1
         L = K+M-1
         READ(LUNIT,102,END=30)  (XREAL(I),I=K,L)
         IF (IMG .NE. 0) READ(LUNIT,102,END=30)  (XIMAG(I),I=K,L)
   25 CONTINUE
      RETURN
   29 WRITE(6,*) 'ERROR IN READING FILE'
C
C     END OF FILE
C
   30 M = 0
      N = 0
      RETURN
      END
C
C
C             F-15 AIRCRAFT
C        FORTRAN SUBROUTINE TO GENERATE
C        REFERENCE CONTROL SETTINGS FOR SYMMETRIC AND
C        NONSYMMETRIC FLIGHT TEST TRAJECTORIES
C
C        INPUTS :  ALTITUDE, MACH NUMBER,LOAD FACTOR
C                  OR ANGLE OF ATTACK
C        OUTPUTS:
C                  LOAD FACTOR,
C                  ANGLE OF ATTACK,
C                  ANGLE OF SIDESLIP,
C                  LIFT,
C                  THRUST,
C                  DRAG,
C                  ROLL ATTITUDE,
C                  PITCH ATTITUDE,
C                  ROLL BODY RATE,
C                  PITCH BODY RATE,
C                  YAW BODY RATE,
C                  THROTTLE
C                  ELEVATOR,
C                  AILERON,
C                  RUDDER,
C                  DIFFERENTIAL TAIL,
C
C      IERR=1  INDICATES THAT THE POINT IS OUTSIDE THE
C      TABLE RANGE
C
      SUBROUTINE TRIMS(H,XM,XLFAC,ALP,BET,XLIFT,THRST,
     1               DRG,PHIO,THETAO,P,Q,R,THRO,ELV,AIL,
     2                                RUD,DTL,IERR)
      IMPLICIT REAL*8(A-H,O-Z)
      DOUBLE PRECISION LIFT(9,10,6)
      DIMENSION XMACH(10),ALT(9),XN(6)
      DIMENSION ALPHA(9,10,6),BETA(9,10,6),
     1          THRUST(9,10,6),DRAG(9,10,6),PHI(9,10,6),
     2          THETA(9,10,6),ROLLR(9,10,6),PITCHR(9,10,6),
     3          YAWR(9,10,6),THROTT(9,10,6),ELEVAT(9,10,6),
     4          AILERO(9,10,6),RUDDER(9,10,6),DTAIL(9,10,6)
      DIMENSION XDAT(2),YDAT(2),ZDAT(2),ALTEMP(10)
C
      DATA LASTI,LASTJ,LASTK/1,1,1/
      DATA ISTART/0/
      DATA WEIGT,G/40700.D0,32.14352D0/
C     DEGREE TO RADIAN CONVERSION FACTOR
      DR=3.1415927/180.D0
C
```

```
C      INITIALIZATION
C
       IF(ISTART.GT.0)GO TO 100
C
       DO 200 I=1,9
       DO 300 J=1,10
       DO 400 K=1,6
         LIFT(I,J,K)=WEIGT
         DRAG(I,J,K)=0.0
         BETA(I,J,K)=0.0
         ALPHA(I,J,K)=0.0
         PHI(I,J,K)=0.0
         THETA(I,J,K)=0.0
         ROLLR(I,J,K)=0.0
         PITCHR(I,J,K)=0.0
         YAWR(I,J,K)=0.0
         THRUST(I,J,K)=0.0
         ELEVAT(I,J,K)=0.0
         DTAIL(I,J,K)=0.0
         RUDDER(I,J,K)=0.0
         THROTT(I,J,K)=0.0
         AILERO(I,J,K)=0.0
400    CONTINUE
300    CONTINUE
200    CONTINUE
       ISTART=1
C
C      STRAIGHT AND LEVEL/LEVEL TURN TRIMS USED AT EACH
C      LOAD FACTOR ; LOAD FACTORS=ST.  AND LEVEL, 2,4
C
C         0.3   0.4  0.6  0.8  1.0  1.2  1.4  1.6  1.8  2.0
C     10K  *     *    *    *    *    *
C     15K  *     *    *    *    *    *
C     20K  *     *    *    *    *    *
C     25K  *     *    *    *    *    *    *
C     30K        *    *    *    *    *    *    *
C     35K        *    *    *    *    *    *    *    *
C     40K             *    *    *    *    *    *    *    *
C     45K             *    *    *    *    *    *    *    *
C     50K             *    *    *    *    *    *    *    *
C
C      DATA FROM THE LINEARIZATION PROGRAM
C      ===================================
C          REFERENCE  MACH NUMBERS
           XMACH(1)=0.3
           XMACH(2)=0.4
           XMACH(3)=0.6
           XMACH(4)=0.8
           XMACH(5)=1.0
           XMACH(6)=1.2
           XMACH(7)=1.4
           XMACH(8)=1.6
           XMACH(9)=1.8
           XMACH(10)=2.0
           JMAX=10
C          ----------------------------------------
C          REFERENCE ALTITUDES
           ALT(1)=10000.
           ALT(2)=15000.
           ALT(3)=20000.
           ALT(4)=25000.
           ALT(5)=30000.
           ALT(6)=35000.
           ALT(7)=40000.
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```
           ALT(8)=45000.
           ALT(9)=50000.
           IMAX=9
C          ----------------------------------------
C          REFERENCE LOAD FACTORS
           XN(1)=1.D0
           XN(2)=2.D0
           XN(3)=4.D0
           KMAX=3
C          ----------------------------------------
C
C
C          STRAIGHT AND LEVEL TRIMS AT LOAD FACTOR=1.
C          ALT=10000
C
C          MACH=0.30000
           ALPHA(1,1,1)=11.43374
           THRUST(1,1,1)=6586.89893
           DRAG(1,1,1)=6456.14502
           ELEVAT(1,1,1)=-0.10977
           THROTT(1,1,1)=13.72271
C
C          MACH=0.40000
           ALPHA(1,2,1)=6.32867
           THRUST(1,2,1)=3760.49414
           DRAG(1,2,1)=3737.57080
           ELEVAT(1,2,1)=-0.06065
           THROTT(1,2,1)=7.83436
C
C          MACH=0.60000
           ALPHA(1,3,1)=2.74196
           THRUST(1,3,1)=4531.98633
           DRAG(1,3,1)=4526.80420
           ELEVAT(1,3,1)=-0.02294
           THROTT(1,3,1)=9.44164
C
C          MACH=0.80000
           ALPHA(1,4,1)=1.38783
           THRUST(1,4,1)=7484.06982
           DRAG(1,4,1)=7481.85645
           ELEVAT(1,4,1)=-0.00631
           THROTT(1,4,1)=15.59181
C
C          MACH=1.00000
           ALPHA(1,5,1)= 1.04151
           THRUST(1,5,1)=19986.06445
           DRAG(1,5,1)=19982.78320
           ELEVAT(1,5,1)=-0.01518
           THROTT(1,5,1)=41.63763
C
C          MACH=1.20000
           ALPHA(1,6,1)=0.68266
           THRUST(1,6,1)=43616.82813
           DRAG(1,6,1)=43613.79688
           ELEVAT(1,6,1)=0.02884
           THROTT(1,6,1)=90.86839
C          ----------------------------------------
C          ALT(2)=15000.
C
C          MACH=0.30000
           ALPHA(2,1,1)=14.12306
           THRUST(2,1,1)=8196.08789
           DRAG(2,1,1)=7948.37109
           ELEVAT(2,1,1)=-0.14029
```

```
      THROTT(2,1,1)=17.07518
C
C
      MACH=0.40000
      ALPHA(2,2,1)=7.76064
      THRUST(2,2,1)=4492.39600
      DRAG(2,2,1)=4451.17578
      ELEVAT(2,2,1)=-0.07477
      THROTT(2,1,1)=9.35916
C
C
      MACH=0.60000
      ALPHA(2,3,1)=3.33402
      THRUST(2,3,1)=4014.46143
      DRAG(2,3,1)=4007.66357
      ELEVAT(2,3,1)=-0.02746
      THROTT(2,3,1)=8.36346
C
C
      MACH=0.80000
      ALPHA(2,4,1)=1.69465
      THRUST(2,4,1)=6128.60889
      DRAG(2,4,1)=6126.50049
      ELEVAT(2,4,1)=-0.00840
      THROTT(2,4,1)=12.76793
C
C
      MACH=1.00000
      ALPHA(2,5,1)=1.22059
      THRUST(2,5,1)=16509.15625
      DRAG(2,5,1)=16504.97070
      ELEVAT(2,5,1)=-0.01869
      THROTT(2,5,1)=34.39407
C
C
      MACH=1.20000
      ALPHA(2,6,1)=0.85345
      THRUST(2,6,1)=39445.27344
      DRAG(2,6,1)=39440.91406
      ELEVAT(2,6,1)=0.02145
      THROTT(2,6,1)=82.17765
C----------------------------------------------
C
C     ALT(3)=20000.
C
C
      MACH=0.30000
      ALPHA(3,1,1)=17.87607
      THRUST(3,1,1)=10237.47266
      DRAG(3,1,1)=9742.47266
      ELEVAT(3,1,1)=-0.19544
      THROTT(3,1,1)=21.32807
C
C
      MACH=0.40000
      ALPHA(3,2,1)=9.57196
      THRUST(3,2,1)=5120.00635
      DRAG(3,2,1)=5048.73633
      ELEVAT(3,2,1)=-0.09187
      THROTT(3,2,1)=10.66668
C
C
      MACH=0.60000
      ALPHA(3,3,1)=4.09133
      THRUST(3,3,1)=3823.92310
      DRAG(3,3,1)=3814.17993
      ELEVAT(3,3,1)=-0.03343
      THROTT(3,3,1)=7.96651
C
C
      MACH=0.80000
      ALPHA(3,4,1)=2.08757
      THRUST(3,4,1)=4988.27979
      DRAG(3,4,1)=4984.80859
```



```
      ELEVAT(3,4,1)=-0.01109
      THROTT(3,4,1)=10.39225
C
C
      MACH=1.00000
      ALPHA(3,5,1)=1.45005
      THRUST(3,5,1)=13561.25488
      DRAG(3,5,1)=13556.93457
      ELEVAT(3,5,1)=-0.02321
      THROTT(3,5,1)=28.25261
C
C
      MACH=1.20000
      ALPHA(3,6,1)=1.07207
      THRUST(3,6,1)=32175.04688
      DRAG(3,6,1)=32169.41211
      ELEVAT(3,6,1)=0.01202
      THROTT(3,6,1)=67.03135
C----------------------------------------------
C
C     ALT(4)=25000.
C
C
      MACH=0.30000
      ALPHA(4,1,1)=23.36872
      THRUST(4,1,1)=13549.41016
      DRAG(4,1,1)=12438.00781
      ELEVAT(4,1,1)=-0.32833
      THROTT(4,1,1)=28.22794
C
C
      MACH=0.40000
      ALPHA(4,2,1)=11.81394
      THRUST(4,2,1)=6817.70898
      DRAG(4,2,1)=6673.23438
      ELEVAT(4,2,1)=-0.11645
      THROTT(4,2,1)=14.20356
C
C
      MACH=0.60000
      ALPHA(4,3,1)=5.05511
      THRUST(4,3,1)=3672.75806
      DRAG(4,3,1)=3658.4646
      ELEVAT(4,3,1)=-0.04267
      THROTT(4,3,1)=7.65158
C
C
      MACH=0.80000
      ALPHA(4,4,1)=2.58838
      THRUST(4,4,1)=4046.82544
      DRAG(4,4,1)=4042.58105
      ELEVAT(4,4,1)=-0.01454
      THROTT(4,4,1)=8.43089
C
C
      MACH=1.00000
      ALPHA(4,5,1)=1.74225
      THRUST(4,5,1)=11112.50000
      DRAG(4,5,1)=11108.81348
      ELEVAT(4,5,1)=-0.02903
      THROTT(4,5,1)=23.15104
C
C
      MACH=1.20000
      ALPHA(4,6,1)=1.34828
      THRUST(4,6,1)=26115.28516
      DRAG(4,6,1)=26108.00391
      ELEVAT(4,6,1)=0.00017
      THROTT(4,6,1)=54.40685
C
C
      MACH=1.40000
      ALPHA(4,7,1)=0.91263
      THRUST(4,7,1)=34461.49219
```

```
        DRAG(4,7,1)=34455.99219
        ELEVAT(4,7,1)=0.03125
        THROTT(4,7,1)=71.79477
C--------------------------------------------------
C       ALT(5)=30000.
C
C       MACH=0.40000
        ALPHA(5,2,1)=15.01142
        THRUST(5,2,1)=8834.26074
        DRAG(5,2,1)=8532.79199
        ELEVAT(5,2,1)=-0.14890
        THROTT(5,2,1)=18.40471
C
C       MACH=0.60000
        ALPHA(5,3,1)=6.29819
        THRUST(5,3,1)=3736.00391
        DRAG(5,3,1)=3713.16992
        ELEVAT(5,3,1)=-0.05459
        THROTT(5,3,1)=7.78334
C
C       MACH=0.80000
        ALPHA(5,4,1)=3.24018
        THRUST(5,4,1)=3675.09839
        DRAG(5,4,1)=3669.20386
        ELEVAT(5,4,1)=-0.01907
        THROTT(5,4,1)=7.65646
C
C       MACH=1.00000
        ALPHA(5,5,1)=2.12347
        THRUST(5,5,1)=9070.81055
        DRAG(5,5,1)=9064.57910
        ELEVAT(5,5,1)=-0.03670
        THROTT(5,5,1)=18.89752
C
C       MACH=1.20000
        ALPHA(5,6,1)=1.70491
        THRUST(5,6,1)=21034.03711
        DRAG(5,6,1)=21025.73242
        ELEVAT(5,6,1)=-0.01504
        THROTT(5,6,1)=43.82091
C
C       MACH=1.40000
        ALPHA(5,7,1)=1.20179
        THRUST(5,7,1)=27754.65234
        DRAG(5,7,1)=27747.45703
        ELEVAT(5,7,1)=0.02093
        THROTT(5,7,1)=57.82219
C
C       MACH=1.60000
        ALPHA(5,8,1)=0.92773
        THRUST(5,8,1)=34857.53125
        DRAG(5,8,1)=34852.75781
        ELEVAT(5,8,1)=0.03172
        THROTT(5,8,1)=72.61986
C--------------------------------------------------
C       ALT(6)=35000.
C
C       MACH=0.40000
        ALPHA(6,2,1)=19.60772
        THRUST(6,2,1)=11780.97754
        DRAG(6,2,1)=11097.64063
        ELEVAT(6,2,1)=-0.22205
        THROTT(6,2,1)=24.54370
C
```



```
C       MACH=0.60000
        ALPHA(6,3,1)=7.88297
        THRUST(6,3,1)=4551.47559
        DRAG(6,3,1)=4508.51270
        ELEVAT(6,3,1)=-0.06980
        THROTT(6,3,1)=9.48224
C
C       MACH=0.80000
        ALPHA(6,4,1)=4.08973
        THRUST(6,4,1)=3515.22437
        DRAG(6,4,1)=3506.24780
        ELEVAT(6,4,1)=-0.02513
        THROTT(6,4,1)=7.32338
C
C       MACH=1.00000
        ALPHA(6,5,1)=2.62183
        THRUST(6,5,1)=7394.08496
        DRAG(6,5,1)=7386.25391
        ELEVAT(6,5,1)=-0.04689
        THROTT(6,5,1)=15.40434
C
C       MACH=1.20000
        ALPHA(6,6,1)=2.16504
        THRUST(6,6,1)=16848.63867
        DRAG(6,6,1)=16836.59570
        ELEVAT(6,6,1)=-0.03449
        THROTT(6,6,1)=35.10133
C
C       MACH=1.40000
        ALPHA(6,7,1)=1.57863
        THRUST(6,7,1)=22229.19336
        DRAG(6,7,1)=22218.51563
        ELEVAT(6,7,1)=0.00749
        THROTT(6,7,1)=46.31082
C
C       MACH=1.60000
        ALPHA(6,8,1)=1.24392
        THRUST(6,8,1)=27907.37891
        DRAG(6,8,1)=27900.78516
        ELEVAT(6,8,1)=0.02165
        THROTT(6,8,1)=58.14037
C
C       MACH=1.80000
        ALPHA(6,9,1)=0.92244
        THRUST(6,9,1)=34814.69922
        DRAG(6,9,1)=34809.92578
        ELEVAT(6,9,1)=0.03189
        THROTT(6,9,1)=72.53062
C--------------------------------------------------
C       ALT(7)=40000.
C
C       MACH=0.60000
        ALPHA(7,3,1)=10.07970
        THRUST(7,3,1)=5843.59961
        DRAG(7,3,1)=5753.18750
        ELEVAT(7,3,1)=-0.08769
        THROTT(7,3,1)=12.17417
C
C       MACH=0.80000
        ALPHA(7,4,1)=5.18231
        THRUST(7,4,1)=3393.83130
        DRAG(7,4,1)=3379.91748
        ELEVAT(7,4,1)=-0.03420
        THROTT(7,4,1)=7.07048
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C
C         MACH=1.00000
          ALPHA(7,5,1)=3.26914
          THRUST(7,5,1)=6617.98682
          DRAG(7,5,1)=6607.24072
          ELEVAT(7,5,1)=-0.06038
          THROTT(7,5,1)=13.78747
C
C         MACH=1.20000
          ALPHA(7,6,1)=2.75515
          THRUST(7,6,1)=13462.85840
          DRAG(7,6,1)=13447.48145
          ELEVAT(7,6,1)=-0.05916
          THROTT(7,6,1)=28.04762
C
C         MACH=1.40000
          ALPHA(7,7,1)=2.06871
          THRUST(7,7,1)=17758.31250
          DRAG(7,7,1)=17746.40039
          ELEVAT(7,7,1)=-0.00991
          THROTT(7,7,1)=36.99648
C
C         MACH=1.60000
          ALPHA(7,8,1)=1.65511
          THRUST(7,8,1)=22288.36523
          DRAG(7,8,1)=22278.38477
          ELEVAT(7,8,1)=0.00851
          THROTT(7,8,1)=46.43409
C
C         MACH=1.80000
          ALPHA(7,9,1)=1.24741
          THRUST(7,9,1)=27701.25391
          DRAG(7,9,1)=27694.62891
          ELEVAT(7,9,1)=0.02153
          THROTT(7,9,1)=57.71095
C
C         MACH=2.00000
          ALPHA(7,10,1)=0.95571
          THRUST(7,10,1)=33752.45313
          DRAG(7,10,1)=33747.78125
          ELEVAT(7,10,1)=0.03083
          THROTT(7,10,1)=70.31761
C-----------------------------------------------------------
C         ALT(8)=45000.
C
C         MACH=0.60000
          ALPHA(8,3,1)=12.94587
          THRUST(8,3,1)=7824.69189
          DRAG(8,3,1)=7625.76953
          ELEVAT(8,3,1)=-0.11453
          THROTT(8,3,1)=16.30144
C
C         MACH=0.80000
          ALPHA(8,4,1)=6.55472
          THRUST(8,4,1)=4002.17065
          DRAG(8,4,1)=3976.03906
          ELEVAT(8,4,1)=-0.04578
          THROTT(8,4,1)=8.33786
C
C         MACH=1.00000
          ALPHA(8,5,1)=4.09879
          THRUST(8,5,1)=6171.10059
          DRAG(8,5,1)=6155.27441
          ELEVAT(8,5,1)=-0.07825
```



```
          THROTT(8,5,1)=12.85646
C
C         MACH=1.20000
          ALPHA(8,6,1)=3.49376
          THRUST(8,6,1)=11060.85254
          DRAG(8,6,1)=11040.61035
          ELEVAT(8,6,1)=-0.08991
          THROTT(8,6,1)=23.04344
C
C         MACH=1.40000
          ALPHA(8,7,1)=2.69042
          THRUST(8,7,1)=14250.15430
          DRAG(8,7,1)=14234.53125
          ELEVAT(8,7,1)=-0.03193
          THROTT(8,7,1)=29.68782
C
C         MACH=1.60000
          ALPHA(8,8,1)=2.17759
          THRUST(8,8,1)=17876.81055
          DRAG(8,8,1)=17864.27930
          ELEVAT(8,8,1)=-0.00825
          THROTT(8,8,1)=37.24335
C
C         MACH=1.80000
          ALPHA(8,9,1)=1.66031
          THRUST(8,9,1)=22117.89844
          DRAG(8,9,1)=22108.58789
          ELEVAT(8,9,1)=0.00834
          THROTT(8,9,1)=46.07896
C
C         MACH=2.00000
          ALPHA(8,10,1)=1.29021
          THRUST(8,10,1)=26857.76758
          DRAG(8,10,1)=26851.88477
          ELEVAT(8,10,1)=0.02017
          THROTT(8,10,1)=55.95368
C-----------------------------------------------------------
C         ALT(9)=50000.
C
C         MACH=0.60000
          ALPHA(9,3,1)=17.14475
          THRUST(9,3,1)=10430.85449
          DRAG(9,3,1)=9967.41992
          ELEVAT(9,3,1)=-0.16728
          THROTT(9,3,1)=21.73095
C
C         MACH=0.80000
          ALPHA(9,4,1)=8.37713
          THRUST(9,4,1)=4699.29346
          DRAG(9,4,1)=4648.51465
          ELEVAT(9,4,1)=-0.06158
          THROTT(9,4,1)=9.79019
C
C         MACH=1.00000
          ALPHA(9,5,1)=5.21505
          THRUST(9,5,1)=5824.53369
          DRAG(9,5,1)=5800.21240
          ELEVAT(9,5,1)=-0.10767
          THROTT(9,5,1)=12.13445
C
C         MACH=1.20000
          ALPHA(9,6,1)=4.51515
          THRUST(9,6,1)=10089.23828
          DRAG(9,6,1)=10057.99707
```

```
      ELEVAT(9,6,1)=-0.13590
      THROTT(9,6,1)=21.01925
C
C     MACH=1.40000
      ALPHA(9,7,1)=3.48176
      THRUST(9,7,1)=11492.67285
      DRAG(9,7,1)=11471.37109
      ELEVAT(9,7,1)=-0.05983
      THROTT(9,7,1)=23.94307
C
C     MACH=1.60000
      ALPHA(9,8,1)=2.84358
      THRUST(9,8,1)=14410.39453
      DRAG(9,8,1)=14391.90820
      ELEVAT(9,8,1)=-0.02969
      THROTT(9,8,1)=30.02166
C
C     MACH=1.80000
      ALPHA(9,9,1)=2.18668
      THRUST(9,9,1)=17727.35547
      DRAG(9,9,1)=17714.55469
      ELEVAT(9,9,1)=-0.00854
      THROTT(9,9,1)=36.93199
C
C     MACH=2.00000
      ALPHA(9,10,1)=1.71658
      THRUST(9,10,1)=21436.30664
      DRAG(9,10,1)=21427.59766
      ELEVAT(9,10,1)=0.00654
      THROTT(9,10,1)=44.65897
C
C     SINCE LIFT DATA FOR SYMMETRIC FLIGHT HAS
C     NOT BEEN STORED, COMPUTE IT
C     FROM THRUST, ANGLE OF ATTACK AND WEIGHT, THETA=ALFA
C
      DO 801  IN=1,IMAX
      DO 900  JN=1,JMAX
      ALRDAB=ALPHA(IN,JN,1)*3.1415927D0/180.D0
      LIFT(IN,JN,1)=WEIGT-THRUST(IN,JN,1)*DSIN(ALRDAB)
      THETA(IN,JN,1)=ALPHA(IN,JN,1)
900   CONTINUE
801   CONTINUE
C
C
C     ================================================================
C
C     LEVEL TURN WHILE VARYING ALPHA
C
C     ================================================================
C
C     LOAD FACTOR=2.0
C
C     ================================================================
C
C     ----------------------------------------------------------------
C     ALTITUDE=10000
C
C     MACH=0.4
      LIFT(1,2,2)=81322.34375
      DRAG(1,2,2)=16002.16016
      BETA(1,2,2)=0.20755
      ALPHA(1,2,2)=14.03178
      PHI(1,2,2)=62.29918
      THETA(1,2,2)=6.81347
      ROLLR(1,2,2)=-0.93527
      PITCHR(1,2,2)=6.93060
      YAWR(1,2,2)=3.63877
      THRUST(1,2,2)=16494.32422
      ELEVAT(1,2,2)=-0.17681
      DTAIL(1,2,2)=-0.00683
      RUDDER(1,2,2)=-0.01629
      THROTT(1,2,2)=34.36317
      AILERO(1,2,2)=-0.02278
C
C     MACH=0.6
      LIFT(1,3,2)=81324.18750
      DRAG(1,3,2)=7520.99805
      BETA(1,3,2)=0.07205
      ALPHA(1,3,2)=5.66266
      PHI(1,3,2)=60.42597
      THETA(1,3,2)=2.86451
      ROLLR(1,3,2)=-0.24961
      PITCHR(1,3,2)=4.33864
      YAWR(1,3,2)=2.46209
      THRUST(1,3,2)=7557.78125
      ELEVAT(1,3,2)=-0.05961
      DTAIL(1,3,2)=-0.00090
      RUDDER(1,3,2)=-0.00625
      THROTT(1,3,2)=15.74538
      AILERO(1,3,2)=-0.00300
C
C     MACH=0.8
      LIFT(1,4,2)=81322.66406
      DRAG(1,4,2)=8050.01514
      BETA(1,4,2)=0.03316
      ALPHA(1,4,2)=2.88765
      PHI(1,4,2)=60.19688
      THETA(1,4,2)=1.46493
      ROLLR(1,4,2)=-0.09524
      PITCHR(1,4,2)=3.23173
      YAWR(1,4,2)=1.85107
      THRUST(1,4,2)=8060.24609
      ELEVAT(1,4,2)=-0.01999
      DTAIL(1,4,2)=-0.00038
      RUDDER(1,4,2)=-0.00327
      THROTT(1,4,2)=16.79218
      AILERO(1,4,2)=-0.00127
C
C     MACH=1.0
      LIFT(1,5,2)=81317.89844
      DRAG(1,5,2)=21260.25391
      BETA(1,5,2)=0.01684
      ALPHA(1,5,2)=1.91904
      PHI(1,5,2)=60.30110
      THETA(1,5,2)=0.96567
      ROLLR(1,5,2)=-0.05048
      PITCHR(1,5,2)=2.60144
      YAWR(1,5,2)=1.48377
      THRUST(1,5,2)=21272.15820
      ELEVAT(1,5,2)=-0.03307
      DTAIL(1,5,2)=-0.00026
      RUDDER(1,5,2)=-0.00215
      THROTT(1,5,2)=44.31699
      AILERO(1,5,2)=-0.00088
C
C     MACH=1.2
      LIFT(1,6,2)=81322.88281
      DRAG(1,6,2)=44835.46484
```

```
      BETA(1,6,2)=0.00804
      ALPHA(1,6,2)=1.52935
      PHI(1,6,2)=60.48763
      THETA(1,6,2)=0.76051
      ROLLR(1,6,2)=-0.03339
      PITCHR(1,6,2)=2.18899
      YAWR(1,6,2)=1.23910
      THRUST(1,6,2)=44851.43750
      ELEVAT(1,6,2)=-0.00820
      DTAIL(1,6,2)=-0.00018
      RUDDER(1,6,2)=-0.00167
      THROTT(1,6,2)=93.44050
      AILERO(1,6,2)=-0.00061
C     ------------------------------------------------
C     ALTITUDE=15000
C
C     MACH=0.4
      LIFT(2,2,2)=81281.48438
      DRAG(2,2,2)=20832.15430
      BETA(2,2,2)=0.23665
      ALPHA(2,2,2)=18.27243
      PHI(2,2,2)=63.80337
      THETA(2,2,2)=8.51193
      ROLLR(2,2,2)=-1.24015
      PITCHR(2,2,2)=7.43510
      YAWR(2,2,2)=3.65798
      THRUST(2,2,2)=21940.05273
      ELEVAT(2,2,2)=-0.23985
      DTAIL(2,2,2)=-0.00863
      RUDDER(2,2,2)=-0.02101
      THROTT(2,2,2)=45.70844
      AILERO(2,2,2)=-0.02877
C
C     MACH=0.6
      LIFT(2,3,2)=81284.10938
      DRAG(2,3,2)=8269.13281
      BETA(2,3,2)=0.07800
      ALPHA(2,3,2)=6.85644
      PHI(2,3,2)=60.58232
      THETA(2,3,2)=3.44813
      ROLLR(2,3,2)=-0.30719
      PITCHR(2,3,2)=4.44093
      YAWR(2,3,2)=2.50414
      THRUST(2,3,2)=8328.68945
      ELEVAT(2,3,2)=-0.07164
      DTAIL(2,3,2)=-0.00105
      RUDDER(2,3,2)=-0.00671
      THROTT(2,3,2)=17.35144
      AILERO(2,3,2)=-0.00349
C
C     MACH=0.8
      LIFT(2,4,2)=81295.99219
      DRAG(2,4,2)=7632.95557
      BETA(2,4,2)=0.03490
      ALPHA(2,4,2)=3.51073
      PHI(2,4,2)=60.23729
      THETA(2,4,2)=1.77472
      ROLLR(2,4,2)=-0.11763
      PITCHR(2,4,2)=3.29561
      YAWR(2,4,2)=1.88457
      THRUST(2,4,2)=7646.93066
      ELEVAT(2,4,2)=-0.02459
      DTAIL(2,4,2)=-0.00041
      RUDDER(2,4,2)=-0.00346
```

```
      THROTT(2,4,2)=15.93111
      AILERO(2,4,2)=-0.00136
C
C     MACH=1.0
      LIFT(2,5,2)=81285.80469
      DRAG(2,5,2)=17773.39844
      BETA(2,5,2)=0.01764
      ALPHA(2,5,2)=2.28268
      PHI(2,5,2)=60.30553
      THETA(2,5,2)=1.14657
      ROLLR(2,5,2)=-0.06104
      PITCHR(2,5,2)=2.64932
      YAWR(2,5,2)=1.51080
      THRUST(2,5,2)=17787.41406
      ELEVAT(2,5,2)=-0.04055
      DTAIL(2,5,2)=-0.00029
      RUDDER(2,5,2)=-0.00225
      THROTT(2,5,2)=37.05711
      AILERO(2,5,2)=-0.00095
C     ------------------------------------------------
C     ALTITUDE=20000
C
C     MACH=0.6
      LIFT(3,3,2)=81246.71875
      DRAG(3,3,2)=9649.65039
      BETA(3,3,2)=0.08615
      ALPHA(3,3,2)=8.41573
      PHI(3,3,2)=60.84391
      THETA(3,3,2)=4.19833
      ROLLR(3,3,2)=-0.38376
      PITCHR(3,3,2)=4.56550
      YAWR(3,3,2)=2.54698
      THRUST(3,3,2)=9754.68652
      ELEVAT(3,3,2)=-0.08665
      DTAIL(3,3,2)=-0.00131
      RUDDER(3,3,2)=-0.00732
      THROTT(3,3,2)=20.32226
      AILERO(3,3,2)=-0.00438
C
C     MACH=0.8
      LIFT(3,4,2)=81247.26563
      DRAG(3,4,2)=7292.51221
      BETA(3,4,2)=0.03716
      ALPHA(3,4,2)=4.30461
      PHI(3,4,2)=60.29356
      THETA(3,4,2)=2.16853
      ROLLR(3,4,2)=-0.14667
      PITCHR(3,4,2)=3.36444
      YAWR(3,4,2)=1.91955
      THRUST(3,4,2)=7312.87744
      ELEVAT(3,4,2)=-0.03082
      DTAIL(3,4,2)=-0.00045
      RUDDER(3,4,2)=-0.00369
      THROTT(3,4,2)=15.23516
      AILERO(3,4,2)=-0.00150
C
C     MACH=1.0
      LIFT(3,5,2)=81245.67969
      DRAG(3,5,2)=14766.45898
      BETA(3,5,2)=0.01856
      ALPHA(3,5,2)=2.74857
      PHI(3,5,2)=60.31479
      THETA(3,5,2)=1.37810
      ROLLR(3,5,2)=-0.07477
```

```
      PITCHR(3,5,2)=2.70026
      YAWR(3,5,2)=1.53928
      THRUST(3,5,2)=14783.45508
      ELEVAT(3,5,2)=-0.05024
      DTAIL(3,5,2)=-0.00031
      RUDDER(3,5,2)=-0.00237
      THROTT(3,5,2)=30.79886
      AILERO(3,5,2)=-0.00104
C
C
      MACH=1.2
      LIFT(3,6,2)=81246.67188
      DRAG(3,6,2)=33376.49609
      BETA(3,6,2)=0.00903
      ALPHA(3,6,2)=2.30240
      PHI(3,6,2)=60.55615
      THETA(3,6,2)=1.14012
      ROLLR(3,6,2)=-0.05208
      PITCHR(3,6,2)=2.27888
      YAWR(3,6,2)=1.28638
      THRUST(3,6,2)=33403.44922
      ELEVAT(3,6,2)=-0.04116
      DTAIL(3,6,2)=-0.00025
      RUDDER(3,6,2)=-0.00182
      THROTT(3,6,2)=69.59052
      AILERO(3,6,2)=-0.00085
C     ---------------------------------------------------------
C     ALTITUDE=25000
C
C
      MACH=0.6
      LIFT(4,3,2)=81199.57813
      DRAG(4,3,2)=12575.88477
      BETA(4,3,2)=0.10038
      ALPHA(4,3,2)=10.57505
      PHI(4,3,2)=61.35437
      THETA(4,3,2)=5.20321
      ROLLR(4,3,2)=-0.49201
      PITCHR(4,3,2)=4.74157
      YAWR(4,3,2)=2.59009
      THRUST(4,3,2)=12793.17871
      ELEVAT(4,3,2)=-0.10793
      DTAIL(4,3,2)=-0.00213
      RUDDER(4,3,2)=-0.00831
      THROTT(4,3,2)=26.65246
      AILERO(4,3,2)=-0.00711
C
C
      MACH=0.8
      LIFT(4,4,2)=81200.09375
      DRAG(4,4,2)=7021.35449
      BETA(4,4,2)=0.04045
      ALPHA(4,4,2)=5.30818
      PHI(4,4,2)=60.37205
      THETA(4,4,2)=2.66510
      ROLLR(4,4,2)=-0.18415
      PITCHR(4,4,2)=3.43894
      YAWR(4,4,2)=1.95581
      THRUST(4,4,2)=7052.07275
      ELEVAT(4,4,2)=-0.03949
      DTAIL(4,4,2)=-0.00052
      RUDDER(4,4,2)=-0.00397
      THROTT(4,4,2)=14.69182
      AILERO(4,4,2)=-0.00172
C
C
      MACH=1.0
      LIFT(4,5,2)=81205.17969
```

```
      DRAG(4,5,2)=13663.21680
      BETA(4,5,2)=0.01960
      ALPHA(4,5,2)=3.34309
      PHI(4,5,2)=60.36426
      THETA(4,5,2)=1.67157
      ROLLR(4,5,2)=-0.09264
      PITCHR(4,5,2)=2.75925
      YAWR(4,5,2)=1.56975
      THRUST(4,5,2)=13686.49902
      ELEVAT(4,5,2)=-0.06282
      DTAIL(4,5,2)=-0.00035
      RUDDER(4,5,2)=-0.00250
      THROTT(4,5,2)=28.51354
      AILERO(4,5,2)=-0.00116
C
C
      MACH=1.2
      LIFT(4,6,2)=81204.76563
      DRAG(4,6,2)=27308.66602
      BETA(4,6,2)=0.00967
      ALPHA(4,6,2)=2.84451
      PHI(4,6,2)=60.57278
      THETA(4,6,2)=1.40686
      ROLLR(4,6,2)=-0.06556
      YAWR(4,6,2)=1.31163
      THRUST(4,6,2)=27342.36719
      ELEVAT(4,6,2)=-0.06393
      DTAIL(4,6,2)=-0.00031
      RUDDER(4,6,2)=-0.00191
      THROTT(4,6,2)=56.96326
      AILERO(4,6,2)=-0.00102
C
C
      MACH=1.4
      LIFT(4,7,2)=81204.61719
      DRAG(4,7,2)=36057.69922
      BETA(4,7,2)=0.00587
      ALPHA(4,7,2)=2.14089
      PHI(4,7,2)=60.55597
      THETA(4,7,2)=1.05789
      ROLLR(4,7,2)=-0.04225
      PITCHR(4,7,2)=1.99266
      YAWR(4,7,2)=1.12482
      THRUST(4,7,2)=36083.16406
      ELEVAT(4,7,2)=-0.01267
      DTAIL(4,7,2)=-0.00027
      RUDDER(4,7,2)=-0.00156
      THROTT(4,7,2)=75.17326
      AILERO(4,7,2)=-0.00089
C     ---------------------------------------------------------
C     ALTITUDE=30000
C
C
      MACH=0.6
      LIFT(5,3,2)=81168.92969
      DRAG(5,3,2)=17106.69336
      BETA(5,3,2)=0.12090
      ALPHA(5,3,2)=13.74951
      PHI(5,3,2)=62.32314
      THETA(5,3,2)=6.59289
      ROLLR(5,3,2)=-0.65416
      PITCHR(5,3,2)=5.01229
      YAWR(5,3,2)=2.62893
      THRUST(5,3,2)=17611.40430
      ELEVAT(5,3,2)=-0.13957
      DTAIL(5,3,2)=-0.00351
      RUDDER(5,3,2)=-0.00966
```

```
      THROTT(5,3,2)=36.69043
      AILERO(5,3,2)=-0.01169
C
C     MACH=0.8
      LIFT(5,4,2)=81162.42969
      DRAG(5,4,2)=8255.35938
      BETA(5,4,2)=0.04465
      ALPHA(5,4,2)=6.61738
      PHI(5,4,2)=60.55319
      THETA(5,4,2)=3.30323
      ROLLR(5,4,2)=-0.23412
      PITCHR(5,4,2)=3.53236
      YAWR(5,4,2)=1.99418
      THRUST(5,4,2)=8310.72852
      ELEVAT(5,4,2)=-0.05094
      DTAIL(5,4,2)=-0.00060
      RUDDER(5,4,2)=-0.00432
      THROTT(5,4,2)=17.31402
      AILERO(5,4,2)=-0.00200
C
C     MACH=1.00000
      LIFT(5,5,2)=81172.07813
      DRAG(5,5,2)=12753.33301
      BETA(5,5,2)=0.02089
      ALPHA(5,5,2)=4.13008
      PHI(5,5,2)=60.43553
      THETA(5,5,2)=2.05866
      ROLLR(5,5,2)=-0.11670
      PITCHR(5,5,2)=2.82380
      YAWR(5,5,2)=1.60182
      THRUST(5,5,2)=12786.47266
      ELEVAT(5,5,2)=-0.08002
      DTAIL(5,5,2)=-0.00039
      RUDDER(5,5,2)=-0.00265
      THROTT(5,5,2)=26.63848
      AILERO(5,5,2)=-0.00131
C
C     MACH=1.2
      LIFT(5,6,2)=81165.62500
      DRAG(5,6,2)=22873.98047
      BETA(5,6,2)=0.01047
      ALPHA(5,6,2)=3.54796
      PHI(5,6,2)=60.61400
      THETA(5,6,2)=1.75178
      ROLLR(5,6,2)=-0.08342
      PITCHR(5,6,2)=2.37662
      YAWR(5,6,2)=1.33839
      THRUST(5,6,2)=22917.91602
      ELEVAT(5,6,2)=-0.09375
      DTAIL(5,6,2)=-0.00038
      RUDDER(5,6,2)=-0.00201
      THROTT(5,6,2)=47.74566
      AILERO(5,6,2)=-0.00125
C
C     MACH=1.6
      LIFT(5,7,2)=81163.09375
      DRAG(5,7,2)=36848.21484
      BETA(5,7,2)=0.00461
      ALPHA(5,7,2)=2.21020
      PHI(5,7,2)=60.58639
      THETA(5,7,2)=1.08988
      ROLLR(5,7,2)=-0.03893
      PITCHR(5,7,2)=1.78260
      YAWR(5,7,2)=1.00500
      THRUST(5,7,2)=36876.02734
      ELEVAT(5,7,2)=-0.00904
      DTAIL(5,7,2)=-0.00027
      RUDDER(5,7,2)=-0.00167
      THROTT(5,7,2)=76.82506
      AILERO(5,7,2)=-0.00089
C
C     MACH=1.8
      LIFT(5,8,2)=81167.07031
      DRAG(5,8,2)=41267.72656
      BETA(5,8,2)=0.00370
      ALPHA(5,8,2)=1.68706
      PHI(5,8,2)=60.49760
      THETA(5,8,2)=0.83422
      ROLLR(5,8,2)=-0.02640
      PITCHR(5,8,2)=1.57804
      YAWR(5,8,2)=0.89290
      THRUST(5,8,2)=41285.56250
      ELEVAT(5,8,2)=0.00823
      DTAIL(5,8,2)=-0.00019
      RUDDER(5,8,2)=-0.00131
      THROTT(5,8,2)=86.01159
      AILERO(5,8,2)=-0.00062
C     -------------------------------------------
C     ALTITUDE=3500
C
C     MACH=0.6
      LIFT(6,3,2)=81125.78906
      DRAG(6,3,2)=25121.12891
      BETA(6,3,2)=0.13794
      ALPHA(6,3,2)=19.16866
      PHI(6,3,2)=64.49668
      THETA(6,3,2)=8.64137
      ROLLR(6,3,2)=-0.93476
      PITCHR(6,3,2)=5.55142
      YAWR(6,3,2)=2.64829
      THRUST(6,3,2)=26595.68555
      ELEVAT(6,3,2)=-0.22453
      DTAIL(6,3,2)=-0.00405
      RUDDER(6,3,2)=-0.01256
      THROTT(6,3,2)=55.40768
      AILERO(6,3,2)=-0.01349
C
C     MACH=0.8
      LIFT(6,4,2)=81133.85938
      DRAG(6,4,2)=9618.19336
      BETA(6,4,2)=0.05329
      ALPHA(6,4,2)=8.43525
      PHI(6,4,2)=60.84182
      THETA(6,4,2)=4.17941
      ROLLR(6,4,2)=-0.30493
      PITCHR(6,4,2)=3.64410
      YAWR(6,4,2)=2.03313
      THRUST(6,4,2)=9723.81641
      ELEVAT(6,4,2)=-0.06713
      DTAIL(6,4,2)=-0.00071
      RUDDER(6,4,2)=-0.00512
      THROTT(6,4,2)=20.25795
      AILERO(6,4,2)=-0.00236
C
C     MACH=1.0
      LIFT(6,5,2)=81127.73438
      DRAG(6,5,2)=12013.45215
      BETA(6,5,2)=0.02288
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      ALPHA(6,5,2)=5.21196
      PHI(6,5,2)=60.54324
      THETA(6,5,2)=2.58840
      ROLLR(6,5,2)=-0.15036
      PITCHR(6,5,2)=2.89616
      YAWR(6,5,2)=1.63569
      THRUST(6,5,2)=12063.65234
      ELEVAT(6,5,2)=-0.10903
      DTAIL(6,5,2)=-0.00048
      RUDDER(6,5,2)=-0.00287
      THROTT(6,5,2)=25.13261
      AILERO(6,5,2)=-0.00161
C
C     MACH=1.2
      LIFT(6,6,2)=81127.46875
      DRAG(6,6,2)=20889.64648
      BETA(6,6,2)=0.01179
      ALPHA(6,6,2)=4.55320
      PHI(6,6,2)=60.74050
      THETA(6,6,2)=2.23933
      ROLLR(6,6,2)=-0.10940
      PITCHR(6,6,2)=2.44082
      YAWR(6,6,2)=1.36746
      THRUST(6,6,2)=20955.77930
      ELEVAT(6,6,2)=-0.13913
      DTAIL(6,6,2)=-0.00049
      RUDDER(6,6,2)=-0.00218
      THROTT(6,6,2)=43.65788
      AILERO(6,6,2)=-0.00162
C
C     MACH=1.6
      LIFT(6,8,2)=81130.55469
      DRAG(6,8,2)=29889.12109
      BETA(6,8,2)=0.00470
      ALPHA(6,8,2)=2.85663
      PHI(6,8,2)=60.62601
      THETA(6,8,2)=1.40618
      ROLLR(6,8,2)=-0.05139
      PITCHR(6,8,2)=1.82440
      YAWR(6,8,2)=1.02691
      THRUST(6,8,2)=29926.24805
      ELEVAT(6,8,2)=-0.02997
      DTAIL(6,8,2)=-0.00032
      RUDDER(6,8,2)=-0.00177
      THROTT(6,8,2)=62.34635
      AILERO(6,8,2)=-0.00107
C
C     MACH=1.8
      LIFT(6,9,2)=81120.92969
      DRAG(6,9,2)=36804.26953
      BETA(6,9,2)=0.00380
      ALPHA(6,9,2)=2.19715
      PHI(6,9,2)=60.58247
      THETA(6,9,2)=1.08289
      ROLLR(6,9,2)=-0.03514
      PITCHR(6,9,2)=1.61914
      YAWR(6,9,2)=0.91299
      THRUST(6,9,2)=36831.98828
      ELEVAT(6,9,2)=-0.00821
      DTAIL(6,9,2)=-0.00022
      RUDDER(6,9,2)=-0.00138
      THROTT(6,9,2)=76.73331
      AILERO(6,9,2)=-0.00074
```

```
C     ------------------------------------------
C     ALTITUDE=40000
C
C     MACH=0.8
      LIFT(7,4,2)=81068.21875
      DRAG(7,4,2)=14734.15625
      BETA(7,4,2)=0.06168
      ALPHA(7,4,2)=11.35962
      PHI(7,4,2)=61.64415
      THETA(7,4,2)=5.50539
      ROLLR(7,4,2)=-0.41309
      PITCHR(7,4,2)=3.77167
      YAWR(7,4,2)=2.03558
      THRUST(7,4,2)=15028.41602
      ELEVAT(7,4,2)=-0.09250
      DTAIL(7,4,2)=-0.00128
      RUDDER(7,4,2)=-0.00586
      THROTT(7,4,2)=31.30920
      AILERO(7,4,2)=-0.00425
C
C     MACH=1.0
      LIFT(7,5,2)=81090.48438
      DRAG(7,5,2)=13232.69336
      BETA(7,5,2)=0.02454
      ALPHA(7,5,2)=6.61524
      PHI(7,5,2)=60.77803
      THETA(7,5,2)=3.26198
      ROLLR(7,5,2)=-0.19166
      PITCHR(7,5,2)=2.93486
      YAWR(7,5,2)=1.64171
      THRUST(7,5,2)=13321.38086
      ELEVAT(7,5,2)=-0.14653
      DTAIL(7,5,2)=-0.00058
      RUDDER(7,5,2)=-0.00304
      THROTT(7,5,2)=27.75288
      AILERO(7,5,2)=-0.00195
C
C     MACH=1.2
      LIFT(7,6,2)=81088.27344
      DRAG(7,6,2)=19292.47070
      BETA(7,6,2)=0.01306
      ALPHA(7,6,2)=5.85336
      PHI(7,6,2)=60.91299
      THETA(7,6,2)=2.86456
      ROLLR(7,6,2)=-0.14127
      PITCHR(7,6,2)=2.46714
      YAWR(7,6,2)=1.37246
      THRUST(7,6,2)=19393.58789
      ELEVAT(7,6,2)=-0.19502
      DTAIL(7,6,2)=-0.00064
      RUDDER(7,6,2)=-0.00230
      THROTT(7,6,2)=40.40331
      AILERO(7,6,2)=-0.00214
C
C     MACH=1.4
      LIFT(7,7,2)=81088.53906
      DRAG(7,7,2)=21800.05273
      BETA(7,7,2)=0.00781
      ALPHA(7,7,2)=4.52625
      PHI(7,7,2)=60.76378
      THETA(7,7,2)=2.22100
      ROLLR(7,7,2)=-0.09352
      PITCHR(7,7,2)=2.10425
      YAWR(7,7,2)=1.17777
```

```
      THRUST(7,7,2)=21868.25195
      ELEVAT(7,7,2)=-0.10316
      DTAIL(7,7,2)=-0.00046
      RUDDER(7,7,2)=-0.00198
      THROTT(7,7,2)=45.55886
      AILERO(7,7,2)=-0.00154
C
C     MACH=1.6
      LIFT(7,8,2)=81087.07031
      DRAG(7,8,2)=24260.49805
      BETA(7,8,2)=0.00457
      ALPHA(7,8,2)=3.69707
      PHI(7,8,2)=60.67663
      THETA(7,8,2)=1.81650
      ROLLR(7,8,2)=-0.06677
      PITCHR(7,8,2)=1.83548
      YAWR(7,8,2)=1.03101
      THRUST(7,8,2)=24311.77148
      ELEVAT(7,8,2)=-0.05722
      DTAIL(7,8,2)=-0.00038
      RUDDER(7,8,2)=-0.00181
      THROTT(7,8,2)=50.64952
      AILERO(7,8,2)=-0.00127
C
C     MACH=1.8
      LIFT(7,9,2)=81097.53125
      DRAG(7,9,2)=29682.07422
      BETA(7,9,2)=0.00376
      ALPHA(7,9,2)=2.86130
      PHI(7,9,2)=60.62327
      THETA(7,9,2)=1.40777
      ROLLR(7,9,2)=-0.04594
      PITCHR(7,9,2)=1.62883
      YAWR(7,9,2)=0.91693
      THRUST(7,9,2)=29718.66406
      ELEVAT(7,9,2)=-0.02962
      DTAIL(7,9,2)=-0.00026
      RUDDER(7,9,2)=-0.00141
      THROTT(7,9,2)=61.91388
      AILERO(7,9,2)=-0.00086
C
C     MACH=2.0
      LIFT(7,10,2)=81064.25000
      DRAG(7,10,2)=35739.31250
      BETA(7,10,2)=0.00311
      ALPHA(7,10,2)=2.26260
      PHI(7,10,2)=60.58380
      THETA(7,10,2)=1.11442
      ROLLR(7,10,2)=-0.03269
      PITCHR(7,10,2)=1.46387
      YAWR(7,10,2)=0.82539
      THRUST(7,10,2)=35767.04688
      ELEVAT(7,10,2)=-0.00996
      DTAIL(7,10,2)=-0.00018
      RUDDER(7,10,2)=-0.00113
      THROTT(7,10,2)=74.51468
      AILERO(7,10,2)=-0.00061
C     ---------------------------------------------
C     ALTITUDE=45000
C
C     MACH=0.8
      LIFT(8,4,2)=81050.51563
      DRAG(8,4,2)=21814.13477
      BETA(8,4,2)=0.08002
      ALPHA(8,4,2)=16.28868
      PHI(8,4,2)=63.35456
      THETA(8,4,2)=7.53903
      ROLLR(8,4,2)=-0.59440
      PITCHR(8,4,2)=4.01430
      YAWR(8,4,2)=2.01419
      THRUST(8,4,2)=22726.44922
      ELEVAT(8,4,2)=-0.19221
      DTAIL(8,4,2)=-0.00216
      RUDDER(8,4,2)=-0.00829
      THROTT(8,4,2)=47.34677
      AILERO(8,4,2)=-0.00718
C
C     MACH=1.0
      LIFT(8,5,2)=81051.78125
      DRAG(8,5,2)=14852.18457
      BETA(8,5,2)=0.02836
      ALPHA(8,5,2)=8.56993
      PHI(8,5,2)=61.16088
      THETA(8,5,2)=4.18251
      ROLLR(8,5,2)=-0.24830
      PITCHR(8,5,2)=2.97428
      YAWR(8,5,2)=1.63777
      THRUST(8,5,2)=15019.90723
      ELEVAT(8,5,2)=-0.19276
      DTAIL(8,5,2)=-0.00070
      RUDDER(8,5,2)=-0.00349
      THROTT(8,5,2)=31.29147
      AILERO(8,5,2)=-0.00233
C
C     MACH=1.2
      LIFT(8,6,2)=81040.35938
      DRAG(8,6,2)=18841.87109
      BETA(8,6,2)=0.01485
      ALPHA(8,6,2)=7.43313
      PHI(8,6,2)=61.17528
      THETA(8,6,2)=3.61231
      ROLLR(8,6,2)=-0.17937
      PITCHR(8,6,2)=2.48918
      YAWR(8,6,2)=1.36984
      THRUST(8,6,2)=19001.48438
      ELEVAT(8,6,2)=-0.26022
      DTAIL(8,6,2)=-0.00085
      RUDDER(8,6,2)=-0.00247
      THROTT(8,6,2)=39.58643
      AILERO(8,6,2)=-0.00284
C
C     MACH=1.4
      LIFT(8,7,2)=81051.44531
      DRAG(8,7,2)=20431.61133
      BETA(8,7,2)=0.00858
      ALPHA(8,7,2)=5.86934
      PHI(8,7,2)=60.96077
      THETA(8,7,2)=2.86419
      ROLLR(8,7,2)=-0.12125
      PITCHR(8,7,2)=2.11879
      YAWR(8,7,2)=1.17636
      THRUST(8,7,2)=20539.75781
      ELEVAT(8,7,2)=-0.16447
      DTAIL(8,7,2)=-0.00057
      RUDDER(8,7,2)=-0.00211
      THROTT(8,7,2)=42.79116
      AILERO(8,7,2)=-0.00191
C
```

```
C         MACH=1.6
          LIFT(8,8,2)=81062.45313
          DRAG(8,8,2)=22251.68945
          BETA(8,8,2)=0.00487
          ALPHA(8,8,2)=4.82793
          PHI(8,8,2)=60.83395
          THETA(8,8,2)=2.36137
          ROLLR(8,8,2)=-0.08717
          PITCHR(8,8,2)=1.84594
          YAWR(8,8,2)=1.03023
          THRUST(8,8,2)=22330.33594
          ELEVAT(8,8,2)=-0.09768
          DTAIL(8,8,2)=-0.00045
          RUDDER(8,8,2)=-0.00199
          THROTT(8,8,2)=46.52153
          AILERO(8,8,2)=-0.00149
C
C         MACH=1.8
          LIFT(8,9,2)=81050.97656
          DRAG(8,9,2)=24089.63086
          BETA(8,9,2)=0.00361
          ALPHA(8,9,2)=3.70487
          PHI(8,9,2)=60.67407
          THETA(8,9,2)=1.81964
          ROLLR(8,9,2)=-0.05942
          PITCHR(8,9,2)=1.63054
          YAWR(8,9,2)=0.91599
          THRUST(8,9,2)=24140.02930
          ELEVAT(8,9,2)=-0.05695
          DTAIL(8,9,2)=-0.00030
          RUDDER(8,9,2)=-0.00143
          THROTT(8,9,2)=50.29173
          AILERO(8,9,2)=-0.00101
C
C         MACH=2.0
          LIFT(8,10,2)=81048.16406
          DRAG(8,10,2)=28837.06055
          BETA(8,10,2)=0.00303
          ALPHA(8,10,2)=2.94627
          PHI(8,10,2)=60.62562
          THETA(8,10,2)=1.44880
          ROLLR(8,10,2)=-0.04253
          PITCHR(8,10,2)=1.46529
          YAWR(8,10,2)=0.82478
          THRUST(8,10,2)=28874.82813
          ELEVAT(8,10,2)=-0.03199
          DTAIL(8,10,2)=-0.00021
          RUDDER(8,10,2)=-0.00114
          THROTT(8,10,2)=60.15589
          AILERO(8,10,2)=-0.00071
C         ------------------------------------------------
C         ALTITUDE=50000
C
C         MACH=1.0
          LIFT(9,5,2)=81011.07813
          DRAG(9,5,2)=18314.33203
          BETA(9,5,2)=0.03350
          ALPHA(9,5,2)=11.89992
          PHI(9,5,2)=62.01752
          THETA(9,5,2)=5.67674
          ROLLR(9,5,2)=-0.34516
          PITCHR(9,5,2)=3.06640
          YAWR(9,5,2)=1.62923
          THRUST(9,5,2)=18716.57227
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          DTAIL(9,5,2)=-0.00097
          RUDDER(9,5,2)=-0.00406
          THROTT(9,5,2)=38.99286
          AILERO(9,5,2)=-0.00324
C
C         MACH=1.2
          LIFT(9,6,2)=81011.61719
          DRAG(9,6,2)=20272.80664
          BETA(9,6,2)=0.01747
          ALPHA(9,6,2)=9.28838
          PHI(9,6,2)=61.61195
          THETA(9,6,2)=4.46170
          ROLLR(9,6,2)=-0.22433
          PITCHR(9,6,2)=2.52927
          YAWR(9,6,2)=1.36689
          THRUST(9,6,2)=20542.12695
          ELEVAT(9,6,2)=-0.32499
          DTAIL(9,6,2)=-0.00101
          RUDDER(9,6,2)=-0.00284
          THROTT(9,6,2)=42.79610
          AILERO(9,6,2)=-0.00338
C
C         MACH=1.4
          LIFT(9,7,2)=80998.95313
          DRAG(9,7,2)=19329.42383
          BETA(9,7,2)=0.00972
          ALPHA(9,7,2)=7.52520
          PHI(9,7,2)=61.21634
          THETA(9,7,2)=3.64804
          ROLLR(9,7,2)=-0.15542
          PITCHR(9,7,2)=2.13654
          YAWR(9,7,2)=1.17378
          THRUST(9,7,2)=19496.93945
          ELEVAT(9,7,2)=-0.23057
          DTAIL(9,7,2)=-0.00072
          RUDDER(9,7,2)=-0.00230
          THROTT(9,7,2)=40.61862
          AILERO(9,7,2)=-0.00239
C
C         MACH=1.6
          LIFT(9,8,2)=81013.95313
          DRAG(9,8,2)=21250.80469
          BETA(9,8,2)=0.00514
          ALPHA(9,8,2)=6.29808
          PHI(9,8,2)=61.07397
          THETA(9,8,2)=3.06030
          ROLLR(9,8,2)=-0.11373
          PITCHR(9,8,2)=1.86196
          YAWR(9,8,2)=1.02896
          THRUST(9,8,2)=21379.83008
          ELEVAT(9,8,2)=-0.15187
          DTAIL(9,8,2)=-0.00052
          RUDDER(9,8,2)=-0.00213
          THROTT(9,8,2)=44.54131
          AILERO(9,8,2)=-0.00175
C
C         MACH=1.8
          LIFT(9,9,2)=81025.51563
          DRAG(9,9,2)=22141.71875
          BETA(9,9,2)=0.00384
          ALPHA(9,9,2)=4.84486
          PHI(9,9,2)=60.83381
          THETA(9,9,2)=2.36878
          ROLLR(9,9,2)=-0.07769
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```
PITCHR(9,9,2)=1.64000
YAWR(9,9,2)=0.91530
THRUST(9,9,2)=22221.16406
ELEVAT(9,9,2)=-0.09777
DTAIL(9,9,2)=-0.00035
RUDDER(9,9,2)=-0.00157
THROTT(9,9,2)=46.29409
AILERO(9,9,2)=-0.00118
C
C
MACH=2.0
LIFT(9,10,2)=81011.79688
DRAG(9,10,2)=23407.07813
BETA(9,10,2)=0.00291
ALPHA(9,10,2)=3.81792
PHI(9,10,2)=60.67836
THETA(9,10,2)=1.87433
ROLLR(9,10,2)=-0.05506
PITCHR(9,10,2)=1.46687
YAWR(9,10,2)=0.82390
THRUST(9,10,2)=23459.06055
ELEVAT(9,10,2)=-0.06024
DTAIL(9,10,2)=-0.00025
RUDDER(9,10,2)=-0.00116
THROTT(9,10,2)=48.87304
AILERO(9,10,2)=-0.00083
C
C ================================================
C
C LOAD FACTOR=4.0
C
C -------------------------------------------------
C
C ALTITUDE=10000
C
MACH=0.6
LIFT(1,3,3)=162637.68750
DRAG(1,3,3)=28627.04688
BETA(1,3,3)=0.10448
ALPHA(1,3,3)=11.76942
PHI(1,3,3)=76.34757
THETA(1,3,3)=2.91887
ROLLR(1,3,3)=-0.58383
PITCHR(1,3,3)=11.12673
YAWR(1,3,3)=2.70262
THRUST(1,3,3)=29241.77734
ELEVAT(1,3,3)=-0.13818
DTAIL(1,3,3)=-0.00264
RUDDER(1,3,3)=-0.00857
THROTT(1,3,3)=60.92037
AILERO(1,3,3)=-0.00882
C
C
MACH=0.8
LIFT(1,4,3)=162646.50000
DRAG(1,4,3)=15118.63184
BETA(1,4,3)=0.04100
ALPHA(1,4,3)=5.84141
PHI(1,4,3)=75.73713
THETA(1,4,3)=1.48378
ROLLR(1,4,3)=-0.21646
PITCHR(1,4,3)=8.09903
YAWR(1,4,3)=2.05883
THRUST(1,4,3)=15197.54199
ELEVAT(1,4,3)=-0.04840
DTAIL(1,4,3)=-0.00053
RUDDER(1,4,3)=-0.00400
THROTT(1,4,3)=31.66155
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```
AILERO(1,4,3)=-0.00178
C
C
MACH=1
LIFT(1,5,3)=162640.18750
DRAG(1,5,3)=27455.81641
BETA(1,5,3)=0.01957
ALPHA(1,5,3)=3.65306
PHI(1,5,3)=75.70924
THETA(1,5,3)=0.92187
ROLLR(1,5,3)=-0.10774
PITCHR(1,5,3)=6.48842
YAWR(1,5,3)=1.65276
THRUST(1,5,3)=27511.68164
ELEVAT(1,5,3)=-0.06981
DTAIL(1,5,3)=-0.00035
RUDDER(1,5,3)=-0.00249
THROTT(1,5,3)=57.31601
AILERO(1,5,3)=-0.00117
C
C
MACH=1.2
LIFT(1,6,3)=162646.06250
DRAG(1,6,3)=47224.27344
BETA(1,6,3)=0.00972
ALPHA(1,6,3)=3.12740
PHI(1,6,3)=75.77425
THETA(1,6,3)=0.77869
ROLLR(1,6,3)=-0.07625
PITCHR(1,6,3)=5.43777
YAWR(1,6,3)=1.37857
THRUST(1,6,3)=47294.63672
ELEVAT(1,6,3)=-0.07614
DTAIL(1,6,3)=-0.00032
RUDDER(1,6,3)=-0.00190
THROTT(1,6,3)=98.53049
AILERO(1,6,3)=-0.00107
C -------------------------------------------------
C ALTITUDE=15000
C
C
MACH=0.6
LIFT(2,3,3)=162566.85938
DRAG(2,3,3)=37908.89063
BETA(2,3,3)=0.12299
ALPHA(2,3,3)=15.11119
PHI(2,3,3)=76.88128
THETA(2,3,3)=3.63078
ROLLR(2,3,3)=-0.75936
PITCHR(2,3,3)=11.65481
YAWR(2,3,3)=2.71617
THRUST(2,3,3)=39266.66406
ELEVAT(2,3,3)=-0.17338
DTAIL(2,3,3)=-0.00389
RUDDER(2,3,3)=-0.00962
THROTT(2,3,3)=81.80555
AILERO(2,3,3)=-0.01296
C
C
MACH=0.8
LIFT(2,4,3)=162567.48438
DRAG(2,4,3)=17767.24023
BETA(2,4,3)=0.04479
ALPHA(2,4,3)=7.07972
PHI(2,4,3)=75.83018
THETA(2,4,3)=1.78516
ROLLR(2,4,3)=-0.26636
PITCHR(2,4,3)=8.28621
```

```
      YAWR(2,4,3)=2.09209
      THRUST(2,4,3)=17903.72070
      ELEVAT(2,4,3)=-0.05968
      DTAIL(2,4,3)=-0.00060
      RUDDER(2,4,3)=-0.00432
      THROTT(2,4,3)=37.29942
      AILERO(2,4,3)=-0.00201
C
C     MACH=1.0
      LIFT(2,5,3)=162583.42188
      DRAG(2,5,3)=25803.77148
      BETA(2,5,3)=0.02083
      ALPHA(2,5,3)=4.42098
      PHI(2,5,3)=75.74406
      THETA(2,5,3)=1.11096
      ROLLR(2,5,3)=-0.13244
      PITCHR(2,5,3)=6.61934
      YAWR(2,5,3)=1.68183
      THRUST(2,5,3)=25879.77734
      ELEVAT(2,5,3)=-0.08744
      DTAIL(2,5,3)=-0.00040
      RUDDER(2,5,3)=-0.00264
      THROTT(2,5,3)=53.91620
      AILERO(2,5,3)=-0.00134
C
C     MACH=1.2
      LIFT(2,6,3)=162565.84375
      DRAG(2,6,3)=42154.65625
      BETA(2,6,3)=0.01045
      ALPHA(2,6,3)=3.80848
      PHI(2,6,3)=75.80418
      THETA(2,6,3)=0.94543
      ROLLR(2,6,3)=-0.09442
      PITCHR(2,6,3)=5.54684
      YAWR(2,6,3)=1.40314
      THRUST(2,6,3)=42247.54297
      ELEVAT(2,6,3)=-0.10646
      DTAIL(2,6,3)=-0.00039
      RUDDER(2,6,3)=-0.00198
      THROTT(2,6,3)=88.01571
      AILERO(2,6,3)=-0.00129
C     -------------------------------------------------------------
C     ALTITUDE=20000
C
C     MACH=0.8
      LIFT(3,4,3)=162532.15625
      DRAG(3,4,3)=21283.40039
      BETA(3,4,3)=0.05311
      ALPHA(3,4,3)=8.88117
      PHI(3,4,3)=75.99001
      THETA(3,4,3)=2.21849
      ROLLR(3,4,3)=-0.33979
      PITCHR(3,4,3)=8.51030
      YAWR(3,4,3)=2.12343
      THRUST(3,4,3)=21542.14063
      ELEVAT(3,4,3)=-0.07606
      DTAIL(3,4,3)=-0.00076
      RUDDER(3,4,3)=-0.00509
      THROTT(3,4,3)=44.87946
      AILERO(3,4,3)=-0.00254
C
C     MACH=1.0
      LIFT(3,5,3)=162492.79688
      DRAG(3,5,3)=24331.69727
```



```
      BETA(3,5,3)=0.02259
      ALFHA(3,5,3)=5.41493
      PHI(3,5,3)=75.79254
      THETA(3,5,3)=1.35472
      ROLLR(3,5,3)=-0.16493
      PITCHR(3,5,3)=6.76102
      YAWR(3,5,3)=1.71174
      THRUST(3,5,3)=24440.76367
      ELEVAT(3,5,3)=-0.11539
      DTAIL(3,5,3)=-0.00048
      RUDDER(3,5,3)=-0.00283
      THROTT(3,5,3)=50.91826
      AILERO(3,5,3)=-0.00161
C     -----------------------------------------
C     ALTITUDE=25000
C
C     MACH=0.8
      LIFT(4,4,3)=162410.68750
      DRAG(4,4,3)=30147.55078
      BETA(4,4,3)=0.06214
      ALPHA(4,4,3)=11.54214
      PHI(4,4,3)=76.34508
      THETA(4,4,3)=2.82161
      ROLLR(4,4,3)=-0.44875
      PITCHR(4,4,3)=8.84764
      YAWR(4,4,3)=2.14945
      THRUST(4,4,3)=30769.78320
      ELEVAT(4,4,3)=-0.10122
      DTAIL(4,4,3)=-0.00132
      RUDDER(4,4,3)=-0.00590
      THROTT(4,4,3)=64.10371
      AILERO(4,4,3)=-0.00440
C
C     MACH=1.0
      LIFT(4,5,3)=162413.93750
      DRAG(4,5,3)=27084.75781
      BETA(4,5,3)=0.02477
      ALPHA(4,5,3)=6.68738
      PHI(4,5,3)=75.90145
      THETA(4,5,3)=1.66015
      ROLLR(4,5,3)=-0.20731
      PITCHR(4,5,3)=6.93739
      YAWR(4,5,3)=1.74237
      THRUST(4,5,3)=27270.30469
      ELEVAT(4,5,3)=-0.14957
      DTAIL(4,5,3)=-0.00059
      RUDDER(4,5,3)=-0.00306
      THROTT(4,5,3)=56.81313
      AILERO(4,5,3)=-0.00196
C
C     MACH=1.2
      LIFT(4,6,3)=162394.62500
      DRAG(4,6,3)=39205.00391
      BETA(4,6,3)=0.01320
      ALPHA(4,6,3)=5.92501
      PHI(4,6,3)=75.95746
      THETA(4,6,3)=1.45537
      ROLLR(4,6,3)=-0.15232
      PITCHR(4,6,3)=5.81632
      YAWR(4,6,3)=1.45476
      THRUST(4,6,3)=39415.80859
      ELEVAT(4,6,3)=-0.19933
      DTAIL(4,6,3)=-0.00065
      RUDDER(4,6,3)=-0.00233
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```
      THROTT(4,6,3)=82.11627
      AILERO(4,6,3)=-0.00217
C
C     MACH=1.4
      LIFT(4,7,3)=162410.04688
      DRAG(4,7,3)=41133.01172
      BETA(4,7,3)=0.00789
      ALPHA(4,7,3)=4.58291
      PHI(4,7,3)=75.86076
      THETA(4,7,3)=1.12943
      ROLLR(4,7,3)=-0.10083
      PITCHR(4,7,3)=4.95938
      YAWR(4,7,3)=1.24932
      THRUST(4,7,3)=41264.51563
      ELEVAT(4,7,3)=-0.10593
      DTAIL(4,7,3)=-0.00047
      RUDDER(4,7,3)=-0.00201
      THROTT(4,7,3)=85.96774
      AILERO(4,7,3)=-0.00156
C     ----------------------------------------
C     ALTITUDE=30000
C
C     MACH=1.0
      LIFT(5,5,3)=162333.00000
      DRAG(5,5,3)=29875.87305
      BETA(5,5,3)=0.02956
      ALPHA(5,5,3)=8.49303
      PHI(5,5,3)=76.07033
      THETA(5,5,3)=2.08773
      ROLLR(5,5,3)=-0.26833
      PITCHR(5,5,3)=7.14424
      YAWR(5,5,3)=1.77195
      THRUST(5,5,3)=30206.55469
      ELEVAT(5,5,3)=-0.19283
      DTAIL(5,5,3)=-0.00072
      RUDDER(5,5,3)=-0.00364
      THROTT(5,5,3)=62.93032
      AILERO(5,5,3)=-0.00241
C
C     MACH=1.2
      LIFT(5,6,3)=162331.64063
      DRAG(5,6,3)=38183.48438
      BETA(5,6,3)=0.01547
      ALPHA(5,6,3)=7.39328
      PHI(5,6,3)=76.07425
      THETA(5,6,3)=1.80379
      ROLLR(5,6,3)=-0.19381
      PITCHR(5,6,3)=5.97335
      YAWR(5,6,3)=1.48110
      THRUST(5,6,3)=38503.61328
      ELEVAT(5,6,3)=-0.26033
      DTAIL(5,6,3)=-0.00088
      RUDDER(5,6,3)=-0.00258
      THROTT(5,6,3)=80.21586
      AILERO(5,6,3)=-0.00294
C     ------------------------------------------------
C     ALTITUDE=35000
C
C     MACH=1.0
      LIFT(6,5,3)=162252.50000
      DRAG(6,5,3)=36575.35938
      BETA(6,5,3)=0.03595
      ALPHA(6,5,3)=11.64956
      PHI(6,5,3)=76.45950
      THETA(6,5,3)=2.79922
      ROLLR(6,5,3)=-0.37485
      PITCHR(6,5,3)=7.45342
      YAWR(6,5,3)=1.79498
      THRUST(6,5,3)=37344.71484
      ELEVAT(6,5,3)=-0.26145
      DTAIL(6,5,3)=-0.00104
      RUDDER(6,5,3)=-0.00436
      THROTT(6,5,3)=77.80149
      AILERO(6,5,3)=-0.00345
C
C     MACH=1.2
      LIFT(6,6,3)=162255.09375
      DRAG(6,6,3)=39361.97656
      BETA(6,6,3)=0.01884
      ALPHA(6,6,3)=9.15001
      PHI(6,6,3)=76.25133
      THETA(6,6,3)=2.21074
      ROLLR(6,6,3)=-0.24489
      PITCHR(6,6,3)=6.16192
      YAWR(6,6,3)=1.50766
      THRUST(6,6,3)=39868.64453
      ELEVAT(6,6,3)=-0.32308
      DTAIL(6,6,3)=-0.00109
      RUDDER(6,6,3)=-0.00306
      THROTT(6,6,3)=83.05968
      AILERO(6,6,3)=-0.00364
C
C     MACH=1.4
      LIFT(6,7,3)=162256.62500
      DRAG(6,7,3)=39437.30469
      BETA(6,7,3)=0.01052
      ALPHA(6,7,3)=7.40734
      PHI(6,7,3)=76.08894
      THETA(6,7,3)=1.80054
      ROLLR(6,7,3)=-0.16967
      PITCHR(6,7,3)=5.23897
      YAWR(6,7,3)=1.29759
      THRUST(6,7,3)=39768.84766
      ELEVAT(6,7,3)=-0.22685
      DTAIL(6,7,3)=-0.00077
      RUDDER(6,7,3)=-0.00250
      THROTT(6,7,3)=82.85177
      AILERO(6,7,3)=-0.00256
C
C     MACH=1.6
      LIFT(6,8,3)=162255.81250
      DRAG(6,8,3)=40620.19922
      BETA(6,8,3)=0.00560
      ALPHA(6,8,3)=6.18902
      PHI(6,8,3)=75.99258
      THETA(6,8,3)=1.50901
      ROLLR(6,8,3)=-0.12386
      PITCHR(6,8,3)=4.56184
      YAWR(6,8,3)=1.13802
      THRUST(6,8,3)=40858.48438
      ELEVAT(6,8,3)=-0.14759
      DTAIL(6,8,3)=-0.00056
      RUDDER(6,8,3)=-0.00233
      THROTT(6,8,3)=85.12185
      AILERO(6,8,3)=-0.00188
C
C     MACH=1.8
      LIFT(6,9,3)=161889.98438
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```
      DRAG(6,9,3)=41801.17969
      BETA(6,9,3)=0.00421
      ALPHA(6,9,3)=4.75071
      PHI(6,9,3)=75.87917
      THETA(6,9,3)=1.16562
      ROLLR(6,9,3)=-0.08454
      PITCHR(6,9,3)=4.02938
      YAWR(6,9,3)=1.01367
      THRUST(6,9,3)=41908.77734
      ELEVAT(6,9,3)=-0.09337
      DTAIL(6,9,3)=-0.00038
      RUDDER(6,9,3)=-0.00172
      THROTT(6,9,3)=87.30996
      AILERO(6,9,3)=-0.00127
C     ---------------------------------------------------
C     ALTITUDE=40000
C
C     MACH=1.2
      LIFT(7,6,3)=162178.01563
      DRAG(7,6,3)=44539.42578
      BETA(7,6,3)=0.02214
      ALPHA(7,6,3)=11.54755
      PHI(7,6,3)=76.57835
      THETA(7,6,3)=2.73715
      ROLLR(7,6,3)=-0.30984
      PITCHR(7,6,3)=6.30381
      YAWR(7,6,3)=1.50430
      THRUST(7,6,3)=45459.64453
      ELEVAT(7,6,3)=-0.38773
      DTAIL(7,6,3)=-0.00124
      RUDDER(7,6,3)=-0.00357
      THROTT(7,6,3)=94.70759
      AILERO(7,6,3)=-0.00412
C
C     MACH=1.4
      LIFT(7,7,3)=162179.32813
      DRAG(7,7,3)=42382.75391
      BETA(7,7,3)=0.01254
      ALPHA(7,7,3)=9.68663
      PHI(7,7,3)=76.34529
      THETA(7,7,3)=2.31986
      ROLLR(7,7,3)=-0.22251
      PITCHR(7,7,3)=5.33738
      YAWR(7,7,3)=1.29664
      THRUST(7,7,3)=42995.42969
      ELEVAT(7,7,3)=-0.31858
      DTAIL(7,7,3)=-0.00092
      RUDDER(7,7,3)=-0.00301
      THROTT(7,7,3)=89.57381
      AILERO(7,7,3)=-0.00306
C
C     MACH=1.6
      LIFT(7,8,3)=162179.10938
      DRAG(7,8,3)=39487.53516
      BETA(7,8,3)=0.00633
      ALPHA(7,8,3)=8.01523
      PHI(7,8,3)=76.14453
      THETA(7,8,3)=1.93753
      ROLLR(7,8,3)=-0.16092
      PITCHR(7,8,3)=4.61842
      YAWR(7,8,3)=1.13914
      THRUST(7,8,3)=39877.09766
      ELEVAT(7,8,3)=-0.21663
      DTAIL(7,8,3)=-0.00066
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```
      RUDDER(7,8,3)=-0.00270
      THROTT(7,8,3)=83.07729
      AILERO(7,8,3)=-0.00222
C
C     MACH=1.8
      LIFT(7,9,3)=162177.53125
      DRAG(7,9,3)=40454.16016
      BETA(7,9,3)=0.00447
      ALPHA(7,9,3)=6.19740
      PHI(7,9,3)=75.99183
      THETA(7,9,3)=1.51004
      ROLLR(7,9,3)=-0.11066
      PITCHR(7,9,3)=4.07314
      YAWR(7,9,3)=1.01616
      THRUST(7,9,3)=40691.96875
      ELEVAT(7,9,3)=-0.14666
      DTAIL(7,9,3)=-0.00045
      RUDDER(7,9,3)=-0.00186
      THROTT(7,9,3)=84.77493
      AILERO(7,9,3)=-0.00150
C
C     MACH=2.0
      LIFT(7,10,3)=162178.53125
      DRAG(7,10,3)=41534.83984
      BETA(7,10,3)=0.00346
      ALPHA(7,10,3)=4.90456
      PHI(7,10,3)=75.89043
      THETA(7,10,3)=1.20174
      ROLLR(7,10,3)=-0.07885
      PITCHR(7,10,3)=3.64528
      YAWR(7,10,4)=0.91628
      THRUST(7,10,4)=41687.55859
      ELEVAT(7,10,4)=-0.09810
      DTAIL(7,10,4)=-0.00032
      RUDDER(7,10,4)=-0.00142
      THROTT(7,10,4)=86.84908
      AILERO(7,10,4)=-0.00106
C     ---------------------------------------------
C
C     MACH=1.8
      LIFT(8,9,3)=162214.70313
      DRAG(8,9,3)=39377.40234
      BETA(8,9,3)=0.00512
      ALPHA(8,9,3)=8.03954
      PHI(8,9,3)=76.14635
      THETA(8,9,3)=1.94202
      ROLLR(8,9,3)=-0 14332
      PITCHR(8,9,3)=4.10369
      YAWR(8,9,3)=1.01204
      THRUST(8,9,3)=39840.25391
      ELEVAT(8,9,3)=-0.21633
      DTAIL(8,9,3)=-0.00053
      RUDDER(8,9,3)=-0.00214
      THROTT(8,9,3)=83.00053
      AILERO(8,9,3)=-0.00175
C
C     MACH=2.0
      LIFT(8,10,3)=162104.34375
      DRAG(8,10,3)=40179.00000
      BETA(8,10,3)=0.00364
      ALPHA(8,10,3)=6.38152
      PHI(8,10,3)=76.00535
      THETA(8,10,3)=1.55284
      ROLLR(8,10,3)=-0.10244
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```
      PITCHR(8,10,3)=3.66663
      YAWR(8,10,3)=0.91383
      THRUST(8,10,3)=40429.54297
      ELEVAT(8,10,3)=-0.15258
      DTAIL(8,10,3)=-0.00037
      RUDDER(8,10,3)=-0.00152
      THROTT(8,10,3)=84.22822
      AILERO(8,10,3)=-0.00124
C     ------------------------------------------------------------
C     ALTITUDE=50000
C
C     MACH=1.8
      LIFT(9,9,3)=162025.79688
      DRAG(9,9,3)=45569.39453
      BETA(9,9,3)=0.00601
      ALPHA(9,9,3)=10.78515
      PHI(9,9,3)=76.50813
      THETA(9,9,3)=2.55066
      ROLLR(9,9,3)=-0.19182
      PITCHR(9,9,3)=4.18727
      YAWR(9,9,3)=1.00465
      THRUST(9,9,3)=46389.91016
      ELEVAT(9,9,3)=-0.33956
      DTAIL(9,9,3)=-0.00069
      RUDDER(9,9,3)=-0.00255
      THROTT(9,9,3)=96.64565
      AILERO(9,9,3)=-0.00229
C
C     MACH=2.0
      LIFT(9,10,3)=163487.95313
      DRAG(9,10,3)=39456.94531
      BETA(9,10,3)=0.00408
      ALPHA(9,10,3)=8.40564
      PHI(9,10,3)=76.18526
      THETA(9,10,3)=2.02481
      ROLLR(9,10,3)=-0.13469
      PITCHR(9,10,3)=3.69943
      YAWR(9,10,3)=0.90968
      THRUST(9,10,3)=39840.79688
      ELEVAT(9,10,3)=-0.232086
      DTAIL(9,10,3)=-0.00043
      RUDDER(9,10,3)=-0.00178
      THROTT(9,10,3)=83.00166
      AILERO(9,10,3)=-0.00145
C     -------------------------------------------
100   CONTINUE
C
C     LINEAR INTERPOLATION
C
C     QUANTITIES TO BE INTERPOLATED
C
C     BETA,LIFT,THRUST,DRAG,PHI,THETA,P,Q,R,THROTTLE
C     ELEVATOR,AILERON,RUDDER AND DIFFERENTIAL TAIL
C
C     SEARCH FOR THE LOCATION OF THE GIVEN MACH-ALTITUDE
C     LOAD FACTOR POINT IN THE GIVEN 3-D TABLE
C
C     LOCATE ALTITUDE-MACH INDICES FIRST
C     I-ALTITUDE,J-MACH NO,K-LOAD FACTOR
C
      I=LASTI
10    IF(H.GT.ALT(I+1))I=I+1
      IF(I.GT.IMAX)GO TO 10000
      IF(H.GT.ALT(I+1))GO TO 10
20    IF(H.LT.ALT(I))I=I-1
      IF(I.LT.1)GO TO 10000
      IF(H.LT.ALT(I))GO TO 20
      LASTI=I
C
      J=LASTJ
30    IF(XM.GT.XMACH(J+1))J=J+1
      IF(J.GT.JMAX)GO TO 10000
      IF(XM.GT.XMACH(J+1))GO TO 30
40    IF(XM.LT.XMACH(J))J=J-1
      IF(J.LT.1)GO TO 10000
      IF(XM.LT.XMACH(J))GO TO 40
      LASTJ=J
C
      IPO=I+1
      JPO=J+1
      IOPT=1
      IALP=1
C
C     LOCATE LOAD FACTOR INDEX GIVEN EITHER THE
C     LOAD FACTOR OR THE ANGLE OF ATTACK
C
C     IF XLFAC<0; TURNING FLIGHT WITH ALFA GIVEN
C     IF XLFAC>1; TURNING FLIGHT WITH LOAD FACTOR GIVEN
C     IF XLFAC=1; STRAIGHT AND LEVEL TRIMS
C
      IF(XLFAC.LT.0.0.OR.XLFAC.GT.1.D0)GO TO 50
      K=1
C     SYMMETRIC FLIGHT, DO NOT INTERPOLATE ALONG THE
C     LOAD FACTOR DIRECTION
      IOPT=0
      XLFAC=1.D0
      GO TO 60
50    IF(XLFAC.GT.1.D0)GO TO 70
C     ALFA IN TURNING FLIGHT IS GIVEN
C
      IALP=0
C     DETERMINE THE REFERENCE VALUES OF ANGLE OF ATTACK
C     AT THE GIVEN h,M FOR ALL THE REFERENCE LOAD FACTORS
C     AND STORE IN THE 1-D ARRAY ALTEMP.
C
      DO 800 KT=1,KMAX
800   CALL LINT3D(H,XM,XN(KT),ALT(I),ALT(IPO),XMACH(J),
     1 XMACH(JPO),XN(KT),XN(KT),
     2 ALPHA(I,J,KT),    ALPHA(IPO,J,KT), ALPHA(I,JPO,KT),
     3 ALPHA(IPO,JPO,KT), ALPHA(I,J,KT), ALPHA(IPO,J,KT),
     4 ALPHA(I,JPO,KT),ALPHA(IPO,JPO,KT), ALTEMP(KT),IOPT)
      K=LASTK
80    IF(ALP.GT.ALTEMP(K+1))K=K+1
      IF(K.GT.KMAX)GO TO 10000
      IF(ALP.GT.ALTEMP(K+1))GO TO 80
90    IF(ALP.LT.ALTEMP(K))K=K-1
      IF(K.LT.1)GO TO 10000
      IF(ALP.LT.ALTEMP(K))GO TO 90
C
C     COMPUTE THE LOAD FACTOR CORRESPONDING TO THE
C     GIVEN ANGLE OF ATTACK
C
      DXL=(XN(K+1)-XN(K))/(ALTEMP(K+1)-ALTEMP(K))
      XLFAC=XN(K)+DXL*(ALP-ALTEMP(K))
      LASTK=K
      GO TO 60
C     LOAD FACTOR IN TURNING FLIGHT IS GIVEN
70    K=LASTK
```

```
140    IF(XLFAC.GT.XN(K+1))K=K+1
       IF(K.GT.KMAX)GO TO 10000
       IF(XLFAC.GT.XN(K+1))GO TO 140
110    IF(XLFAC.LT.XN(K))K=K-1
       IF(K.LT.1)GO TO 10000
       IF(XLFAC.LT.XN(K))GO TO 110
       LASTK=K
60     CONTINUE
C
       KPO=K+1
       XDAT(1)=ALT(I)
       XDAT(2)=ALT(IPO)
       YDAT(1)=XMACH(J)
       YDAT(2)=XMACH(JPO)
       ZDAT(1)=XN(K)
       ZDAT(2)=XN(KPO)
C      INTERPOLATE ANGLE OF ATTACK IF THE LOAD FACTOR IS
C      GIVEN
       IF(IALP.EQ.0)GO TO 120
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 ALPHA(I,J,K),      ALPHA(IPO,J,K),  ALPHA(I,JPO,K),
     3 ALPHA(IPO,JPO,K),  ALPHA(I,J,KPO),  ALPHA(IPO,J,KPO),
     4 ALPHA(I,JPO,KPO),ALPHA(IPO,JPO,KPO),  ALP,IOPT)
120    CONTINUE
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 LIFT(I,J,K),      LIFT(IPO,J,K),  LIFT(I,JPO,K),
     3 LIFT(IPO,JPO,K),  LIFT(I,J,KPO),  LIFT(IPO,J,KPO),
     4 LIFT(I,JPO,KPO),LIFT(IPO,JPO,KPO),XLIFT,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 THRUST(I,J,K),    THRUST(IPO,J,K),THRUST(I,JPO,K),
     3 THRUST(IPO,JPO,K),THRUST(I,J,KPO),THRUST(IPO,J,KPO),
     4 THRUST(I,JPO,KPO),THRUST(IPO,JPO,KPO),THRST,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 DRAG(I,J,K),      DRAG(IPO,J,K),  DRAG(I,JPO,K),
     3 DRAG(IPO,JPO,K),  DRAG(I,J,KPO),  DRAG(IPO,J,KPO),
     4 DRAG(I,JPO,KPO),DRAG(IPO,JPO,KPO),  DRG,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 PHI(I,J,K),       PHI(IPO,J,K),  PHI(I,JPO,K),
     3 PHI(IPO,JPO,K),  PHI(I,J,KPO),  PHI(IPO,J,KPO),
     4 PHI(I,JPO,KPO),PHI(IPO,JPO,KPO),  PHIO,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 THETA(I,J,K),      THETA(IPO,J,K),  THETA(I,JPO,K),
     3 THETA(IPO,JPO,K),  THETA(I,J,KPO),  THETA(IPO,J,KPO),
     4 THETA(I,JPO,KPO),THETA(IPO,JPO,KPO),THETAO,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 ROLLR(I,J,K),      ROLLR(IPO,J,K),  ROLLR(I,JPO,K),
     3 ROLLR(IPO,JPO,K),  ROLLR(I,J,KPO),  ROLLR(IPO,J,KPO),
     4 ROLLR(I,JPO,KPO),ROLLR(IPO,JPO,KPO),  P,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 PITCHR(I,J,K),  PITCHR(IPO,J,K),  PITCHR(I,JPO,K),
     3 PITCHR(IPO,JPO,K),  PITCHR(I,J,KPO),PITCHR(IPO,J,KPO),
     4 PITCHR(I,JPO,KPO),PITCHR(IPO,JPO,KPO),  Q  ,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 YAWR(I,J,K),       YAWR(IPO,J,K),  YAWR(I,JPO,K),
     3 YAWR(IPO,JPO,K),  YAWR(I,J,KPO),  YAWR(IPO,J,KPO),
     4 YAWR(I,JPO,KPO),YAWR(IPO,JPO,KPO),  R  ,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 THROTT(I,J,K),   THROTT(IPO,J,K),THROTT(I,JPO,K),
     3 THROTT(IPO,JPO,K),THROTT(I,J,KPO),THROTT(IPO,J,KPO),
     4 THROTT(I,JPO,KPO),THROTT(IPO,JPO,KPO),THRO,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 ELEVAT(I,J,K),  ELEVAT(IPO,J,K),ELEVAT(I,JPO,K),
     3 ELEVAT(IPO,JPO,K),ELEVAT(I,J,KPO),ELEVAT(IPO,J,KPO),
     4 ELEVAT(I,JPO,KPO),ELEVAT(IPO,JPO,KPO),ELV,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 AILERO(I,J,K),  AILERO(IPO,J,K),AILERO(I,JPO,K),
     3 AILERO(IPO,JPO,K),AILERO(I,J,KPO),AILERO(IPO,J,KPO),
     4 AILERO(I,JPO,KPO),AILERO(IPO,JPO,KPO),AIL,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 RUDDER(I,J,K),  RUDDER(IPO,J,K),RUDDER(I,JPO,K),
     3 RUDDER(IPO,JPO,K),RUDDER(I,J,KPO),RUDDER(IPO,J,KPO),
     4 RUDDER(I,JPO,KPO),RUDDER(IPO,JPO,KPO),RUD,IOPT)
C
       CALL LINT3D(H,XM,XLFAC,XDAT(1),XDAT(2),YDAT(1),
     1 YDAT(2),ZDAT(1),ZDAT(2),
     2 DTAIL(I,J,K),      DTAIL(IPO,J,K),  DTAIL(I,JPO,K),
     3 DTAIL(IPO,JPO,K),  DTAIL(I,J,KPO),  DTAIL(IPO,J,KPO),
     4 DTAIL(I,JPO,KPO),DTAIL(IPO,JPO,KPO),  DTL,IOPT)
C
C
C      COORDINATED TURN ASSUMED
C
       BET=0.D0
       IERR=0
       GO TO 20000
C
10000  IERR=1
20000  RETURN
       END
C
C
C
C      3-D LINEAR INTERPOLATION ; IF IOPT=0
C      NO INTERPOLATION ALONG THE Z DIRECTION
C
C      DATA IS ASSUMED TO BE GIVEN AT THE EIGHT
C      CORNERS OF THE CUBE WITHIN WHICH THE ACTUAL
C      POINT IS LOCATED
C
       SUBROUTINE LINT3D(X,Y,Z,XR1,XR2,YR1,YR2,ZR1,ZR2,
     1 A111,A211,A121,A221,A112,A212,A122,A222,AOUT,IOPT)
       IMPLICIT REAL*8(A-H,O-Z)
C
```

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```
C     3-D INTERPOLATION : RIGHT HANDED TRIAD
C                         X-ALTITUDE
C                         Y-MACH NO.
C                         Z-LOAD FACTOR
C
      DX=XR2-XR1
      DY=YR2-YR1
      DZ=ZR2-ZR1
C
      XD=X-XR1
      YD=Y-YR1
      ZD=Z-ZR1
C
C     INTERPOLATE AT THE FIRST LOAD FACTOR
C     ------------------------------------
C     INTERPOLATE ALONG ALTITUDE AT THE FIRST
C     MACH NO.   : A111,A211
C
      V11=A111+((A211-A111)/DX)*XD
C
C     INTERPOLATE ALONG ALTITUDE AT THE SECOND
C     MACH NO.   : A121,A221
C
      V21=A121+((A221-A121)/DX)*XD
C
C     INTERPOLATE ALONG THE MACH DIRECTION
C
      V1=V11+((V21-V11)/DY)*YD
      IF(IOPT.EQ.0)AOUT=V1
      IF(IOPT.EQ.0)GO TO 1000
C
C     INTERPOLATE AT THE SECOND LOAD FACTOR
C     -------------------------------------
C     INTERPOLATE ALONG ALTITUDE AT THE FIRST
C     MACH NO. : A112,A212
C
      V12=A112+((A212-A112)/DX)*XD
C
C     INTERPOLATE ALONG THE ALTITUDE AT THE SECOND
C     MACH NO.   :  A122,A222
C
      V22=A122+((A222-A122)/DX)*XD
C
C     INTERPOLATE ALONG THE MACH DIRECTION
C
      V2=V12+((V22-V12)/DY)*YD
C
C     INTERPOLATE ALONG THE LOAD FACTOR DIRECTION
C     -------------------------------------------
C
      IF(DZ.LE.0.D0)AOUT=V1
      IF(DZ.LE.0.D0)GO TO 1000
      AOUT=V1+((V2-V1)/DZ)*ZD
C
1000  RETURN
      END
C
C
C     ATMOSPHERE MODEL FROM 10000' TO 50000'
C
      SUBROUTINE ATMO(ALTITU,VSOUND,DENSTY,VISCO,DVSDH,DDDH,DVDH)
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION ALT(9),SPEED(9),DENSIT(9),VIS(9)
```



```
      DATA I/1/
C
C     REFERENCE ALTITUDES
      DATA ALT/10000.D0,15000.D0,20000.D0,25000.D0,30000.D0,
     1         35000.D0,40000.D0,45000.D0,50000.D0/
C
C     SPEED OF SOUND
      DATA SPEED/1077.40076,1057.33533,1036.92444,1016.08020,
     1           994.84094,972.93378,968.07001,968.07001,
     2           968.07001/
C
C     AIR DENSITY
      DATA DENSIT/0.00175583,0.00149777,0.00126774,0.00106755,
     1            0.00089129,0.00073921,0.00058837,0.00046347,
     2            0.00036471/
C
C     VISCOSITY
      DATA VIS/1.137,1.104,1.070,1.035,1.000,0.9635,0.9555,
     1         0.9555,0.9555/
C
10    IF(ALTITU.GT.ALT(I+1))I=I+1
      IF(ALTITU.GT.ALT(I+1))GO TO 10
20    IF(ALTITU.LT.ALT(I))I=I-1
      IF(ALTITU.LT.ALT(I))GO TO 20
      K=I+1
      DH=ALT(K)-ALT(I)
      RH=ALTITU-ALT(I)
      DSPEED=(SPEED(K)-SPEED(I))/DH
      VSOUND=SPEED(I)+DSPEED*RH
      DDEN=(DENSIT(K)-DENSIT(I))/DH
      DENSTY=DENSIT(I)+DDEN*RH
      DVIS=(VIS(K)-VIS(I))/DH
      VISCO=VIS(I)+DVIS*RH
      VISCO=VISCO/32.14352D0
C
C     PARTIAL DERIVATIVE OF SONIC SPEED,DENSITY AND
C     VISCOSITY WITH RESPECT TO ALTITUDE
C
      DVSDH=DSPEED
      DDDH=DDEN
      DVDH=DVIS/32.14352D0
C
      RETURN
      END
```

APPENDIX D

LINEAR TIME VARYING SIMULATION IN SYSTEM-BUILD

LINEAR TIME VARYING SIMULATION IN SYSTEM BUILD

Linear time varying simulation can be built around a Fortran block evaluating the matrix equation

$$y = A(t)X + B(t)U \tag{D.1}$$

where $y \in \mathbb{R}^{\ell}$, $X \in \mathbb{R}^{n}$, $U \in \mathbb{R}^{m}$. A and B are time varying matrices of compatible dimensions. To use this Fortran block, the A and B matrix elements must be arranged in the following tabular form and transferred to Matrix_x stack.

$$\text{Table} = \begin{bmatrix} t_o & A_{11} & A_{21} & \cdots & A_{n1} & A_{12} & A_{22} \cdots A_{n2} \cdots & A_{nn} & B_{11} & B_{21} & B_{n1} & \cdots & B_{nm} \\ t_1 & A_{11} & A_{21} & \cdots & A_{n1} & A_{12} & A_{22} \cdots A_{n2} \cdots & A_{nn} & B_{11} & B_{21} & B_{n1} & \cdots & B_{nm} \\ t_2 & A_{11} & A_{21} & \cdots & A_{n1} & A_{12} & A_{22} \cdots A_{n2} \cdots & A_{nn} & B_{11} & B_{21} & B_{n1} & \cdots & B_{nm} \\ \cdot & \cdot & \cdot & & \cdot & \cdot & \cdot \quad \cdot & \cdot & \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot & \cdot & \cdot \quad \cdot & \cdot & \cdot & \cdot & \cdot & & \cdot \end{bmatrix} \tag{D.2}$$

↑

independent
variable

To build in the Fortran block, two distinct steps are necessary. The first one consists of building a dummy superblock with the name TABLE(N), where N could be any number from 0 to 9. The Table D.2 is built as a linear interpolation table block in this superblock, say at relative location M.

Next, the superblock(s) including the time varying Fortran block may be built with the following responses for the queries

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Dimension of RP & IP: 0,2 (no real parameters, two real parameters)

enter IP : N,M (Dummy superblock Table number, relative location)

Note that to complete the time varying simulation, one has to define an independent string of ℓ integrators. A schematic flow chart for building the time varying linear system with this FORTRAN block is given in Figure D.1.

The SYSTEM_BUILD™ block diagram for linear time varying simulation for the aircraft example discussed in this Appendix is given in Figure D.1. The first block in this diagram computes the derivatives of the states using the Fortran block. These are then integrated in block 2. Block 3 essentially routes various inputs and outputs. The reference trajectory is generated in Block 4 while the wind is generated in Block 5. Block 6 implements the time varying gains or gain schedules, again using the Fortran block.

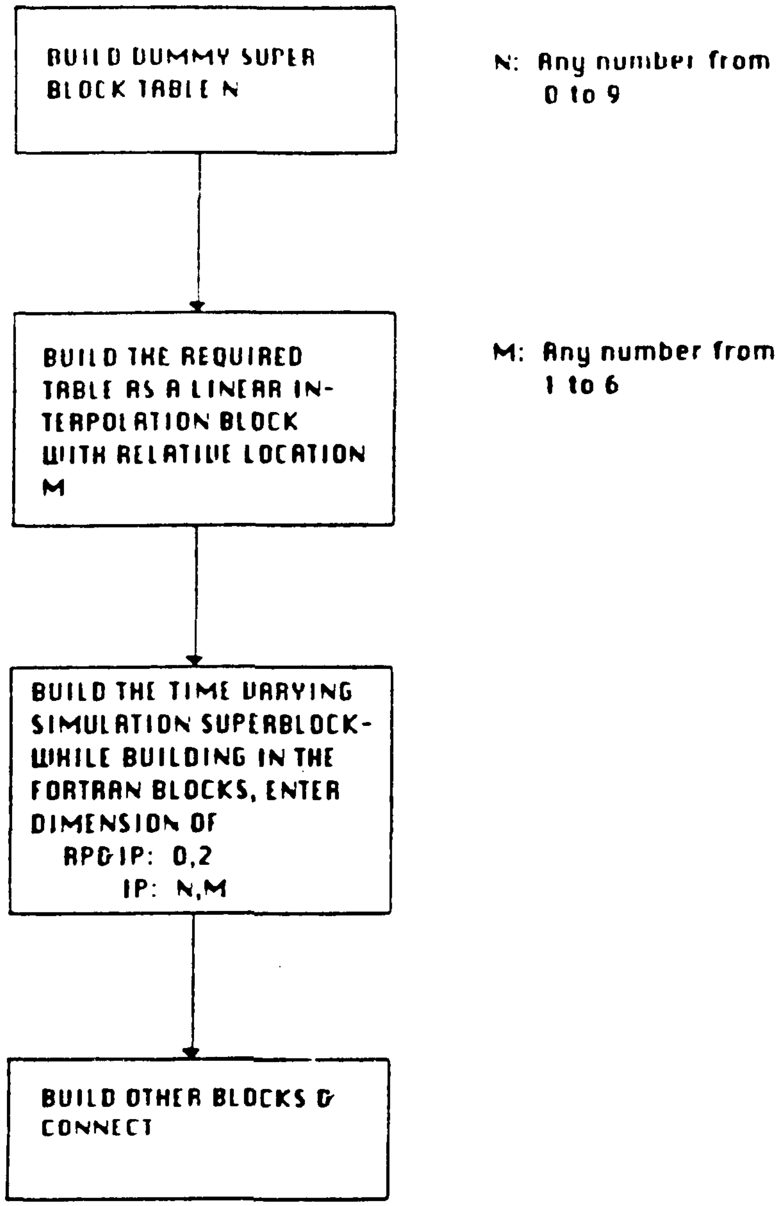

Figure D.1. Flow Chart for Building Linear Time Varying Simulation on SYSTEM-BUILD

APPENDIX E

MINIMUM ERROR EXCITATION OUTPUT FEEDBACK DESIGNS

MINIMUM ERROR EXCITATION OUTPUT FEEDBACK DESIGNS

This appendix gives the performance index specification for the control laws designed at each flight condition. Together with the algorithm description of section 4.2.2, these performance indeces completely specify how the 30 sets of output gains can be reproduced.

LQR Performance Index

$$J = \int_0^\infty e^{-2\alpha t}(x^T H A_y H x + u^T R_{uu} u)dt, \text{ with}$$

$$A_y = \mathrm{Diag}\left[\frac{1}{(50)^2}, \frac{1}{(0.01)^2}, \frac{1}{(0.001)^2}, \frac{1}{(0.001)^2}, \frac{1}{(0.001)^2}, \frac{1}{(0.001)^2}, \frac{1}{(0.001)^2}, \frac{1}{(0.001)^2}, \frac{1}{(0.001)^2}, \frac{1}{(0.005)^2}, \frac{1}{(0.005)^2}, \frac{1}{(0.005)^2}\right]$$

State weighting matrix, $R_{xx} = k\, H^T A_y H$,

here: k is a scalar providing relative state-control weights

H is the system output matrix

The control weighting matrix $R_{uu} = \mathrm{diag}^2(B)$

Table D-1 lists the scalar weight k and the state weighting vector B as a function of the design flight condition.

TABLE E-1. PERFORMANCE INDEX SPECIFICATION FOR EACH FLIGHT CONDITION (Subscript 1 corresponds to the design with all controls, subscript 2 corresponds to the design without throttle control.)

LOAD FACTOR	ALTITUDE AND MACH				
	h = 10k, M = 0.8	h = 20k, M = 1.0	h = 30k, M = 1.2	h = 40k, M = 1.4	h = 50k, M = 1.8
1	B_1 = [0.1 1 1 1] k_1 = 0.002	B_1 = [0.1 1 1 1] k_1 = 0.002	B_1 = [0.1 1 1 1] k_1 = 0.001	B_1 = [0.1 1 1 1] k_1 = 0.001	B_1 = [0.1 1 1 1] k_1 = 0.001
	B_2 = [1 1 1] k_2 = 0.002	B_2 = [1 1 1] k_2 = 0.002	B_2 = [1 1 1] k_2 = 0.005	B_2 = [1 1 1] k_2 = 0.01	B_2 = [1 1 1] k_2 = 0.01
2	B_1 = [5 1 1 1] k_1 = 0.001	B_1 = [5 1 1 1] k_1 = 0.001	B_1 = [5 1 1 1] k_1 = 0.001	B_1 = [5 1 1 1] k_1 = 0.001	B_1 = [5 1 1 1] k_1 = 0.002
	B_2 = [0.1 0.1 1] k_2 = 0.0005	B_2 = [0.1 0.1 1] k_2 = 0.001	B_2 = [0.1 0.1 1] k_2 = 0.001	B_2 = [0.1 0.1 1] k_2 = 0.01	B_2 = [0.1 0.1 1] k_2 = 0.00001
4	B_1 = [5 1 1 1] k_1 = 0.001	B_1 = [5 1 1 1] k_1 = 0.001	B_1 = [5 1 1 1] k_1 = 0.0005	B_1 = [5 1 1 1] k_1 = 0.0005	B_1 = [5 1 1 1] k_1 = 0.00012
	B_2 = [0.1 0.1 1] k_2 = 0.002	B_2 = [0.1 0.1 1] k_2 = 0.002	B_2 = [0.1 0.1 1] k_2 = 0.002	B_2 = [0.1 0.1 1] k_2 = 0.002	B_2 = [0.1 0.1 1] k_2 = 0.00001

Output Feedback Gains

The output feedback Controller has the form

$$u = Cy$$

where

$$u = [\delta T \ \delta e_{ap} \ \delta a_{ap} \ \delta r_{ap}]^T$$

$$y = [\delta h \ \delta M \ \delta\alpha \ \delta\gamma \ \delta\phi \ \delta\beta \ \delta p \ \delta q \ \delta r \ \int\delta\alpha \ \int\delta\phi \ \int\int\delta\phi]^T$$

Flight condition: h=10k ft, M=0.8, n=1

(a) Throttle free

COLUMNS 1 THRU 6

6.1491D-04	1.9996D+03	1.2553D+01	3.9128D+03	3.0025D-02	7.0112D-02
-2.1757D-02	9.3094D+00	-4.8115D+01	-3.8109D+01	-5.8576D-01	-3.0981D-01
-8.5700D-05	2.7476D-02	-2.5024D-01	-1.2745D-01	5.8288D+01	-9.7112D+01
-3.4216D-06	1.3714D-03	-9.5302D-03	-5.2506D-03	6.1841D-01	3.3190D+00

COLUMNS 7 THRU 12

-3.5007D-02	2.7833D+00	-6.4362D-03	-5.8824D+03	1.8056D-02	3.6150D-03
-3.7222D-01	-2.5667D+01	1.6186D-01	-6.4055D+01	-3.1782D-01	-5.4163D-02
2.3275D+01	-1.5444D-01	2.3048D+01	-2.4475D-01	3.2259D+01	5.4872D+00
8.1391D-01	-7.5431D-03	-4.3978D+00	-1.0375D-02	3.7226D-01	6.3560D-02

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-6.9831D-01	-1.7886D+04	-9.4324D+01	-2.5680D+02	-1.9276D-01	-2.7120D-01
-1.9239D-03	-4.9332D+01	-2.6985D-01	-6.9729D-01	5.8289D+01	-9.7113D+01
-1.5775D-05	-4.0474D-01	-2.2771D-03	-5.6596D-03	6.1835D-01	3.3189D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-1.5857D-01	-2.0762D+01	2.0846D-01	0.0000D+00	-9.4988D-02	-1.5752D-02
2.3276D+01	-1.2968D-01	2.3048D+01	0.0000D+00	3.2260D+01	5.4873D+00
8.1388D-01	-9.4264D-04	-4.3978D+00	0.0000D+00	3.7223D-01	6.3555D-02

Flight Condition: h=10k ft, M=0.8, n=2

(a) Throttle free

COLUMNS 1 THRU 6

2.9627D-02	8.1168D+02	-2.8592D-02	-7.8192D-01	-1.3855D-01	-3.8065D-01
-8.2939D-02	-1.7109D+03	-4.3457D+01	-4.2727D+01	-3.0855D+00	-5.8524D-01
-6.9160D-03	-3.0315D+02	5.3834D+00	3.8716D+01	4.1267D+01	-4.6182D+01
-3.5156D-04	-6.7290D+01	3.0272D+00	1.6798D+01	-9.9049D-01	1.2926D+01

COLUMNS 7 THRU 12

-8.1273D-03	-3.1193D-01	6.5570D-02	7.7035D+01	-2.8132D-01	-8.7290D-02
-1.6231D+00	-1.0912D+01	-2.1829D+00	-1.9868D+02	-6.1947D-01	-5.4515D-01
1.7513D+01	1.8824D+00	-3.1690D+00	-4.6712D+01	2.4901D+01	4.0680D+00
-1.5747D-01	7.6861D-02	-3.2354D+00	-1.4266D+01	7.7021D-01	-7.0858D-03

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.000[illegible]
-9.4567D-01	-2.2554D+04	-1.7541D+02	-3.7794D+02	8.7822D+01	-1.3809D+02
5.4520D-02	-1.5096D+03	3.5769D+00	2.0487D+01	1.7270D+02	-6.2175D+01
-1.8692D-02	-5.2788D+02	2.5422D+00	5.5214D+00	6.6557D+00	5.6499D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
4.0991D+01	-1.2821D+02	9.6703D+01	-2.1918D+03	3.4846D+01	6.0921D-00
8.3971D+01	1.7401D+00	-1.9941D+00	-1.5238D+02	9.8190D+01	1.6852D+01
3.9233D+00	-3.6830D+00	2.7026D+00	-5.4415D+01	4.5116D+00	7.3470D-01

Flight Condition: h=10k ft, M=0.8, n=4

(a) Throttle free

COLUMNS 1 THRU 6

2.2794D-03	7.1210D+01	4.0241D-01	-1.1510D+00	-6.1276D-02	-2.4384D-01
-4.3918D-02	-9.4806D+02	-4.5341D+01	-8.3475D+00	-1.6230D+01	1.4902D+01
-3.3214D-04	-2.5846D+02	2.8570D+00	5.7110D+01	3.9784D+01	-4.6713D+01
2.0198D-03	-6.1265D+01	1.0238D+00	2.2273D+01	-2.9065D+00	1.5259D+01

COLUMNS 7 THRU 12

9.7857D-03	-8.7439D-02	1.9166D-02	1.8054D+01	-3.3040D-01	-1.2460D-01
-1.7379D-01	-7.5154D+00	-1.8527D+00	-2.8085D+02	7.6036D+00	6.2348D-02
1.6825D+01	2.3431D+00	-3.2140D+00	-7.6799D+01	2.9976D+01	5.1782D-0[illegible]
-6.3254D-01	2.4454D-01	-3.4999D+00	-2.0067D+01	2.1467D+00	2.4978D-01

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-2.4868D-01	-4.5480D+03	-1.9039D+02	-1.8448D+02	5.2790D+01	-3.5337D-01
-1.3103D-02	-2.0613D+02	1.2893D+00	1.7878D+01	2.6314D+02	-6.6656D+01
1.9612D-03	-3.6559D+01	1.6883D-01	1.4573D+01	2.4480D+00	8.1336D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
2.7615D+01	-1.6666D+02	4.0532D+01	-1.3112D+03	2.1815D+01	3.1686D+00
1.3028D+02	4.3779D+00	-2.2701D+00	-5.5957D+01	1.5131D+02	2.6108D+01
8.0487D-01	-6.8981D-01	-2.305[illegible]	-1.2346D-01	3.0843D+00	4.9332D-01

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Flight Condition: h=20k ft, M=1.0, n=1

(a) Throttle free

COLUMNS 1 THRU 6

-3.0028D-02	1.4232D+03	-1.4150D+02	1.2419D+04	1.5656D-01	2.5076D-01
-2.4707D-02	3.9892D+00	-1.3192D+02	2.1845D+01	-2.2288D-01	-3.9225D-01
-6.2268D-05	1.0190D-02	-2.5252D-01	6.6599D-02	5.6690D+01	-1.0369D+02
-1.5270D-06	3.3189D-04	-6.0395D-03	1.8372D-03	1.0355D+00	3.7093D+00

COLUMNS 7 THRU 12

-3.1757D-02	-9.4699D+00	-2.8527D-02	-1.7748D+04	8.6553D-02	1.6153D-02
-1.9513D-01	-2.3818D+01	2.9430D-01	-1.8270D+02	-1.2200D-01	-2.0972D-02
2.2984D+01	-1.3557D-01	2.5598D+01	-4.6193D-01	3.1368D+01	5.3333D+00
1.0205D+00	-4.0981D-03	-4.4825D+00	-1.2099D-02	6.0750D-01	1.0334D-01

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-1.4623D-01	-3.0862D+03	-1.3772D+02	-2.5546D+02	-2.3182D-01	-3.5661D-01
-3.4606D-04	-7.3324D+00	-3.2365D-01	-5.9666D-01	5.6691D+01	-1.0369D+02
-8.5753D-06	-1.8118D-01	-7.6613D-03	-1.4886D-02	1.0355D+00	3.7093D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+[illegible]
-1.8998D-01	-2.1146D+01	2.7138D-01	0.0000D+00	-1.1843D-01	-2.0058[illegible]
2.2985D+01	-1.4990D-01	2.5599D+01	0.0000D+[illegible]	3.1368D[illegible]	5.3334[illegible]
1.0205D+00	-4.2346D-03	-4.4824D+00	0.0000D+[illegible]	6.0749[illegible]	1.0334[illegible]

Flight Condition: h=20k ft, M=1.0, n=2

(a) Throttle free

COLUMNS 1 THRU 6

6.9042D-03	1.9549D+02	1.5364D+00	-8.5917D-01	1.1123D-01	-4.6072D-01
-8.0054D-02	-1.6813D+03	-9.5674D+01	-3.7453D+01	-1.7710D+01	1.1887D+01
-3.1811D-03	-1.9103D+02	7.1812D+00	4.0158D+01	4.1578D+01	-4.8085D+01
7.3580D-04	-2.9358D+01	3.8067D+00	1.8625D+01	-1.0029D+00	1.2088D+01

COLUMNS 7 THRU 12

1.1787D-01	-3.2178D-02	1.3241D-01	1.8588D+01	-1.5842D-01	-5.7223D-02
-1.2003D+01	-1.7947D+01	-8.0714D+00	-2.1281D+02	-7.5076D+00	-1.4183D+00
1.7896D+01	1.8398D+00	-2.7051D+00	-3.4723D+01	2.4838D+01	4.0935D+00
8.7576D-03	-2.7686D-02	-3.0579D+00	-1.0897D+01	9.1879D-01	-1.1976D-02

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-2.5821D-01	-5.1355D+03	-1.8856D+02	-2.4846D+02	2.3176D+01	-5.6307D+01
-3.3381D-03	-1.8932D+02	8.8631D+00	3.0696D+01	2.0976D+02	-5.8322D+01
-1.4984D-03	-9.3411D+01	1.1209D+00	1.3272D+01	2.8245D+00	7.2034D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
9.7017D+00	-1.1540D+02	2.1620D+01	-5.6373D+02	6.8088D+00	1.0118D+00
1.0345D+02	7.8005D+00	-3.3573D+00	-2.3474D+01	1.1937D+02	2.0505D+01
1.2950D+00	-1.1666D+00	-2.2116D+00	-1.4181D+01	2.4988D+00	3.6095D-01

Flight Condition: h = 20k ft, M=1.0, n=4

(a) Throttle free

COLUMNS 1 THRU 6

-2.9947D-05	3.6599D+00	5.5165D-01	-4.3026D-01	1.0464D-01	-1.4545D-01
-2.4350D-02	-1.6104D+02	-9.3784D+01	-5.3770D+01	9.3674D+00	-2.0784D+01
8.9437D-03	-5.3990D+01	5.8315D+00	6.7524D+01	3.8510D+01	-4.8181D+01
4.1491D-03	-1.8467D+01	5.9942D-01	2.9591D+01	-3.6880D+00	1.6136D+01

COLUMNS 7 THRU 12

1.7035D-02	1.0704D-01	1.9226D-02	1.4165D+00	-3.8941D-02	-1.7625D-02
3.7699D-01	-2.8745D+01	1.1755D+00	-9.7631D+01	4.2783D-01	2.9496D-01
1.6541D+01	1.7075D+00	-3.4304D+00	-2.9706D+01	2.9120D+01	5.0757D+00
-1.9703D+00	-3.2254D-01	-4.4090D+00	-1.1588D+01	9.5902D-01	1.5582D-01

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-6.0133D-02	-4.3196D+02	-1.5452D+02	-1.3945D+02	1.1041D+01	-4.5528D+01
1.3187D-03	9.5875D+00	1.5789D+01	3.1355D+01	2.5958D+02	-6.5193D+01
3.5796D-03	-4.9691D-01	1.9333D+00	1.9762D+01	3.1445D-01	7.3005D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
3.4082D+00	-1.4477D+02	3.1317D+00	-2.7722D+02	-5.3801D+00	-1.2555D+00
1.2898D+02	1.7756D+01	-3.4610D+00	9.5732D+00	1.4989D+02	2.5871D+01
-4 7916D-01	2.1208D+00	-4.1433D+00	-1.0686D+00	1.6873D+00	2.9084D-01

Flight condition: h = 30k ft, M=1.2, n=1

(a) Throttle free

COLUMNS 1 THRU 6

-4.6088D-02	1.6086D+03	-4.0862D+01	7.7420D+03	5.0626D-01	2.2822D-01
-5.7504D-02	-2.4481D+01	-1.9418D+02	5.1413D+01	1.9622D+00	4.4702D-01
-4.0537D-05	1.7568D-02	-2.0662D-01	1.4692D-01	4.2962D+01	-7.5834D+01
-7.3106D-08	1.2564D-04	-2.9104D-04	2.9682D-04	-2.2994D-01	8.0850D+00

COLUMNS 7 THRU 12

2.5531D-01	1.9677D+01	-8.0973D-03	-6.7504D+03	2.9316D-01	5.1002D-02
1.0298D+00	-5.9481D+00	1.6625D-01	-2.3518D+02	1.1180D+00	1.9185D-01
1.6729D+01	-7.8761D-02	1.1728D+01	-3.0407D-01	2.3583D+01	4.0053D+00
6.7563D-01	-1.0035D-03	-5.5422D+00	-7.5542D-04	-4.1457D-02	-4.9060D-03

(b) Fixed Throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-2.2035D-01	-4.5955D+03	-2.4374D+02	-4.8065D+02	1.4541D+00	-1.1746D-01
-3.9297D-04	-8.2035D+00	-3.9043D-01	-8.4043D-01	7.7573D+01	-9.1042D+01
-9.4818D-06	-1.9769D-01	-9.3204D-03	-2.0343D-02	1.9012D+00	2.6540D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
7.5137D-01	-1.7241D+01	2.9844D-01	0.0000D+00	8.2581D-01	1.4191D-01
3.4197D+01	-1.5816D-01	2.8032D+01	0.0000D+00	4.3223D+01	7.3793D+00
1.3758D+00	-4.1546D-03	-5.1448D+00	0.0000D+00	1.0546D+00	1.7917D-01

Flight Condition: h=30k ft, M=1.2, n=2

(a) Throttle free

COLUMNS 1 THRU 6

6.6424D-03	2.0838D+02	2.4550D+00	-4.6783D+00	2.7707D+00	-2.5482D+0[illegible]
-7.9027D-02	-1.9271D+03	-1.7763D+02	3.9364D+01	-1.1536D+02	5.3945D+0[illegible]
-2.5690D-03	-2.0704D+02	9.0405D+00	4.7758D+01	4.4819D+01	-3.8343D+0[illegible]
1.9215D-03	-2.3017D+00	6.6459D+00	1.9007D+01	2.1634D+00	7.7438D+0[illegible]

COLUMNS 7 THRU 12

1.3539D+00	1.8265D-02	1.0172D+00	4.1165D+01	9.1485D-01	1.2343D-01
-8.0765D+01	-1.9153D+01	-3.1558D+01	-4.4553D+02	-5.0057D+01	-7.8047D+0[illegible]
1.8876D+01	1.3449D+00	-3.4281D+00	-5.0063D+01	2.6362D+01	4.3945D+00
2.4501D+00	5.2374D-01	-1.5152D+00	-3.9816D+00	3.1590D+00	2.5665D-01

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-2.7603D-01	-5.6529D+03	-2.9060D+02	-3.6612D+02	5.2588D+01	-8.8793D+01
-1.0980D-02	-4.1304D+02	3.7056D+00	4.2548D+01	2.1125D+02	-3.8144D+01
-2.3001D-03	-1.2616D+02	1.4133D+00	1.8791D+01	3.0150D+00	9.2470D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.8824D+01	-9.4044D+01	4.0305D+01	-1.1392D+03	2.0379D+01	3.5850D+00
1.0450D+02	4.1414D+00	-7.5652D+00	-8.7991D+01	1.2094D+02	2.0762D+01
2.2519D+00	-2.2669D+00	-2.0448D-0[illegible]	-2.9238D+01	3.5012D+00	4.7414D-01

Flight Conditions: h=30k ft, M=1.2, n=4

(a) Throttle free

COLUMNS 1 THRU 6

4.1769D-04	3.6498D+01	1.4851D+00	-3.4841D+00	2.1042D+00	-1.3394D+0[illegible]
-6.6101D-02	-1.0172D+03	-2.1118D+02	-1.4182D+02	-1.1462D+01	-7.4184D+01
6.4192D-03	-2.8674D+02	4.5654D+00	1.1561D+02	2.7896D+01	-2.6873D+01
4.5633D-03	-4.2698D+01	4.9646D+00	4.3199D+01	-6.6763D+00	2.0181D+01

COLUMNS 7 THRU 12

6.3631D-01	4.8008D-02	3.3416D-01	1.4069D+01	5.3312D-01	9.1566D-02
-3.1037D+01	-2.6264D+01	1.7762D+00	-4.0761D+02	3.2469D+00	7.1053D+00
1.0313D+01	8.3152D-01	-4.9400D+00	-1.1891D+02	2.7199D+01	4.8492D+00
-2.4702D+00	3.2870D-01	-4.1412D+00	-2.0022D+01	9.2925D-01	-2.3495D-02

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-1.4369D-01	-2.6046D+03	-2.7650D+02	-2.2663D+02	1.8778D+01	-6.0432D+01
-1.8925D-03	-1.9404D+02	2.7848D+00	6.7997D+01	2.8567D+02	-3.9003D+01
2.3785D-03	-4.3929D+01	-1.3042D+00	2.6549D+01	-4.3513D+00	1.0744D+01

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
3.3267D+00	-1.3238D+02	2.5597D+01	-1.0794D+03	-2.4847D+00	-7.8123D-01
1.4358D+02	5.4095D+00	-1.5841D+01	-7.9803D+01	1.6880D+02	2.9097D+01
-2.1208D+00	-8.7326D-01	-4.3539D+00	-1.9425D+01	2.8894D-01	4.0536D-0[illegible]

Flight Condition: h=40k ft, m=1.4, n=1

(a) Throttle free

COLUMNS 1 THRU 6

-4.0290D-02	1.4738D+03	-7.8132D+01	1.2733D+04	2.5962D+00	4.7039D-01
-3.3645D-02	-3.4998D+01	-2.2104D+02	2.6056D+02	8.6121D+00	1.6425D+00
-2.2849D-05	1.0441D-02	-1.9676D-01	4.0965D-01	4.4062D+01	-5.9481D+01
7.4382D-07	-2.6323D-04	6.3096D-03	-1.3187D-02	-1.5759D+00	1.1276D+01

COLUMNS 7 THRU 12

1.5059D+00	2.1803D+01	1.5995D-01	-7.5485D+03	1.4565D+00	2.4843D-01
4.9056D+00	-1.1218D+00	4.6368D-01	-3.3457D+02	4.7969D+00	8.1530D-01
1.8275D+01	-7.3752D-02	6.8008D+00	-3.9080D-01	2.4078D+01	4.0875D+00
1.2100D-01	1.6192D-03	-7.5773D+00	1.2509D-02	-7.5866D-01	-1.2434D-01

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-1.7781D-01	-1.0549D+04	-1.9624D+02	-9.2410D+02	1.1114D+01	6.7530D-01
-3.6355D-04	-2.1593D+01	-3.6862D-01	-1.8757D+00	1.0197D+02	-7.4840D+01
-5.8903D-06	-3.4989D-01	-5.9813D-03	-3.0397D-02	2.2552D+00	6.3920D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
6.0610D+00	-1.7085D+01	9.1804D-02	0.0000D+00	6.2255D+00	1.0664D+00
4.7744D+01	-1.6007D-01	2.1718D+01	0.0000D+00	5.6830D+01	9.7189D+00
1.7109D+00	-2.6749D-03	-8.6307D+00	0.0000D+00	1.2089D+00	2.0712D-01

Flight Condition: h=40k ft, m=1.4, n=2

(a) Throttle free

COLUMNS 1 THRU 6

6.8518D-03	5.0683D+02	4.0818D+00	-5.6239D+00	3.0230D+00	-1.7841D+00
-4.4551D-02	-2.3251D+03	-1.8765D+02	-7.0742D+01	-5.8678D+01	1.4762D+00
-9.5491D-04	-3.2593D+02	9.9991D+00	7.9025D+01	4.3050D+01	-3.0872D+01
2.1000D-03	-1.5805D+01	9.0181D+00	4.9655D+01	-4.8933D+00	1.5230D+01

COLUMNS 7 THRU 12

1.4281D+00	-1.3268D-01	7.7201D-01	8.0912D+01	7.3992D-01	7.2793D-02
-6.5057D+01	-1.5583D+01	-1.2903D+01	-4.1372D+02	-2.4749D+01	-1.9782D+00
1.8056D+01	1.2552D+00	-4.8808D+00	-6.2475D+01	2.5905D+01	4.2967D+00
-6.8358D-01	5.6624D-01	-5.3267D+00	-8.8420D+00	6.9321D-01	-3.1452D-01

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-4.5737D-01	-2.4801D+04	-7.2826D+02	-1.2147D+03	4.2798D+02	-2.8449D+02
-2.7317D-02	-2.0654D+03	-4.2632D+00	8.0166D+01	4.9573D+02	-2.0063D+01
-1.3001D-02	-8.8348D+02	-1.3085D+01	1.1110D+01	1.9376D+01	7.4667D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
2.0012D+02	-3.0735D+02	1.5434D+02	-4.0026D+03	1.9950D+02	3.6184D+01
2.5032D+02	7.0155D+00	-8.5866D+00	-3.3909D+02	2.8377D+02	4.8903D+01
1.2102D+01	-1.0560D+01	-6.1567D-01	-1.4738D+02	1.4019D+01	2.1601D+00

Flight Condition: h=40k ft, m=1.4, n=4

(a) Throttle free

COLUMNS 1 THRU 6

4.1124D-04	5 0036D+01	1.5631D+00	-3.1841D+00	1.3668D+00	-5.9777D-01
-2.3227D-02	-1.1466D+03	-1.6878D+02	-5.7583D+01	-8.9560D+00	-1.7275D+01
4.3573D-03	-3.1217D+02	1.0447D+00	1.4759D+02	2.6414D+01	-2.7939D+01
3.9995D-03	-4.5419D+01	4.3753D+00	7.6267D+01	-1.0108D+01	2.5654D+01

COLUMNS 7 THRU 12

3.5106D-01	-4.7050D-02	2.0038D-01	1.5471D+01	5.5993D-02	1.5265D-02
-3.3450D+01	-1.5111D+01	-8.9972D+00	-3.6314D+02	1.6913D+01	1.3191D+01
1.0563D+01	6.9894D-01	-4.0463D+00	-1.0337D+02	2.8584D+01	5.1314D+00
-3.8184D+00	2.8959D-02	-6.4589D+00	-1.7890D+01	1.5474D+00	2.1119D-01

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-7 4833D-02	-3.1628D+03	-3.0725D+02	-2.2405D+02	5.2112D+01	-4.3588D+01
-3.1778D-03	-2.5123D+02	-1.0373D+00	5.6016D+01	2.9213D+02	-4.4807D+01
2.4617D-03	-5.0406D+01	-7.3654D-01	5.1439D+01	-1.3608D+01	1.6665D+01

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.7193D+01	-1.2755D+02	9.9949D+00	-1.0546D+03	1.3909D+01	2.5306D+00
1.4775D+02	6.0470D+00	-6.7478D+00	-8 0806D+01	1.7152D+02	2.9610D+01
-6.2548D+00	-3.7364D-01	-8.3168D+00	-1.8416D+01	-2.9529D+00	-5.2277D-01

Flight Condition: h=50k ft, m=1.8, n=1

(a) Throttle free

COLUMNS 1 THRU 6

-1.2428D-02	1.4946D+03	-1.7242D+02	1.8657D+04	6.6881D-01	2.9641D-01
-2.5982D-02	-1.2215D+01	-1.7927D+02	-1.7245D+01	8.9805D-01	1.0008D-01
-1.5234D-05	4.5541D-03	-1.6558D-01	6.9925D-02	4.4274D+01	-4.7749D+01
2.6681D-07	1.5175D-05	2.4938D-03	-1.1575D-03	-2.1426D+00	1.2960D+01

COLUMNS 7 THRU 12

3.1504D-01	-1.1959D+01	-7.9929D-02	-8.0056D+03	3.8123D-01	6.6208D-02
4.4714D-01	-1.2251D+01	8.1814D-02	-1.2989D+02	5.1817D-01	8.9977D-02
1.9214D+01	-6.8022D-02	4.8313D+00	-1.4003D-01	2.4148D+01	4.0977D+00
-1.8412D-01	-3.1292D-04	-9 0948D+00	2.1152D-03	-1.0517D+00	-1.7169D-01

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-3.9688D-01	-3.8011D+04	-1.7061D+02	-3.6535D+03	2.5598D+02	2.4961D+01
-8.5073D-04	-8.1553D+01	-3.4003D-01	-7.8179D+00	1.0221D+02	-5.7779D+01
-6.3987D-06	-6.1356D-01	-2.5685D-03	-5.8789D-02	1.4993D+00	1.0648D+01

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
1.4115D+02	-1.6571D+01	-9.4218D+00	0.0000D+00	1.4298D+02	2.4462D+01
4.8944D+01	-1.4756D-01	1.4088D+01	0.0000D+00	5.6839D+01	9.7199D+00
1.4580D+00	-1.1025D-03	-1.1752D+01	0.0000D+00	7.7799D-01	1.3455D-01

C-3

Flight Condition: h=50k ft, m=1.8, n=2

(a) Throttle free

COLUMNS 1 THRU 6

3.5959D-03	4.6794D+02	3.5335D+00	-1.1105D+01	1.8649D+00	-8.0395D-01
-2.8089D-02	-1.8184D+03	-1.3708D+02	-1.4276D+02	3.3696D+01	-3.5020D+01
-2.7227D-03	-8.1445D+02	8.1206D+00	1.3217D+02	2.2062D+01	-2.0562D+01
-6.3217D-04	-4.5145D+02	7.5518D+00	1.0742D+02	-9.6043D+00	2.2742D+01

COLUMNS 7 THRU 12

4.6028D-01	-3.5162D-01	2.6473D-01	7.7890D+01	1.0763D-01	-1.1116D-01
-1.6152D+01	-6.4189D+00	-2.1512D+00	-3.1546D+02	3.0005D+01	7.0640D+00
7.4751D+00	1.2381D+00	-1.7457D+00	-1.4860D+02	1.4924D+01	2.3107D+00
-4.0962D+00	6.7878D-01	-7.0306D+00	-8.6670D+01	-1.4925D+00	-7.2027D-01

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-6.0982D-02	-4.1785D+03	-2.5111D+02	-2.8238D+02	-6.9991D+01	-7.1699D+01
-3.6150D-03	-5.4820D+02	-9.6721D-01	3.8862D+01	4.1818D+01	-4.1017D+01
-1.4051D-03	-2.8559D+02	4.3810D-01	3.2729D+01	-7.6396D+00	6.2683D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-7.2926D+01	-3.0622D+01	1.9139D+01	-7.2199D+02	-3.7145D+01	-5.9716D+0[illegible]
1.8956D+01	6.3265D-01	2.6529D+00	-9.4700D+01	2.4460D+01	4.1671D+00
1.5019D+00	-9.5266D-02	-1.8004D+00	-5.0892D+01	-1.3886D-01	-1.681[illegible]

Flight Condition: h=50k ft, m=1.8, n=4

(a) Throttle free

COLUMNS 1 THRU 6

-8.7236D-06	3.3564D+01	1.3407D+00	-2.8980D+00	5.8841D-01	-2.1908D-01
-1.4706D-02	-9.3343D+02	-1.4934D+02	-3.1412D+01	3.4538D+01	-2.7494[illegible]
9.5740D-03	-2.8197D+02	-1.1045D+00	2.3251D+02	1.3507D+01	-2.1212D+01
6.8283D-03	-8.9545D+01	-2.3177D+00	1.4395D+02	-1.5042D+01	3.3745D+01

COLUMNS 7 THRU 12

3.9985D-02	-6.0302D-02	5.0477D-02	1.1111D+01	-1.1816D-01	-8.0972D-03
-7.0423D+00	-1.6189D+00	-5.6683D+00	-3.0429D+02	5.0324D+01	1.7827D+01
5.1013D+00	7.2874D-01	-3.3023D-01	-1.0184D+02	2.4240D+01	4.4423D+00
-4.8778D+00	2.6307D-03	-7.9269D+00	-3.6055D+01	8.3040D-01	4.2546D-01

(b) Fixed throttle

COLUMNS 1 THRU 6

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
-1.7721D-02	-9.5730D+02	-1.7563D+02	-9.2676D+01	5.9326D+01	-2.8669D+01
1.0931D-03	-8.2717D+01	-2.1945D+00	4.2145D+01	4.4064D+01	-6.5929D+01
1.2398D-03	-4.0076D+01	-3.3685D+00	3.5458D+01	-7.1816D+00	7.5126D+00

COLUMNS 7 THRU 12

0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00	0.0000D+00
8.9326D+00	-1.3331D+01	9.2995D+00	-3.4701D+02	3.1186D+01	8.2989D+00
1.9945D+01	4.7141D-01	6.5710D+00	-2.9380D+01	2.7616D+01	4.7279D+00
-4.1092D-01	-4.0034D-01	-1.8719D+00	-1.5270D+01	-2.1025D+00	-1.6154D-01

1. Report No. NASA CR-179428	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Aircraft Flight Test Trajectory Control		5. Report Date January 1988
		6. Performing Organization Code
7. Author(s) P.K.A. Menon and R.A. Walker		8. Performing Organization Report No. H-1345
		10. Work Unit No. RTOP 505-66-11
9. Performing Organization Name and Address Integrated Systems, Inc. 101 University Avenue Palo Alto, California 94301		11. Contract or Grant No. NAS 2-11877
		13. Type of Report and Period Covered Contractor Report - Final
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code

15. Supplementary Notes

NASA Technical Monitor: Eugene L. Duke, Ames Research Center, Dryden Flight Research Facility, Edwards, California 93523-5000

16. Abstract

This report describes two design techniques for linear flight test trajectory controllers (FTTCs): Eigenstructure assignment and the minimum error excitation technique. The two techniques are used to design FTTCs for an F-15 aircraft model for eight different maneuvers at thirty different flight conditions. An evaluation of the FTTCs is presented.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Aircraft control Control law synthesis F-15 Flight test maneuver autopilot Trajectory guidance	Unclassified — Unlimited Subject category 08

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	218	A10

*For sale by the National Technical Information Service, Springfield, Virginia 22161.