AFWAL-TR-80-3015

AD A091014

DESIGN OF A LATERAL STABILITY AUGMENTATION SYSTEM FOR THE F-106 TO IMRPOVE LATERAL HANDLING QUALITIES DURING TRACKING

Richard D. Holdridge, Captain, USAF

Flight Control ADP Branch
Flight Control Division

July 198C

TECHNICAL REPORT AFWAL-TR-80-3015

Final Report for Period May 1977 to January 1979

Approved for public release; distribution unlimited

FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR-FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This technical report has been reviewed and is approved for publication.

Richard D. Holdridge

RICHARD D. HOLDRIDGE, Captain, USAF
Project Engineer
Flight Control ADP Branch

William F. Swartz

WILLIAM F. SWARTZ
Chief, Flight Control ADP Branch

FOR THE COMMANDER:

Robert C. Ettinger

ROBERT C. ETTINGER, Lt Col, USAF
Chief, Flight Control Division

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/FIGX, W-P AFB, OH 45433 to help us maintain a current mailing list".

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIR FORCE/56780/16 October 1980 — 220

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

14

1. REPORT NUMBER: AFWAL-TR-80-3015

2. GOVT ACCESSION NO.: AD-A091014

3. RECIPIENT'S CATALOG NUMBER

9

4. TITLE (and Subtitle): DESIGN OF A LATERAL STABILITY AUGMENTATION SYSTEM FOR THE F-106 TO IMPROVE LATERAL HANDLING QUALITIES DURING TRACKING.

6

5. TYPE OF REPORT & PERIOD COVERED: Technical Report, May 77 — Jan 79,

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): Richard D. Holdridge, Captain, USAF

10

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Flight Dynamics Laboratory (AFWAL/FIGX)
Air Force Wright Aeronautical Laboratories
Wright-Patterson AFB, Ohio 45433

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
Program Element 62201F,
2403, Task 240302,
Work Unit 24030209

11. CONTROLLING OFFICE NAME AND ADDRESS:
Flight Dynamics Laboratory (AFWAL/FIG)
Air Force Wright Aeronautical Laboratories
Wright-Patterson AFB, Ohio 45433

11

12. REPORT DATE: Jul[redacted]80

13. NUMBER OF PAGES: 165

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

12 165

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Air-to-Air Gunnery	Man-Machine Dynamics
Flight Control	Simulation
Handling Qualities	Handling Qualities During Tracking
Gunnery	Aircraft Dynamics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An improved lateral stability augmentation system has been developed to improve the handling qualities of the F-106 in the air-to-air tracking task. The existing yaw rate and roll rate feedbacks, as well as the aileron to rudder interconnect, were removed and replaced with calculated sideslip rate and measured sideslip feedbacks. An advanced root locus technique, the root map was used to set the gains on sideslip and sideslip rate. The resulting system was evaluated using a nonpiloted hybrid simulation as well as a digital

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

392662 DW

20. ABSTRACT (Concluded)

frequency domain analysis program. The system was then evaluated by operational F-106 pilots using the Flight Dynamics Laboratory's LAMARS motion based simulator. Based on simulator results, the system was installed on an F-106 and flight tested at Tyndall AFB, Florida. The results of basic analyses, nonpiloted simulations, piloted simulations, and flight test are presented.

FOREWORD

This report documents an effort to use conventional design methods in the design of an improved stability augmentation system for the F-106.

Acknowledged is the guidance and direction given by Dr. Robert Huber of the Flight Dynamics Laboratory in the application of the design and analysis methods used for this project, the assistance provided in data collection and data analysis methods by Lt Cliff Alston, Capt Mitchell Cary, Mr. Frank George and Mr David Potts, the timely criticisms and assistance provided by Dr. David Quam of the University of Dayton, and the assistance in the preparation of the final draft of this report by Miss Celeste Brown and Mrs. Jayna Haller.

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONCLUDED)

LIST OF TABLES

LIST OF SYMBOLS

$A_y)_{acc}$	Accelerometer measured lateral acceleration (ft/sec^2)
b	Wingspan (ft)
$\bar{c}$	Mean aerodynamic chord (ft)
C_D	Non-dimensional drag coefficient
C_L	Non-dimensional lift coefficient
C_l	Non-dimensional rolling moment coefficient
C_m	Non-dimensional pitching moment coefficient
C_n	Non-dimensional yawing moment coefficient
C_y	Non-dimensional sideforce coefficient
F_x	Total force in body x-direction (lb)
F_y	Total force in body y-direction (lb)
F_z	Total force in body z-direction (lb)
g	Gravitational acceleration, 32.174 ft/sec^2
I_x	Moment of inertia about body x-axis (slug ft^2)
I_y	Moment of inertia about body y-axis (slug ft^2)
I_z	Moment of inertia about body z-axis (slug ft^2)
I_{xz}	Moment of inertia xz cross-product (slug ft^2)
K	Transfer function gain for $\beta/\delta r$
K_I	Gain on integrator in proportional plus integral compensator
K_p	Gain from rudder pedals to control system (rad/in)
K_β	Gain on sideslip angle feedback (rad/rad)
$K_{\dot{\beta}}$	Gain on sideslip angle rate feedback (rad/rad/sec)
L	Total rolling moment (ft-lb)
M	Total pitching moment (ft-lb)
M	Mach number
m	Mass (slugs)

N	Total yawing moment (ft-lb)
n.p.	Neutral Point (ft)
p	Roll rate (rad/sec)
q	Pitch rate (rad/sec)
$\bar{q}$	Dynamic pressure (lb/ft^2)
r	Yaw rate (rad/sec)
S	Wing area (ft^2)
u	Velocity in body x-direction (ft/sec)
U	Total velocity (ft/sec)
v	Velocity in body y-direction (ft/sec)
$\bar{v}_b$	Body velocity vector (ft/sec)
$\dot{\bar{v}}_b$	Body acceleration vector (ft/sec^2)
$\dot{\bar{v}}_b$	Inertial acceleration vector (ft/sec^2)
w	Velocity in body z-direction (ft/sec)
$x_{c.g.}$	Center of Gravity (ft)
α	Angle of attack (rad)
β	Sideslip angle (rad)
$\dot{\beta}_a$	Sideslip angle rate (rad/sec)
δ_a'	Aileron deflection (rad)
δ_e	Elevator deflector (rad)
δ_r	Rudder deflection (rad)
ϕ	Roll angle (rad)
θ	Pitch angle (rad)
$\bar{\omega}$	Body angular rate vector (rad/sec)

SECTION I

INTRODUCTION

An improved lateral stability augmentation system (SAS) for the F-106 has been designed and simulated in both piloted and non-piloted real-time simulations and in a frequency domain simulation. The new system emphasizes improvement in lateral handling qualities for the air-to-air (ATA) tracking task.

The present lateral SAS is composed of washed out yaw rate, for stability purposes, and a combination of washed out roll rate and an aileron to rudder interconnect (ARI), for turn coordination. The new system uses sideslip angle (β) and sideslip angle rate ($\dot{\beta}$) to achieve both improved stability and improved turn coordination. The design also includes a direct electrical signal from the pilot through the rudder pedals to the control system to allow for direct command of sideslip angle or sideslip rate.

The new system eliminates large unintentional sideslip perturbations caused by the pilot's attempts to place the gunsight reticle, or pipper, on the target aircraft. The system also allows the pilot to point more accurately the aircraft when azimuth tracking error is small. An added benefit provided by the system is an improvement in elevation tracking error through a reduction of pilot workload in the lateral task.

A piloted simulation was conducted to evaluate the new lateral SAS. Two Air Defense Command (ADCOM) flight test pilots, both current in the F-106, spent a week flying approximately 150 ATA tracking passes. Several configurations of the improved system were flown and compared with the existing system. The pilots typically achieved reductions of 30% in both elevation and azimuth tracking error using the improved lateral SAS. The system was then installed on an F-106 and flight tested. The performance improvements were similar to those measured during piloted simulations.

SECTION II

BACKGROUND

1. AIR-TO-AIR TRACKING

Before continuing with a specific discussion of the F-106, it is perhaps instructive to look at the ATA tracking task and how the difficulty of the task is heavily influenced by the aircraft flight control system. ATA tracking is typically a high-g maneuver which has superimposed on it the extremely difficult task of precise aircraft pointing. The task is further complicated because the aircraft is not being pointed as an end in itself but to enable the pilot to place a gunsight reticle (pipper), either fixed or computed and displayed, on the target aircraft. Since the pipper is a representation of a target for which the gun is presently correctly aimed, it will be depressed some angle from the aircraft body x-axis. This depression is due to target aircraft acceleration, attacker velocity and acceleration, and bullet gravity drop; its magnitude is further dependent on the angle of the gun with respect to the aircraft (gun depression angle). Figure 1 shows this situation and how it is viewed by the pilot in the headup display (HUD). Figure 1 also shows how elevation tracking error is defined. The tracking error is usually measured in angular units of milliradians (mil). In the situation shown in Figure 1, the pilot's task is simple: he pitches the aircraft up until the reticle is superimposed on the target.

Unfortunately, when a large azimuth error also exists, the pilot cannot simply move the reticle onto the target. To zero a large azimuth tracking error, the pilot must first roll the aircraft to approximately null the azimuth error and then pitch the aircraft to null the remaining elevation error. After these large azimuch errors have been nulled, the rudder pedals can be used to zero the remaining error. This sequence of first nulling azimuth error then elevation error is the basis upon which each pilot developes his own technique.

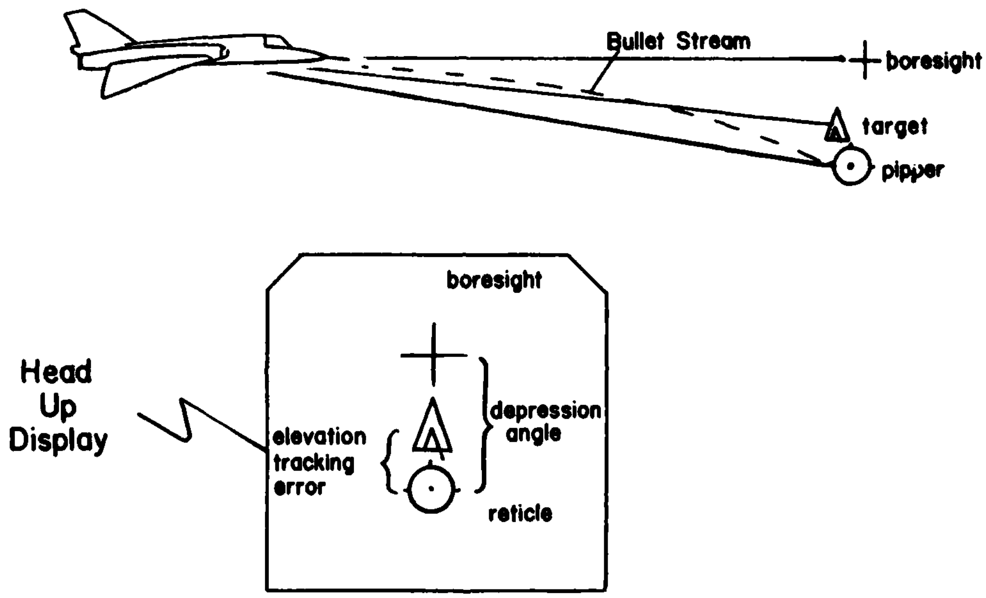


Figure 1. Reticle Depression Angle and Tracking Error

2. FACTORS AFFECTING ATA TRACKING

There are many factors which affect the pilot's ability to track a target. Some of these factors are turbulence, evasive target maneuvers, gunsight dynamics, and the attacker's own vehicle dynamics. The first two are factors that cannot be controlled or changed by modifications to the attacking aircraft. The third term can have a significant effect on tracking performance and to a large extent can be controlled or changed by modifications to the fire control system of the attacking aircraft. The study of gunsight dynamics and other associated fire control problems is, however, beyond the scope of this paper. To simplify the effects of gunsight dynamics, a fixed depressed reticle was used for the remainder of this study. A fixed depressed reticle, as the name implies, is a gunsight reticle which is depressed a constant angle from the boresight cross. Figure 2 shows a simple fixed depressed reticle as seen on the HUD. The fourth factor affecting the pilot's ability to track the target is vehicle dynamics. Like gunsight dynamics, vehicle dynamics can be changed by modifications to the attacking aircraft.

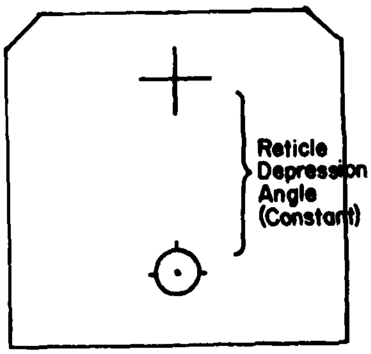


Figure 2. Fixed Depressed Reticle

To see how the vehicle dynamics affect the tracking error, one must compare what the pilot sees through the HUD to what the aircraft is doing within the airmass. Consider the HUD display in Figure 3(a) with a fixed depressed reticle. Since the pipper is left of the target, the pilot must null the azimuth error. Since the pilot cannot move his aircraft laterally, he must first roll the aircraft right and then turn to zero the error. Herein lies the problem. If the aircraft is unaugmented or contains just simple yaw damping, the aileron deflection will cause the aircraft to rotate about its nearest principle axis. For a rolling moment, this principle axis is very near the x-axis of the aircraft or, from the pilot's point of view, the boresight axis. This roll/sideslip coupling is shown in Figure 4. What then happens from the pilot's viewpoint is shown in Figure 3(b). When he rolls the aircraft, he rolls approximately about the boresight cross thus generating a transient sideslip angle which causes the pipper to move in the direction opposite that desired by the pilot. The pilot perceives this as an increased azimuth error, so he rolls the aircraft more to the right (Figure 3(c)), compounding the problem. This phenomenon of the pipper rotating under the boresight cross is known as the pendulum effect and has a destabilizing effect on ATA tracking.

The pendulum effect can be eliminated or greatly reduced by lateral augmentation of the aircraft. Figures 3 and 4 show that the pendulum effect is caused by the aircraft's natural trndency to roll about its own x-axis. This results in the angle-of-attack changing into sideslip as the roll angle goes from 0 to 90 degrees. Of course, this sideslip will die out at the aircraft's dutch roll frequency and damping, but this is too slow for the tracking task.

Another aspect of aircraft dynamics that affects the pilot's ability to track becomes obvious only when large tracking errors have been eliminated and the pilot is using the rudder to point the aircraft. When the pilot is using the rudder for fine control of azimuth error, the dutch roll frequency and damping become critical to the tracking task. To be effective during this precise phase of tracking, the aircraft should respond quickly to the pilot's input with a damping ratio which eliminates large overshoots and at the same time avoids the excessive lag of an

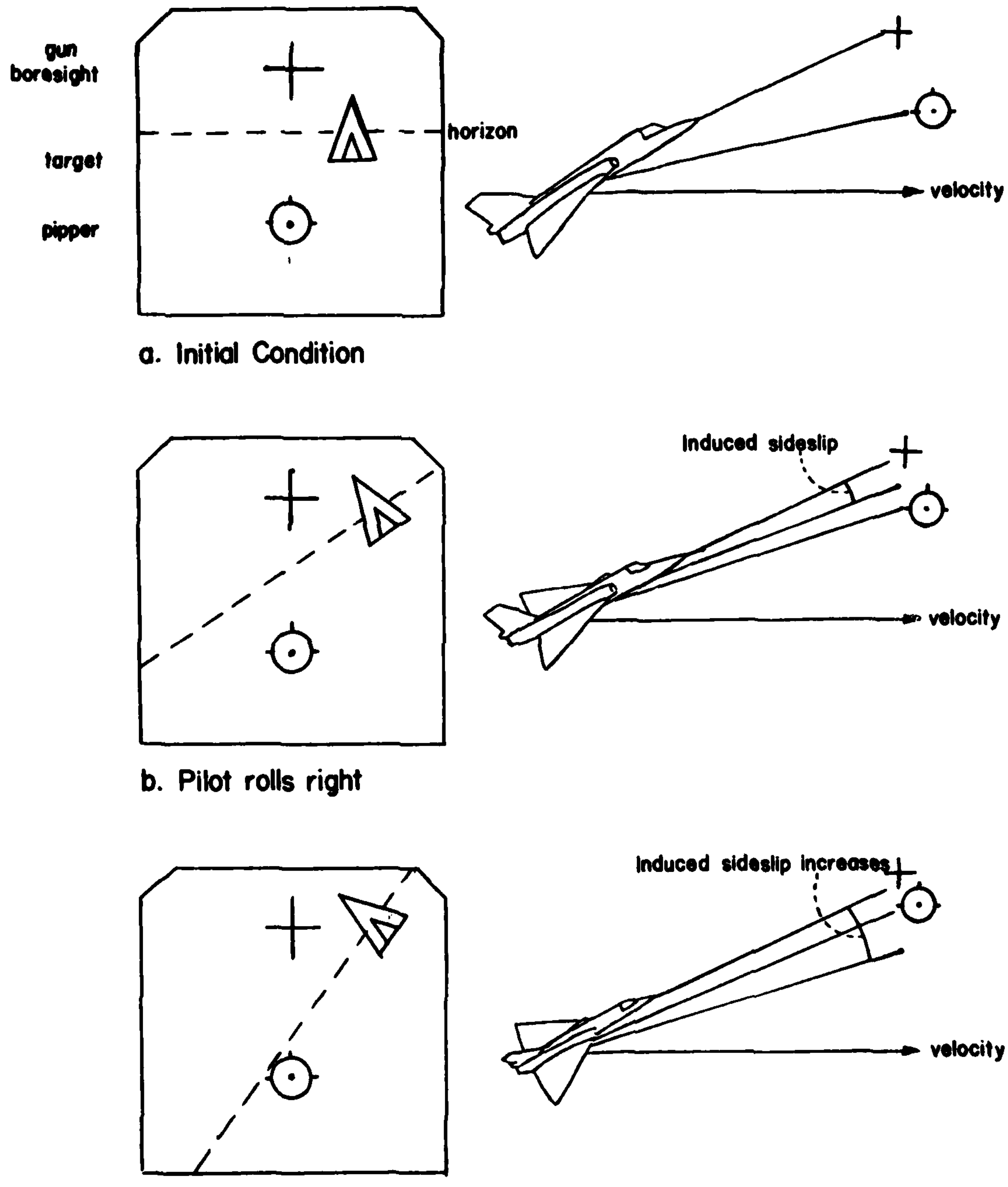


Figure 3. The Pendulum Effect

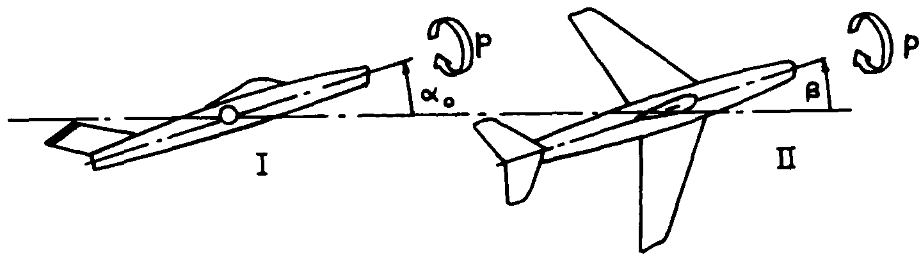


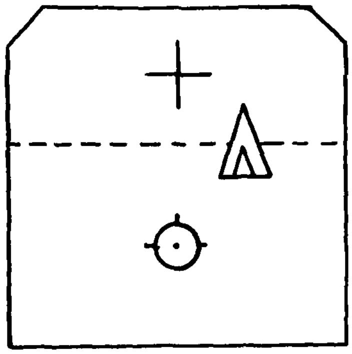
Figure 4. Roll/Sideslip Coupling

overdamped response. An overdamped response could result in the airplane becoming too sluggish as perceived by the pilot. Typically a dutch roll damping ratio of .7 to 1 is adequate. In this precise lateral pointing, the pilot desires to yaw the aircraft without significant roll coupling.

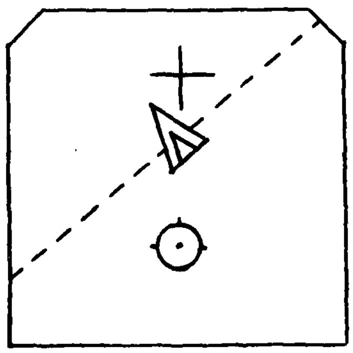
3. CONTROL SYSTEMS FOR AIR-TO-AIR TRACKING

After seeing how an unaugmented aircraft behaves when used to track a target, the possibilities of improvement using augmentation are obviously significant. The answer is found by looking again at Figures 3 and 4. If the aircraft were to roll about the velocity vector instead of the x-axis, the pendulum effect could be eliminated or greatly reduced. Figure 5 shows the same initial conditions as Figure 3 but shows how the pilot's task would be simplified if the aircraft was forced to roll about the velocity vector.

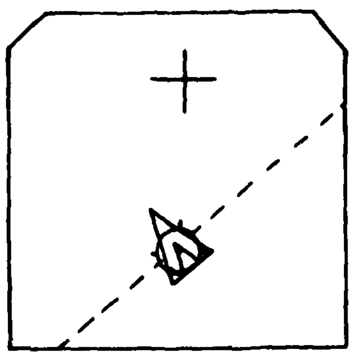
The design of a control system to improve aircraft dynamics for ATA tracking is based on this capability of rolling about the velocity vector. The result of rolling about the x-axis in the case of an unaugmented aircraft, is the increase of sideslip and reduction of angle of attack. This induced sideslip is the basis for the design of the control system. If the sideslip angle is kept at zero during the roll, then the aircraft is rolling about the velocity vector. The desired control system is therefore an accurate and responsive turn coordinator. The feedbacks needed to achieve this turn coordination are sideslip angle and sideslip



a. Initial Condition



b. Roll Right to Zero Azimuth Error



c. Pitch Up to Null Final Elevation Error

Figure 5. Rolling about Velocity Vector

angle rate. A simplified block diagram of this control system is shown in Figure 6. Since sideslip angle and sideslip rate are also the aircraft states which can be controlled by the pilot with the rudder pedals, this control system will also affect the aircraft response to rudder pedal input. This means that the pilot's task of fine lateral pointing can be improved using the system of Figure 6.

4. F-106 DYNAMICS

A hybrid simulation of the F-106 was conducted on the Aeronautcial Systems Division Hybrid Computer to study the F-106 in a real-time situation. The simulation was validated by checking angle of attack and elevator deflection at numerous flight conditions throughout the F-106 flight envelope. Dynamic longitudinal and lateral checks were also made at various flight conditions. The model used in the simulation proved to be an accurate representation of the real aircraft. A description of the simulation is included in Appendix A.

The purpose of the hybrid simulation was to look at the aircraft with the present control system and determine if it did demonstrate characteristics detrimental to ATA tracking. The two characteristics most likely to be encountered were the roll/sideslip coupling and the underdamped dutch roll. The standard SAS is shown in Figures 7a and 7b. The yaw rate feedback is present primarily to achieve the needed dutch roll damping. The roll rate feedback and ARI exist primarily to achieve turn coordination or, equivalently, to allow the aircraft to roll approximately about the velocity vactor.

The responses of the bare airframe (SAS turned off) to a 60-degree roll input are shown in Figure 8. The roll angles were input using a roll autopilot with a 1-second time constant. These responses show sideslip perturbations of more than 1 degree with very low damping, on the order of .15. Both characteristics would indicate the F-106 with the SAS turned off could have deficient lateral handling qualities during ATA tracking. The 60-degree roll angle command was also input to the F-106 at the same flight conditions but with the standard SAS turned on. The results, shown in Figure 9, are significantly better than the bare airframe.

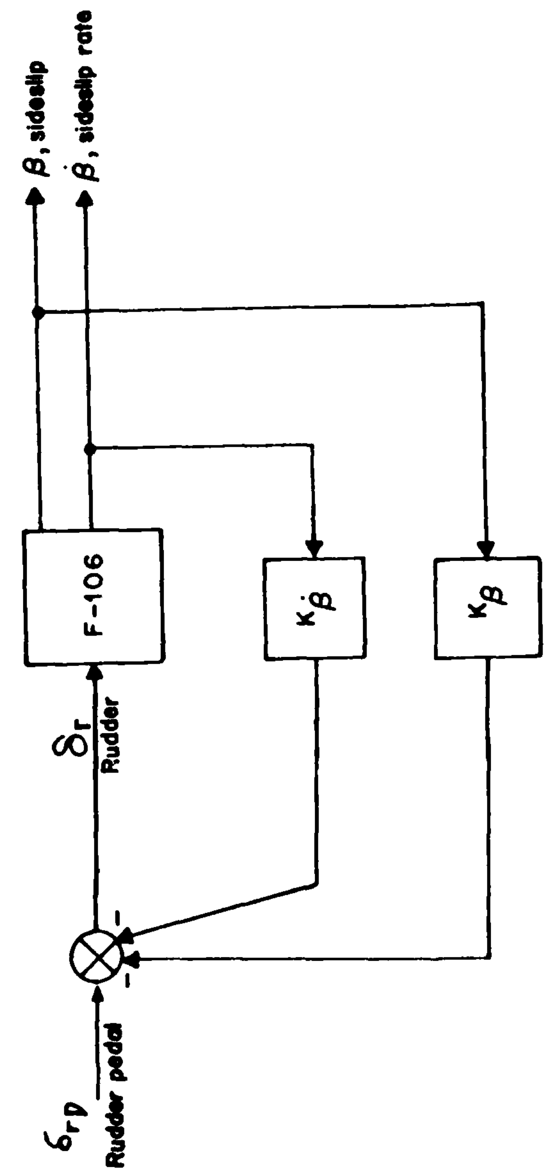
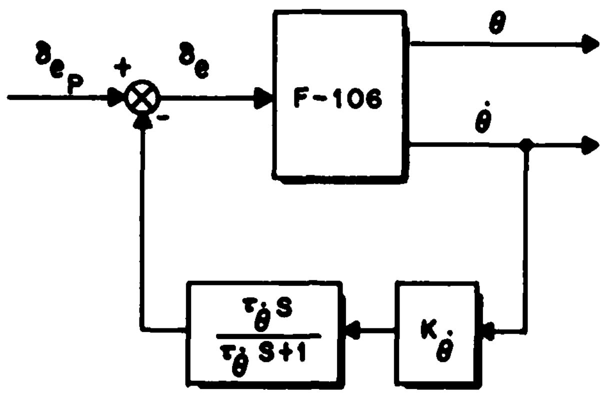


Figure 6. Sideslip Control System



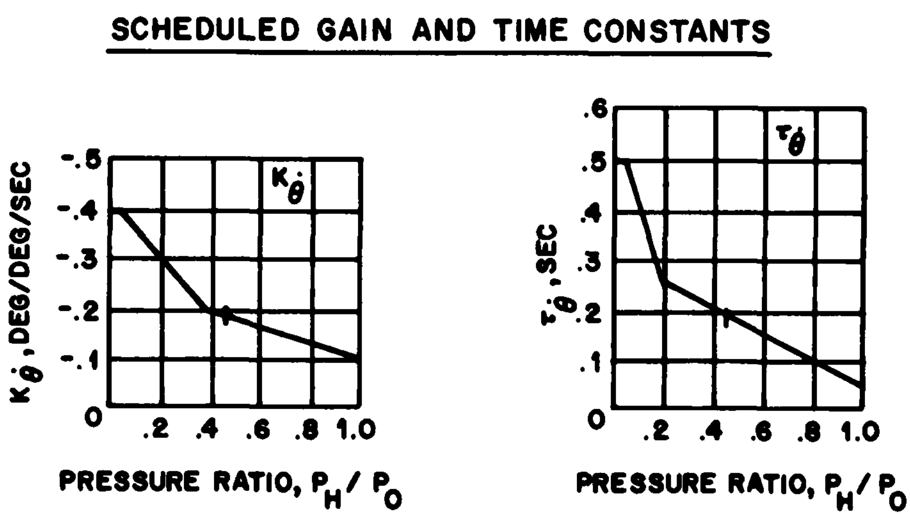


Figure 7a. F-106 Longitudinal SAS

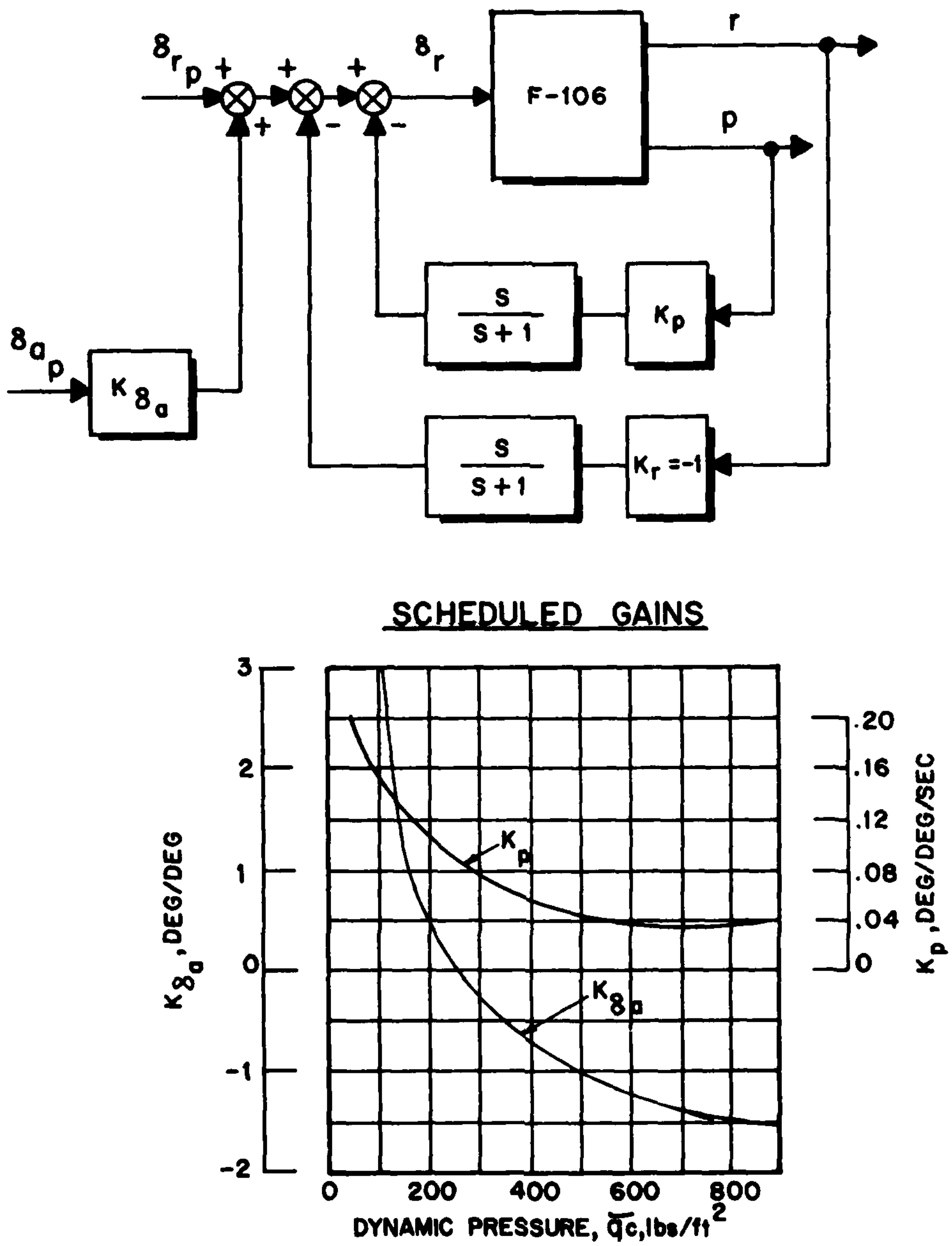


Figure 7b. F-106 Lateral SAS

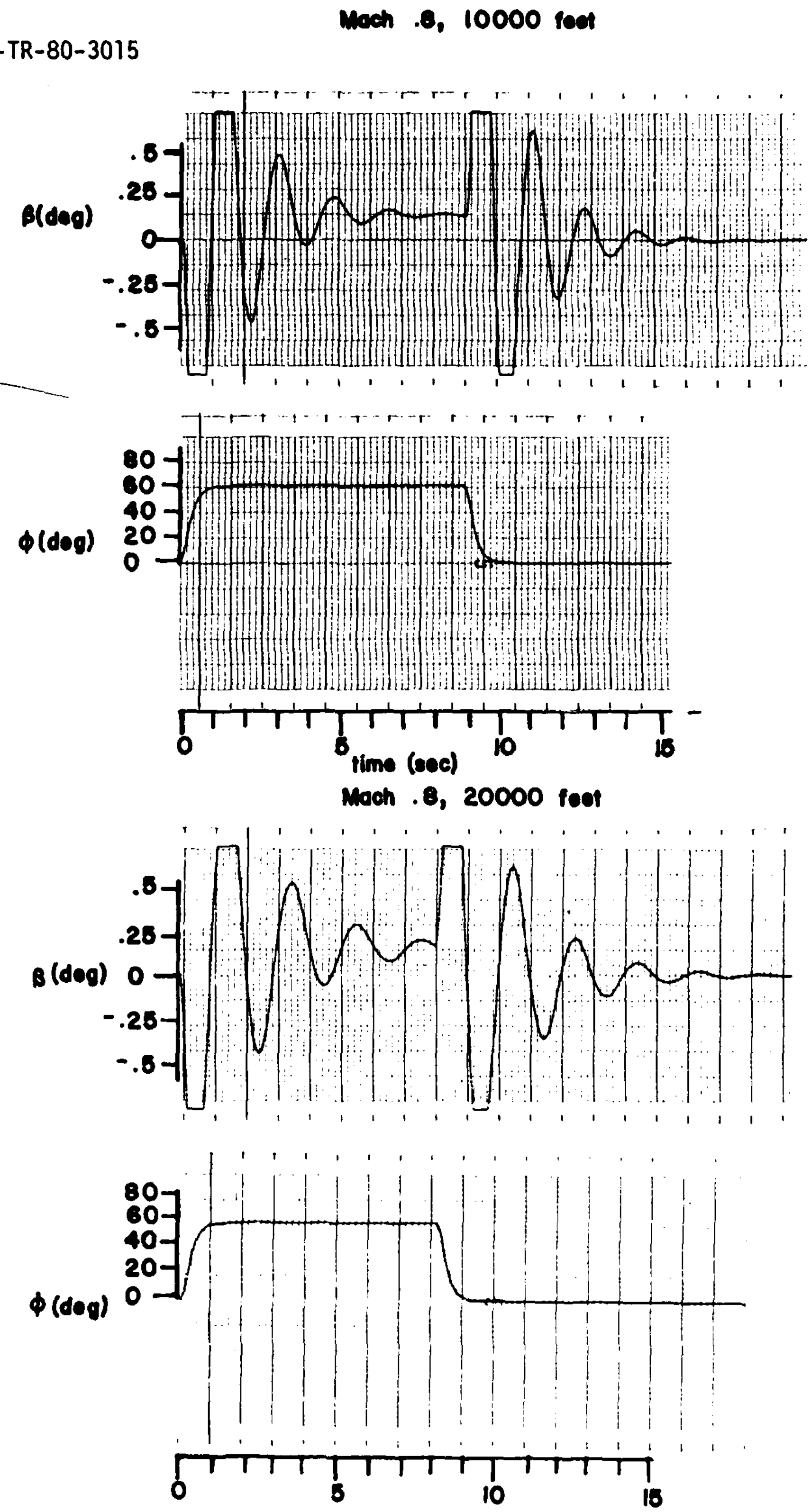


Figure 8. Bare Airframe Response to 60° Band Angle

The damping increases markedly from about .1 to .7. Although the standard SAS improves the underdamped dutch roll characteristic, the large sideslip perturbation, as seen in the bare airframe responses, is also present in the standard SAS. This roll/sideslip coupling indicates a factor which will affect the lateral tracking characteristics of the aircraft.

This preliminary analysis of the F-106 indicates possible areas of improvement in the lateral handling qualities. The bare airframe is obviously undesirable in terms of both dutch roll damping and roll/sideslip coupling. The standard SAS improves dutch roll damping considerably but the roll/sideslip perturbations are still large. Figures 8 and 9 show the dynamic responses for the standard SAS due to roll angle inputs from straight and level, 1 g flight. At higher g loadings, typical for air-to-air tracking, the induced sideslip angle would be larger than those shown in Figures 8 and 9. Based on these significant sideslip perturbations, it therefore seemed appropriate to consider a sideslip angle/sideslip angle rate (β-$\dot{\beta}$) control system, as mentioned earlier, for use on the F-106.

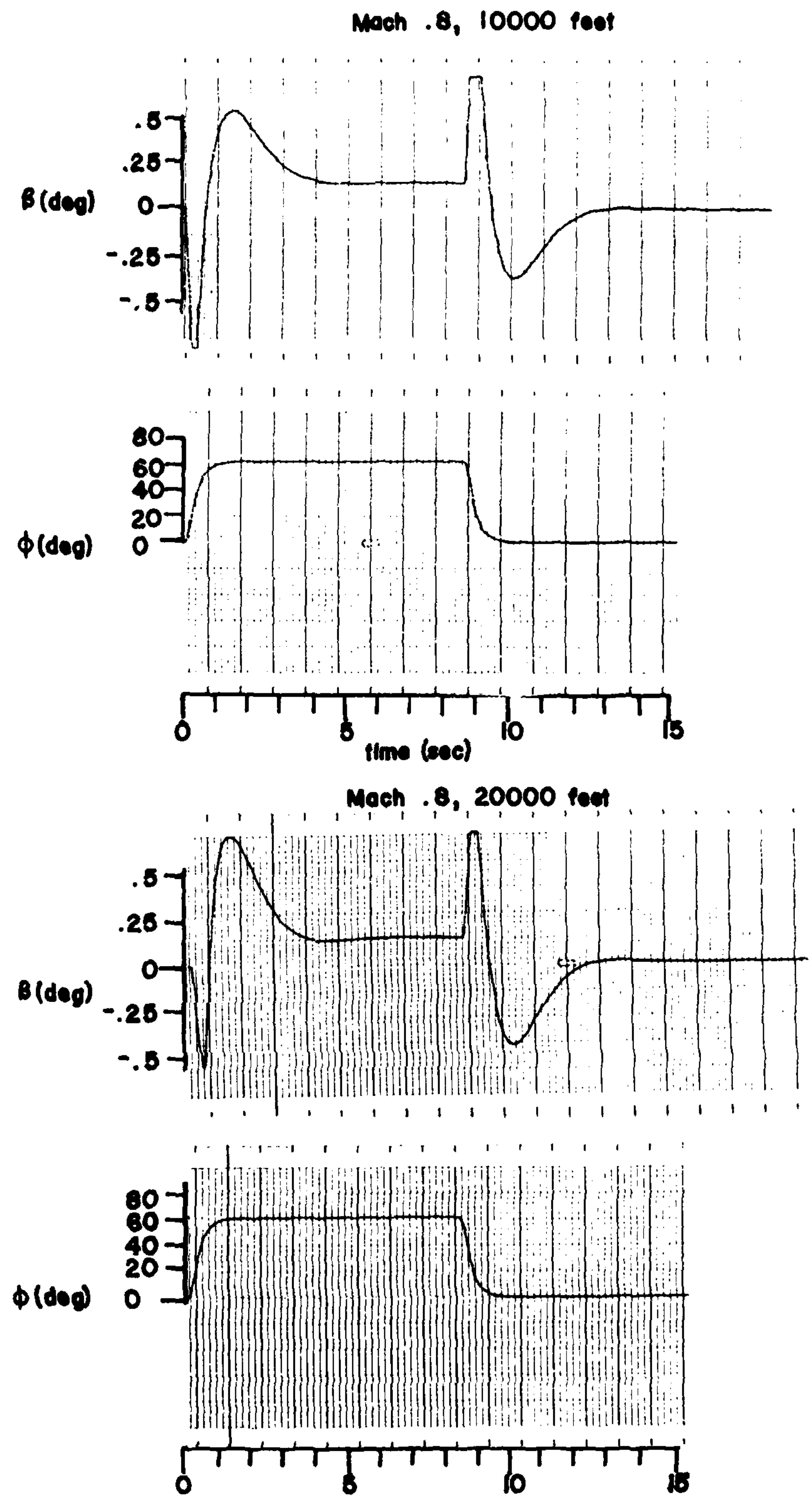


Figure 9. Standard SAS Response to 60° Bank Angle

SECTION III

SYSTEM DESCRIPTION

1. PRELIMINARY DESIGN MODEL

The system shown in Figure 10 is the basis for a preliminary design of a β-$\dot{\beta}$ SAS for the F-106. By design, the system will tend to cause the aircraft to maintain coordinated flight or, equivalently, to roll about the velocity vector; therefore, the task remaining in the preliminary design is to find the gains K_β and $K_{\dot{\beta}}$ to provide sufficient damping and adequate speed of response. The proportional plus integral compensator is included to remove the steady-state error resulting from the β feedback. The integral gain K_I is nominally set to .2 for the analysis.

2. ROOT MAP ANALYSIS

The closed-loop dynamic characteristics of the system are analyzed using the root map technique (Reference 3). This technique involves closing one loop at a constant gain, either sideslip or sideslip rate, then plotting the root locus by allowing the other gain to vary from zero to infinity. For generating a root locus at a constant K_β, the system model appears as Figure 11. The simplified transfer function, $\beta/\delta r$, is based on McRuer's (Reference 7) fourth order model and is shown below.

$$\beta/\delta r = \frac{K(s + a)}{s^2 + bs + c}$$

$$K = Y^*_{\delta r} \qquad b = -(Y_v + N'_r)$$

$$a = -(Y^*_{\delta r} N'_r + N'_{\delta r})/Y^*_{\delta r} \qquad c = (N'_\beta + Y_v N'_r) \tag{1}$$

The dimensional aerodynamic derivatives making up the transfer function are described in Reference 7 and the resulting transfer functions are displayed in Appendix B.

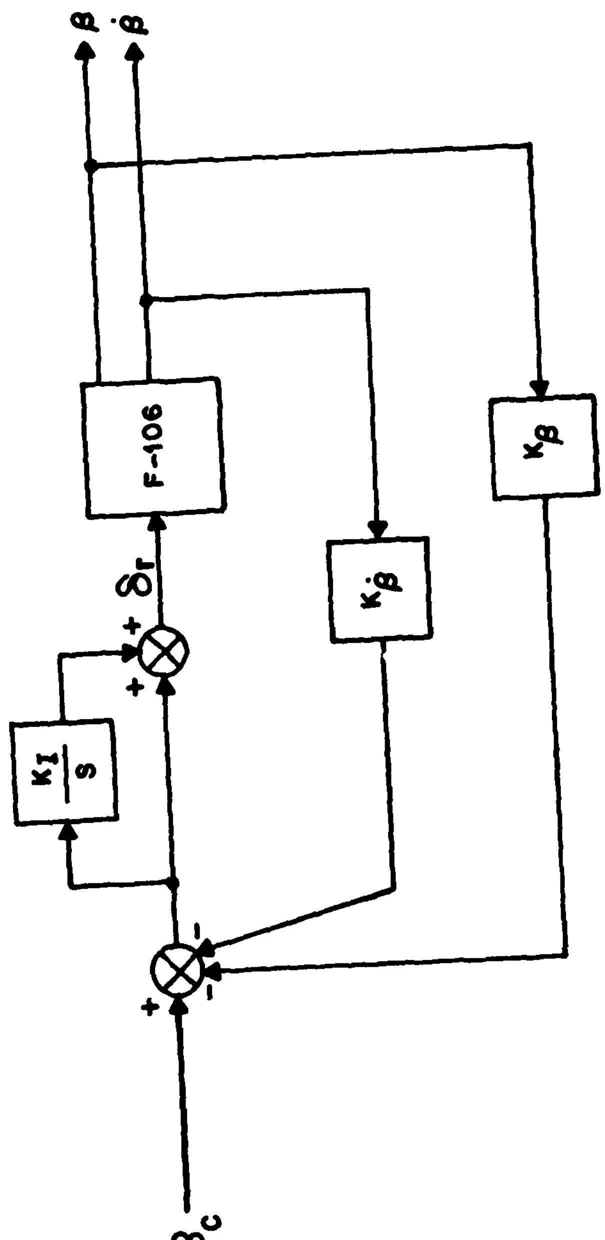


Figure 10. Preliminary Design Model

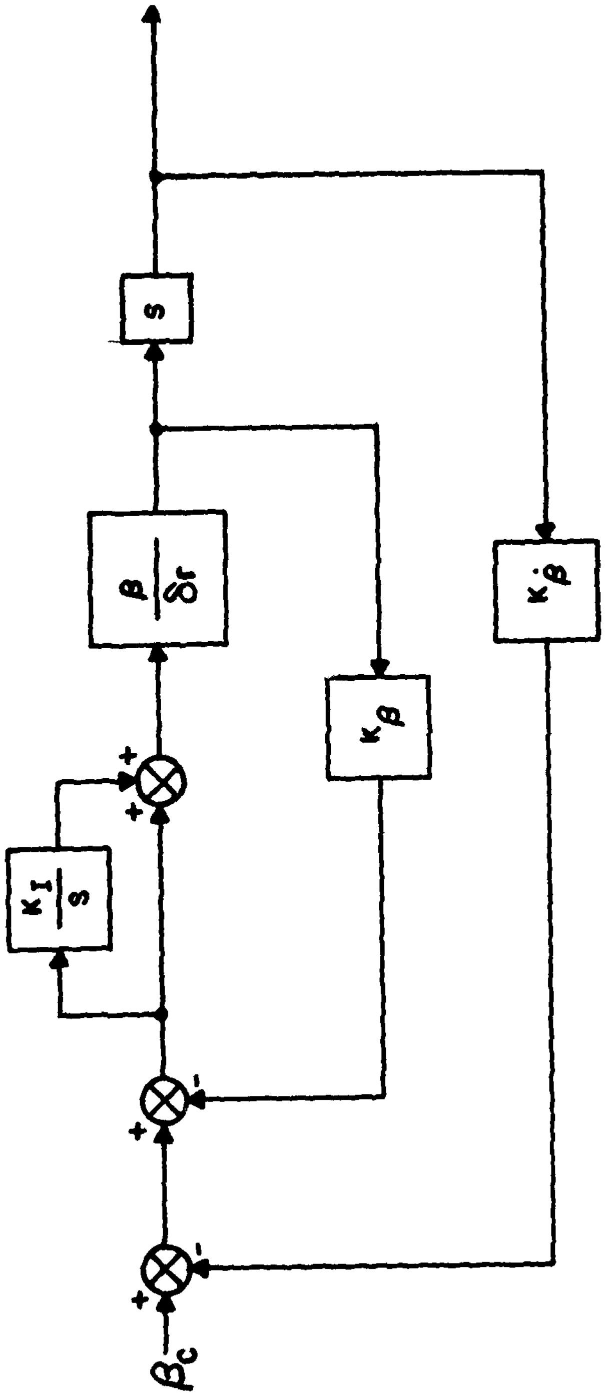


Figure 11. System Model for Constant K_β

To generate a root locus for a varying $K_{\dot{\beta}}$, the beta inner loop must first be closed at a given value of K_β and the inner loop transfer function calculated.

$$\left.\frac{G}{1+GH}\right)_{\substack{\text{Inner Loop}\\ \text{const } K_\beta}} = \frac{\dfrac{K(s+a)(s+K_I)}{s(s^2+bs+c)}}{1+\dfrac{K_\beta K(s+a)(s+K_I)}{s(s^2+bs+c)}} \qquad (2)$$

Simplifying.

$$\left.\frac{G}{1+GH}\right)_{\substack{\text{Inner Loop}\\ \text{const } K_\beta}} =$$

$$\frac{K(s+a)(s+K_I)}{s^3+(b+KK_\beta)s^2+[c+KK_\beta(K_I+a)]s+KK_IK_\beta a} \qquad (3)$$

The open loop transfer function for the complete system is now obtained by multiplying the inner loop transfer function, Equation 3, by $sK_{\dot{\beta}}$

$$GH)_{\substack{\text{Overall}\\ \text{Const } K_\beta}} = \frac{K_{\dot{\beta}}Ks(s+a)(s+K_I)}{s^3+(b+KK_\beta)\,s^2+[c+KK_\beta(K_I+a)]S+KK_IK_\beta a} \qquad (4)$$

Using Equation 4, root locus plots are drawn for different values of K_β. These plots show the closed loop poles for a given value of K_β as $K_{\dot{\beta}}$ varies from zero to infinity. Unfortunately, the gain $K_{\dot{\beta}}$ is not explicit on the root locus. The desired closed-loop pole location must be chosen and then compared with the tabular output to find the corresponding value of $K_{\dot{\beta}}$. This is an extremely time consuming process when responses at given values of K_β and $K_{\dot\beta}$ must be compared throughout the flight envelope. To simplify this process of gain selection, root loci were also drawn at constant values of $K_{\dot\beta}$.

A procedure similar to the method described above is used to get these root locus plots at constant values of $K_{\dot\beta}$. Figure 12 shows the system model used for this procedure. The transfer function $\dot\beta/\delta r$ is just $s\beta/\delta r$, as shown below, where $\beta/\delta r$ is the same as Equation 1.

$$\dot\beta/\delta r = \frac{Ks(s + a)}{s^2 + bs + c} \tag{5}$$

Using Figure 12, the betadot inner loop is closed first to obtain the inner-loop transfer function.

$$\left.\frac{G}{1 + GH}\right|_{\substack{\text{Inner Loop}\\ \text{Const } K_{\dot\beta}}} = \frac{\dfrac{Ks(s + a)(s + K_I)}{s(s^2 + bs + c)}}{1 + \dfrac{K_{\dot\beta}K(s + a)(s + K_I)s}{s(s^2 + bs + c)}} \tag{6}$$

Simplifying.

$$\left.\frac{G}{1 + GH}\right|_{\substack{\text{Inner Loop}\\ \text{Const } K_{\dot\beta}}} = \frac{\dfrac{K}{1 + K_{\dot\beta}K}s(s + a)(s + K_I)}{s^3 + \dfrac{b + K_{\dot\beta}K(K_I + a)}{1 + K_{\dot\beta}K}s^2 + \dfrac{c + K_{\dot\beta}K_IKa}{1 + K_{\dot\beta}K}s} \tag{7}$$

The open-loop transfer function for the complete system is obtained by multiplying the inner loop transfer function, Equation 7, by K_β/s.

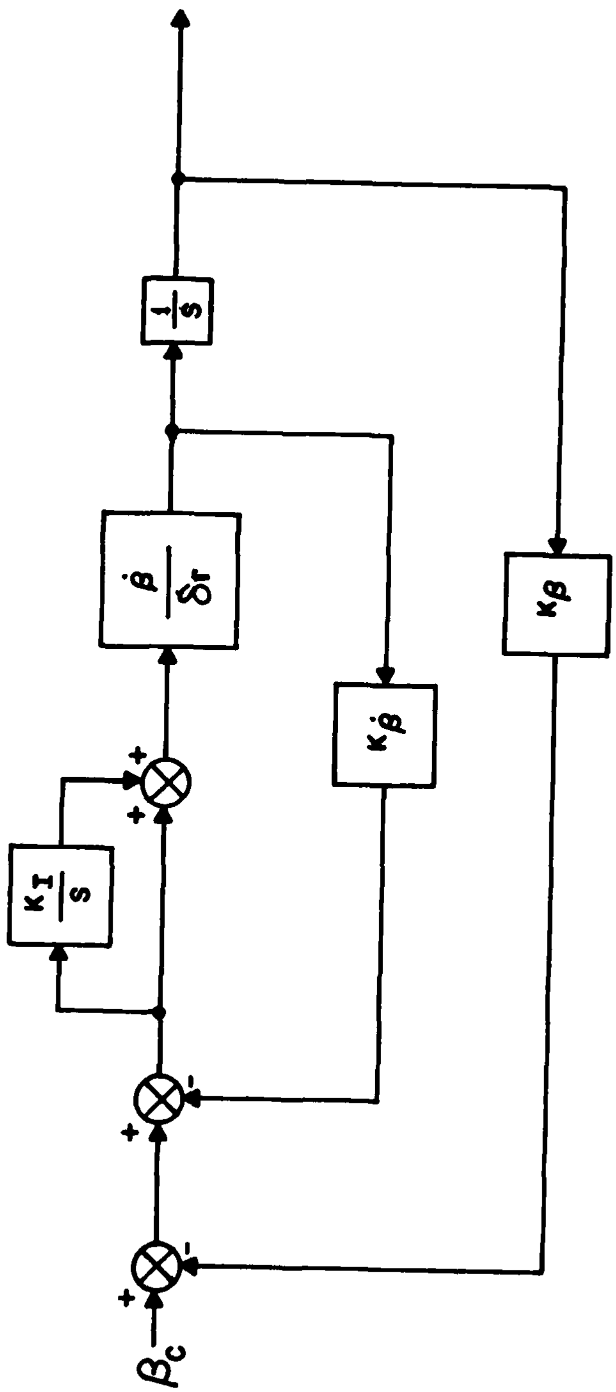


Figure 12. System Model for Constant $K_{\dot{\beta}}$

$$GH)_{\substack{\text{Overall}\\ \text{Const } K_{\dot\beta}}} = \frac{\dfrac{K_\beta K}{1 + K_{\dot\beta}K}(s + a)(s + K_I)}{s^3 + \dfrac{b + K_{\dot\beta}K(K_I + a)}{1 + K_{\dot\beta}K}s^2 + \dfrac{c + K_{\dot\beta}K_I Ka}{1 + K_{\dot\beta}K}s} \qquad (8)$$

Using Equation 8, root locus plots for different values of $K_{\dot\beta}$ can be drawn. Poles and zeros of Equations 4 and 8 are tabulated in Appendix B for the flight condition analyzed.

To construct a root map, root loci are calculated, using Equations 4 and 8. Constant K_β root locus plots are drawn by setting K_β constant in Equation 4 and letting $K_{\dot\beta}$ varying from zero to infinity. Values of K_β from 1 to 15 are used. The constant $K_{\dot\beta}$ root locus plots are drawn in the same manner except that $K_{\dot\beta}$ is fixed and K_β varies. Values of $K_{\dot\beta}$ from 1 to 7 are used. The root map consists of these 22 root locus plots displayed on the same s-plane.

Root maps were constructed for the flight conditions shown in Table 1 to insure that the gains chosen for K_β and $K_{\dot\beta}$ are adequate for the entire flight envelope. Figures 13a through 13i show these root maps. Also displayed on the maps is the boundary for a good response, a response acceptable for ATA tracking. The boundary represents specifications of the damping ratio from .65 to .75 and the natural frequency from 3.5 to 6 rad/sec. The specified damping ratio would provide good lateral damping while the specified natural frequency provides adequate speed of response.

TABLE 1

ROOT MAP FLIGHT CONDITIONS

Map	Mach	Altitude
1	.4	S.L.
2	.9	S.L.
3	.7	10000
4	.6	15000
5	.9	15000
6	1.2	15000
7	.6	30000
8	.9	30000
9	1.4	30000

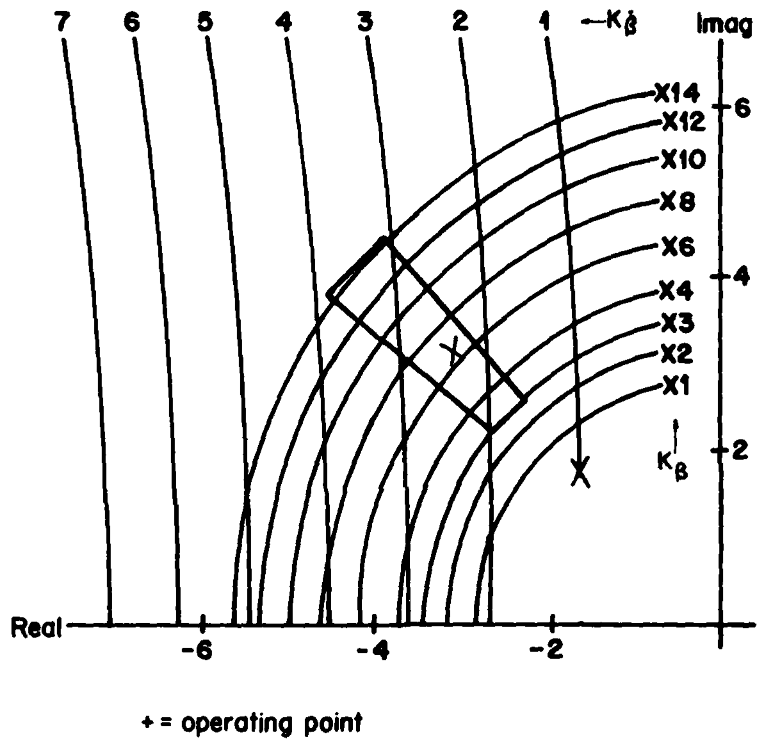


Figure 13a. Root Map at Mach .4, Sea Level

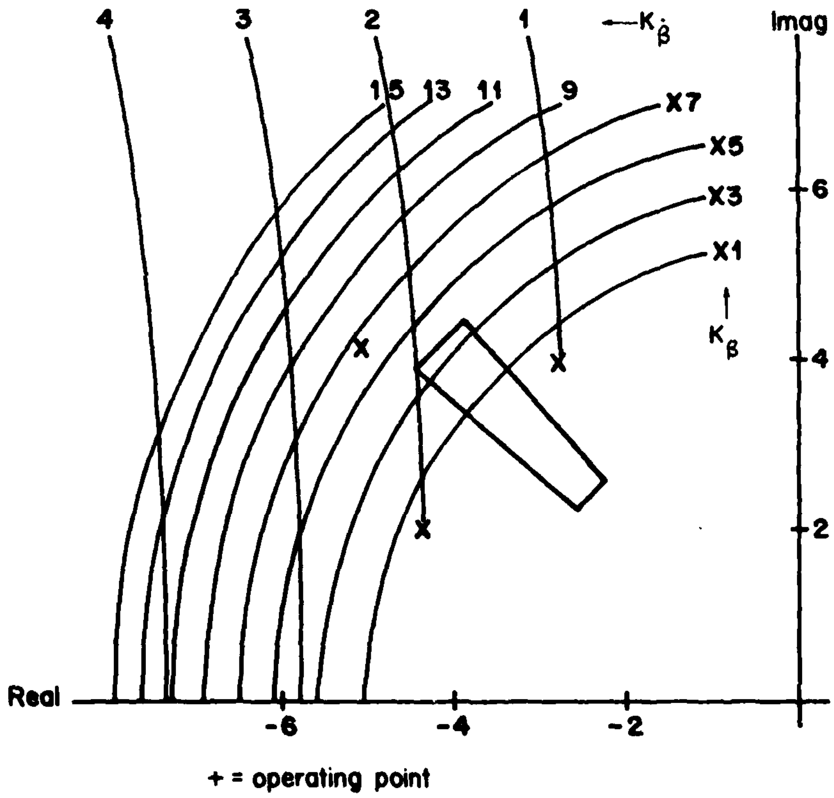


Figure 13b. Root Map at Mach .9, Sea Level

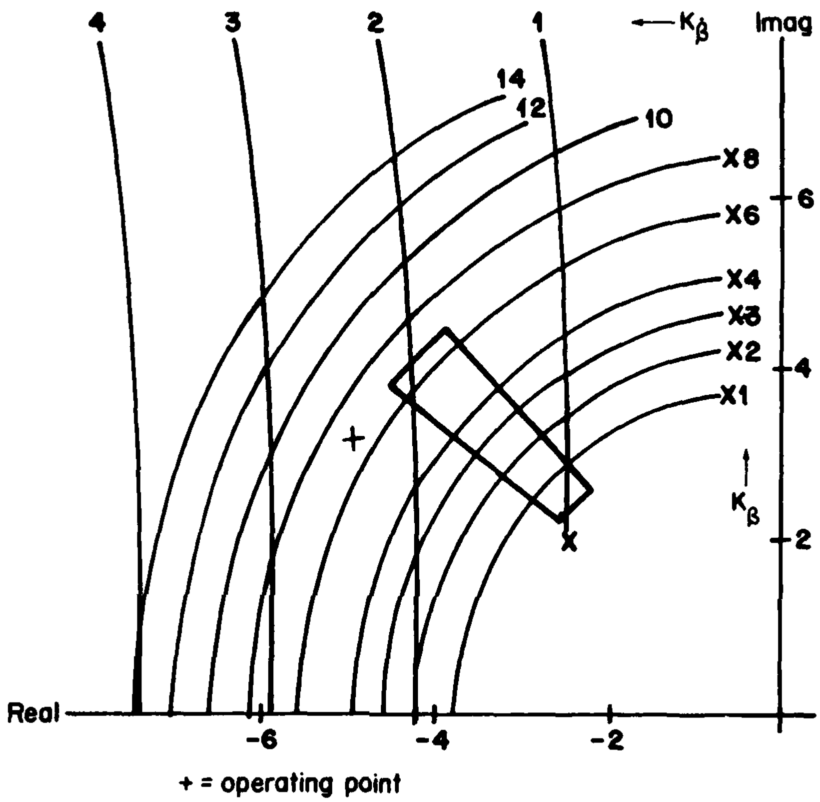


Figure 13c. Root Map at Mach .7, 10000 Feet

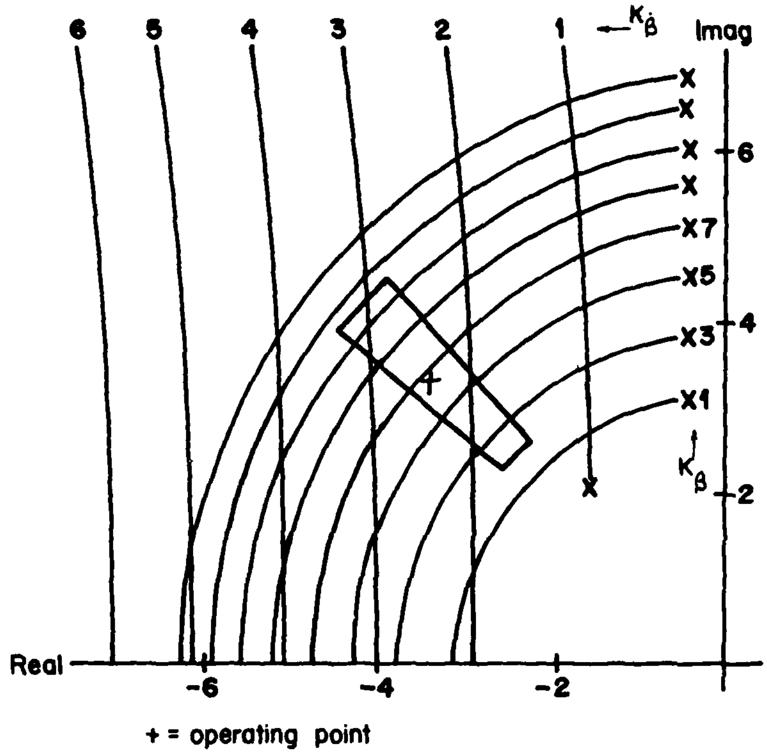


Figure 13d. Root Map at Mach .6, 15000 Feet

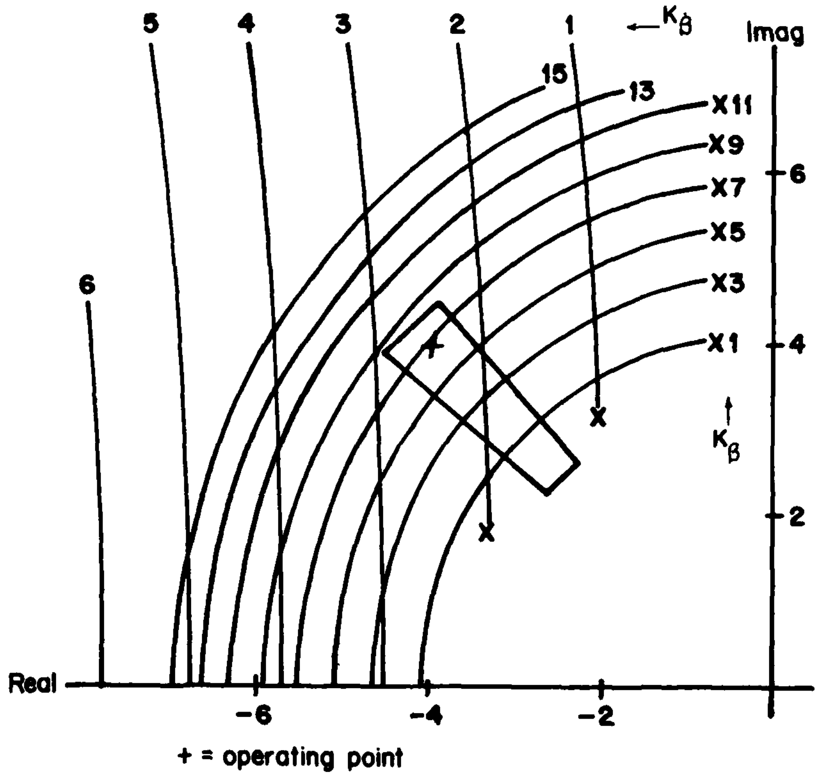


Figure 13e. Root Map at Mach .9, 15000 Feet

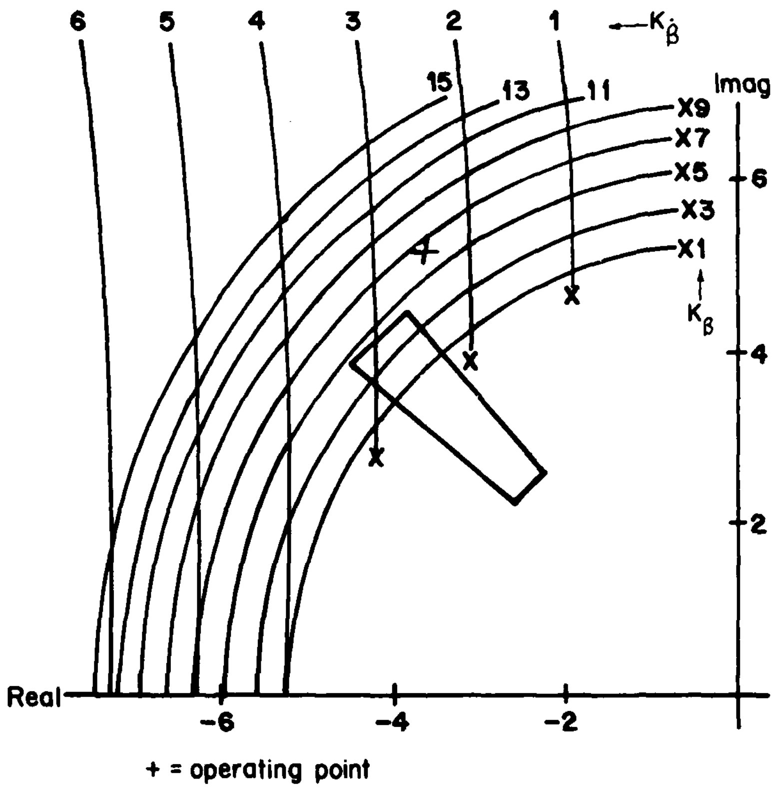


Figure 13f. Root Map at Mach 1.2, 15000 Feet

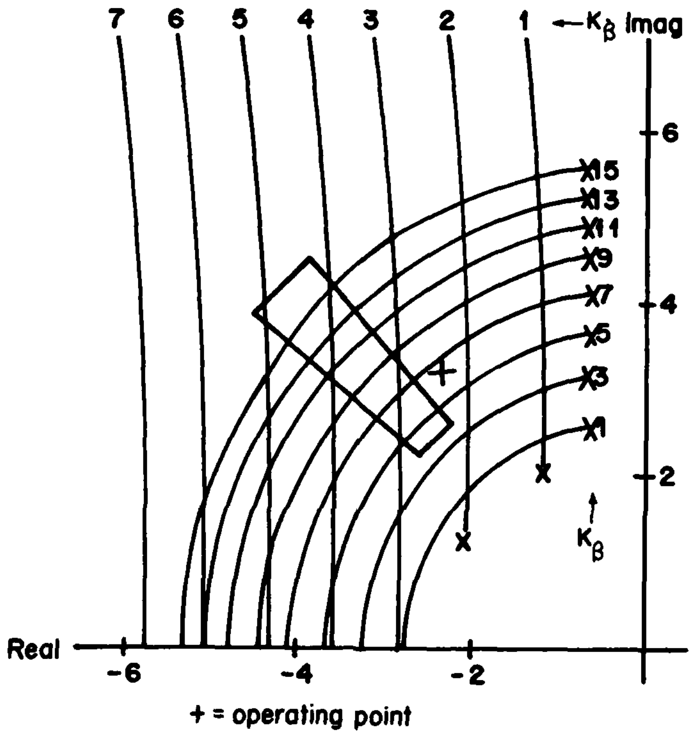


Figure 13g. Root Map at Mach .6, 30000 Feet

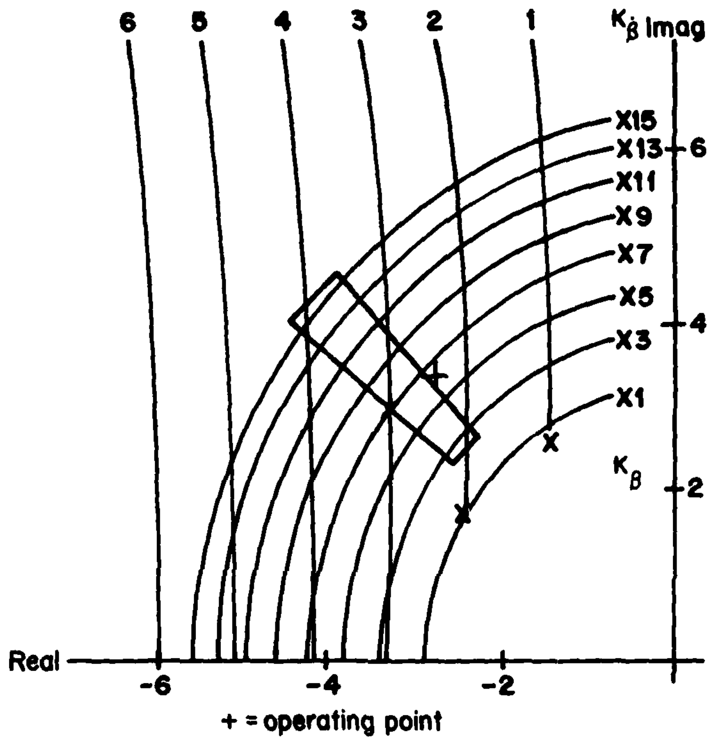


Figure 13h. Root Map at Mach .9, 30000 Feet

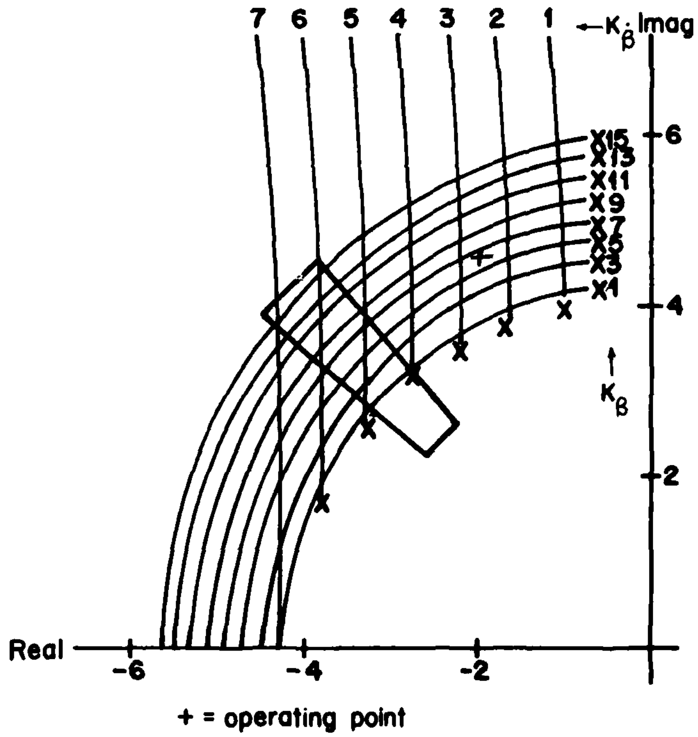


Figure 13i. Root Map at Mach 1.4, 30000 Feet

To simplify the design, the option of gain scheduling K_β and $K_{\dot{\beta}}$ is eliminated. This means that the values of K_β and $K_{\dot{\beta}}$ should be set to obtain an adequate response throughout the envelope but, if possible, a good response at flight conditions typical for ATA tracking. ATA tracking typically occurs at high subsonic Mach numbers at low and middle altitudes. Using this somewhat subjective criterion, values of K_β and $K_{\dot{\beta}}$ were chosen as 6.5 and 2.5, respectively. These values are shown on the root maps as the operating gains. Table 2 shows the response of the aircraft in terms of damping and natural frequency at these operating gains.

TABLE 2

F-106 RESPONSE AT K_β = 6.5 AND $K_{\dot{\beta}}$ = 2.5

Map	Mach, Altitude	Damping Ratio	Natural Frequency (rad/sec)
Figure 13a	.4, S.L.	.71	4.5
Figure 13b	.9, S.L.	.79	6.6
Figure 13c	.7, 10000	.86	5.8
Figure 13d	.6, 15000	.67	4.8
Figure 13e	.9, 15000	.71	5.6
Figure 13f	1.2, 15000	.6	6.4
Figure 13g	.6, 30000	.6	4.0
Figure 13h	.9, 30000	.68	4.4
Figure 13i	1.4, 30000	.4	5.0

Table 2 shows that the chosen gains for K_β and $K_{\dot{\beta}}$ of 6.5 and 2.5 do provide a good response at the lower altitude, subsonic flight conditions. At the two supersonic conditions, however, the response is somewhat underdamped. This tendency of an underdamped response at supersonic Mach numbers should not be important since almost no tracking is done supersonically.

3. FREQUENCY RESPONSE ANALYSIS

The preliminary design of the β-$\dot{\beta}$ system using the model from Figure 10 shows that acceptable responses can be achieved using gains of 6.5 and 2.5 for K_β and $K_{\dot{\beta}}$. This acceptability criteria is based subjectively on the values of dutch roll damping and natural frequency. Since these gains come from the root map analysis, which assumes a second-order-linear aircraft model, it is appropriate to look at these gains in a more sophisticated model. The EASY Dynamic Analysis Program (Reference 2) is used to achieve this more elaborate model. Appendix C contains a short description of the EASY program and contains the input data for the frequency analyses.

The EASY program was used to obtain closed-loop frequency plots for the following transfer functions: $\beta/\delta r$, $\phi/\delta r$, $\beta/\delta a$. These plots are shown for flight conditions of Mach .8 at 10000 feet and Mach .6 at 30000 feet. The first condition is somewhat typical of an ATA engagement and the second is representative of a low dynamic pressure situation for the aircraft. The three transfer functions above are chosen specifically because each shows information significant to the ATA tracking task. The frequencies of greatest importance for ATA tracking are those around the dutch roll frequency. These frequencies are important because the dutch roll mode is continually being excited during tracking. The frequencies range from about two to seven rad/sec depending on control system and flight condition. $\beta/\delta r$ gives an indication of the ease with which the pilot can point the aircraft using the rudder. $\phi/\delta r$ shows the coupling effect of rudder into roll angle and it can also give an indication of the ease with which the pilot can point the aircraft. An aircraft with a control system designed to facilitate ATA tracking should have a large magnitude for $\beta/\delta r$ (near 0 db) to provide adequate pointing capability while maintaining a low magnitude for $\phi/\delta r$, or low roll/sideslip coupling. The effect of a large $\phi/\delta r$ would be an increase in pilot workload due to the inadvertent roll angles. $\beta/\delta a$ is an indicator of how well the aircraft is maintaining coordinated flight, or equivalently, how precisely the aircraft is rolling about the velocity vector. A low magnitude for $\beta/\delta a$ is most advantageous for ATA tracking.

The closed-loop frequency plots for the two flight conditions are shown for the bare airframe, standard SAS, and β-$\dot{\beta}$ SAS. Figures 14a - 14c and Figures 15a - 15c show the frequency response for $\beta/\delta r$ for both flight conditions. The plots show that the desirable quality of a relatively large $\beta/\delta r$ is achieved by both the bare airframe and the β-$\dot{\beta}$ SAS at both flight conditions. Figures 16a - 16c and Figures 17a - 17c show $\phi/\delta r$ at the two flight conditions. The bare airframe $\phi/\delta r$ is unacceptably large, but the standard SAS and the β-$\dot{\beta}$ SAS both have much lower magnitudes and are therefore more desirable. This same desirable quality of low coupling magnitude is also shown by the standard and β-$\dot{\beta}$ SAS's in their $\beta/\delta a$ frequency plots. These frequency plots are shown in Figures 18a - 18c and Figures 19a - 19c.

Based on these frequency plots, the bare airframe is obviously least desirable for ATA tracking due to its large $\phi/\delta r$ and $\beta/\delta a$ ratios. On the other hand the standard SAS and the β-$\dot{\beta}$ SAS have much smaller magnitudes for $\beta/\delta a$ and $\phi/\delta r$ and therefore are probably more applicable to ATA tracking. The β-$\dot{\beta}$ SAS shows a larger magnitude $\beta/\delta r$ than the standard SAS, possibly making it easier for the pilot to point the aircraft, but the standard SAS has smaller $\phi/\delta r$ and $\beta/\delta a$ coupling magnitudes, possibly decreasing pilot workload. In summary, the bare airframe is probably not adequate for the tracking task while both the standard and β-$\dot{\beta}$ SAS's appear to be about equal in their capabilities.

4. DETAILED DESIGN MODEL

The preliminary design model from Figure 12 provided a basis for the engineering analysis of the β-$\dot{\beta}$ control. A more detailed model is now presented which includes "real world" criteria in its design. The very first question asked on seeing the preliminary design model is, "Can β and $\dot{\beta}$ be measured?" The answer is yes for the sideslip angle. Beta vanes provide adequate, though somewhat noisy, measurements of β. Sideslip angle rate, on the other hand, is not so easily measured. The beta signal is too noisy to differentiate; hence, some other source for $\dot{\beta}$ must be found.

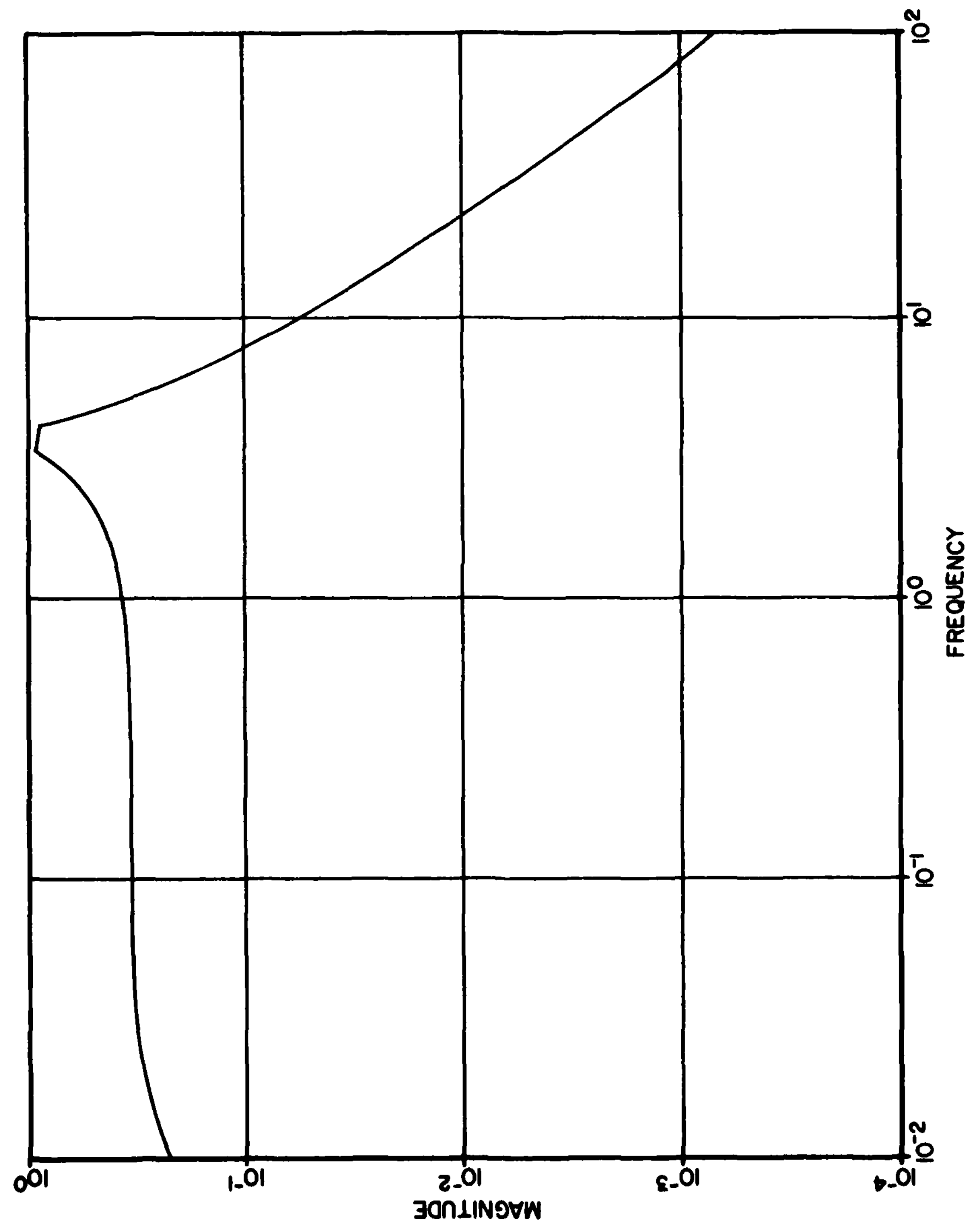


Figure 14a. Bare Airframe Beta/Delta Rudder .8, 10000

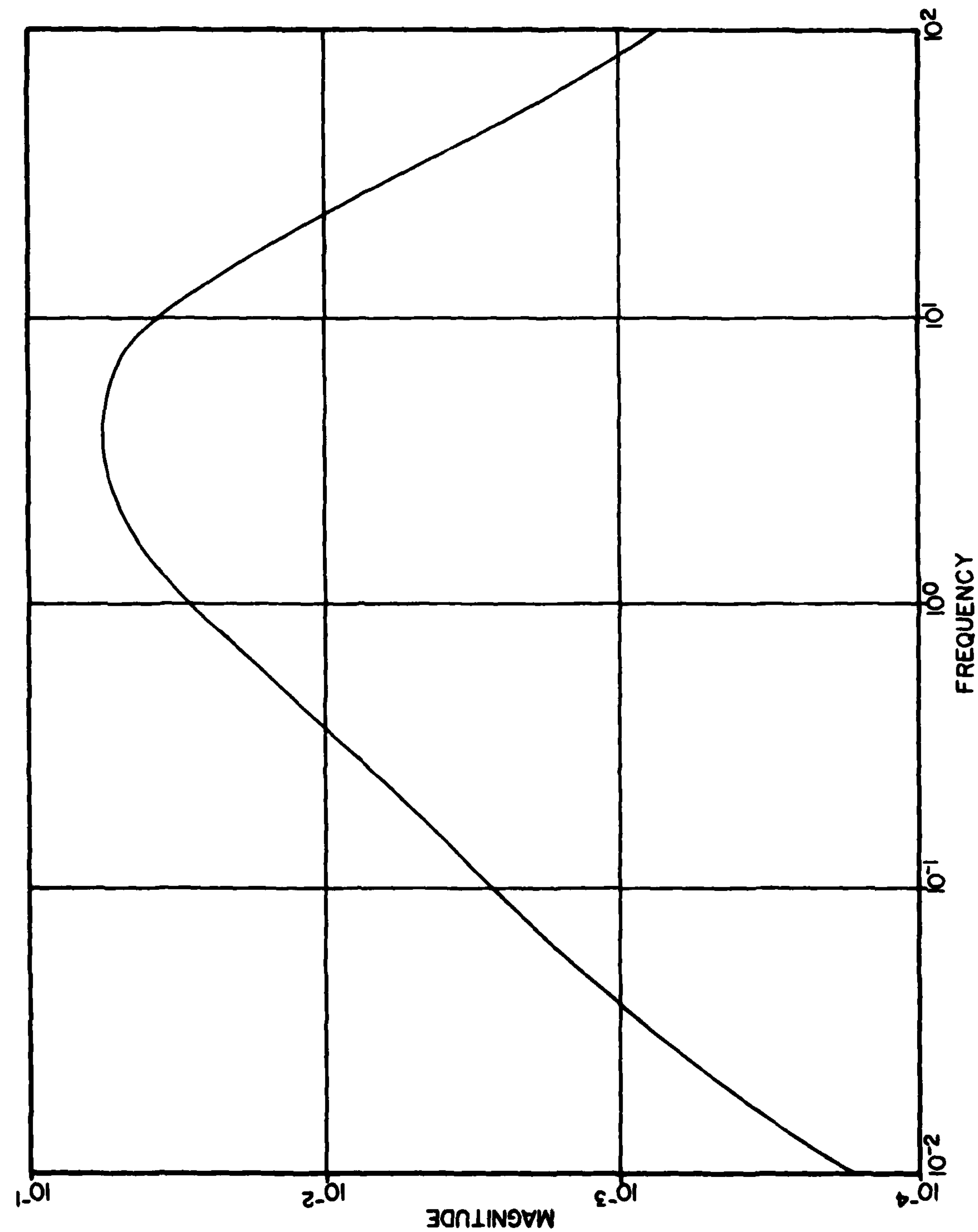


Figure 14b. Standard SAS Beta/Delta Rudder .8, 10000

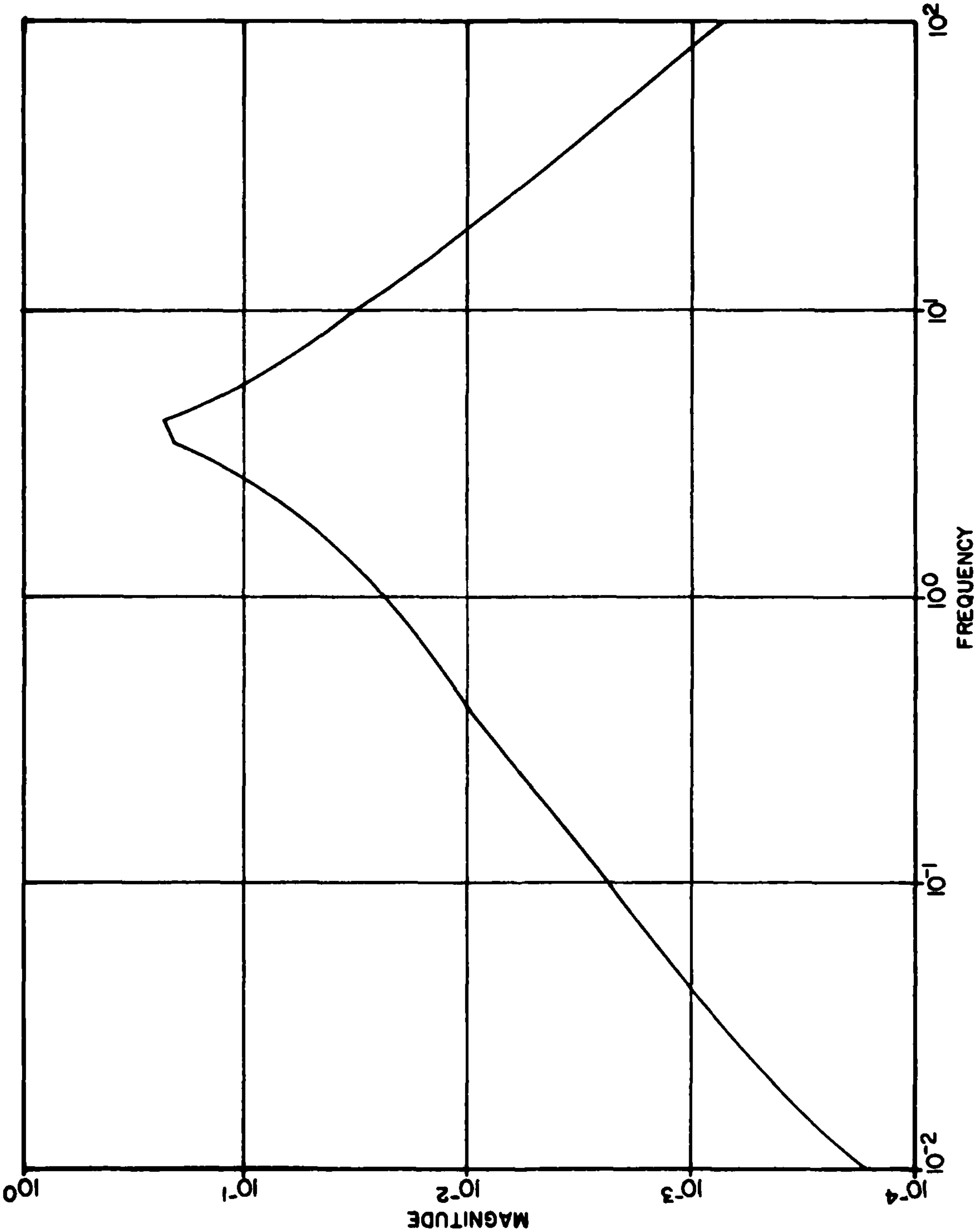


Figure 14c. Betadot SAS Beta/Delta Rudder .8, 10000

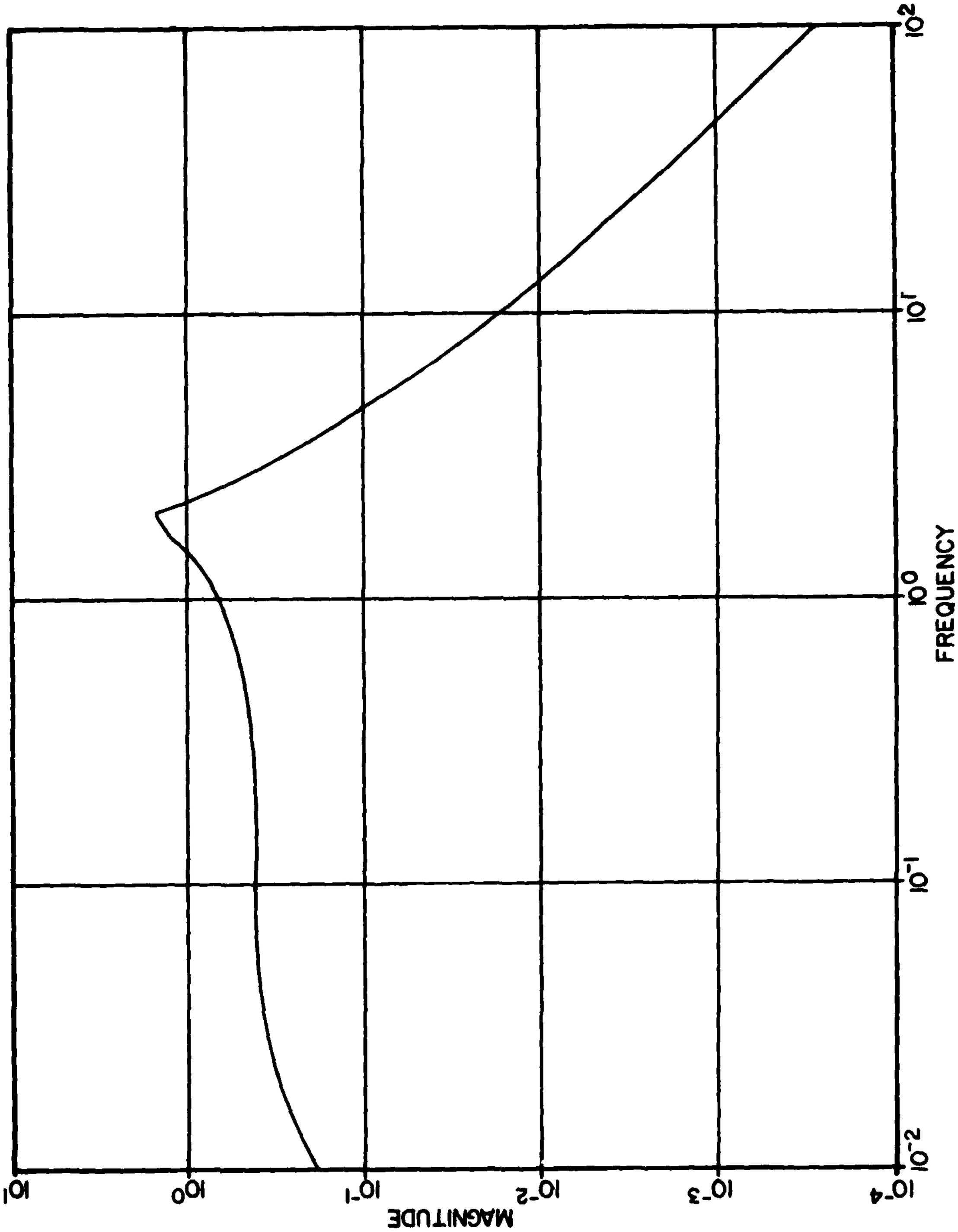


Figure 15a. Bare Airframe Beta/Delta Rudder .6, 30000

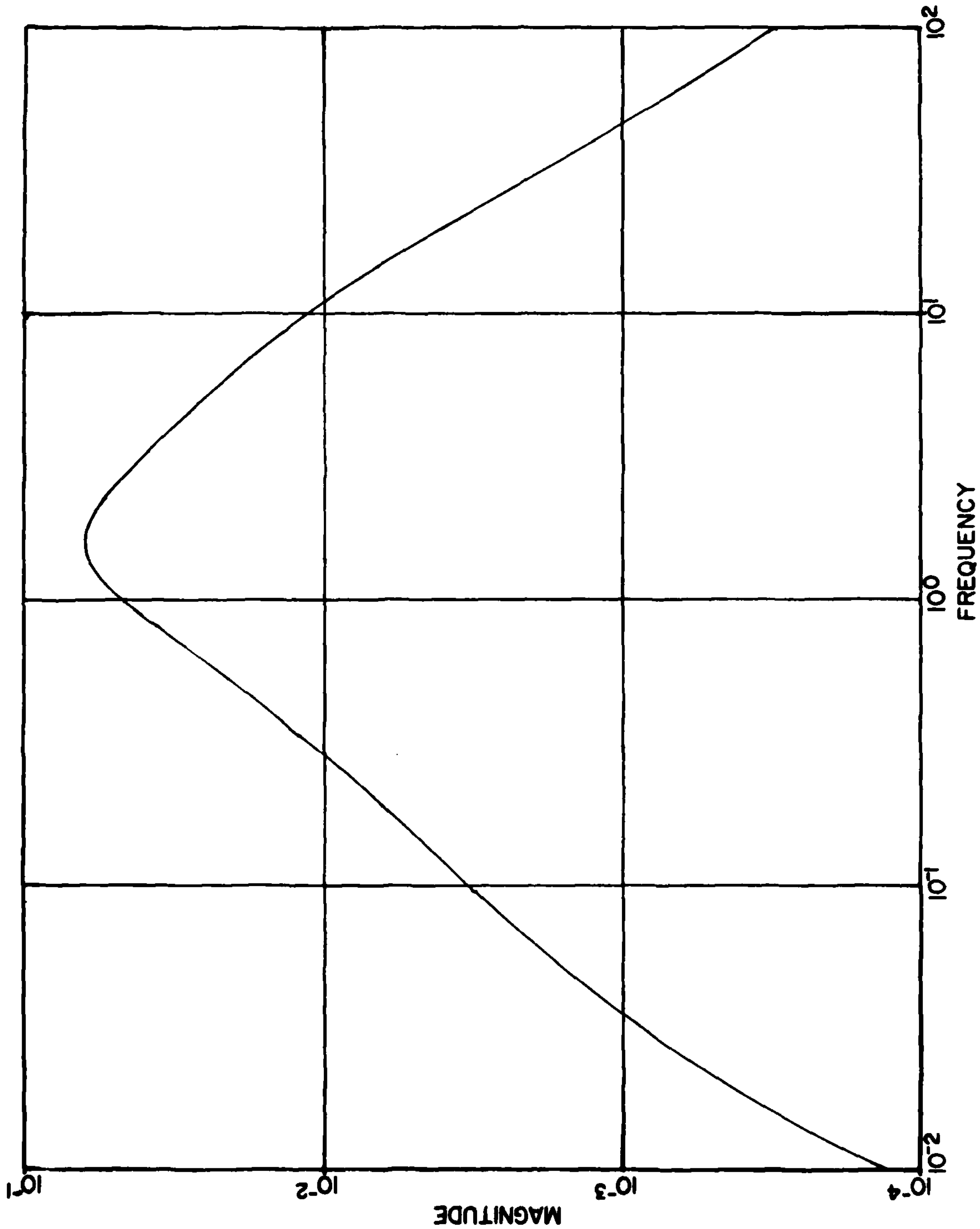


Figure 15b. Standard SAS Beta/Delta Rudder .6, 30000

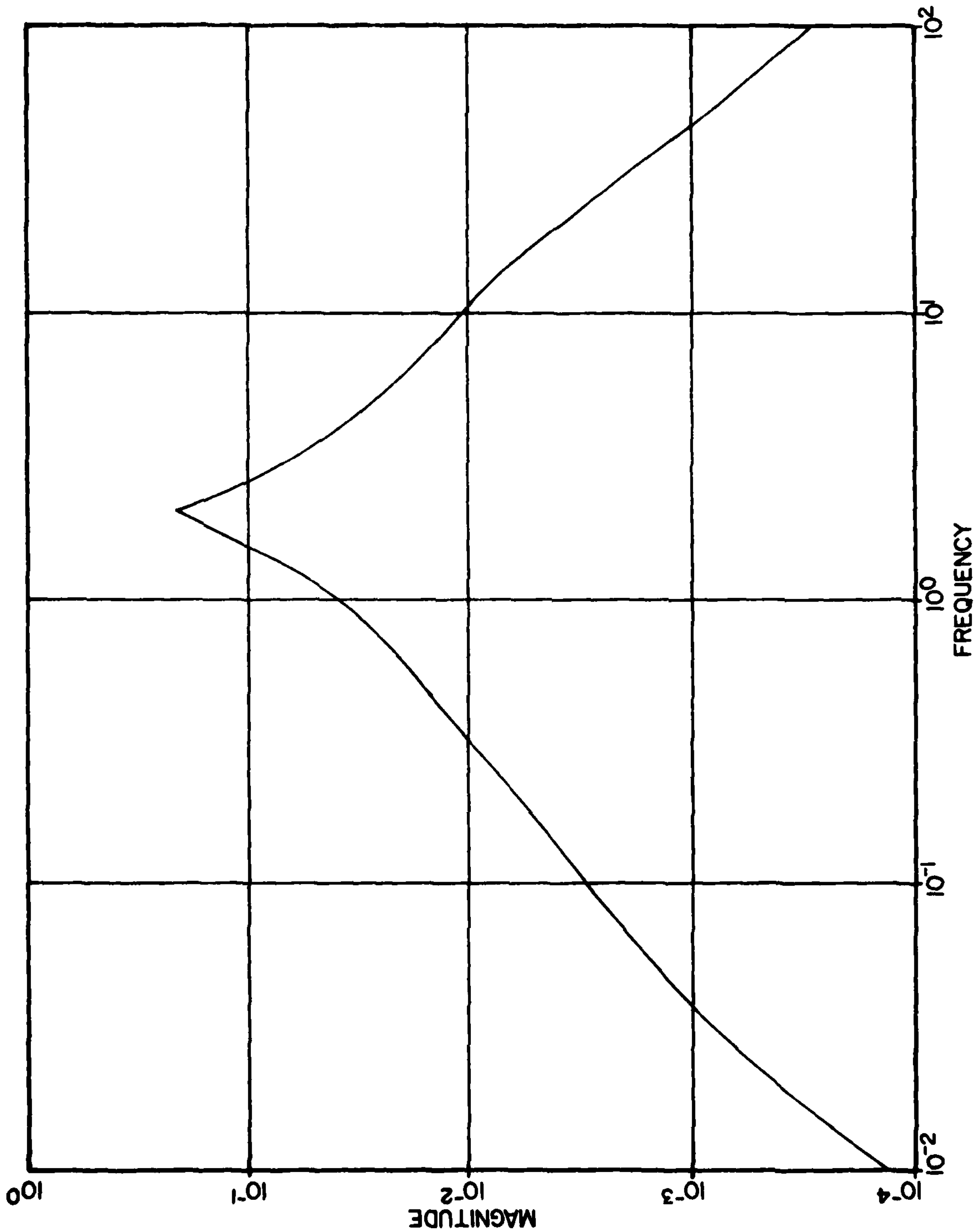


Figure 15c. Betadot SAS Beta/Delta Rudder .6, 30000

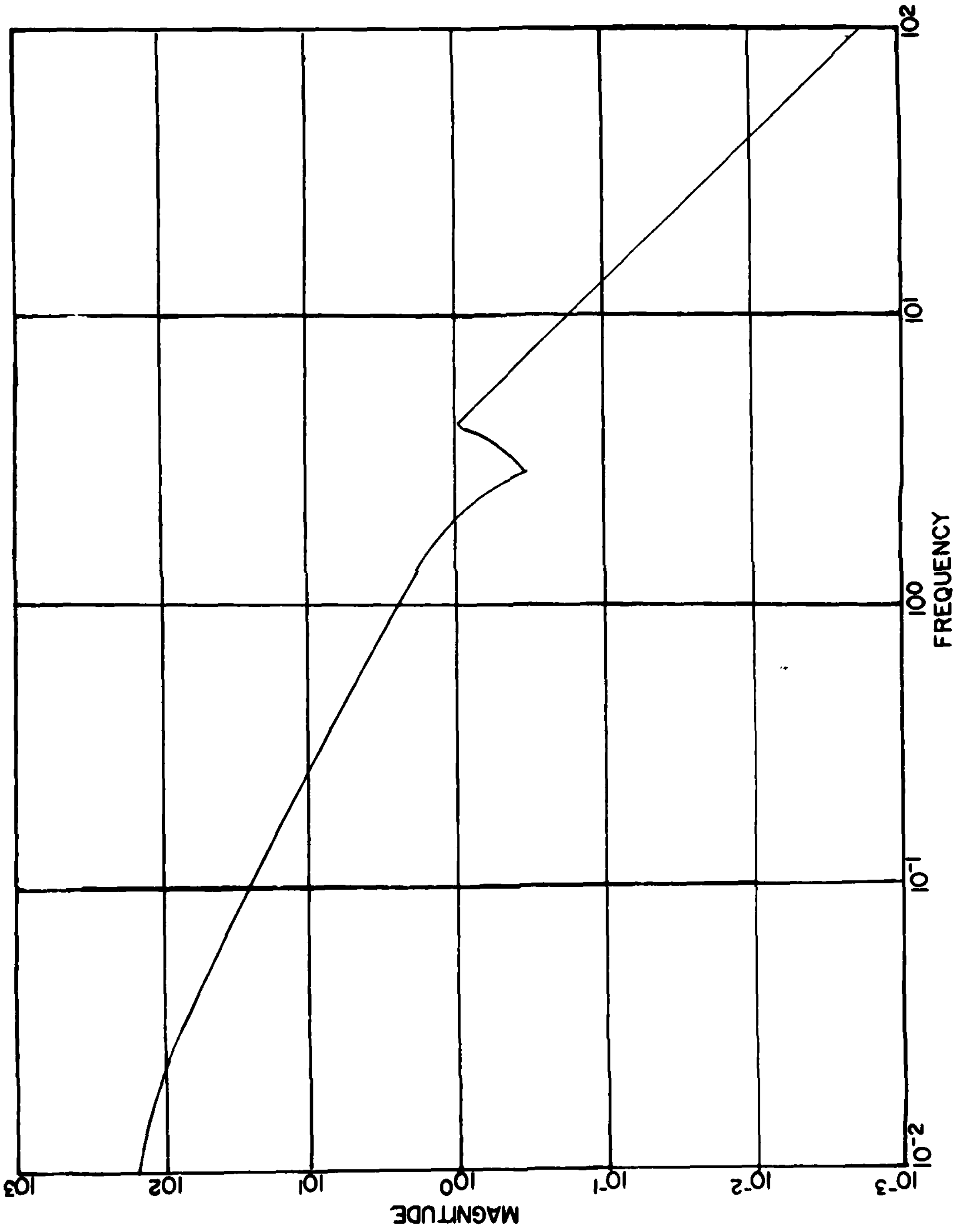


Figure 16a. Bare Airframe Phi/Delta Rudder .8, 10000

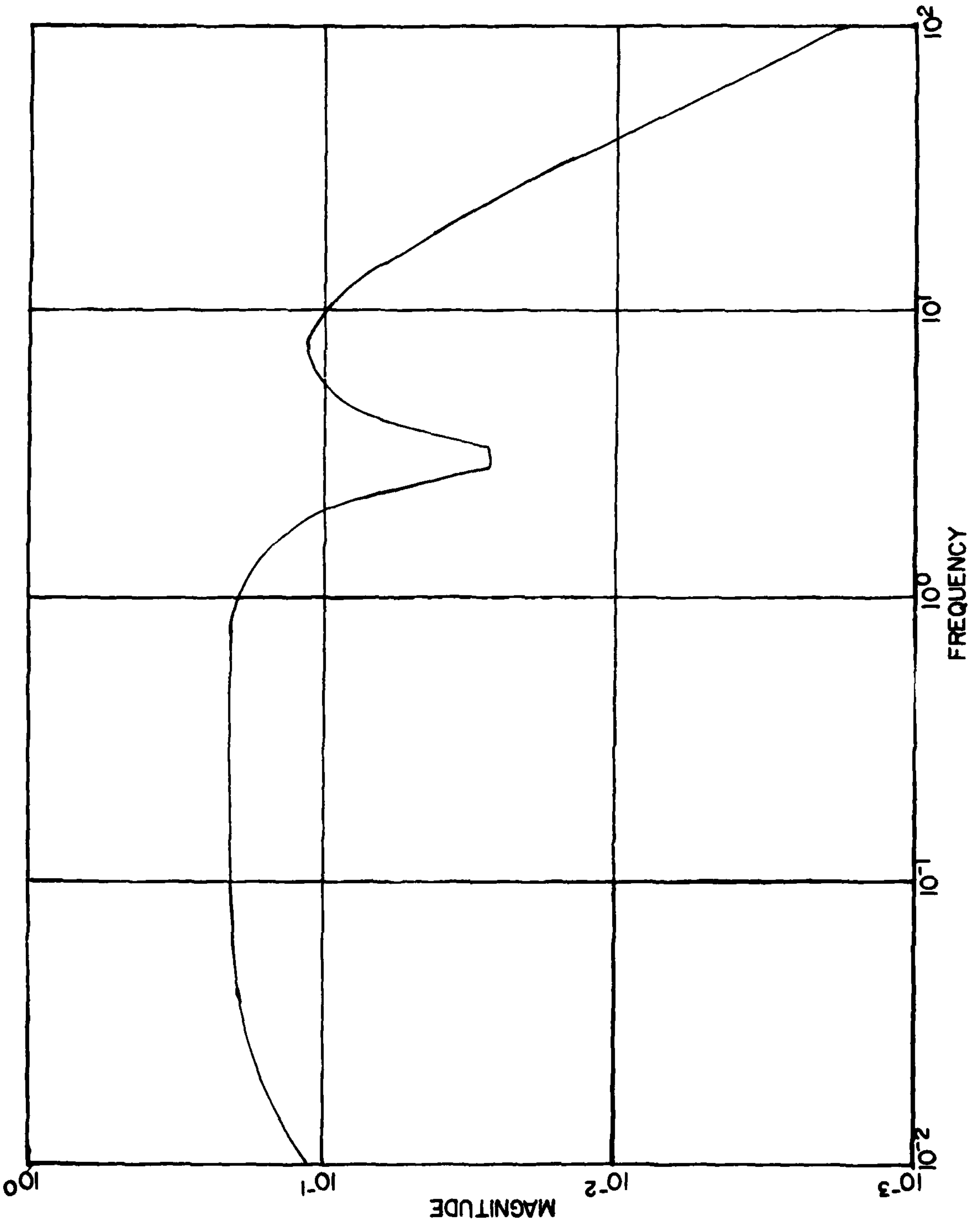


Figure 16b. Standard SAS Phi/Delta Rudder .8, 10000

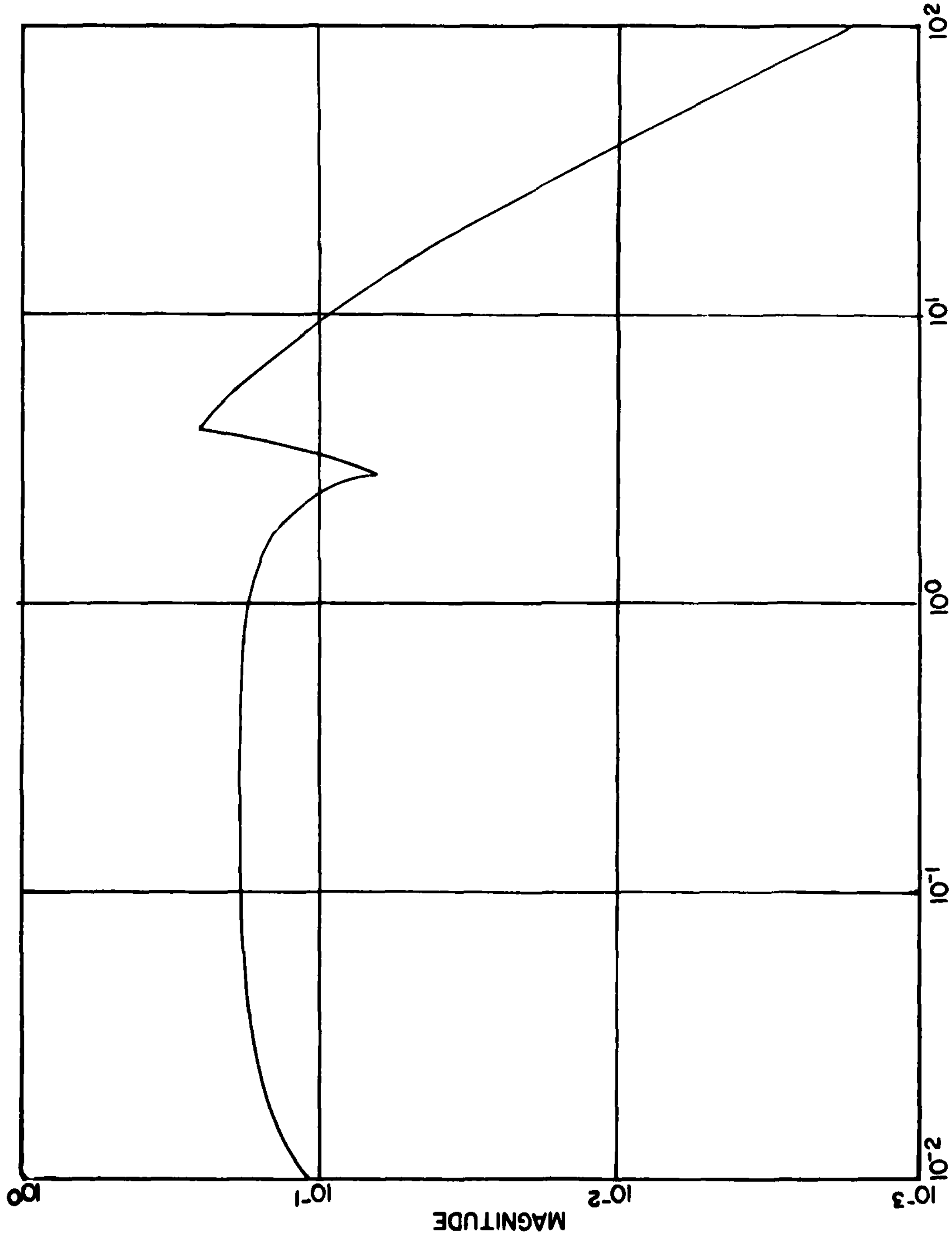


Figure 16c. Betadot SAS Phi/Delta Rudder .8, 10000

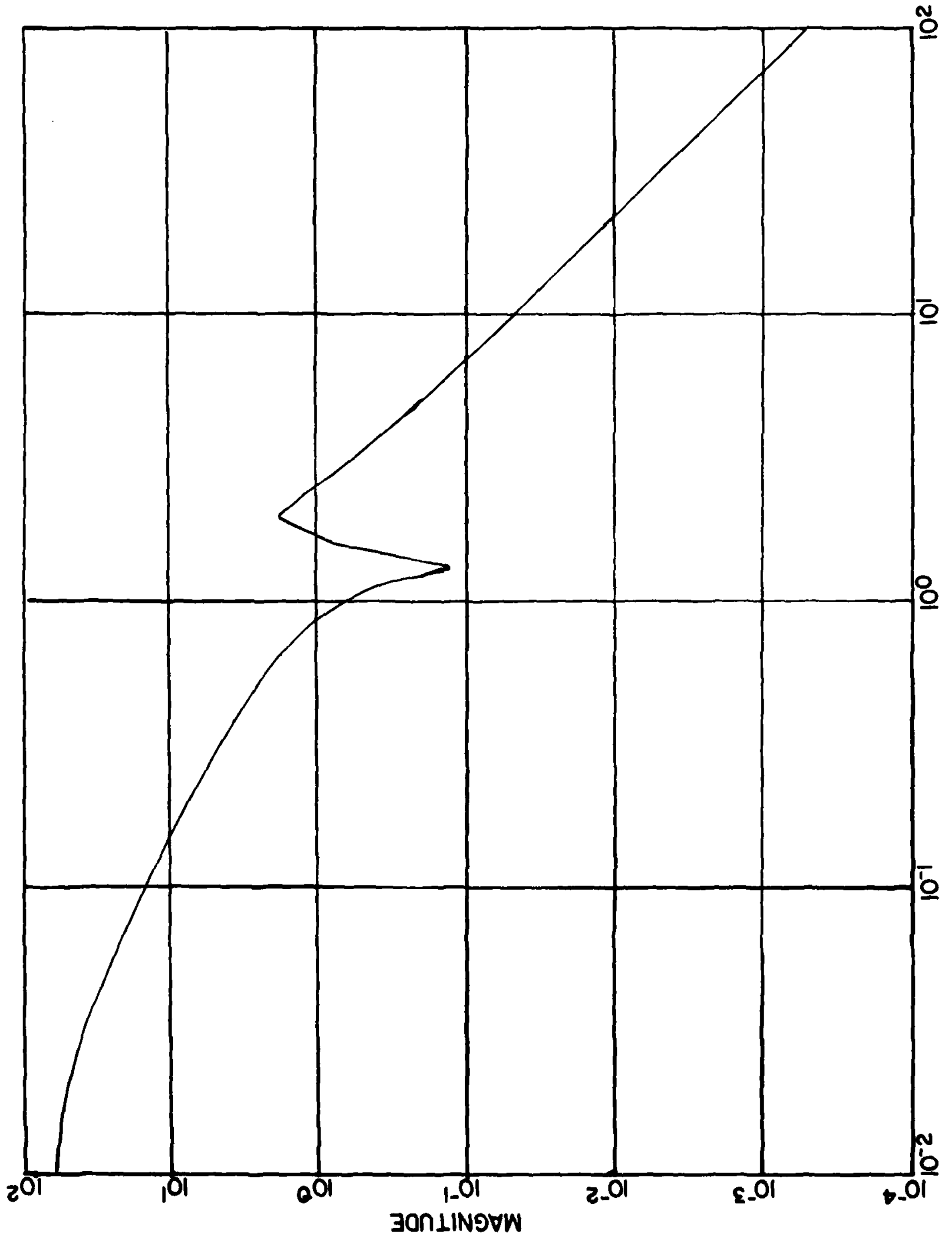


Figure 17a. Bare Airframe Phi/Delta Rudder .6, 30000

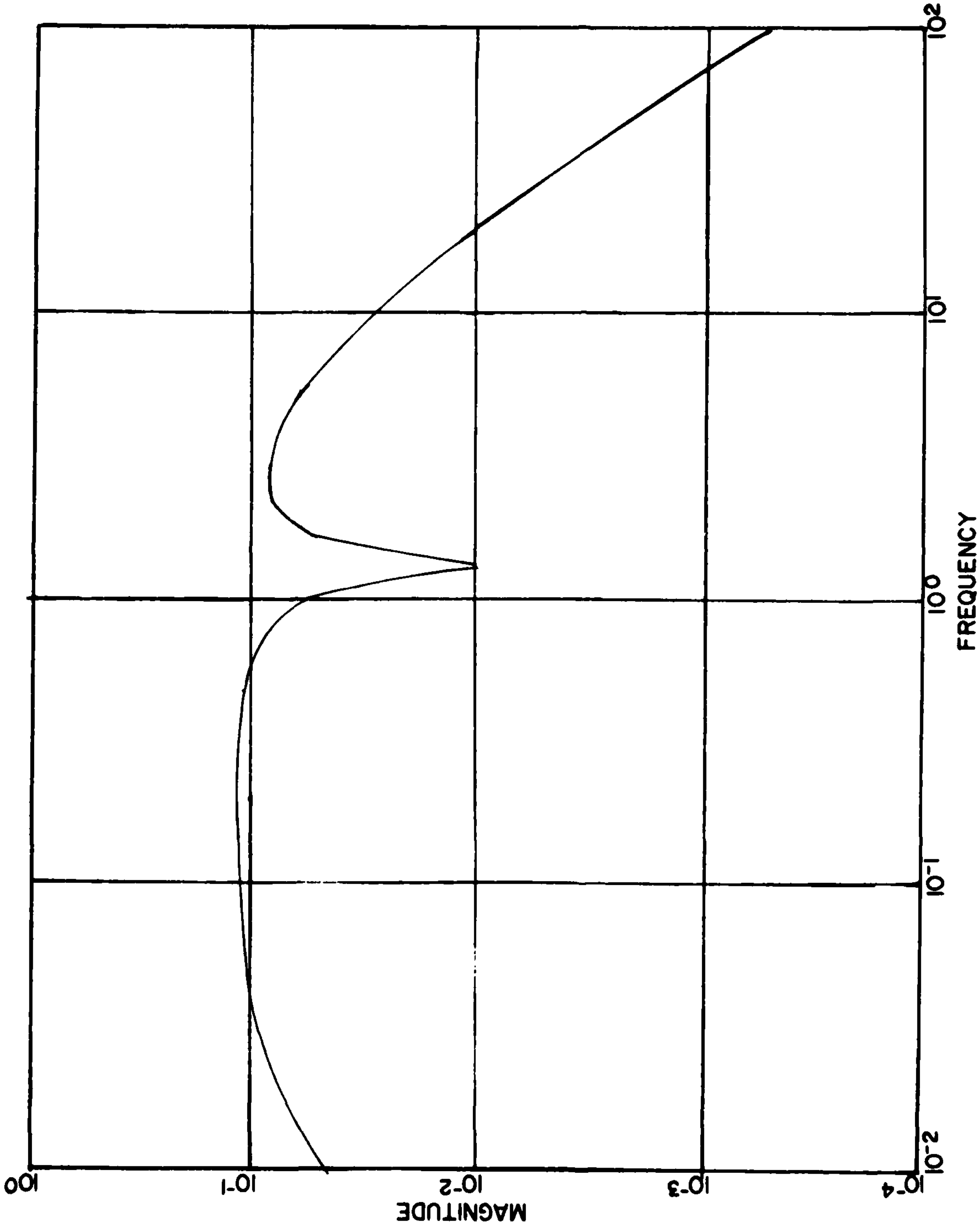


Figure 17b. Standard SAS Phi/Delta Rudder .6, 30000

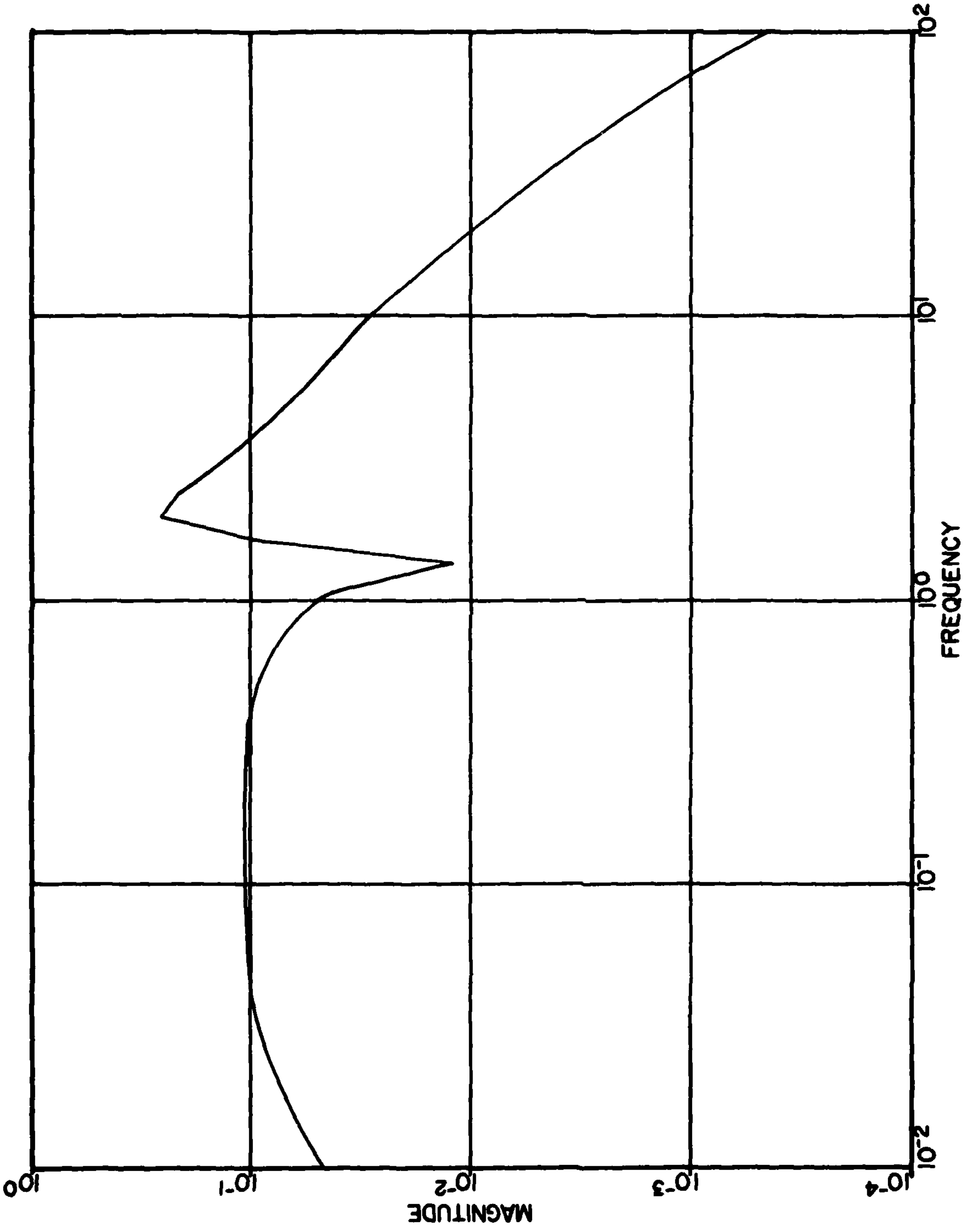


Figure 17c. Betadot SAS Phi/Delta Rudder .6, 30000

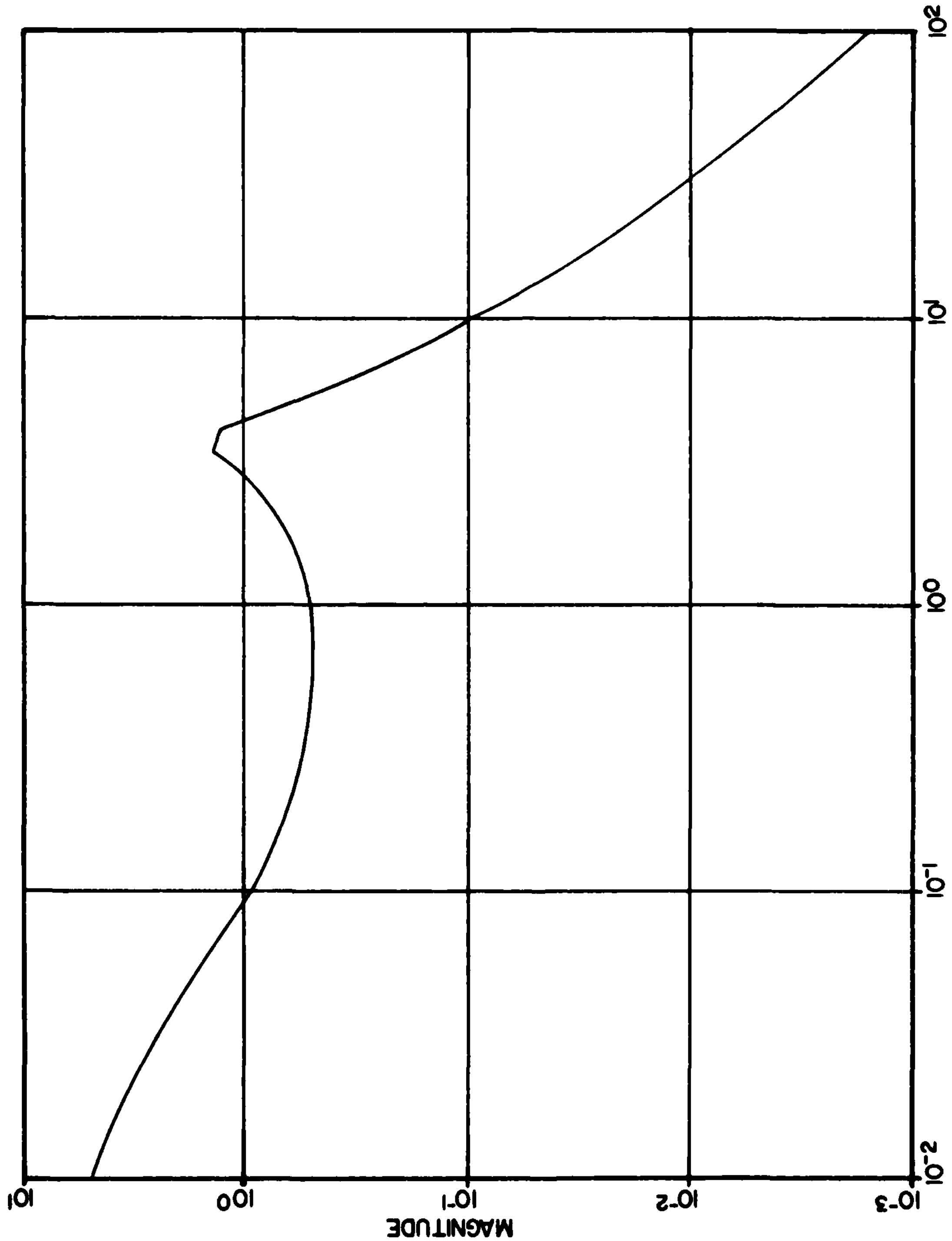


Figure 18a. Bare Airframe Beta/Delta Aileron .8, 10000

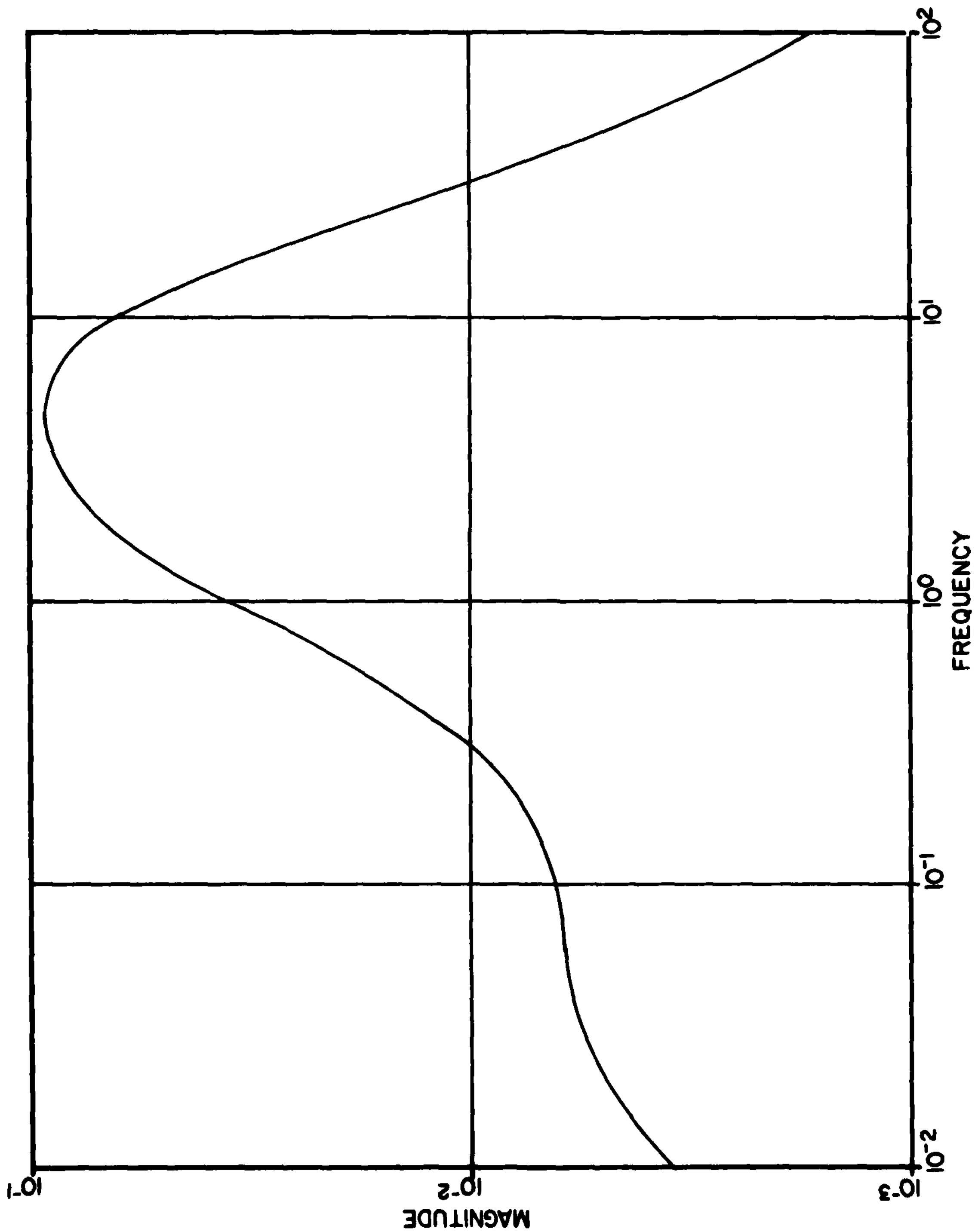


Figure 18b. Standard SAS Beta/Delta Aileron .8, 10000

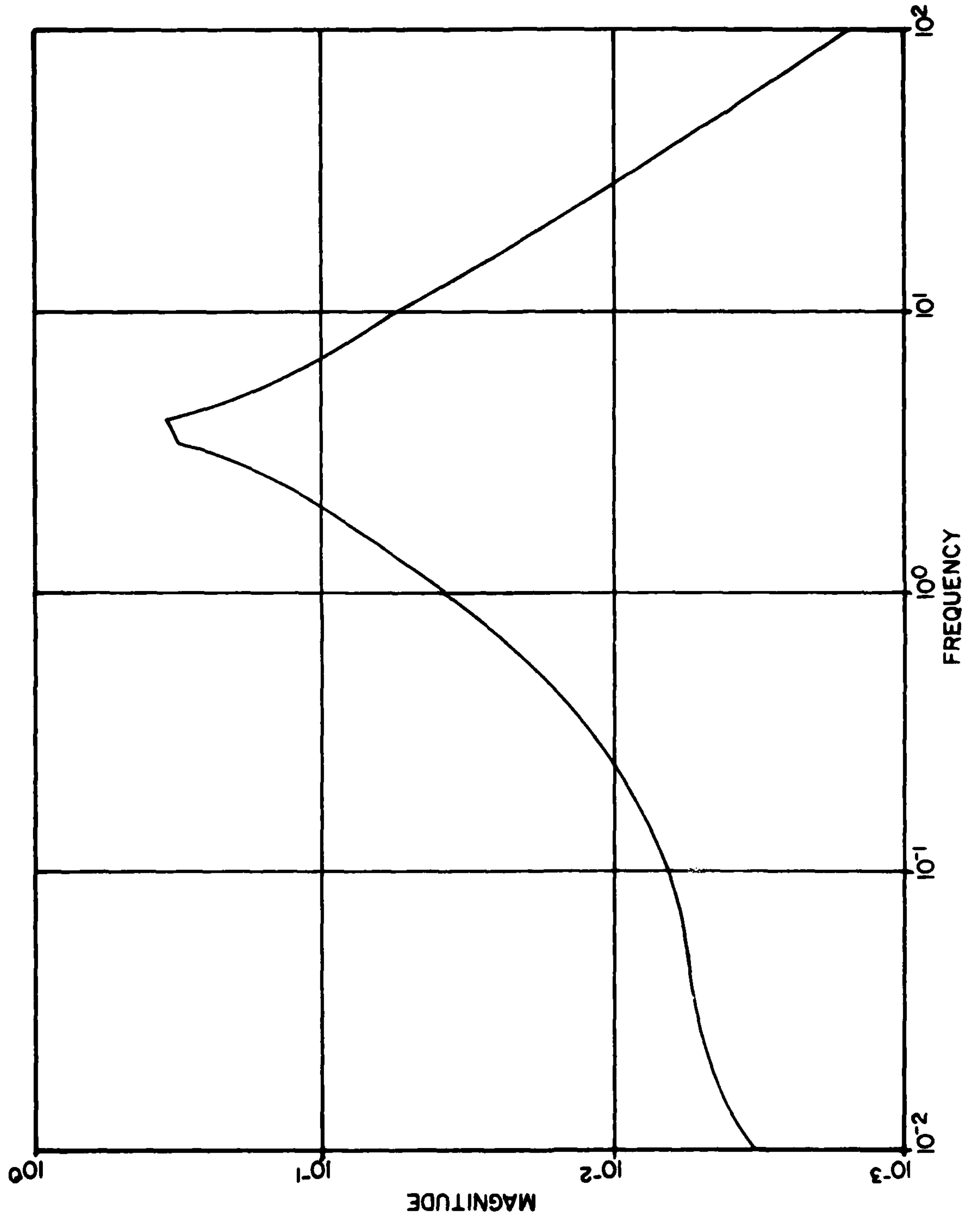


Figure 18c. Betadot SAS Beta/Delta Aileron .8, 10000

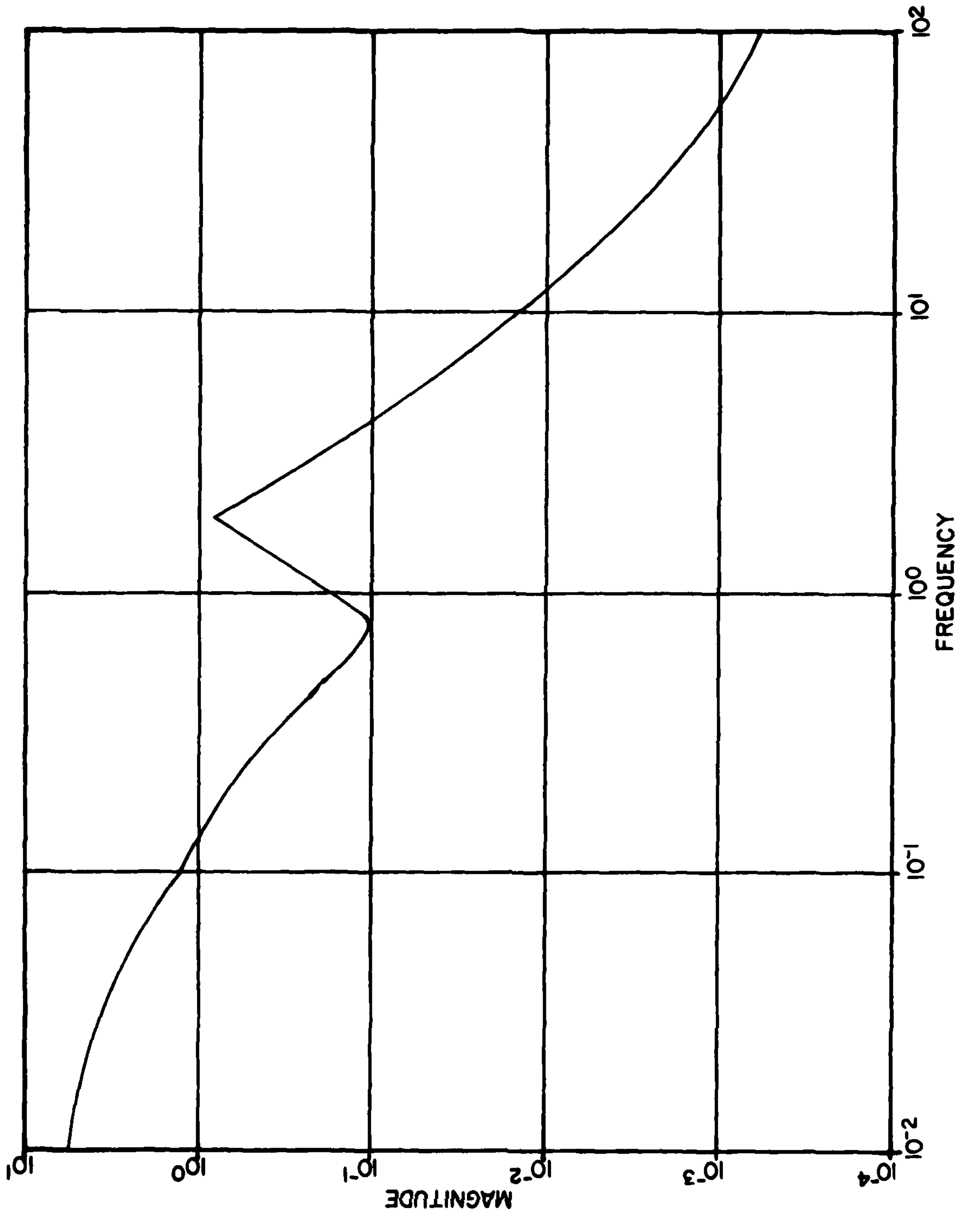


Figure 19a. Bare Airframe Beta/Delta Aileron .6, 30000

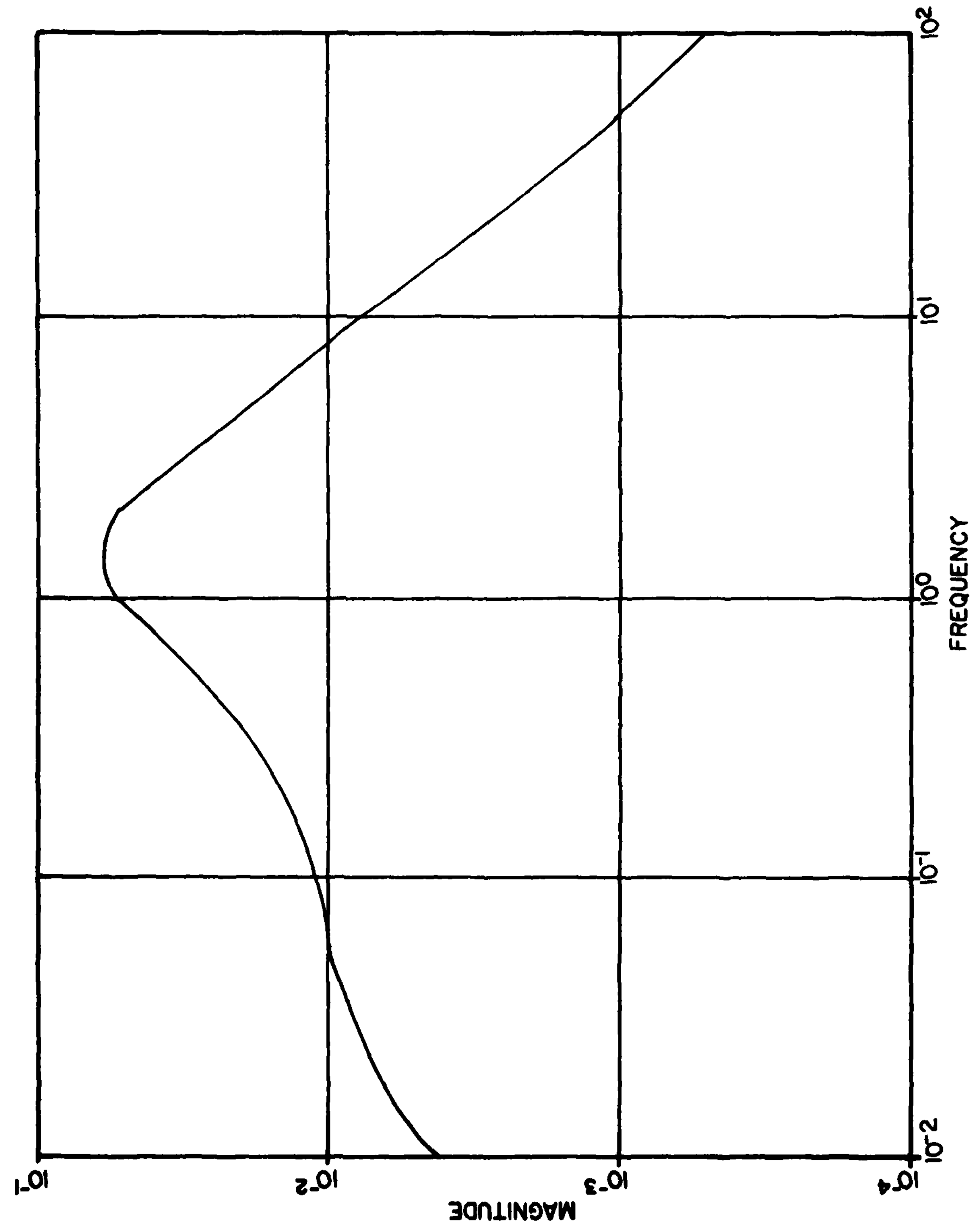


Figure 19b. Standard SAS Beta/Delta Aileron .6, 30000

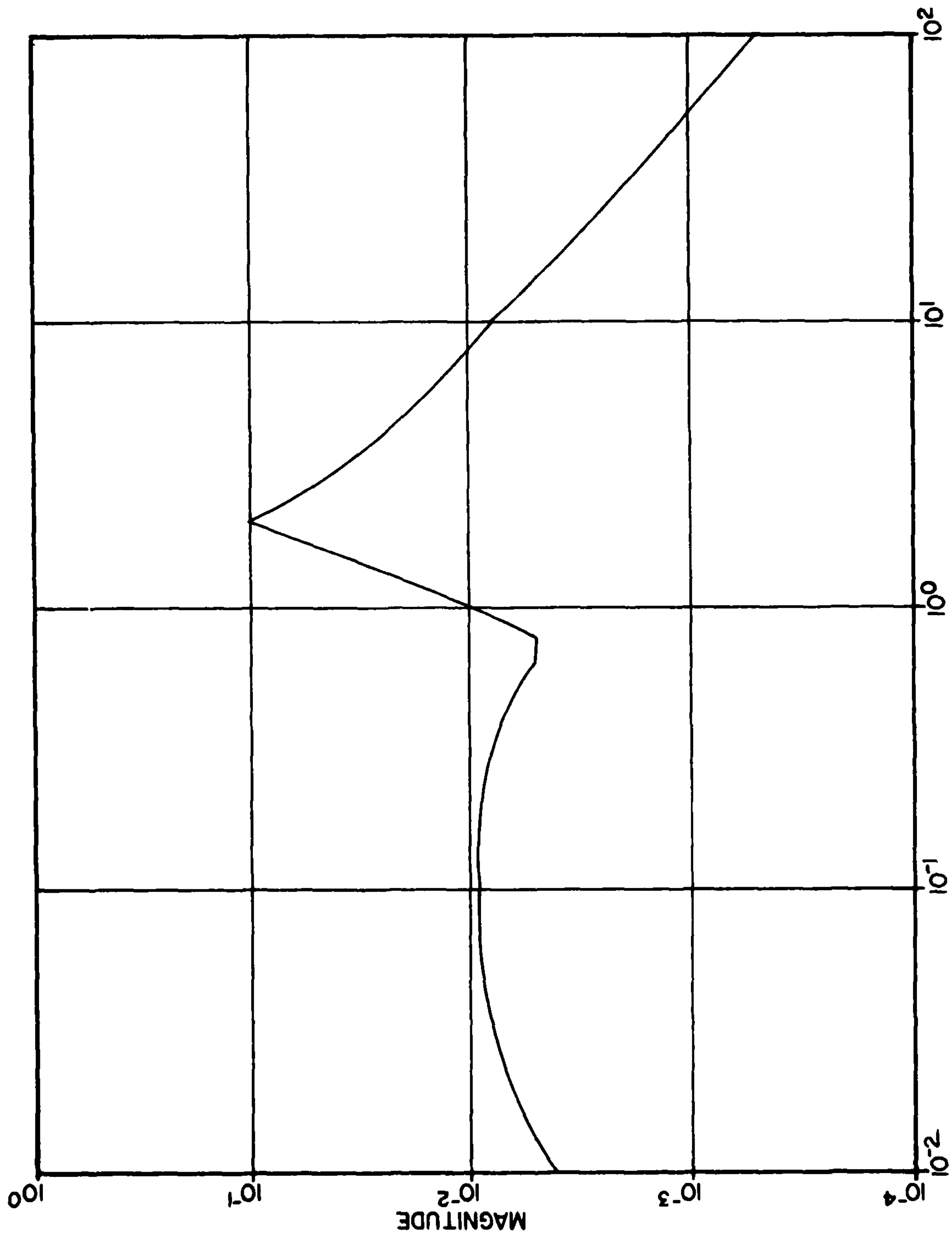


Figure 19c. Betadot SAS Beta/Delta Aileron .6, 30000

Using the definition of β, an approximation of $\dot{\beta}$ can be derived which consists of parameters measurable on the F-106. Appendix D shows this derivation which provides an approximate, through fairly accurate, synthesis of $\dot{\beta}$. The synthesized $\dot{\beta}$ is shown below:

$$\dot{\beta} = p\alpha - r + \frac{A_{y_{acc}}}{U} + \frac{g}{U}\cos\theta\sin\phi$$

p = roll rate (rad/sec)

α = angle of attack (rad)

r = yaw rate (rad/sec)

$A_{y_{acc}}$ = accelerometer lateral acceleration

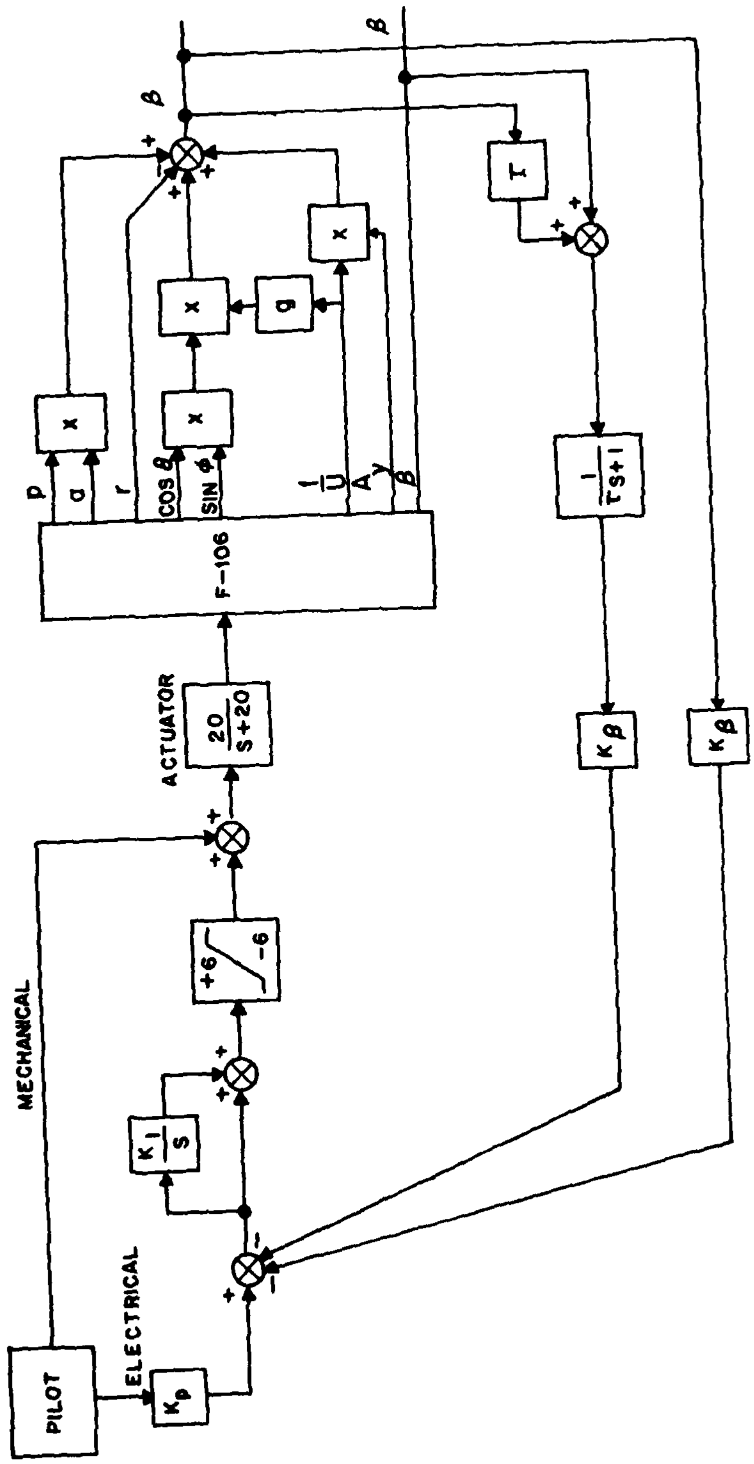
U = true airspeed (ft/sec)

g = gravity constant (32.174 ft/sec^2)

θ = pitch angle (rad)

ϕ = roll angle (rad)

Based on this synthesis of $\dot{\beta}$, a detailed design of the system is shown in Figure 20. Figure 20 includes the ± 6 degree hardware limits present on the existing F-106 SAS as well as a complementary filter on the β signal. This complementary filter, with time constant τ, allows high frequency components of β to come from the $\dot{\beta}$ signal. The electrical signal from the pilot comes from rudder pedal potentiometers and allows the pilot to command sideslip angle directly or, if K_β and K_I are zero, to command sideslip rate. A value of K_p, the pilot's gain, cannot be determined in this nonpiloted simulation. A proportional plus integral forward-loop compensator is included to get rid of the steady-state error caused by the feedbacks.



$K_\beta = 6.5$

$K_\beta = 2.5$

$K_I = .2$

Figure 20. Detailed Design Model

This detailed design of the β-$\dot{\beta}$ SAS was programmed on the Aeronautical Systems Division Hybrid Computer to be compared to the present SAS. Use of the β-$\dot{\beta}$ system showed significant improvement in both sideslip perturbation and dutch roll damping. Figure 21 emphasizes the reduction of sideslip perturbation during a 60 degree roll at different flight conditions. The same response for the bare airframe and the standard SAS were shown previously in Figures 8 and 9. Figure 22 shows the increased speed of response and improved dutch roll damping provided by the β-$\dot{\beta}$ system.

Based on the hybrid simulation runs and previous root locus and frequency response results, Figure 20 shows the configuration of a fixed-gain β-$\dot{\beta}$ SAS which provides significantly better performance than the standard SAS in terms of sideslip perturbations due to roll, speed of response, and dutch roll damping. The system also uses signals realistically available on high performance aircraft, including the F-106.

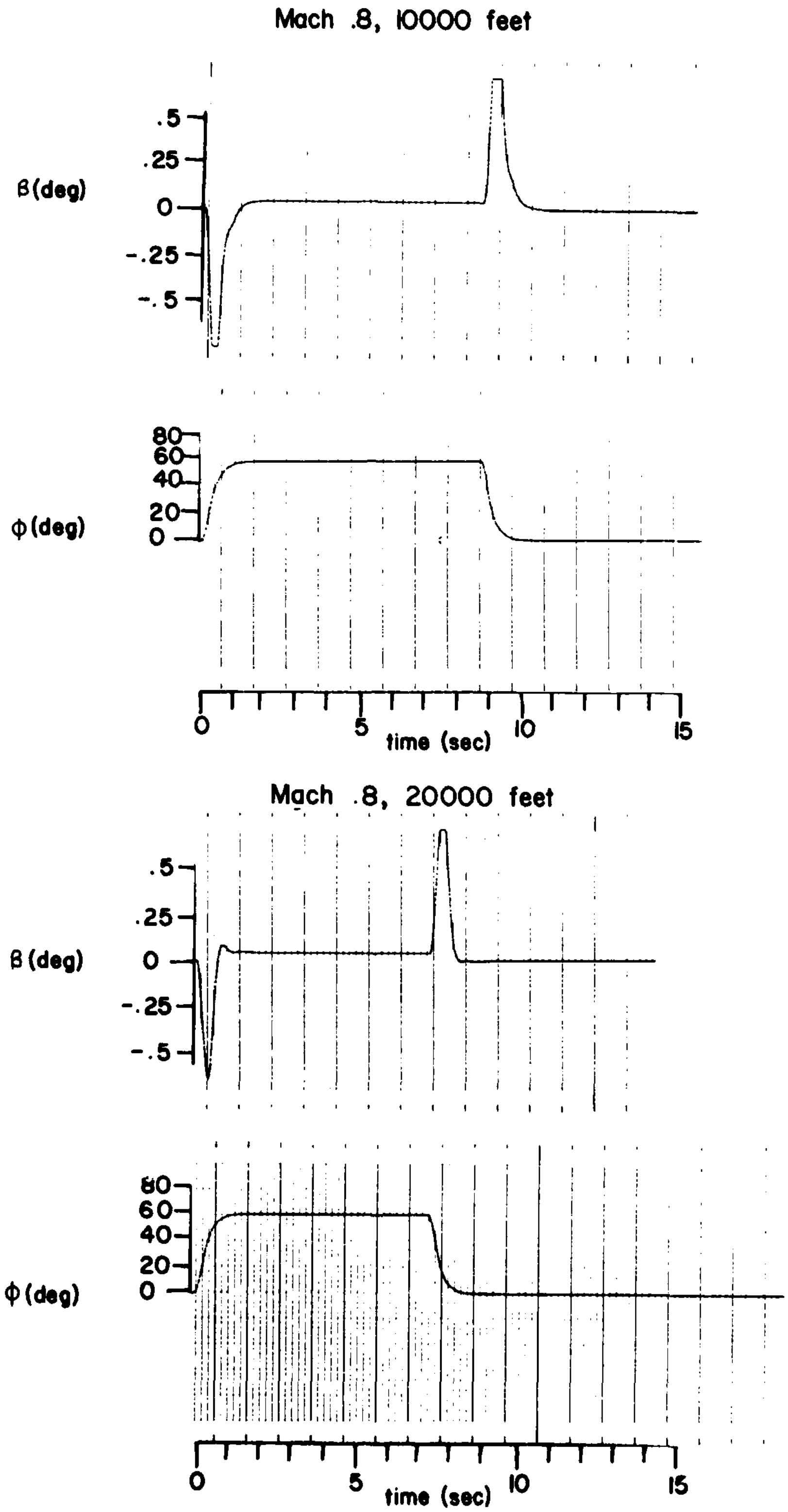


Figure 21. β-$\dot{\beta}$ SAS Response to 60° Bank Angle

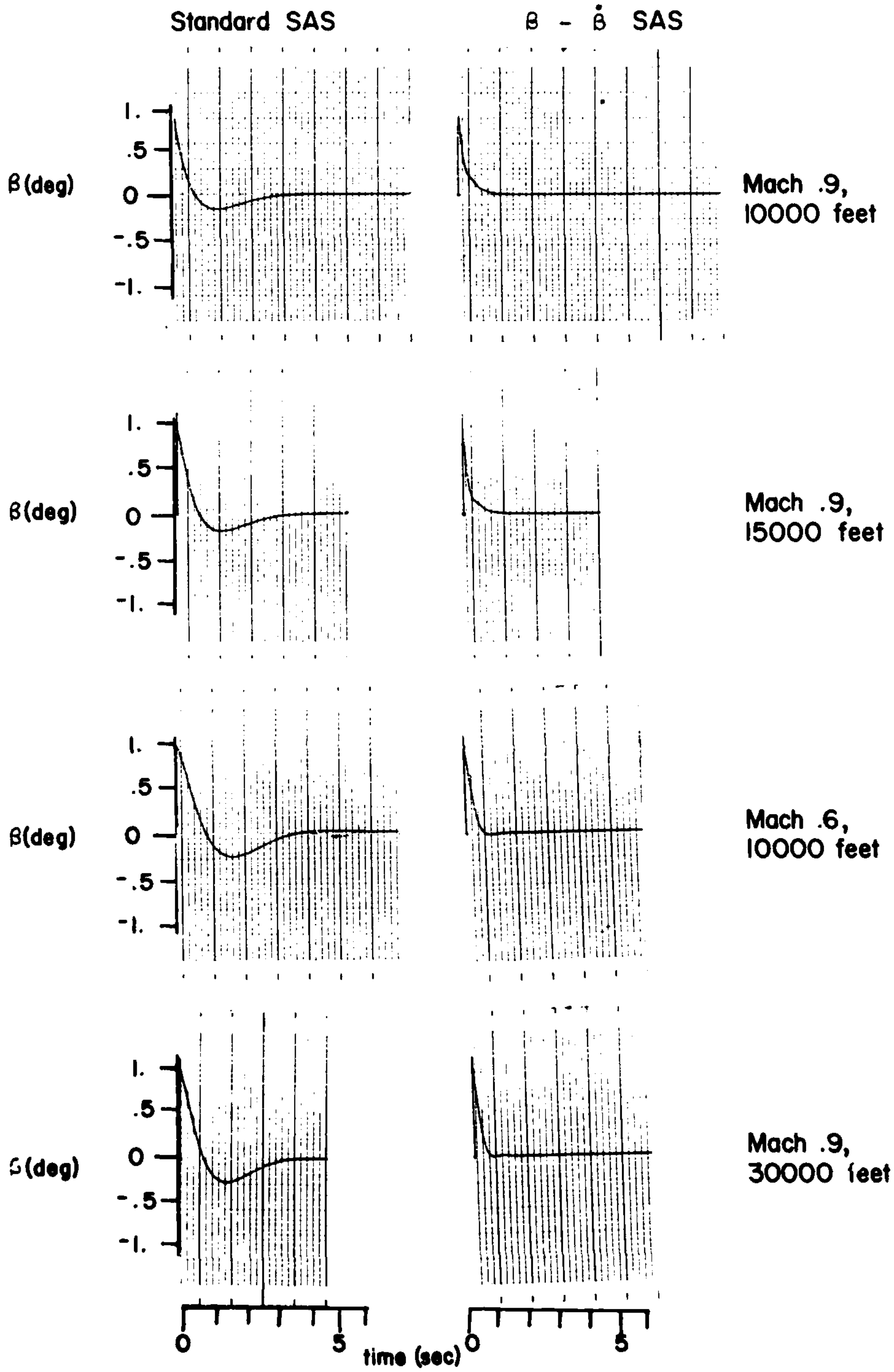


Figure 22. Response to One Degree Sideslip

SECTION IV

F-106 LAMARS SIMULATION

1. SIMULATION DESCRIPTION

Based on root locus, frequency response, and time response analysis methods, the β-$\dot{\beta}$ system appears superior to the standard SAS in terms of sideslip perturbations, speed of response, and dutch roll damping. None of these three measures of merit, however, can be considered the ultimate measure of the system's capability. The ultimate measure of merit is the pilot's ability to track another aircraft. To evaluate these systems using tracking performance as a measure of merit, a man-in-the-loop simulation was used. Using the Flight Dynamics Laboratory's Large Amplitude Multimode Aerospace Research Simulator (LAMARS), an experiment was conducted to evaluate the new system.

The experiment was set up to compare the standard SAS, from Figure 6, and two configurations of the β-$\dot{\beta}$ SAS, from Figure 20. One configuration is as shown in Figure 20 with $K_\beta = 6.5$ and $K_{\dot{\beta}} = 1.9$. The second configuration had K_β and K_I both set to zero with $K_{\dot{\beta}} = 1.9$. This configuration, the $\dot{\beta}$ system, allows only sideslip rate to be fed back to the rudder. This $\dot{\beta}$ system provides a sideslip rate control capability to the pilot. This configuration is included because the pilots are most familiar with rate control which is provided by the standard SAS. The $\dot{\beta}$ system also provides a significant reduction in system complexity because the β measurement and all integrations are removed. The value of $K_{\dot{\beta}}$ was changed from 2.5 to 1.9 after the system was installed and validated in the simulator. The change was based on pilot opinion and engineering judgment. A value of K_p of 10 was chosen to provide the same steady state sideslip rate as the standard system. The units of K_p for the $\dot{\beta}$ configuration are deg/sec sideslip rate per inch of rudder pedal travel. This provides the pilot with the capability to command sideslip rate up to the $\pm 6°$ SAS rudder actuator limits. The units for K_p in the β-$\dot{\beta}$ system are degrees sideslip angle per inch of rudder travel again up to the $\pm 6°$ actuator limits. Figures 23a and 23b show a comparison of these three systems at a high dynamic pressure, Mach .9 at 10000 feet, and a low dynamic pressure,

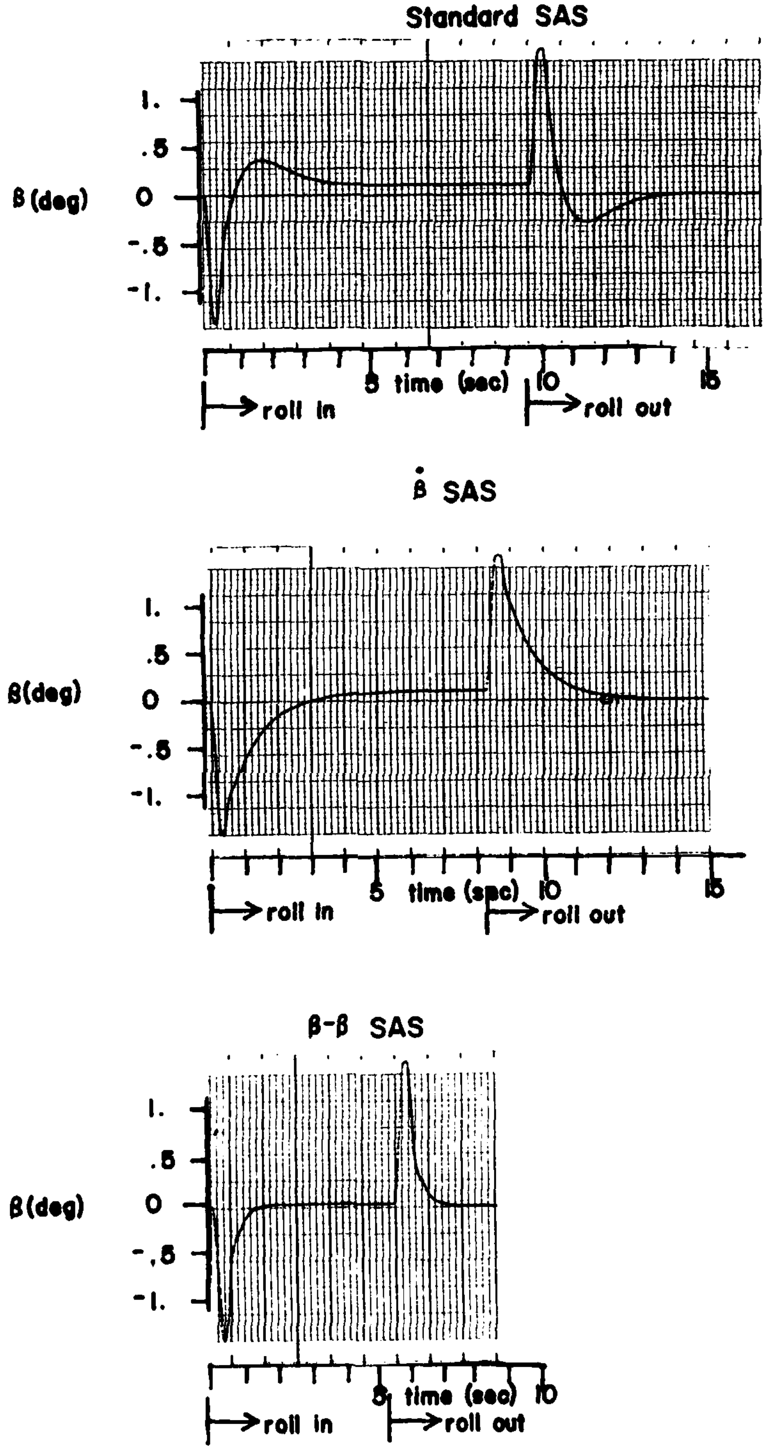


Figure 23a. SAS Comparison at Mach .9, 10000 Feet

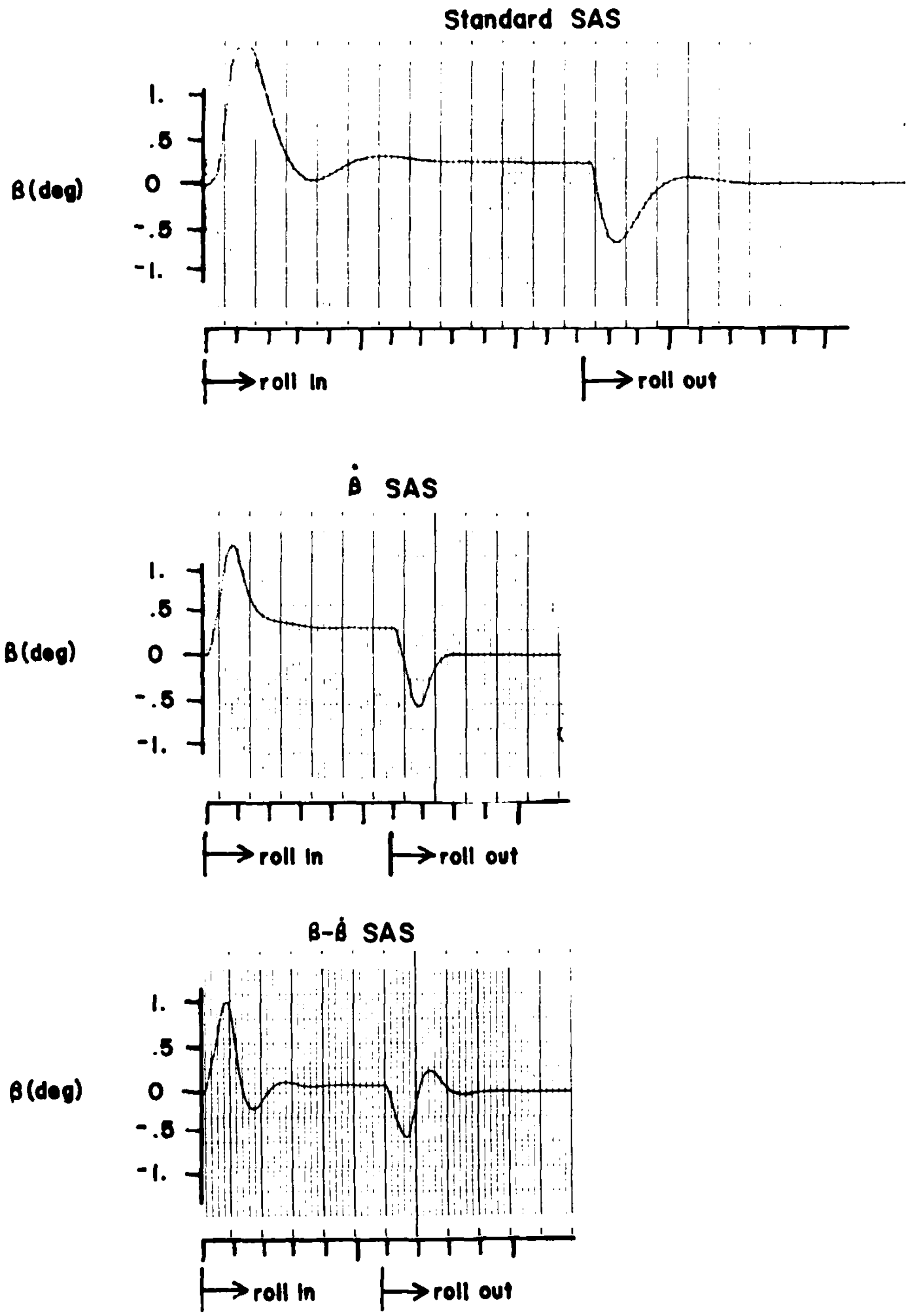


Figure 23b. SAS Comparison at Mach .6, 30000 Feet

Mach .6 at 30000 feet. The responses to a 60° roll input followed by a rollout show that both the $\dot{\beta}$ and the β-$\dot{\beta}$ system eliminate the overshoot at high dynamic pressures and reduce maximum sideslip excursion at low dynamic pressure.

The experiment was set up using two pilots flying each of the three control systems four times. The pilots were flight test pilots experienced and current in the F-106. The task performed by the pilots was tracking a constant g target. The experiment was run at the following three flight conditions: Mach .72 at 10000 feet with 3 g target, Mach .9 at 10000 feet with 3 g target, and Mach .9 at 10000 feet with 6 g target. These flight conditions were chosen to provide realistic ATA tracking conditions. The tracking was performed using a fixed reticle depressed 50 milliradians from the waterline.

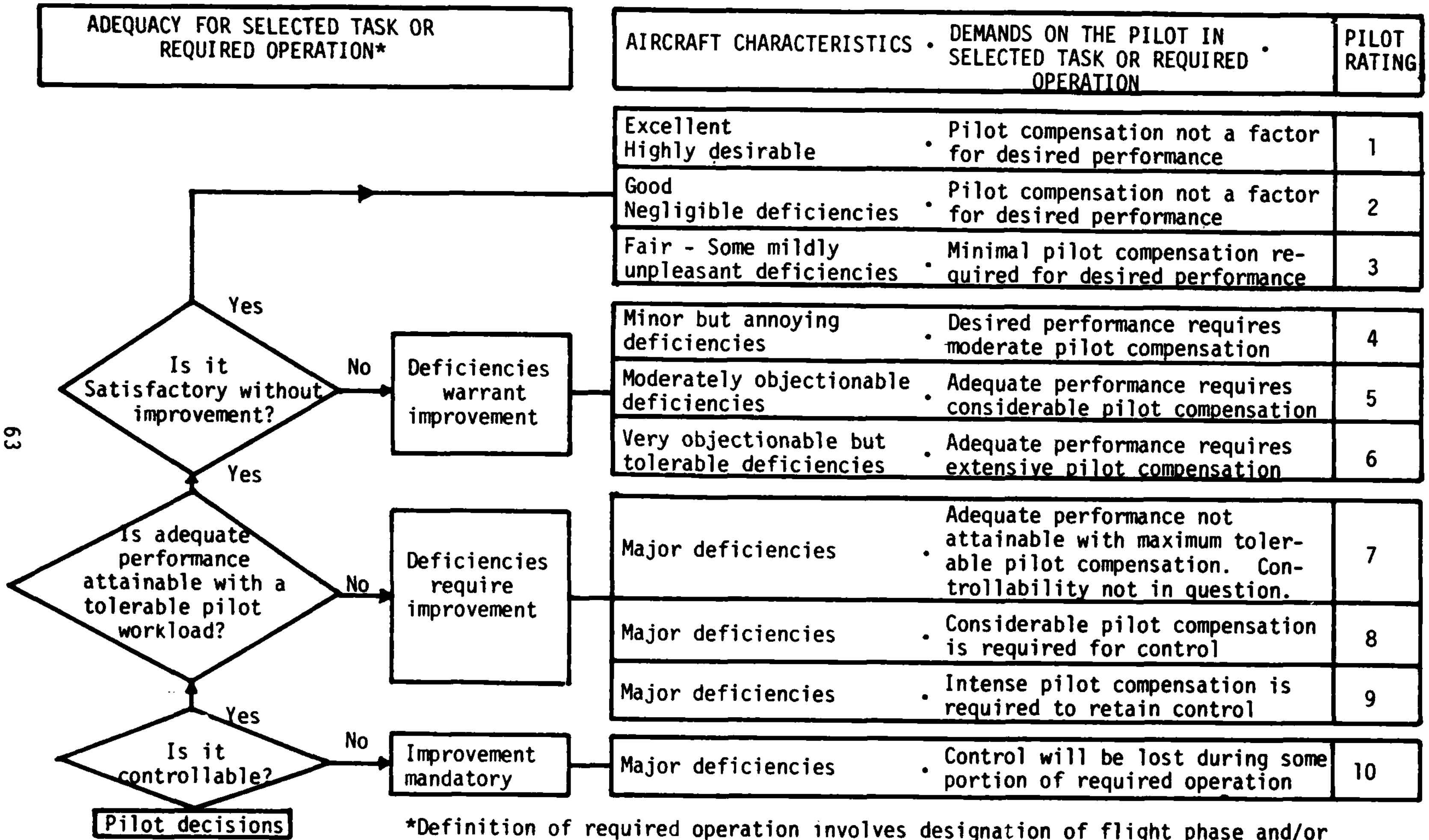
The experiment was designed specifically to measure the difficulty of the tracking task using the three SAS models and was set up similar to handling qualities during tracking (HQDT) tests, with some minor modifications. As in HQDT tests, the pilot's task was to keep the pipper superimposed on the target. Unlike normal HQDT tests, the pilots were allowed to use rudder pedals for aircraft control. This use of rudder pedals during tracking, not normally allowed in an HQDT test, was allowed because the pilots indicated that the rudder was the main lateral control used at large angles of attack. Initially the pilots were not told which system they were flying; this was done to avoid any biasing of the results. Later and for all the data runs, the pilots were informed of the system being flown. This was necessary because the pilots had developed different techniques for flying with each system.

Since the purpose of the new system is to improve lateral tracking, a quantitative measure of merit for this improvement was needed. This measure of merit was chosen to be the standard deviation of the tracking error. Since the system tested acts only on the lateral modes, the total error was divided into elevation and azimuth errors. The elevation and azimuth means are also included as an indicator of the actual point about which the pilot was tracking. To make the steady state tracking error statistics valid, the acquisition transients at the beginning of each run were deleted. During this acquisition phase, the pilots often generate large tracking errors while attempting to establish an in-plane steady-state tracking turn behind the target. The errors are extremely difficult to analyze quantitatively and are large relative to the steady tracking errors; therefore, if included, they would have decreased the usefulness of the standard deviation as a quantitative measure of merit. In addition to these quantitative measures, the pilot opinions were obtained in the form of pilot ratings based on the Cooper-Harper Scale (Figure 24). These ratings, along with the means and standard deviations of the tracking errors, provided the measures of merit for evaluating the three SAS's.

2. SIMULATION RESULTS

Approximately 75 runs provided data which could be used for evaluating the systems. Table 3 shows the results of these runs in terms of the quantitative measures of merit described earlier. To eliminate the acquisition transients, the middle 30 seconds of the 60-second runs were used for calculating the error statistics for the 3 g runs. For the 6 g runs, the middle 20 seconds of the 45-second runs were used.

Although the mean tracking errors for three SAS's are shown, they provide little insight into the relative merits of the different systems. These mean values are more a function of pilot technique than of the quality of the SAS. This is evident in the azimuth means where Table 3 shows pilot 1 to consistently track left of the target and pilot 2 to consistently track right of the target. These different means could also be due to the position of the pilot's head and his resulting view through the HUD. The elevation means show that the pilots tracked consistently below the target with large error magnitudes as g and airspeed increased with little apparent relation to the SAS's. The elevation means could also have been effected by bias in the data measurement system in the LAMARS facility or again by the pilots' head location.



*Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Figure 24. Cooper-Harper Rating Scale

TABLE 3

SIMULATION RESULTS

M = .72, 3 g, 10000 FEET

System	Pilot 1 Azimuth Error Mean	Pilot 1 Azimuth Error SD	Pilot 1 Elevation Error Mean	Pilot 1 Elevation Error SD	Pilot 1 Total Error SD	Pilot 2 Azimuth Error Mean	Pilot 2 Azimuth Error SD	Pilot 2 Elevation Error Mean	Pilot 2 Elevation Error SD	Pilot 2 Total Error SD
Standard	-4.54	11.18	-8.58	6.38	12.87	2.21	12.58	-1.91	7.32	14.56
$\dot{\beta}$	- .47	6.28	-10.66	3.88	7.38	2.82	9.43	-3.06	5.82	11.08
β-$\dot{\beta}$	-1.27	6.3	-9.1	3.25	7.09	2.99	9.88	-3.57	5.23	11.18
M = .9, 3 g, 10000 FEET										
Standard	-1.91	13.14	-9.79	3.93	13.72	3.82	13.4	-5.52	5.71	14.57
$\dot{\beta}$	-1.9	9.08	-9.01	4.06	9.95	5.36	9.89	-4.47	4.15	10.73
β-$\dot{\beta}$	1.71	12.11	-8.97	4.23	12.83	.92	15.94	-3.74	4.71	16.62
M = .9, 6 g, 10000 FEET										
Standard	-3.75	15.02	-17.13	11.89	19.6	1.73	17.41	-10.95	12.79	21.6
$\dot{\beta}$	-2.04	13.01	-18.71	11.34	17.26	5.48	17.08	-7.55	10.59	20.1
β-$\dot{\beta}$	-1.75	18.72	-17.72	7.47	20.16	8.87	21.54	-8.55	12.67	25

The most important quantitative measure of merit is the standard deviation of the tracking errors. The standard deviation shows the precision with which the pilot can hold the pipper on the target. The smaller the standard deviation, the more precisely the pilot can hold the pipper on the target.

To determine the statistical significance of the SAS effects on the results, a three-way analysis of variance was performed on azimuth, elevation, and total error (vector sum of azimuth and elevation error). The analysis is shown in Appendix E. The three error sources were SAS, pilot, and flight condition. The results are shown in Table 4 (a through c) in terms of level of significance for the different error sources. These levels of significance describe the probability of mistakenly attributing changes in tracking error to one of the error sources when in fact that error source was not the factor causing the change. For instance, the .0173 level of significance of the SAS as an error source in azimuth error means that there is a .0173 probability that the changes, which occurred in azimuth tracking error when the SAS was changed, were not due to the SAS at all but were either random errors or due to some other factor. The results show that the SAS was indeed significant as an error source. The results also show that the pilot and flight condition were even more significant as error sources.

Since the analysis of variance shows the SAS effects to be significant, the results from Table 3 can be examined in more detail. The percentage improvement over the standard SAS, in terms of standard deviation of the tracking error, is shown in Table 5. There are quite large improvements at Mach .72, 10000 feet but as the Mach number and g loading increase, the levels of improvement become smaller. This decrease in percentage improvement is probably due to the increasing difficulty of the task itself, which tends to overwhelm and mask the SAS differences. This is also evident in the analysis of variance, which shows the flight condition to have a highly significant effect on the results. Pilot skill also appears to be important to the results. Pilot 1 consistently had smaller tracking errors and also had consistently higher levels of improvement. As with flight condition, this pilot

TABLE 4

ANALYSIS OF VARIANCE RESULTS

Error Source	Level of Significance
Pilot	.0163
Flt Cond	.00003
SAS	.0173

a. Azimuth Error

Error Source	Level of Significance
Pilot	.0201
Flt Cond	.00001
SAS	.044

b. Elevation Error

Error Source	Level of Significance
Pilot	.0053
Flt Cond	.00001
SAS	.0135

c. Total Error

TABLE 5

PERCENT IMPROVEMENTS OVER STANDARD SAS*

M = .72, 3 g, 10000 FEET

	Pilot 1			Pilot 2		
System	Azimuth Error	Elevation Error	Total Error	Azimuth Error	Elevation Error	Total Error
$\dot{\beta}$	44	39	43	25	20	24
β-$\dot{\beta}$	44	49	45	21	29	23
M = .9, 3 g, 10000 FEET						
$\dot{\beta}$	31	-3	27	26	27	26
β-$\dot{\beta}$	8	-8	6	-19	18	-14
M = .9, 6 g, 10000 FEET						
$\dot{\beta}$	13	5	10	2	17	7
β-$\dot{\beta}$	-25	37	-5	-24	1	-16

*Negative value indicates a degradation

effect was evident in the analysis of variance. Based on the quantitative measures of merit in Tables 3 and 5, the $\dot{\beta}$ SAS appears to be best, followed by the standard SAS and the β-$\dot{\beta}$ SAS.

The three SAS's were also compared qualitatively using the Cooper-Harper rating scale. These ratings, for the 3 g runs, are shown in Table 6. These qualitative measures follow very closely the quantitative measures of Tables 3 and 5. They show the $\dot{\beta}$ system to be best followed by the standard and the β-$\dot{\beta}$ system. Figures 25a-25c show representative pipper traces at the Mach .9, 3 g flight condition using each of the three SAS's. These pipper traces are from runs flown by pilot 1. The improvement is evident in the $\dot{\beta}$ SAS, Figure 25c. Figure 26 also shows the improvement provided by the $\dot{\beta}$ SAS. In Figure 26, the standard SAS was being flown by the pilot as he tracked a 3 g target; at the point shown, the standard SAS was turned off and the $\dot{\beta}$ SAS turned on. The improvement is evidenced by the elimination of the low frequency oscillation.

TABLE 6

COOPER-HARPER RATINGS (3 g ENCOUNTERS)

System	Pilot 1	Pilot 2
Standard	3	4
$\dot{\beta}$	2	3
β-$\dot{\beta}$	5	5

Although the nonpiloted simulations indicated that the β $\dot{\beta}$ system was better than the $\dot{\beta}$ system, in terms of dynamic response, the pilots preferred and performed better with the $\dot{\beta}$ system, a rate control. This apparent discrepancy can probably be attributed to the fact that the pilots were most familiar with rate control, as with the standard SAS; the position control of the β-$\dot{\beta}$ system was therefore, something new which the pilots had to learn how to use as they evaluated it. This lack of experience in using position control of sideslip might have put a bias on the results. Unfortunately, this possible bias cannot be measured using the data and should not, therefore, enter the results.

In summary, the LAMARS simulation showed that the $\dot{\beta}$ SAS provides a significant improvement over the standard SAS. This improvement was evidenced by both quantitative measures of merit, tracking error, and qualitative measures of merit, pilot ratings.

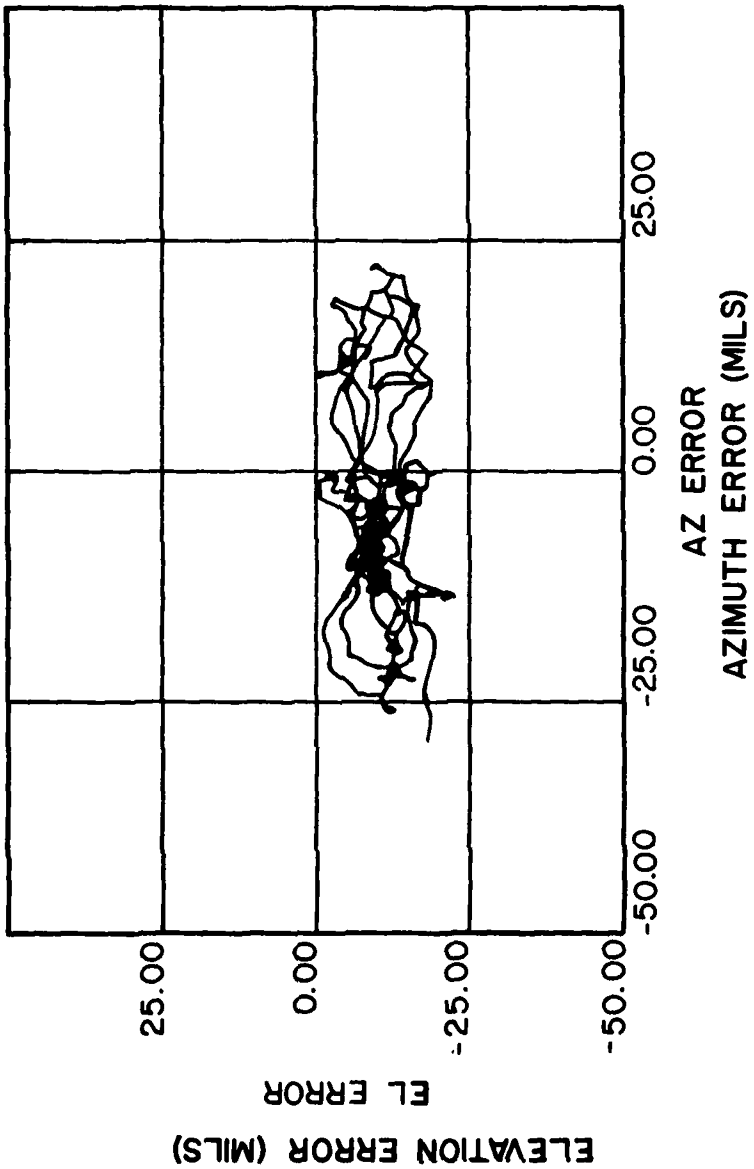


Figure 25a. Standard SAS Pipper Trace at Mach .9, 10000 Feet, 3 g

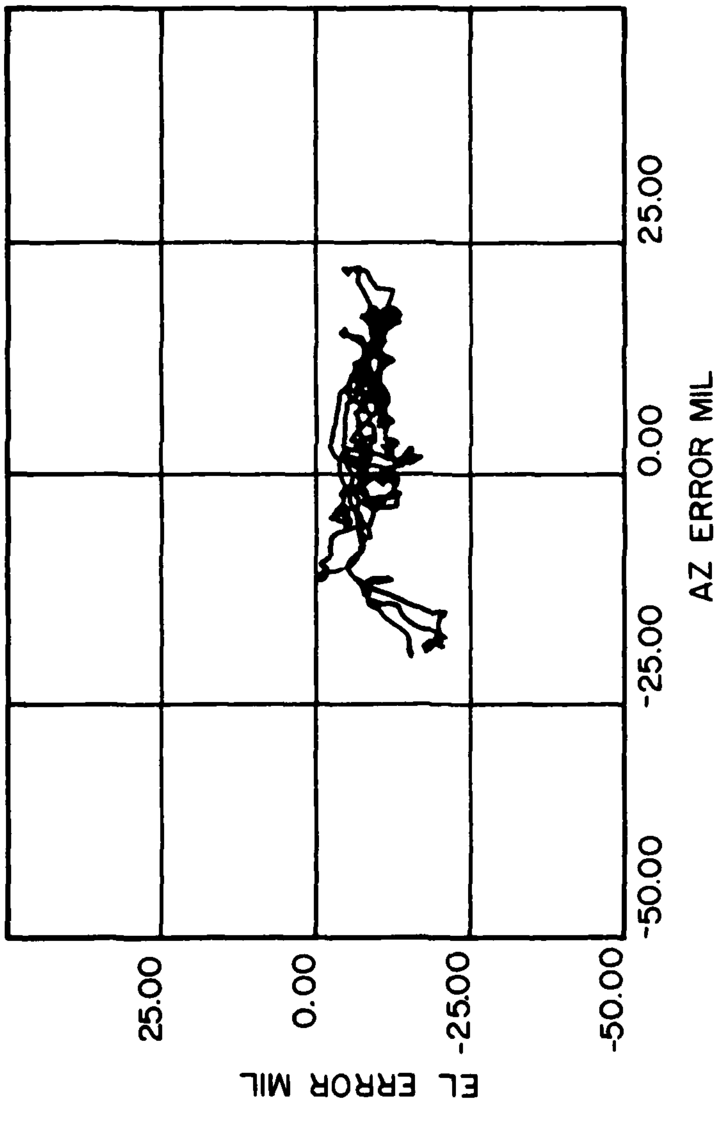


Figure 25b. β-$\dot{\beta}$ SAS Pipper Trace at Mach .9, 10000 Feet, 3 g

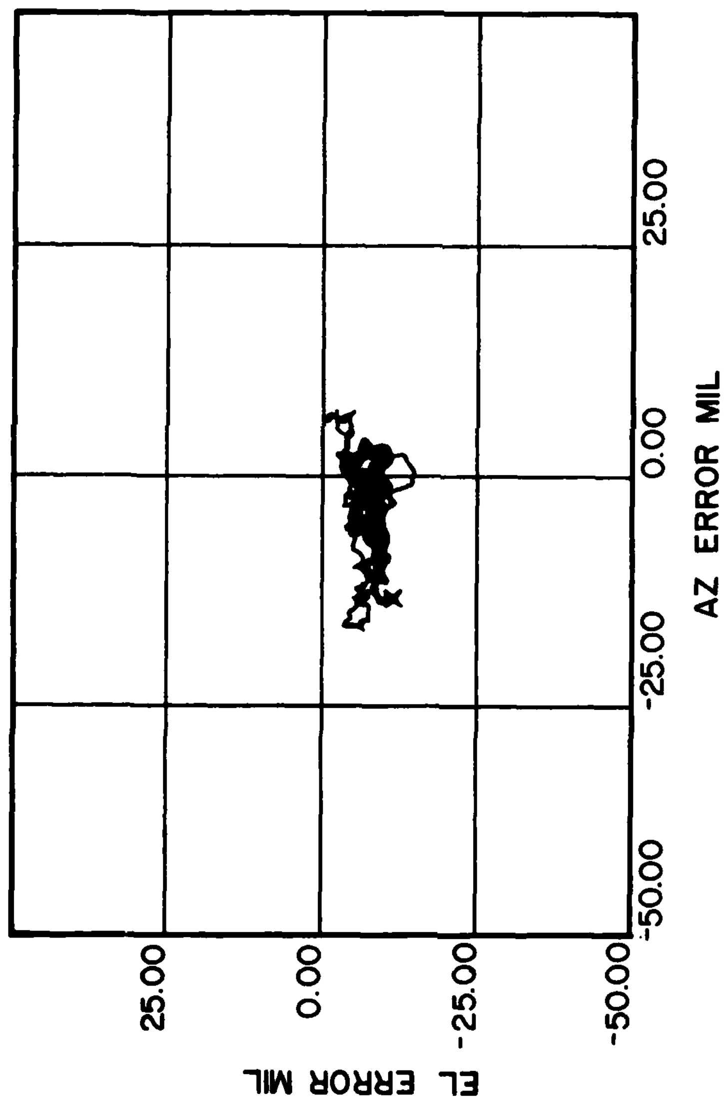


Figure 25c. $\dot{\beta}$ SAS Pipper Trace at Mach .9, 10000 Feet, 3 g

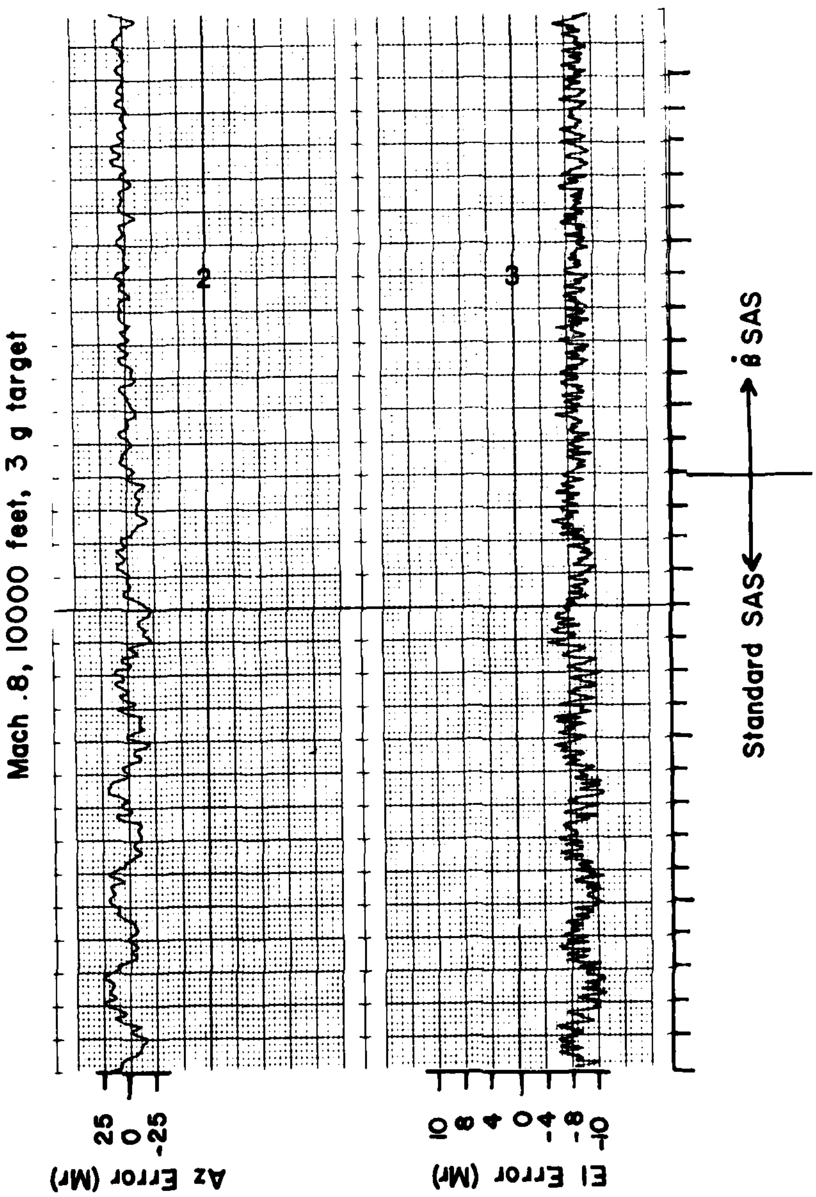


Figure 26. Tracking Error Reduction with $\dot{\beta}$ SAS

SECTION V

F-106 FLIGHT TEST

1. SYSTEM CONFIGURATION AND IMPLEMENTATION

Based on the results of the piloted simulation, both analysis results and pilot comments, the Aerospace Defense Command (ADCOM/DOV) gave the Flight Dynamics Laboratory approval to flight test the modified SAS on an F-106 at Tyndall AFB, Florida. The Flight Dynamics Laboratory, with assistance from the 475th Test Squadron from Tyndall AFB, designed a flight test implementation which allowed for much flexibility during the flight test. The Class II modification package based on this design was approved by Air Force Systems Command. The design for flight test included only provisions to evaluate the sideslip rate ($\dot{\beta}$) feedback. The reasons for looking at only the $\dot{\beta}$ feedback are twofold. Primarily, the pilot comments and performance measures from the piloted simulation shows this system to have a much greater performance improvement potential than the β-$\dot{\beta}$ system. Also, the cost for implementing the $\dot{\beta}$ system was considerably less because no integrations were required in the control law.

During the design of the flight test implementation, the Flight Dynamics Laboratory presented an option to ADCOM which would allow for the addition of a roll SAS to the F-106 being tested. The reasons for including this option were that the F-106 did not have roll rate feedback to the SAS, the pilot controlled the elevon position directly, and the change would be very simple, involving only a circuit change to the existing control system. ADCOM/DOV approved this addition to the flight test, and the roll SAS design was included and approved in the Class II modification package.

The F-106 avionics system and flight control system were well suited for testing the $\dot{\beta}$ SAS and roll SAS because they required only minor modifications to the existing system. The Hughes-built IRAM computer was used for all SAS calculations, both yaw and roll. Since the IRAM computer is part of the MA-1 fire control and automatic intercept system, existing electrical paths from the IRAM computer to the 464821 flight control interface box were used to carry the calculated SAS commands to the flight control system actuators. Figure 27 shows a conceptual block diagram of the system implementation.

The standard yaw SAS is a single-thread analog system located in the 821 unit. The sensor outputs from the turn rate transmitter (TRT), yaw rate and roll rate, are input to this 821 unit which does the analog SAS calculation for roll and pitch and then sent to the rudder actuator and the two elevon actuators.

The rudder actuator mechanically limits the SAS command rudder movement to $\pm 6°$. Likewise, the pitch SAS commands are mechanically limited to $\pm 1°$ by the elevon actuators. This pitch authority ($\pm 1°$) was also the limit for the roll SAS since the roll SAS consisted of using the existing pitch system but in a differential manner.

The $\dot{\beta}$ SAS implementation is shown in Figure 28. Figure 29 further describes the inputs and switching used in the $\dot{\beta}$ SAS. To have all the quantities necessary to solve the $\dot{\beta}$ equation in the MA-1 IRAM computer, some standard inputs to the computer had to be removed and replaced with sensor measurements needed by the $\dot{\beta}$ SAS. The pitch rate normally input to the computer was replaced by an angle of attack (α) signal from an α vane located on the pitot-static boom. The lateral acceleration (A_y), which came from a Honeywell inertial reference platform (IRP), replaced the existing gunsight sideslip measurement. Rudder pedal position (δ_{rp}) replaced the right elevon position. These three signals, α, A_y, and δ_{rp}, were available from instrumentation installed previously for an F-106 parameter identification flight test.

The roll SAS implementation was set up in the same way as the $\dot{\beta}$ SAS. Figures 30 and 31 show the implementation and switching logic used for the roll SAS. The lateral stick position needed by the roll control law is taken from a lateral stick position potentiometer and input to the computer in the location normally containing left elevon position.

The computer program was set up to enable a maximum amount of flexibility in both system checkout and flight test validation. The program had an option for a ground check by using the aircraft short system

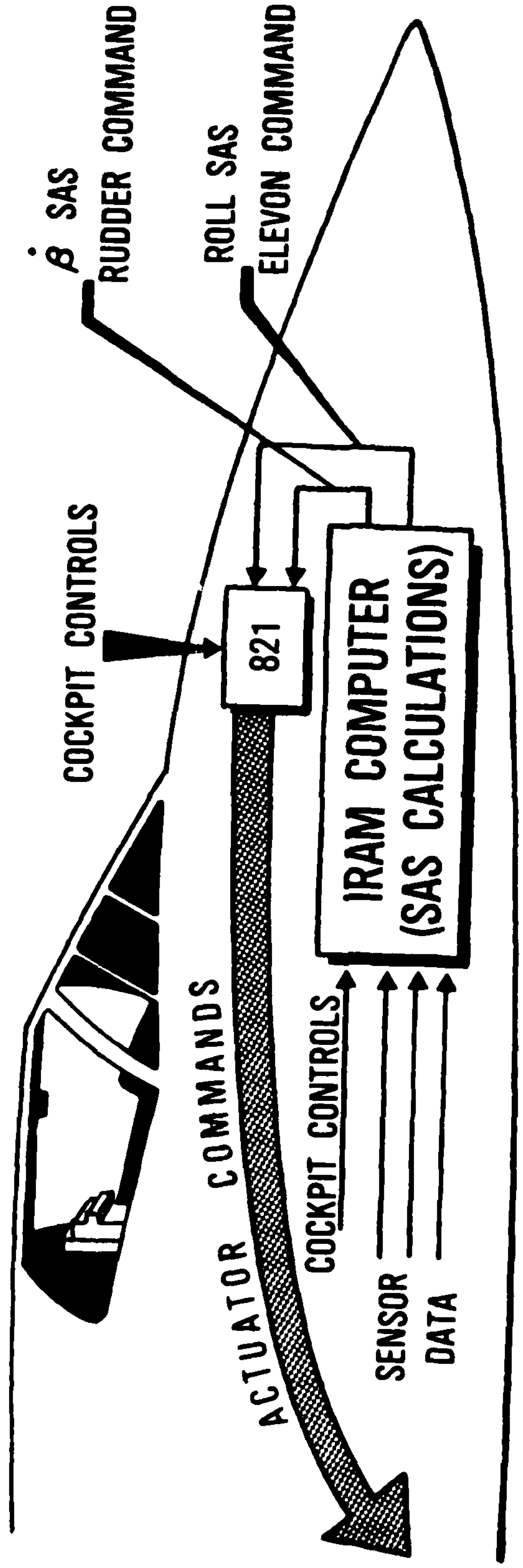


Figure 27. F-106 SAS Conceptual Block Diagram

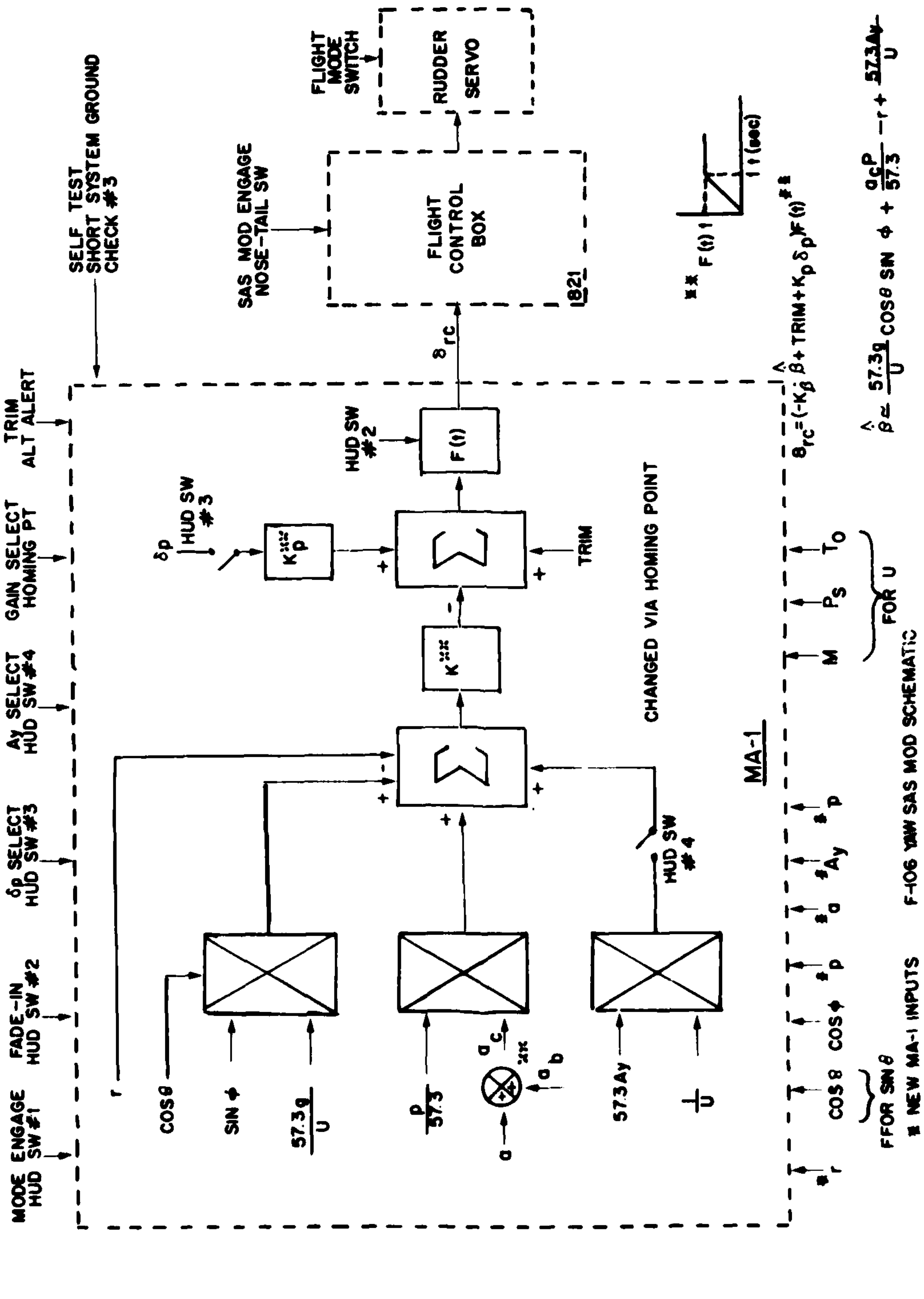


Figure 28. $\hat{\beta}$ SAS Implementation

$$\delta_{rc} = (K_p\delta_p + TRIM - K_{\dot\beta}\hat{\dot\beta})\,F(t)$$

where $\hat{\dot\beta} = \left[\frac{p(\alpha + \alpha_b)}{57.3} - r + 57.3\,\frac{K_A A_y}{U} + 57.3\,\frac{g}{U}\cos\theta\sin\phi\right]$

$$g = 32.2\ \text{ft/sec}^2$$

COMPUTER OUTPUT	OUTPUT LOCATION	SCALING	RANGE
δ_{rc}	LH Elevon Command (deg)	8.33 V/deg	0-100V, ±6°

Computer Inputs (Variables)	Source	Input Location	Scaling	Range
p (roll rate, deg/sec)	TRT	existing (E18a)	10 deg/sec/V	±5V
α (angle of attack, deg)	boom	pitch rate (E25)	9 deg/volt	±5V, ±45°
r (yaw rate, deg/sec)	TRT	existing (E16a)	4 deg/sec/V	∓5V
A_y (lateral acceleration, ft/sec)	Honeywell IRP	gunsight β (E26)	212 ft/sec/volt	±4.025V, ±800 ft/sec
U (airspeed, ft/sec)	existing	existing		
sin θ (cos θ calculated from sin θ)	existing	existing		
sin φ (roll angle)	existing	existing		
δ_p (rudder pedal position, in)	rudder pot	RT elevon position(A22)		50V±30V,±3.25 in
TRIM (System electrical trim, deg)	Altitude warning	existing		±6°

(Variable gains)

α_b (angle of attack, bias deg)

$K_{\dot\beta}$ ($\dot\beta$ gain, deg/deg/sec)

K_p (pilot rudder pedal position gain, deg/in)

These variable gains are set using the Homing Point Selector as a logic indicator to set these gains as shown in Table 1.

(Discretes)	Function
HUD Switch #1	Betadot Mode Select
HUD Switch #2	Fade-in and Fade-out control for SAS via F(t)
HUD Switch #3	Selects δ_p: ON K_p = values in Table 1; OFF K_p = 0
HUD Switch #4	Selects A_y: ON K_A = 1; OFF K_A = 0

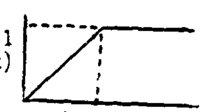


Figure 29. $\dot\beta$ SAS Inputs and Switching Logic

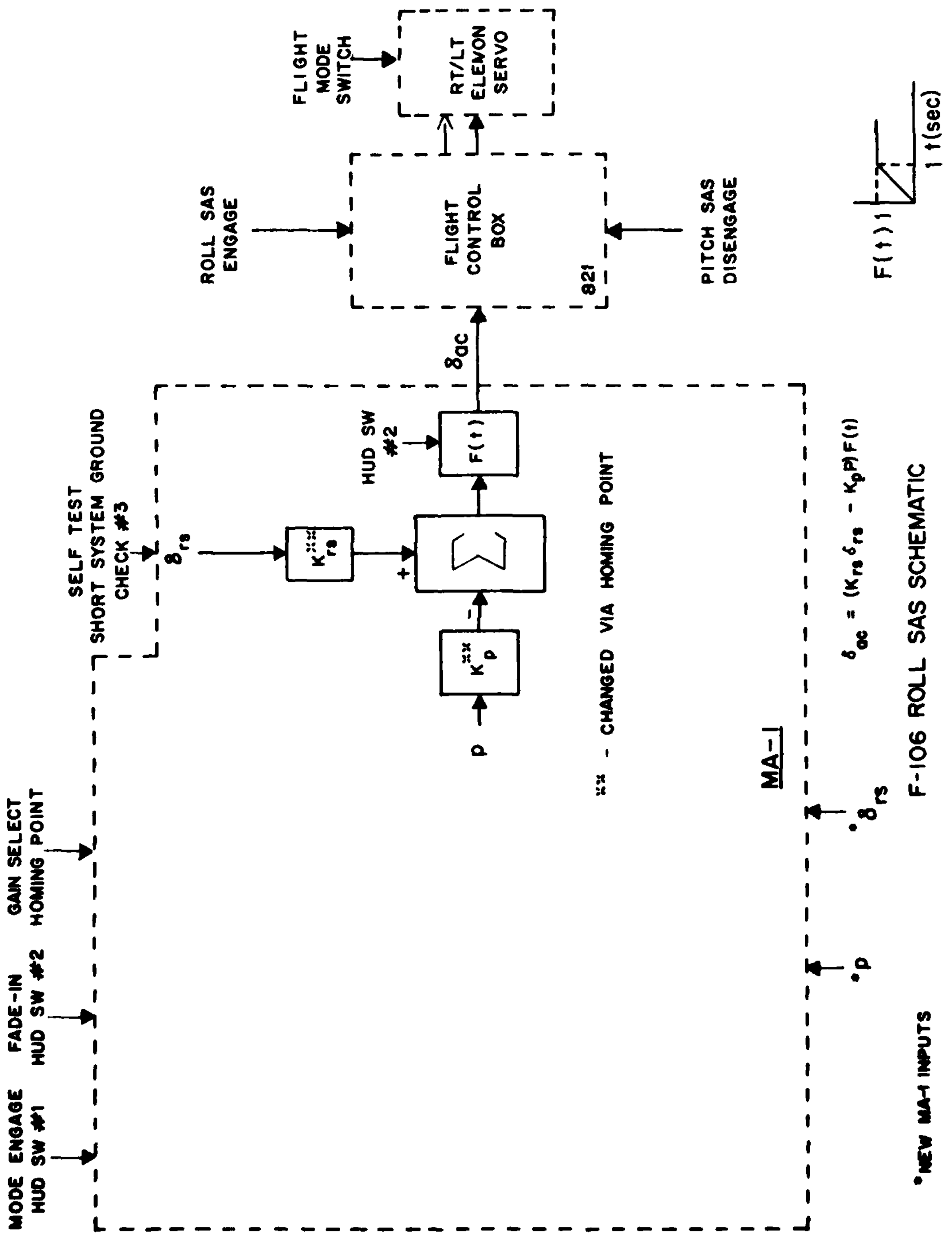


Figure 30. Roll SAS Implementation

$$\delta_{ac} = (K_s \delta_{ps} - K_{rr} P)F(t)$$

COMPUTER OUTPUT	OUTPUT LOCATION	SCALING	RANGE
δ_{ac}	RH Elevon Command (deg)	50 V/deg	0-100V, ±1°

COMPUTER INPUTS	SOURCE	INPUT LOCATION	SCALING	RANGE
(Variables)				
P (roll rate, deg/sec)	IRP	existing (E25)	10.0 deg/sec/V	±5V
δ_{ps} (lateral stick position, in	stick potentiometer	LH Elevon Position (A21)	50±30V	±3.5 in

(Variable gains)

K_s (stick gain, deg/in

K_{rr} (roll rate gain, deg/deg/sec)

These gains will be set using the Homing Point Indicator as a logic indicator to set these gains as shown in Table 1.

(Discretes)	Function
HUD Switch #1	Selects roll SAS mode
HUD Switch #2	Fades in and out control law via F(t)

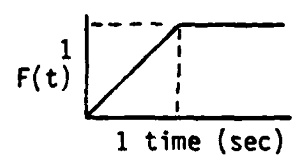


Figure 31. Roll SAS Inputs and Switching Logic

ground check number three (SSGC #3). When SSGC was engaged, the computer would read stored data locations instead of the sensor input. The control law was computed using these values for the sensor measurements. The resulting rudder deflection was then compared with the rudder deflection which should theoretically have occurred. These ground check calculations are shown in Figure 32.

Flight test flexibility was achieved by designing the system with variable gains and SAS mode switching logic. To achieve variable gains in the control law itself, the homing point selector (an existing navigation control) was used as a gain select. For each switch location on the homing point select, a different set of gains were used in the SAS calculations. Table 7 shows the homing point values and the associated gains. In addition to the variable gains, adjusted by the homing point select, an electrical bias or trim was available using the altitude alert switch, an existing digital input to the computer. This electrical bias allowed the pilot to trim out the bias resulting from an accumulation of sensor biases. This electrical trim was used in place of the normal trim because the normal rudder trim uses part of the ±6° SAS authority of rudder actuator. By using the electrical trim, the SAS control law still had even ±6° authority instead of an uneven authority such as +5°, -7° which could occur if a 1° bias was eliminated using the standard rudder trim.

TABLE 7

HOMING POINT SELECT GAIN VALUES

HD	$K_{\dot{\beta}}$	K_p	α_b	K_{rr}	K_s
A	1.9	5	4	.15	3
B	1.9	5	1	.15	3
C	1.25	3.28	4	.15	3
D	2.25	5	4	.15	3
E	1.5	3.45	4	.15	3
F	1.9	5	3	.15	3
G	1.9	5	6.36	.15	3
H	1.9	2.5	4	.15	3
I	1.9	10	4	.25	3
J	1.9	5	2	.15	3
K	1.9	5	4	.15	2
L	1.9	5	4	.15	4
M	1.9	5	4	.1	3
N	1.9	5	4	.2	3

Rudder Check

$\delta_{rc} = (K_p \delta_p + \text{TRIM} - K_{\dot{\beta}} \hat{\dot{\beta}})$

$$\hat{\dot{\beta}} = \frac{p(\alpha + \alpha_b)}{57.3} - r + \frac{57.3A_y}{U} + \frac{57.3g\cos\theta\sin\phi}{U}$$

$p = 5$ deg/sec	$\theta = -5°$
$\alpha = 7$ deg	$\phi = -15°$
$r = 5$ deg/sec	TRIM = 0
$A_y = -3$ ft/sec^2	$\delta_p = -1.25$ in
$U = 862$ ft/sec[1]	

$$\hat{\dot{\beta}} = \frac{5(7 + \alpha_b)}{57.3} - 5 + \frac{57.3(-3)}{862} + \frac{57.3(32.2)\cos(-5°)\sin(-15°)}{862}$$

$$= .611 + .0873\alpha_b - 5 - .199 - .552$$

$$= .0873\alpha_b - 5.14$$

$$\delta_{rc} = [K_p * 1.25 + 0 - K_{\dot{\beta}}(.0873\alpha_b - 5.14)]$$

$$= -1.25K_p - K_{\dot{\beta}}(.0873\alpha_b - 5.14)$$

Aileron Check

$\delta_{ac} = (K_g\ \delta_{ps} - K_{rr}\ p)$

$p = 5$ deg/sec

$\delta_{ps} = 0$

$\delta_{ac} = 0K_g - 5K_{rr}$

$= -5K_{rr}$

Figure 32. Built-in-Test

The switching logic also allowed some of the parameters in the $\dot{\beta}$ SAS control law to be deleted from the control law calculation. Specifically, the heads up display (HUD) switches 3 and 4 were used to delete pilot rudder pedal position (δ_{rp}) and lateral acceleration (A_y) respectively. These options proved very helpful, both in debugging the system and in picking the best overall system configuration. HUD switch 1 was used to start the computer calculations and HUD switch 2 was used to fade-in the control law. The fade-in consisted of a 1-second ramp from zero to one. This fade-in is shown as F(t) on Figures 28-31.

The actual computer program which did the SAS calculations is shown in Appendix F. This IRAM assembly code shown did the $\dot{\beta}$ and roll SAS calculations, the rudder trim, gain changes, and also displayed a fixed reticle depressed 50 mils from the water line and 15 mils right of centerline. The cross was placed off center so that the vision splitter on the 106 did not interfere with the HUD camera. The computer program is located on the magnetic memory drum at the same location as the gunsight program; therefore, to load the program, the pilot selected Special Weapons (SPL WPM) on the weapon control panel.

2. FLIGHT TEST RESULTS

After several system checkout flights, the system was debugged and data flights were flown. The 475th Test Squadron flew the $\dot{\beta}$ and roll SAS during the months of June, July, and August of 1978. The system was flown by three different pilots during this period. Both basic handling qualities tests and handling qualities during tracking (HQDT) tests were flown by all three pilots.

The roll SAS proved to be the least effective of the two systems tested. This ineffectiveness was due primarily to limitations in the way the system was implemented. Since the roll SAS had only ± 1 degree of elevon authority, small biases in roll rate and lateral stick position measurements saturated the system. This saturation meant that the control law would operate only in one direction. In spite of these limitations, the pilots felt that when the system was operating properly, it was very effective and desirable for air-to-air tracking. Unfortunately, the stick position and roll rate biases were present during most of the flights, thereby making the roll SAS, on the whole, ineffective. Additionally, instrumentation problems precluded the reduction of aircraft data for the roll SAS flights.

The $\dot{\beta}$ SAS was shown to be effective in the ATA tracking task by reductions in the tracking error shown on gun camera film. The lateral acceleration (A_y) term in the $\dot{\beta}$ control law was switched out during the data gathering flights because it was very noisy and added no real improvement to the response. The system also showed to be an improvement over the standard SAS in terms of reduction in pilot workload. These conclusions are based primarily on pilot comments and on gun camera film taken during many of the tracking encounters. There is also some strip chart data of aircraft parameters which aided somewhat in system evaluation. Unfortunately, the parameters most critical to the $\dot{\beta}$ system evaluation, β and r, were not measured during the tests due to instrumentation problems.

Figures 33 and 34 show a direct comparison between the standard SAS and the $\dot{\beta}$ SAS with Homing Point E gains ($K_{\dot{\beta}}$=1.5, K_p=3.45). The long straight line in the pipper trace of Figure 33 is caused by a data dropout in the instrumentation system. The flight condition was Mach = .8, 10,000 ft. These figures show tracking error data during an aileron reversal. In this case, the difficulty of the task masked much of the SAS differences, although one can see a higher frequency content in the $\dot{\beta}$ SAS error time plots. This higher frequency content is indicative of the faster response available when the aircraft was flying with the $\dot{\beta}$ SAS engaged. Pilot comments confirmed the faster response time with the $\dot{\beta}$ SAS. They also indicated this faster response to be a desirable capability during ATA tracking.

Figures 35 and 36 show similar tracking error comparisons between the standard SAS and the $\dot{\beta}$ SAS. Both a right and left 4 g turn at Mach .8 and 10,000 feet are shown. The right turn shows little difference between the two systems other than the decreased response time of $\dot{\beta}$ SAS as indicated qualitatively by the higher frequency content of the error

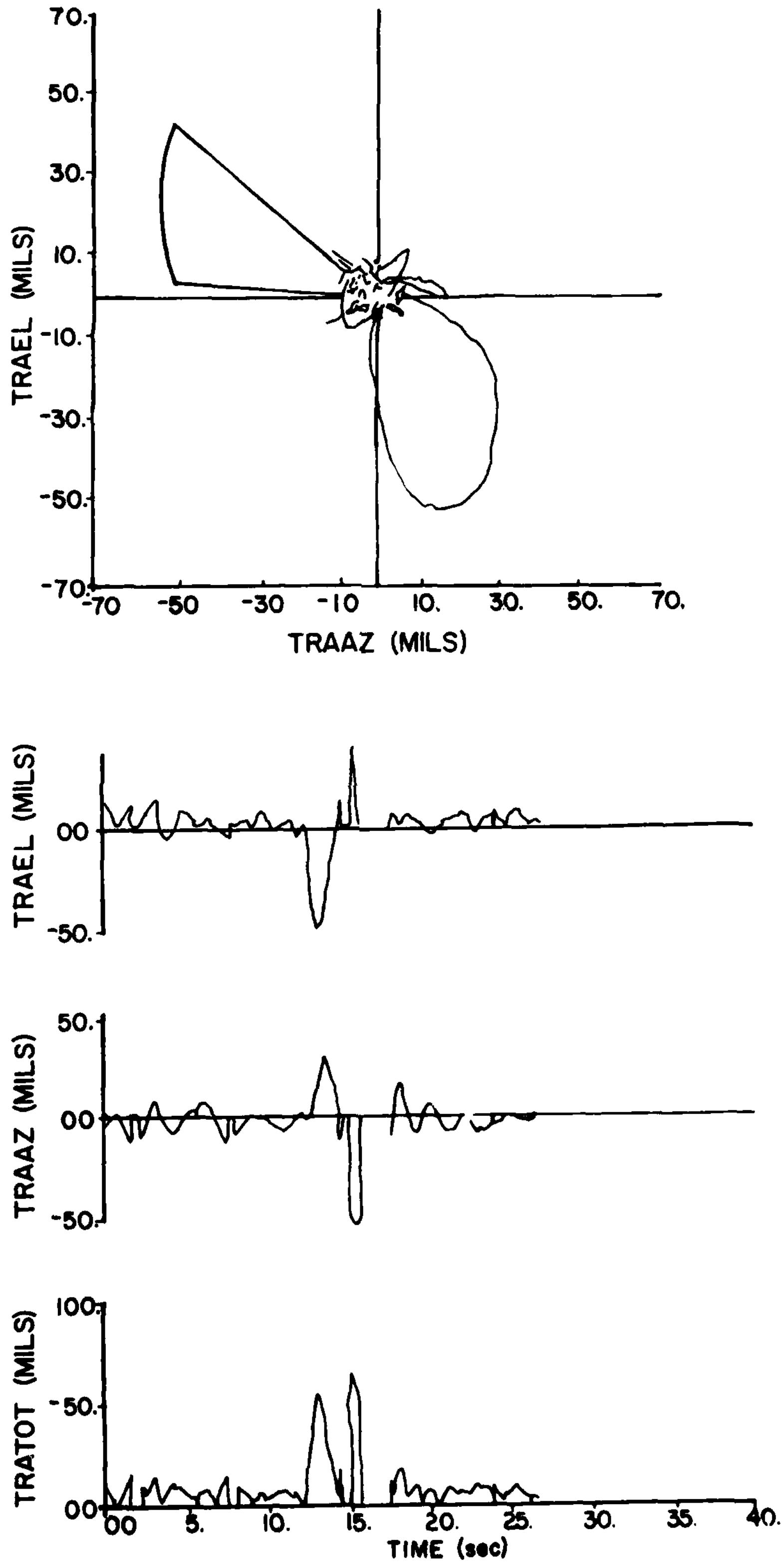


Figure 33. Standard SAS, Aileron Reversal, Mach .8, 10000 Feet

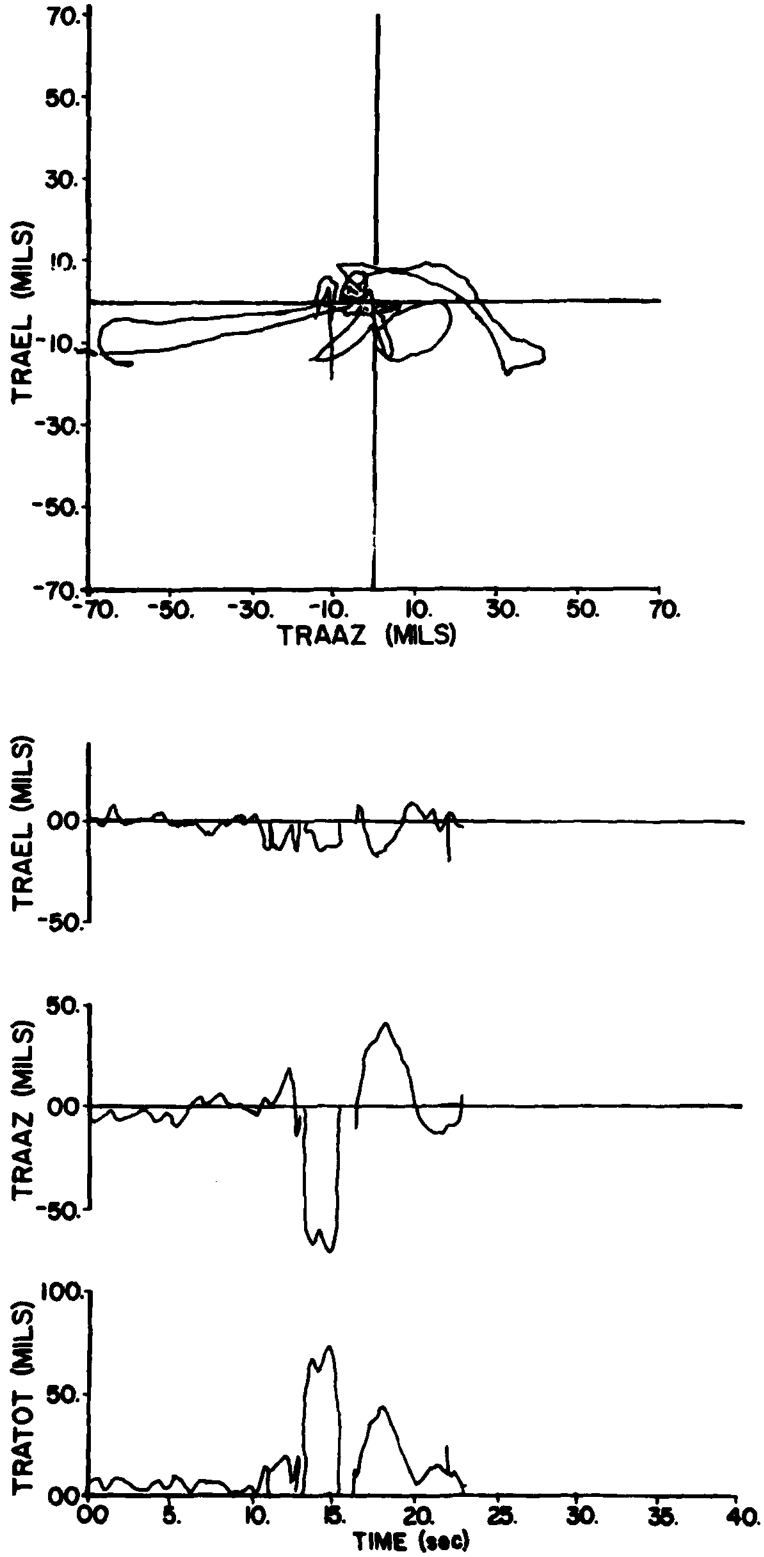


Figure 34. $K_{\dot{\beta}}$= 1.5, K_p=3.45, Aileron Reversal, Mach .8, 10000 Feet

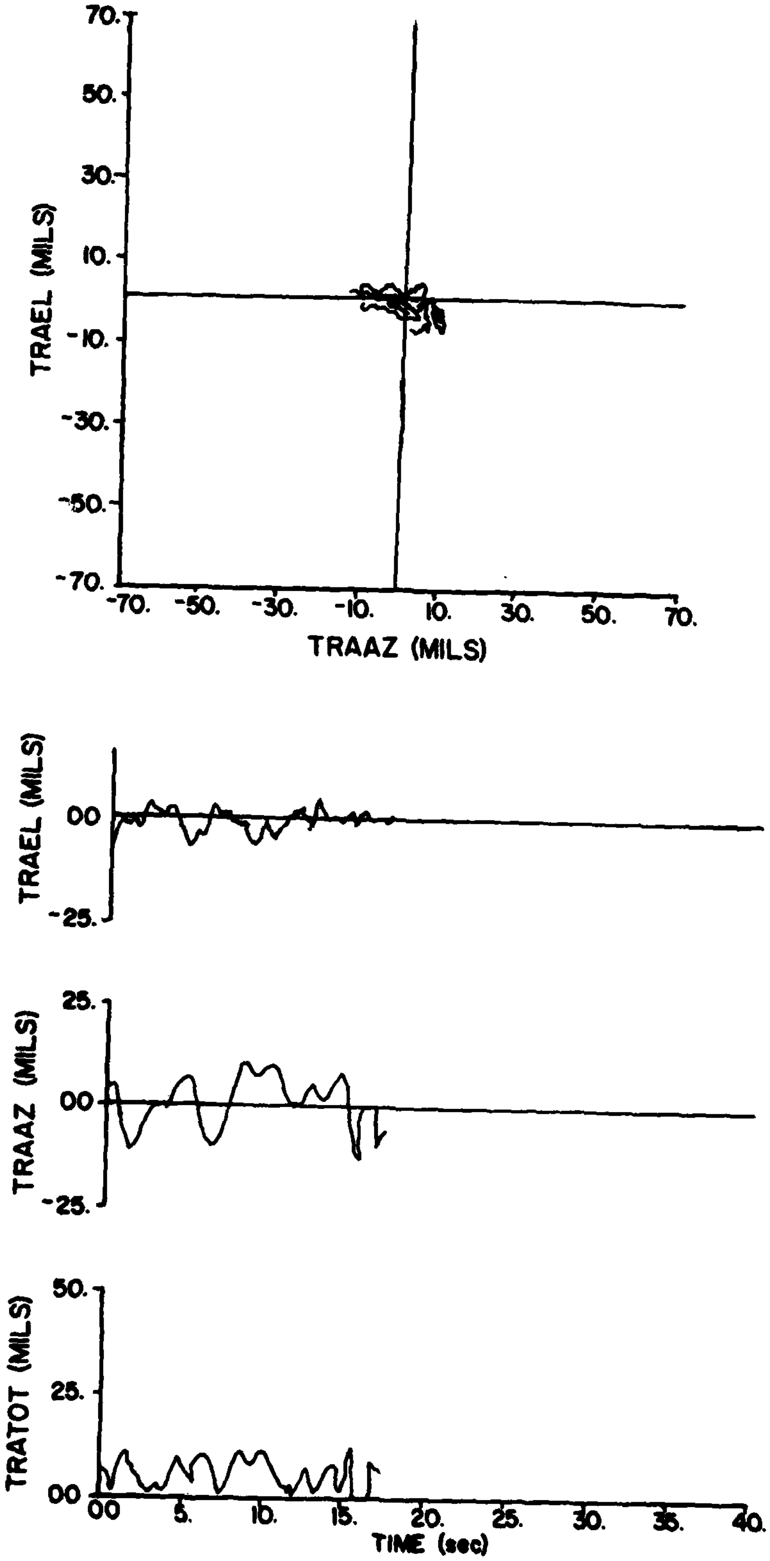


Figure 35. Standard SAS, 4 g Turn, Mach .8, 10000 Feet

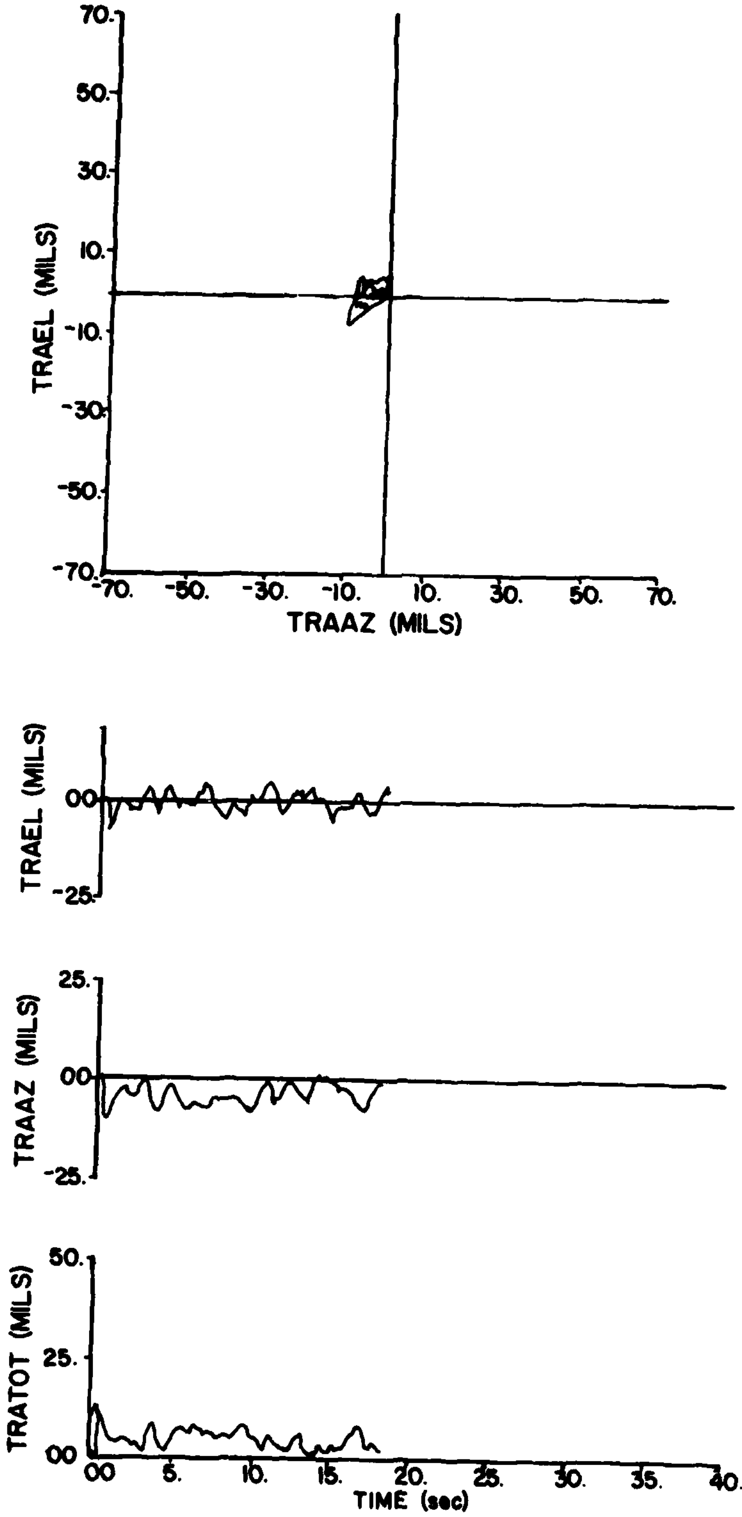


Figure 36. $K_{\dot{\beta}}$= 1.5, K_p=3.45, 4 g Turn, Mach .8, 10000 Feet

time plots. The left turn, however, does show a significant decrease in tracking error on both the pipper plot and the error time plots.

Figures 37 through 42 show additional flight test results for constant 3.5 to 4 g turns. The standard SAS results, Figure 37, show a fairly large pipper trace with excursions as high as $\pm$25 mils in both elevation and traverse. The $\dot{\beta}$ SAS, Figures 38 through 42, shows significant reduction in this aim wander. The results are especially impressive in Figure 38 with $K_{\dot{\beta}}$=1.9 and K_p=3.45, over 50% reduction in aim wander. Although these plots represent tracking performance for only one flight, they are representative of the performance achieved by all the pilots on all the test missions.

In addition to the improvement evidenced by the pipper plots, Figure 43 shows data which is indicative of the reduction in pilot workloads achieved using the system. The time history strip chart recordings from this figure were taken from the pass whose pipper plot is shown in Figure 42. The reduction in pilot workload is evidenced by the reduction in magnitude of the stick and rudder deflections. The decreased response time is evidenced by the higher frequency content of the control movements using the $\dot{\beta}$ SAS. The workload reduction evidenced by Figure 43 is very similar to the workload reduction evidenced by Figure 28 showing simulator results.

A total of three different pilots flew the modified SAS. The roll SAS did not function and was therefore not evaluated. All agreed that the $\dot{\beta}$ SAS was an improvement over the standard SAS during ATA tracking. The pilot comments indicated that the improvement in tracking capability was due to the "crisper", faster response available using the $\dot{\beta}$ SAS. The consensus was that the gains of $K_{\dot{\beta}}$=1.9 and K_p=2.5 were the best of those tested. The pilots felt that these gains made the best system by providing a quick but controllable response.

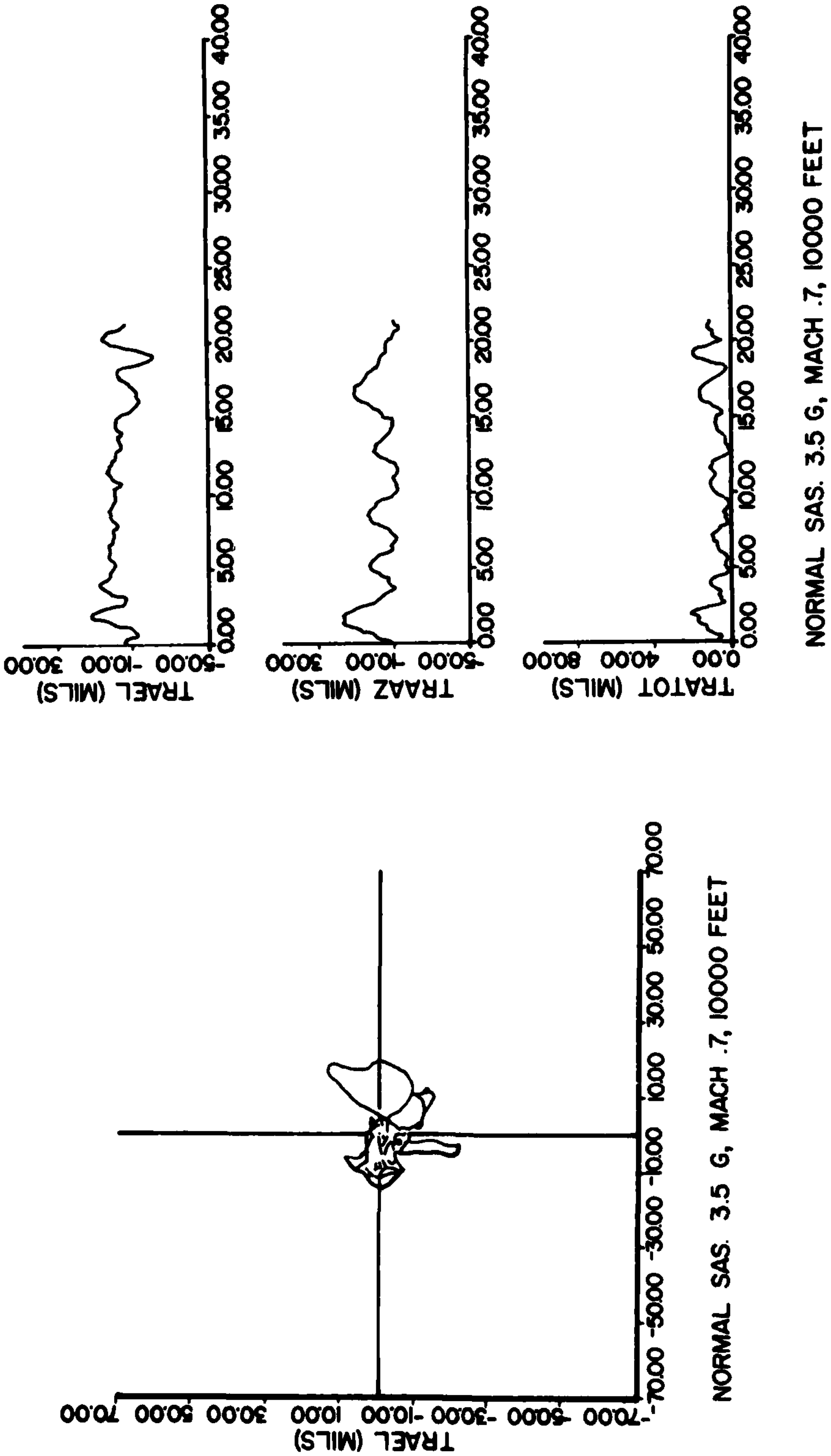
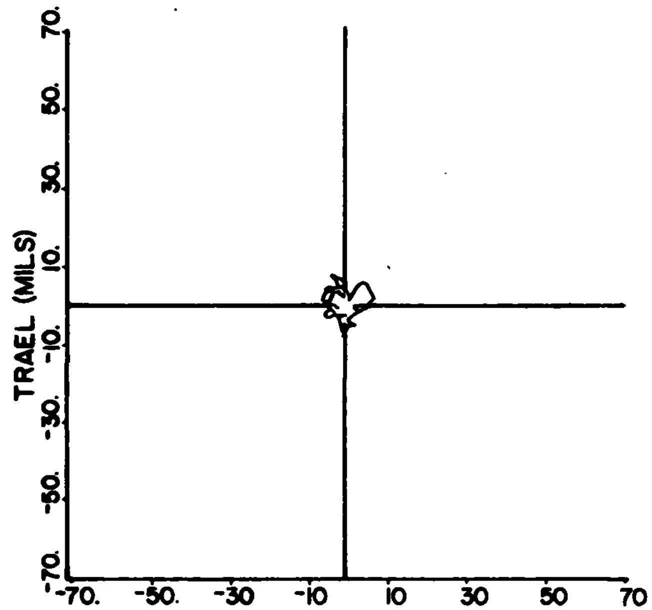
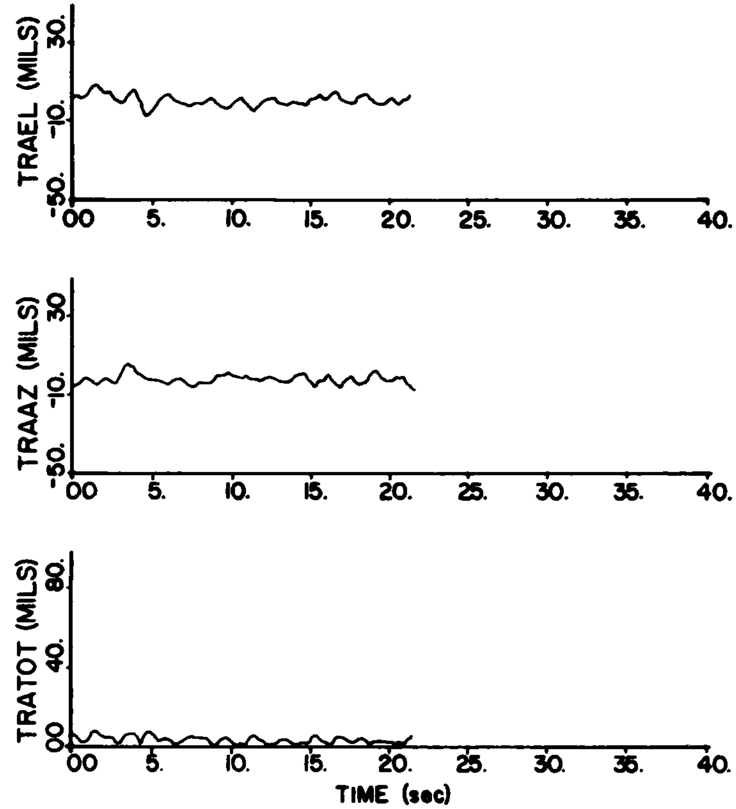


Figure 37. Standard SAS, 3.5 g, Mach .7, 10000 Feet



KBO=1.9. KP=5. 3.7 G, MACH .7, 10000 FEET



KBO=1.9. KP=5. 3.7 G, MACH .7, 10000 FEET

Figure 38. $K_{\dot{\beta}}$=1.9, K_p=5, 3.7 g, Mach .7, 10000 Feet

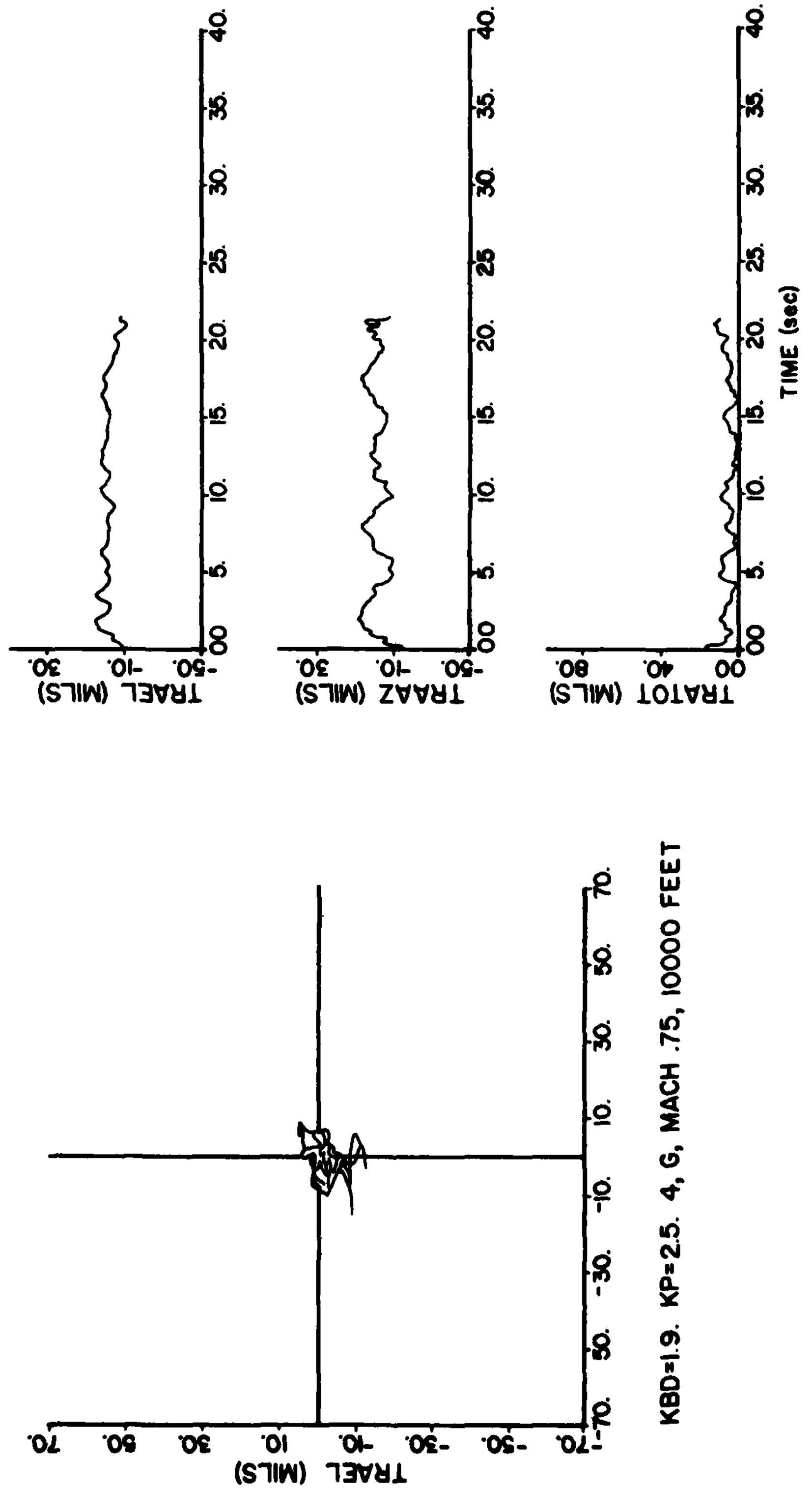
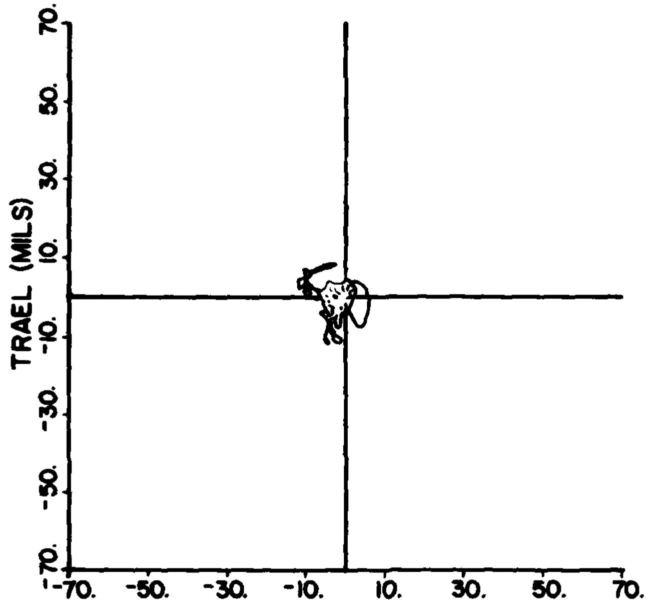
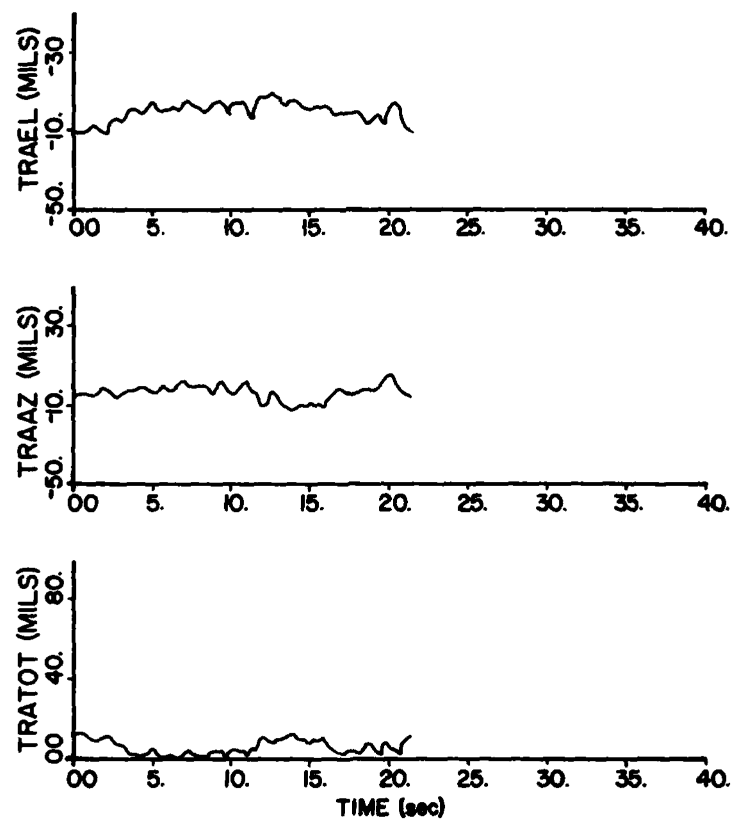


Figure 39. $K_{\dot{\beta}}$=1.9, K_p=2.5, 4 g, Mach .75, 10000 Feet



KBD=1.25. KP=3.28. 4 G, MACH .75, 10000 FEET



KBD=1.25. KP=3.28. 4 G, MACH .75, 10000 FEET

Figure 40. $K_{\dot{\beta}}$=1.25, K_p=3.28, 4 g, Mach .75, 10000 Feet

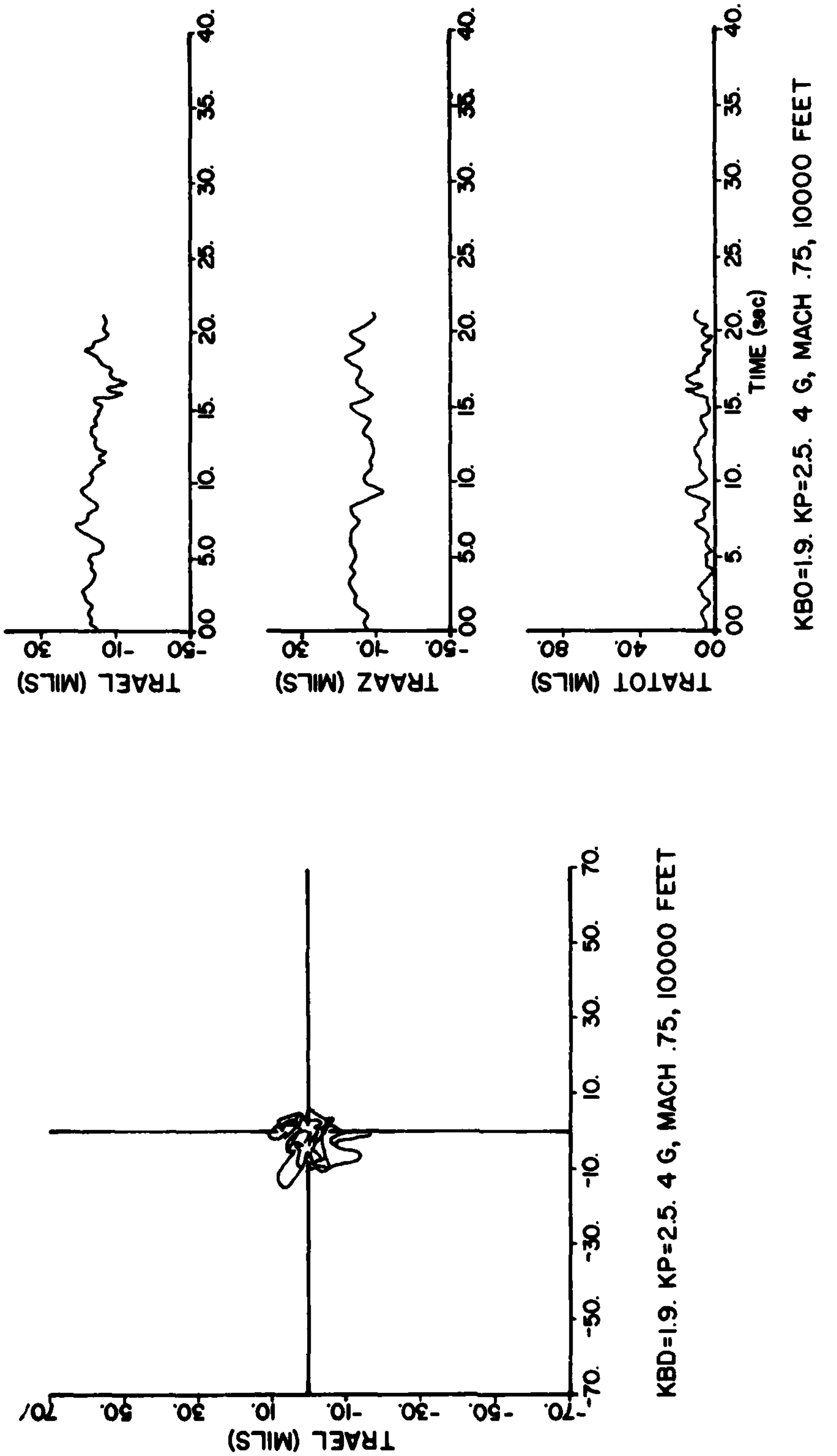
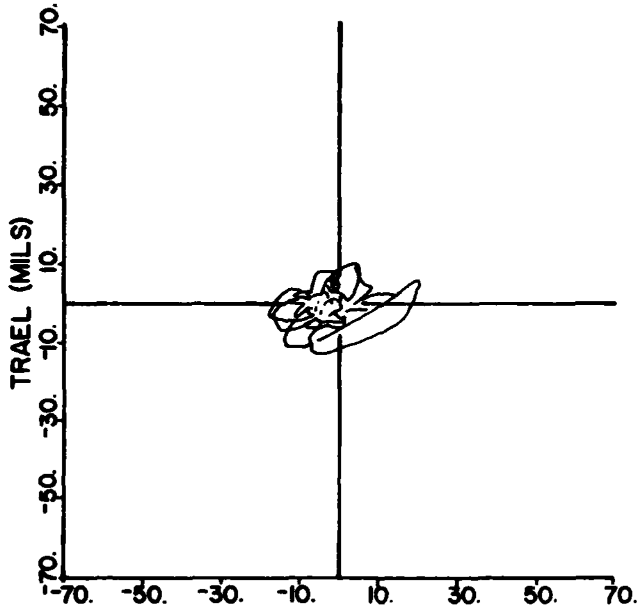
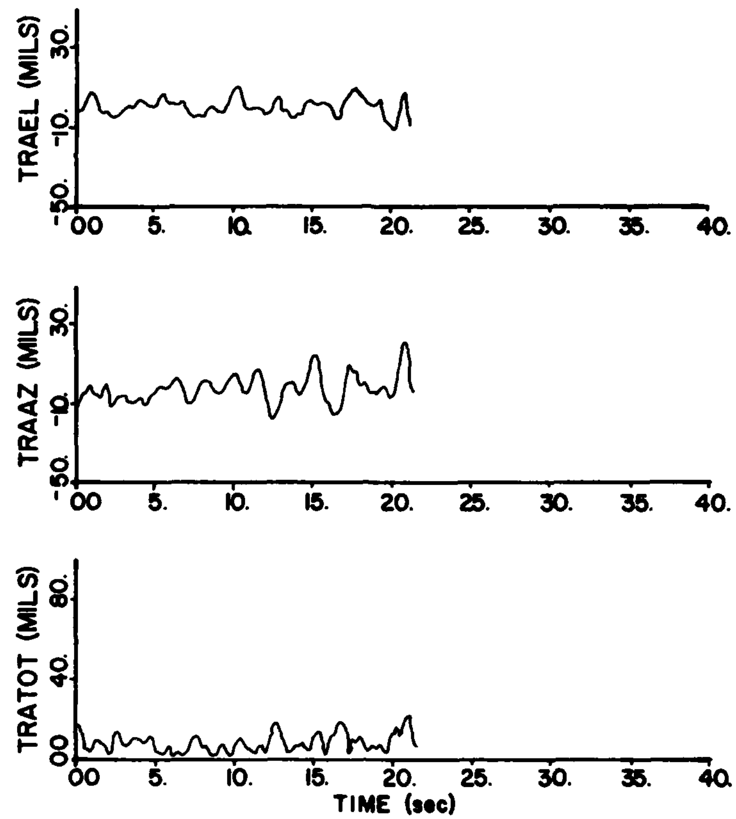


Figure 41. $K_{\dot{\beta}}$=1.9, K_p=2.5, 4 g, Mach .75, 10000 Feet



KBD=1.5. KP=3.45. 4 G, MACH .75, 10000 FEET



KBD=1.5. KP=3.45. 4 G, MACH .75, 10000 FEET

Figure 42. $K_{\dot{\beta}}$=1.5, K_p=3.45, 4 g, Mach .75, 10000 Feet

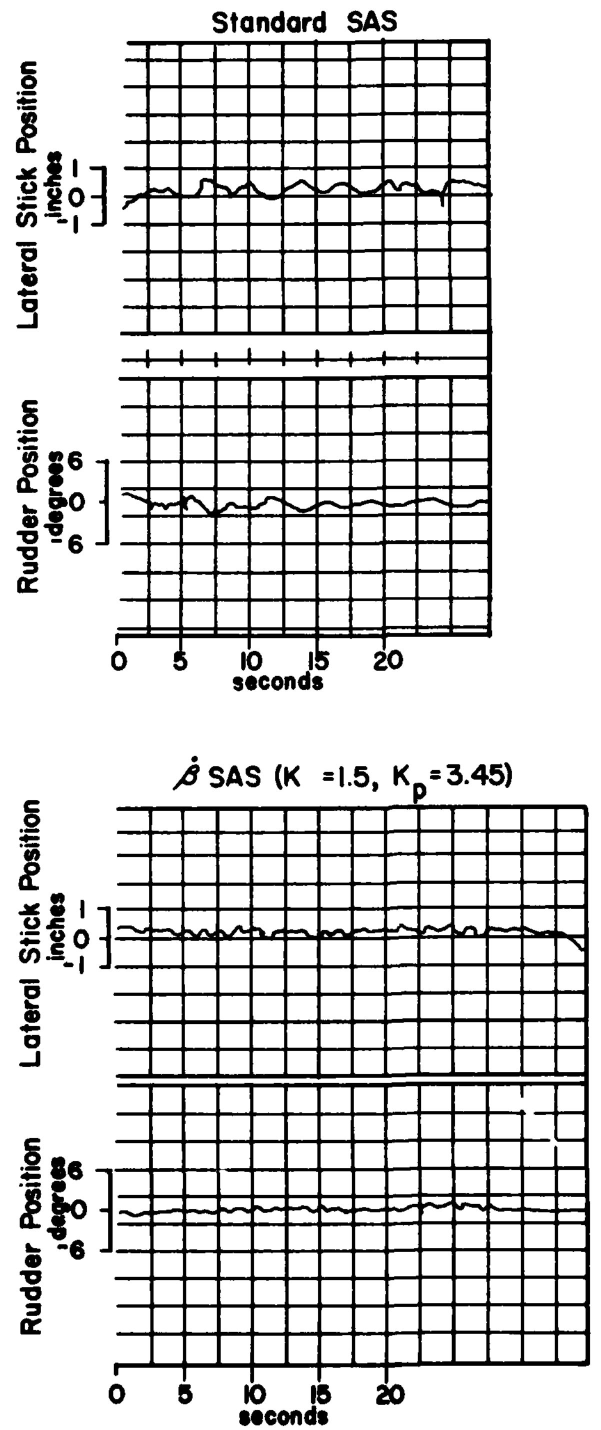


Figure 43. Pilot Workload Comparison, 4 g Tracking Task

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

A lateral stability augmentation system for the F-106 has been designed using sideslip rate and sideslip angle as primary feedbacks. The sideslip rate is synthesized from signals available from sensors on board the aircraft. Both time and frequency domain simulations showed that the dynamic response of the aircraft is improved using the new SAS. A piloted simulation of ATA tracking encounters was also conducted to compare the existing SAS with two configurations of the β-$\dot{\beta}$ SAS. This simulation showed that a configuration of the β-$\dot{\beta}$ SAS which allowed only $\dot{\beta}$ to be fed to the rudder demonstrated substantial improvement over the standard SAS. This improvement in standard deviation of tracking error varied from 5% to 45% depending on pilot and flight condition. Based on these piloted and non-piloted simulations, the use of a $\dot{\beta}$ feedback in place of the existing SAS on the F-106 will significantly improve lateral handling qualities during tracking.

To verify this conclusion, this system was flight tested at Tyndall AFB, Florida. The flight test results, in terms of HUD camera film data and pilot comments, confirmed this conclusion that a $\dot{\beta}$ SAS will improve the F-106 handling qualities during tracking.

2. RECOMMENDATIONS

Based on the flight test results and pilot comments, the Control Systems Development Branch of the Flight Dynamics Laboratory recommended to the Air Defense Command (ADCOM) that this modified system, using $\dot{\beta}$ as primary feedback, be retrofitted to the F-106's now in the inventory. ADCOM/DOV agreed with the conclusion that such a system would improve the F-106 flight control system; however, fiscal considerations forced a negative decision on retrofit.

APPENDIX A

ASD HYBRID SIMULATION

Part of the design process includes looking at the different SAS's in a six degree-of-freedom, nonlinear simulation. This simulation is based on force and moment equations from the GDCA report (Reference 7). The force and moment equations, composed of the aerodynamic coefficients for the F-106, are used in the simulation equations which solve for $\dot{p}$, $\dot{q}$, $\dot{r}$, $\dot{u}$, $\dot{v}$, and $\dot{w}$ (Reference 8). These simulation equations and the force and moment equations are shown below.

1. SIMULATION EQUATIONS

The following equations are the basic differential equations used in the ASD hybrid simulation.

$$\dot{p} = \frac{L}{I_x} + \dot{r}\frac{I_{xz}}{I_x} - qr\frac{(I_z - I_y)}{I_y} + pq\frac{I_{xz}}{I_x} \tag{A-1}$$

$$\dot{q} = \frac{M}{I_y} + pr\frac{(I_z - I_x)}{I_y} + (r^2 - p^2)\frac{I_{xz}}{I_y} \tag{A-2}$$

$$\dot{r} = \frac{N}{I_z} + \dot{p}\frac{I_{xz}}{I_z} - pq\frac{(I_y - I_x)}{I_x} - qr\frac{I_{xz}}{I_z} \tag{A-3}$$

$$\dot{u} = \frac{T + Fx}{m} - g\sin\theta + rv - qw \tag{A-4}$$

$$\dot{v} = \frac{Fy}{m} + g\cos\theta\sin\phi + pw - ru \tag{A-5}$$

$$\dot{w} = \frac{Fz}{m} + g\cos\theta\cos\phi + qu - pv \tag{A-6}$$

2. FORCE AND MOMENT EQUATIONS

The force and moment equations below are used as inputs to the simulation equations above. The equations include both first and second order aerodynamic effects. A more detailed description of the equations and coefficients is found in Reference 6.

$$F_x = (-C_D \cos\alpha + C_L \sin\alpha)\bar{q}S \tag{A-7}$$

$$F_y = \left\{ C_{y_\beta}\beta + C_{y_{\delta a}}\delta a + C_{y_{\delta r}}\delta r + (C_{y_p} p + C_{y_r} r)\frac{b}{2U} + \left[\left(\frac{\partial C_{y_\beta}}{\partial \alpha^2}\alpha + \frac{\partial C_{y_\beta}}{\partial \alpha}\right)\alpha + \frac{\partial C_{y_\beta}}{\partial |\beta|}|\beta|\right]\beta \right\}\bar{q}S \tag{A-8}$$

$$F_z = (-C_L \cos\alpha - C_D \sin\alpha + C_{z_\alpha}\alpha + C_{z_{\delta e}}\delta e)\bar{q}S \tag{A-9}$$

$$L = \left\{ C_{l_p} p + C_{l_r} r)\frac{b}{2U} + C_{l_\beta}\beta + C_{l_{\delta a}}\delta a + C_{l_{\delta r}}\delta r + \left[\left(\frac{\partial C_{l_\beta}}{\partial \alpha |\alpha|}|\alpha| + \frac{\partial C_{l_\beta}}{\partial \alpha}\right)\alpha + \frac{\partial C_{l_\beta}}{\partial |\beta|}|\beta|\right]\beta + \left[\left(\frac{\partial C_{l_p}}{\partial \alpha^2}\alpha + \frac{\partial C_{l_p}}{\partial \alpha}\right)p + \frac{\partial C_{l_r}}{\partial \alpha} r\right]\frac{\alpha b}{2U} \right\}\bar{q}Sb \tag{A-10}$$

$$M = \left[C_m + C_{m_q}\frac{\bar{c}}{2U}(q + \dot{\alpha}) + C_{m_{\delta e}}\delta e\right]\bar{q}S\bar{c} + (n.p. + \bar{c} - x_{c.g.})F_z \tag{A-11}$$

$$N = \left\{ C_{n_\beta}\beta + C_{n_{\delta a}}\delta a + C_{n_{\delta r}}\delta r + (C_{n_p} p + C_{n_r} r)\frac{b}{2U} + \left[\left(\frac{\partial C_{n_\beta}}{\partial \alpha^2}\alpha + \frac{\partial C_{n_\beta}}{\partial \alpha}\right)\alpha + \frac{\partial C_{n_\beta}}{\partial |\beta|}|\beta| + \Delta C_{n_\beta}\right]\beta + \left(\frac{\partial C_{n_{\delta a}}}{\partial \alpha}\alpha + \frac{\partial C_{n_{\delta a}}}{\partial \delta e}\delta e\right)\delta a \right\}\bar{q}Sb \tag{A-12}$$

APPENDIX B

ROOT MAP DATA FOR THE F-106

The root map technique, described in Section III.1, involves finding numerous root loci at each flight condition. Part of the root loci at a given flight condition are generated with fixed values of K_β while the gain $K_{\dot\beta}$ is allowed to vary. The remaining loci have fixed values of $K_{\dot\beta}$ while K_β varies. The transfer function used with a fixed value for K_β is shown below. The derivation is shown in Section III.1.

$$GH)_{\text{Const } K_\beta} = \frac{K_{\dot\beta} K s(s + a)(s + K_I)}{s^3 + b' s^2 + c' s + d'} \qquad \text{(B-1)}$$

A similar transfer function results when $K_{\dot\beta}$ is held constand and K_β varies.

$$GH)_{\text{Const } K_{\dot\beta}} = \frac{\frac{K_\beta K}{1 + K_{\dot\beta} K}(s + a)(s + K_I)}{s(s^2 + b'' s + c'')} \qquad \text{(B-2)}$$

The tables included in this appendix contain the numerator and denominator roots for the transfer functions used to generate the root maps of Section III. The fixed values of $K_{\dot\beta}$ vary from 1 to 7; K_β varies from 1 to 15.

TABLE B-1

TRANSFER FUNCTION DATA FOR MACH .4, SEA LEVEL

Constant $K_{\dot{\beta}}$

$K_{\dot{\beta}}$	$\frac{K}{1 + K_{\dot{\beta}}K}$	Numerator Roots	Denominator Roots
1	.0427	-.2, -53.23	0, -1.64±i1.85
2	.0409		0, -3.57, -1.76
3	.0393		0, -6.17, -1.05
4	.0378		0, -8.16, - .81
5	.0365		0, -9.91, - .68
6	.0352		0, -11,49,-0.6
7	.034		0, -12.96, -.54

Constant K_{β}

K_{β}	K	Numerator Roots	Denominator Roots
1	.0446	0, -.2, -53.23	-.058, -.518±i2.82
2			-.090, -.524±i3.21
3			-.11 , -.535±i3.55
4			-.124, -.551±i3.87
5			-.134, -.568±i4.16
6			-.142, -.587±i4.43
7			-.149, -.606±i4.69
8			-.154, -.626±i4.93
9			-.158, -.646±i5.17
10			-.161, -.667±i5.39
11			-.164, -.688±i5.6
12			-.167, -.709±i5.81
13			-.169, -.730±i6.00
14			-.171, -.750±i6.20
15			-.173, -.774±i6.38

TABLE B-2

TRANSFER FUNCTION DATA FOR MACH .9, SEA LEVEL

Constant $K_{\dot{\beta}}$

$K_{\dot{\beta}}$	$\frac{K}{1 + K_{\dot{\beta}}K}$	Numerator Roots	Denominator Roots
1	.0641	-.2, -57.34	0, -2.77±i3.98
2	.0602		0, -4.34±i2.0
3	.0568		0, -8.99 , -2.46
4	.0538		0, -12.14, -1.78
5	.051		0, -14.72, -1.43
6	.0485		0, -16.94, -1.22
7	.0463		0, -18.91, -1.07

Constant K_{β}

K_{β}	K	Numerator Roots	Denominator Roots
1	.0685	0, -.2, -57.34	-.028, -1.01 ±i5.22
2			-.049, -1.03 ±i5.57
3			-.066, -1.06 ±i5.90
4			-.079, -1.09 ±i6.22
5			-.090, -1.11 ±i6.53
6			-.099, -1.14 ±i6.82
7			-.106, -1.17 ±i7.06
8			-.113, -1.203±i7.36
9			-.119, -1.236±i7.62
10			-.123, -1.268±i7.86
11			-.128, -1.298±i8.10
12			-.132, -1.329±i8.34
13			-.136, -1.362±i8.57
14			-.139, -1.4 ±i8.79
15			-.142, -1.43 ±i9.0

TABLE B-3

TRANSFER FUNCTION DATA FOR MACH .7, 10000 FEET

Constant $K_{\dot{\beta}}$

$K_{\dot{\beta}}$	$\frac{K}{1 + K_{\dot{\beta}} K}$	Numerator Roots	Denominator Roots
1	.0495	-.2, -78.08	0, -2.471±i2.13
2	.0472		0, -6.8, -1.6
3	.0451		0, -10.49, -1.06
4	.0431		0, -13.6, -.83
5	.0413		0, -16.37, -.7
6	.0397		0, -18.88, -.62
7	.0382		0, -21.2, -.56

Constant K_{β}

K_{β}	K	Numerator Roots	Denominator Roots
1	.0521	0, -.2, -78.077	-.056 , -.558±i3.75
2			-.088 , -.566±i4.26
3			-.1085, -.584±i4.71
4			-.1229, -.603±i5.11
5			-.133 , -.624±i5.5
6			-.141 , -.645±i5.85
7			-.147 , -.67 ±i6.19
8			-.152 , -.69 ±i6.51
9			-.156 , -.717±i6.81
10			-.16 , -.74 ±i7.1
11			-.163 , -.765±i7.38
12			-.165 , -.79 ±i7.64
13			-.168 , -.82 ±i7.9
14			-.17 , -.84 ±i8.16
15			-.171 , -.86 ±i8.4

TABLE B-4

TRANSFER FUNCTION DATA FOR MACH .6, 15000 FEET

Constant $K_{\dot{\beta}}$

$K_{\dot{\beta}}$	$\frac{K}{1 + K_{\dot{\beta}} K}$	Numerator Roots	Denominator Roots
1	.024	-.2, -102.85	0, -1.71 ±i2.08
2	.0234		0, -3.82 , -1.96
3	.0229		0, -6.85 , -1.12
4	.0224		0, -9.15 , - .86
5	.022		0, -11.2 , - .72
6	.0214		0, -13.08, - .63
7	.021		0, -14.83, - .57

Constant K_{β}

$K_{\dot{\beta}}$	K	Numerator Roots	Denominator Roots
1	.0391	0, -.2, -68.21	-.056, -.431±i3.07
2			-.087, -.435±i3.48
3			-.107, -.446±i3.84
4			-.121, -.454±i4.17
5			-.132, -.469±i4.48
6			-.14 , -.485±i4.76
7			-.146, -.502±i5.03
8			-.151, -.519±i5.29
9			-.155, -.537±i5.54
10			-.159, -.556±i5.77
11			-.162, -.574±i5.99
12			-.165, -.593±i6.21
13			-.167, -.610±i6.42
14			-.169, -.630±i6.62
15			-.171, -.647±i6.82

TABLE B-5

TRANSFER FUNCTION DATA FOR MACH .9, 15000 FEET

Constant $K_{\dot{\beta}}$

$K_{\dot{\beta}}$	$\frac{K}{1 + K_{\dot{\beta}} K}$	Numerator Roots	Denominator Roots
1	.0443	-.2, -64.51	0, -2.02±i3.19
2	.0424		0, -3.31±i1.81
3	.0407		0, -6.94 , -2.04
4	.0391		0, -9.71 , -1.45
5	.0376		0, -12.01, -1.17
6	.0362		0, -14.04, -1
7	.035		0, -15.91, - .88

Constant K_{β}

$K_{\dot{\beta}}$	K	Numerator Roots	Denominator Roots
1	.0463	0, -.2, -64.51	-.035, -.618±i4.11
2			-.059, -.63 ±i4.45
3			-.077, -.643±i4.77
4			-.091, -.659±i5.08
5			-.102, -.679±i5.36
6			-.11 , -.694±i5.63
7			-.12 , -.715±i5.88
8			-.13 , -.757±i6.13
9			-.13 , -.755±i6.37
10			-.13 , -.777±i6.6
11			-.14 , -.795±i6.82
12			-.14 , -.818±i7.03
13			-.15 , -.842±i7.23
14			-.15 , -.860±i7.44
15			-.15 , -.884±i7.63

TABLE B-6

TRANSFER FUNCTION DATA FOR MACH 1.2, 15000 FEET

$K_{\dot\beta}$	$\frac{K}{1 + K_{\dot\beta}K}$	Constant $K_{\dot\beta}$ Numerator Roots	Denominator Roots
1	.0376	-.2, -88.21	0, -1.91 ±i4.66
2	.0363		0, -3.07 ±i3.97
3	.035		0, -4.18 ±i2.77
4	.0338		0, -6.79 , -3.68
5	.0327		0, -10.01, -2.49
6	.0317		0, -12.4 , -2
7	.0307		0, -14.61, -1.69

Constant K_β

K_β	K	Numerator Roots	Denominator Roots
1	.0246	0, -.2, -102.85	-.018, -.686±i5.24
2			-.033, -.688±i5.48
3			-.046, -.697±i5.70
4			-.057, -.702±i5.92
5			-.067, -.712±i6.12
6			-.075, -.717±i6.33
7			-.082, -.729±i6.52
8			-.089, -.739±i6.72
9			-.095, -.748±i6.90
10			-.100, -.755±i7.08
11			-.105, -.768±i7.25
12			-.109, -.775±i7.42
13			-.113, -.786±i7.59
14			-.117, -.797±i7.75
15			-.120, -.807±i7.91

TABLE B-7

TRANSFER FUNCTION DATA FOR MACH .6, 30000 FEET

Constant $K_{\dot{\beta}}$

$K_{\dot{\beta}}$	$\frac{K}{1 + K_{\dot{\beta}}K}$	Numerator Roots	Denominator Roots
1	.0221	-.2, 78.67	0, -1.18 ,±i2.01
2	.0216		0, -2.013,±i1.272
3	.0212		0, -4.21 , -1.4
4	.0207		0, -6.14 , - .99
5	.0203		0, -7.78 , - .808
6	.0122		0, -9.82 , - .7
7	.0195		0, -10.71, - .62

Constant K_{β}

K_{β}	K	Numerator Roots	Denominator Roots
1	.0226	0, -.2, -78.67	-.051, -.31±i2.62
2			-.081, -.3 ±i2.94
3			-.1 , -.36±i3.23
4			-.12 , -.36±i3.48
5			-.13 , -.31±i3.74
6			-.135, -.32±i3.97
7			-.14 , -.33±i4.18
8			-.147, -.34±i4.39
9			-.151, -.35±i4.59
10			-.155, -.36±i4.78
11			-.157, -.37±i4.96
12			-.16 , -.38±i5.13
13			-.16 , -.39±i5.3
14			-.166, -.40±i5.47
15			-.167, -.41±i5.63

TABLE B-8

TRANSFER FUNCTION DATA FOR MACH .9, 30000 FEET

Constant $K_{\dot{\beta}}$

$K_{\dot{\beta}}$	$\frac{K}{1 + K_{\dot{\beta}}K}$	Numerator Roots	Denominator Roots
1	.0274	-.2, -76.56	0, -1.416±i2.551
2	.0267		0, -2.401±i1.712
3	.026		0, -4.834, -1.83
4	.0253		0, -7.183, -1.257
5	.0247		0, -9.118, -1.007
6	.0241		0, -10.869, -.859

Constant K_{β}

K_{β}	K	Numerator Roots	Denominator Roots
1	.0282	0, -.2, -76.56	-.0413, -.37 ±i3.21
2			-.0686, -.37 ±i3.53
3			-.088 , -.37 ±i3.82
4			-.1 , -.38 ±i4.09
5			-.11 , -.39 ±i4.34
6			-.12 , -.40 ±i4.59
7			-.13 , -.41 ±i4.81
8			-.135 , -.42 ±i5.03
9			-.14 , -.43 ±i5.24
10			-.145 , -.44 ±i5.44
11			-.149 , -.46 ±i5.635
12			-.152 , -.47 ±i5.82
13			-.155 , -.48 ±i6.0
14			-.157 , -.494±i6.2
15			-.159 , -.51 ±i6.35

TABLE B-9

TRANSFER FUNCTION DATA FOR MACH 1.4, 30000 FEET

Constant $K_{\dot{\beta}}$

$K_{\dot{\beta}}$	$\frac{K}{1 + K_{\dot{\beta}}K}$	Numerator Roots	Denominator Roots
1	.0148	-.2, -81.67	0, -1.045±i4.017
2	.0146		0, -1.626±i3.817
3	.0144		0, -2.191±i3.522
4	.0142		0, -2.739±i3.113
5	.014		0, -3.272±i2.544
6	.0138		0, -3.79 ±i1.673
7	.0136		0, -5.43 -3.1593

Constant K

K_{β}	K	Numerator Roots	Denominator Roots
1	.015	0, -.2, -81.67	-.013 , -.448±i4.27
2			-.025 , -.45 ±i4.413
3			-.035 , -.452±i4.55
4			-.044 , -.455±i4.68
5			-.053 , -.458±i4.81
6			-.06 , -.462±i4.93
7			-.067 , -.467±i5.056
8			-.073 , -.471±i5.174
9			-.078 , -.475±i5.29
10			-.083 , -.48 ±i5.14
11			-.088 , -.49 ±i5.52
12			-.0921, -.49 ±i5.625
13			-.096 , -.50 ±i5.73
14			-.1 , -.50 ±i5.836
15			-.103 -.51 ±i5.94

APPENDIX C

EASY DYNAMIC ANALYSIS PROGRAM

Under contract to the USAF, The Boeing Aircraft Company developed the Environmental Systems Analysis (EASY) digital computer program. The program was originally developed to use in designing environmental control systems. It has since been extended to allow time and frequency domain analysis of aircraft systems.

The program is used to describing the system to be analyzed through the use of block diagrams and the associated interconnections. The program supplies generic block diagrams of the airframe and engine and the user supplies the aerodynamic data and the block diagrams representing the control system, pilot model, gunsight algorithm or any aircraft subsystem desired in the analysis. The F-106 was programmed using the same set of force and moment equations as used in the ASD Hybrid Simulation described in Appendix A.

The included listings show an example of the data required to generate the F-106 aircraft system model with both standard and β-$\dot{\beta}$ SAS. Also shown are the models resulting from the data and the data decks required to produce the Bode plots at .8 Mach and 10000 feet. Figures C-1 and C-2 contain the input data and resulting models for the β-$\dot{\beta}$ and standard SAS. Figures C-3 and C-4 contains the analysis data used to draw the Bode plots.

```
MODEL DESCRIPTION       F106 BETADOT AND BETA SAS MODEL
ADD TABLES=CYBA,-53,CNBA,-53,CNBAA,-53,CNBADE,-53
ADD TABLES=CLZ,158,CLB,158,CLBA,110,CLBA2,158,CLBP,158,CLDA,158,
CLDE,158,CLP,158,CLPA2,158,CLR,158,CLRA,158,CMDE,158,CMQ,158,CMO,158,
CNB,158,CNBA2,158,CNDR,158,CNDA,158,CNDP,110,CNP,158,CNR,158,CYB,158,
CYBA2,158,CYDR,158,CYDA,158,CYDP,158,CYP,158,CYR,158,CLA,158,CLDE,158,
TMP,158,CLPA,158,CD0,327,CD25,327,CD5,327,CD10,327,CD15,327
ADD PARAMETERS= ,XCG,YREF,YCG,ZREF,ZCG,RPD
ADD VARIABLES=AX,AY,AZ,BETADOT
LOCATION=56         AV        INPUTS=SD
LOCATION=76         FV        INPUTS=SD(ALT=X),AV(MAC=X)
LOCATION=52         MA        INPUTS=FV(X=C1),LGTT,
LOCATION=2          EM        INPUTS=MA(X=THP)
FORTRAN STATEMENTS
C
C            COMPUTE ACCELERATIONS IN G'S
C
      G=32.2
      AX=EU AV/G
      AY=EV AV/G
      AZ=EW AV/G
CCCCCCCCC
C            COMPUTE LONGITUDINAL FORCE TERMS% FZ EN AND FX EN
CCCCCCCCC
C                        INTERPOLATE TO FIND LIFT COEFFICIENTS
C
      CL0= TBLU2(MACAV,ALTSD,CLZ(9),CLZ(4),CLZ(34),1,1,-25,-5,25,5)
      CLA0= TBLU2(MACAV,ALTSD,CLA(9),CLA(4),CLA(34),1,1,-25,-5,25,5)
      CLDE0=TBLU2(MACAV,ALTSD,CLDE(9),CLDE(4),CLDE(34),1,1,-25,-5,25,5)
C
C                        COMPUTE LIFT,DRAG COEFFICIENTS AND BODY AXIS FORCES
      ELEV= X2 LA E*RPD
      ALPHA= AL AV*RPD
       CL1= CL0 + CLA0*ALPHA + CLDE0*ELEV
C
C                 LINEAR INTERPOLATION OF DRAG BETWEEN ELEVATOR SETTINGS
       DE=-X2 LA E
       IF(DE.GT.2.5) GO TO 10
       DEL=0.
       DDE=.4
       CDL=TBLU2(CL1,MACAV,CD0(16),CD0(4),CD0(40),1,1,24,12,24,12)
       CDU=TBLU2(CL1,MACAV,CD25(16),CD25(4),CD25(40),1,1,24,12,24,12)
       GO TO 40
   10  IF(DE.GT.5.) GO TO 20
       DEL=2.5
       DDE=.4
       CDL=TBLU2(CL1,MACAV,CD25(16),CD25(4),CD25(40),1,1,24,12,24,12)
       CDU=TBLU2(CL1,MACAV,CD5(16),CD5(4),CD5(40),1,1,24,12,24,12)
       GO TO 40
   20  IF(DE.GT.10) GO TO 30
       DEL=5.
       DDE=.2
       CDL=TBLU2(CL1,MACAV,CD5(16),CD5(4),CD5(40),1,1,24,12,24,12)
       CDU=TBLU2(CL1,MACAV,CD10(16),CD10(4),CD10(40),1,1,24,12,24,12)
       GO TO 40
   30  DEL=10.
       DDE=.2
       CDL=TBLU2(CL1,MACAV,CD10(16),CD10(4),CD10(40),1,1,24,12,24,12)
       CDU=TBLU2(CL1,MACAV,CD15(16),CD15(4),CD15(40),1,1,24,12,24,12)
   40  CTO=CDL + (CDU - CDL)*DDE*(DE - DEL)
  200  CALP= COS(ALPHA)
       SALP= SIN(ALPHA)
       FZSAV= FZ EN
```

Figure C-1. EASY Model Generation Data and Resulting Model for β-$\dot{\beta}$ SAS

```
      FXSAV= FX EN
      FZ EN=-QS AV*(CL1*CALP + CDO*SALP) + FZ EN
      FX EN= QS AV*(CL1*SALP - CDO*CALP) + FX EN
CCCCCCCCC
C            COMBINE LONGITUDINAL DYNAMICS IN "LO"
CCCCCCCCC
      MO LO= TBLU2(MACAV,ALTSD,CMO(9),CMO(4),CMO(34),1,1,-25,-5,25,5)
      MO LO=2.*TBLU2(MACAV,ALTSD,CMO(9),CMO(4),CMO(34),1,1,-25,-5,25,5)
      MADLO=MO LO
      MOELO=TBLU2(MACAV,ALTSD,CMOE(9),CMOE(4),CMOE(34),1,1,-25,-5,25,5)
CONATTON=N        LO       INPUTS=AV,LA E(X=ELE),EN
FORTRAN STATEMENTS
CCCCCCCCC
C            ADJUST LONGITUDINAL MOMENTS FOR CG LOCATION
CCCCCCCCC
      TNPO=TBLU2(MACAV,ALTSD,TNP(9),TNP(4),TNP(34),1,1,-25,-5,25,5)
      TY2LO= TY2LO + (ZREF-ZCG)*(FX2LO-FXSAV) - (TNPO*C  LO-XCG)*
     1                    (FZ2LO-FZSAV)
CCCCCCCCC
C           COMPUTE LATERAL DIRECTIONAL NONLINEAR TERMS FY1LO,TX1LO,TZ1LO
CCCCCCCCC
C                          INTERPOLATE TO FIND FY DERIVATIVES
C
      CYBA20= TBLU2(MACAV,ALTSD,CYBA2(9),CYBA2(4),CYBA2(34),1,1,
     1              -25,-5,25,5)
      CYBA0= TBLU1(MACAV,CYBA(4),CYBA(29),1,-25)
      CYBB0= TBLU2(MACAV,ALTSD,CYBB(9),CYBB(4),CYBB(34),1,1,
     1              -25,-5,25,5)
C
C                          COMPUTE NONLINEAR Y FORCES
      BETA = BE AV*RPD
      FY1LO= QS AV*(BETA*(ALPHA*
     1             (CYBA20*ALPHA + CYBA0) + CYBB0*ABS(BETA)))
C
C                          INTERPOLATE TO FIND L=TX DERIVATIVES
      CLBA20= TBLU2(MACAV,ALTSD,CLBA2(9),CLBA2(4),CLBA2(34),1,1,
     1              -25,-5,25,5)
      CLBA0=TBLU2(MACAV,ALTSD,CLBA(9),CLBA(4),CLBA(25),1,1,-17,-5,17,5)
      CLBB0=TBLU2(MACAV,ALTSD,CLBB(9),CLBB(5),CLBB(34),1,1,-25,-5,25,5)
      CLPA20= TBLU2(MACAV,ALTSD,CLPA2(9),CLPA2(4),CLPA2(34),1,1,
     1              -25,-5,25,5)
      CLPA0=TBLU2(MACAV,ALTSD,CLPA(9),CLPA(4),CLPA(34),1,1,-25,-5,25,5)
      CLPB0=TBLU2(MACAV,ALTSD,CLPB(9),CLPB(4),CLPB(34),1,1,-25,-5,25,5)
C
C                          COMPUTE NONLINEAR L=TX TORQUES
      CNOLIN= ((CLBA20*ABS(ALPHA) + CLBA0)*ALPHA + CLBB0*ABS(BETA))
     1             *BETA + ((CLPA20*ALPHA + CLPA0)*P  SD + CLPB0*P  SD)
     2             *ALPHA*B  LO*RPD/(VT AV+VT AV)
       TX1LO=QS AV*B  LO*CNOLIN
C
C                          INTERPOLATE TO FIND N=TZ DERIVATIVES
      CNBA20= TBLU2(MACAV,ALTSD,CNBA2(9),CNBA2(4),CNBA2(34),1,1,
     1              -25,-5,25,5)
      CNBA0= TBLU1(MACAV,CNBA(4),CNBA(29),1,-25)
      CNBB0=TBLU2(MACAV,ALTSD,CNBB(9),CNBB(4),CNBB(34),1,1,-25,-5,25,5)
      CNDAA0= TBLU1(MACAV,CNDAA(4),CNDAA(29),1,-25)
      CDADE0= TBLU1(MACAV,CDADE(4),CNDADE(29),1,-25)
C
C                          COMPUTE NONLINEAR N=TZ TORQUES
      AIL= X2 LA A*RPD
      CNONLI= ALPHA*(CNBA20*ALPHA + CNBA0) + BETA*CNBB0*ABS(BETA)
     1            + (CNDAA0*ALPHA + CDADE0*ELEV)*AIL
      TZ1LO= QS AV*B  LO*CNONLI
CCCCCCCCC
C           LOOK UP LATERAL-DIRECTIONAL LINEAR COEFFICIENTS FOR LO
CCCCCCCCC
```

Figure C-1. (Cont'd)

```
      YB LD=TBLU2(MACAV,ALTSD,CYB(9),CYB(4),CYB(34),1,1,-25,-5,25,5)
      YP LD=TBLU2(MACAV,ALTSD,CYP(9),CYP(4),CYP(34),1,1,-25,-5,25,5)
      YR LD=TBLU2(MACAV,ALTSD,CYR(9),CYR(4),CYR(34),1,1,-25,-5,25,5)
      YDALD=TBLU2(MACAV,ALTSD,CYDA(9),CYDA(4),CYDA(34),1,1,-25,-5,25,5)
      YDRLD=TBLU2(MACAV,ALTSD,CYDR(9),CYDR(4),CYDR(34),1,1,-25,-5,25,5)
      LB LD=TBLU2(MACAV,ALTSD,CLB(9),CLB(4),CLB(34),1,1,-25,-5,25,5)
      LP LD=TBLU2(MACAV,ALTSD,CLP(9),CLP(4),CLP(34),1,1,-25,-5,25,5)
      LR LD=TBLU2(MACAV,ALTSD,CLR(9),CLR(4),CLR(34),1,1,-25,-5,25,5)
      LDALD=TBLU2(MACAV,ALTSD,CLDA(9),CLDA(4),CLDA(34),1,1,-25,-5,25,5)
      LDRLD=TBLU2(MACAV,ALTSD,CLDR(9),CLDR(4),CLDR(34),1,1,-25,-5,25,5)
      NB LD=TBLU2(MACAV,ALTSD,CNB(9),CNB(4),CNB(34),1,1,-25,-5,25,5)
      NDALD=TBLU2(MACAV,ALTSD,CNDA(9),CNDA(4),CNDA(34),1,1,-25,-5,25,5)
      NDRLD=TBLU2(MACAV,ALTSD,CNDR(9),CNDR(4),CNDR(26),1,1,-17,-5,17,5)
      NP LD=TBLU2(MACAV,ALTSD,CNP(9),CNP(4),CNP(34),1,1,-25,-5,25,5)
      NR LD=TBLU2(MACAV,ALTSD,CNR(9),CNR(4),CNR(34),1,1,-25,-5,25,5)
LOCATION=26      LD      INPUTS=AV,LD,LA A(X=AIL),LA R(X=RUD)
FORTRAN STATEMENTS
CCCCCCCCC
C          ADJUST LATERAL MOMENTS FOR CG POSITION
CCCCCCCCC
      TX2LD= TX2LD + (YREF-YCG)*(FZ2LD-FZSAV) - (ZREF-ZCG)*FY2LD
      TZ2LD= TZ2LD +(XREF-XCG)*FY2LD -(YREF-YCG)*(FX2LD-FXSAV)
CCCCCCCCC
C          CONTROL SYSTEM MODEL
CCCCCCCCC
LOCATION=9       SD      INPUTS=LP,LD
FORTRAN STATEMENTS
      BETADOT=(P  SD*AL AV)*RPD**2-P  SD*RPD + G/UO AV*
     1COS(PITSD*RPD)*SIN(ROLSD*RPD) + EV/UO AV
      X1 MC B=BETADOT
      X1 MCBD=BETADOT
LOCATION=102     FUTO      INPUTS=AV(SIG=X)
LOCATION=142     FUKO      INPUTS=AV(SIG=X)
LOCATION=122     LF O      INPUTS=SD(Q=X),FUTO(X=G1),FUKO(X=GAI)
LOCATION=124     SA O      INPUTS=LF O,
LOCATION=144     LA O      INPUTS=SA O,
LOCATION=164     MC E      INPUTS=LA O,,LGET(X=C4)
LOCATION=165     SA E      INPUTS=MC E,
LOCATION=169     LA E      INPUTS=SA E,
LOCATION=223     FU A      INPUTS=AV(QC=X)
LOCATION=203     MA A      INPUTS=FU A(X=C1),LGAT,
LOCATION=207     LA A      INPUTS=MA A,
LOCATION=413     MC B      INPUTS=AV(BE=X)
LOCATION=415     LA B      INPUTS=MC B
LOCATION=435     MCBD      INPUTS=LA B,LGRT(X=C4)
LOCATION=437     LFBD      INPUTS=MCBD
LOCATION=439     SABD      INPUTS=LFBD
LOCATION=459     MABD      INPUTS=SABD
LOCATION=277     LA R      INPUTS=MABD
FORTRAN STATEMENTS
C
C        OUTER LOOP FEEDBACKS FOR TRIM CALCULATIONS
C
LOCATION=312,MAAT,INPUTS=SD(ROL=X)
LOCATION=332,LGAT,INPUTS=MAAT,
LOCATION=314,MART,INPUTS=AV   (EV=X)
LOCATION=334,LGRT,INPUTS=MART,
LOCATION=317,MAET,INPUTS=SD   (ALT=X)
LOCATION=337,LGET,INPUTS=MAET,
LOCATION=329,MATT,INPUTS=AV   (MAC=X)
LOCATION=349,LGTT,INPUTS=MATT,
END OF MODEL
PRINT
```

Figure C-1. (Cont'd)

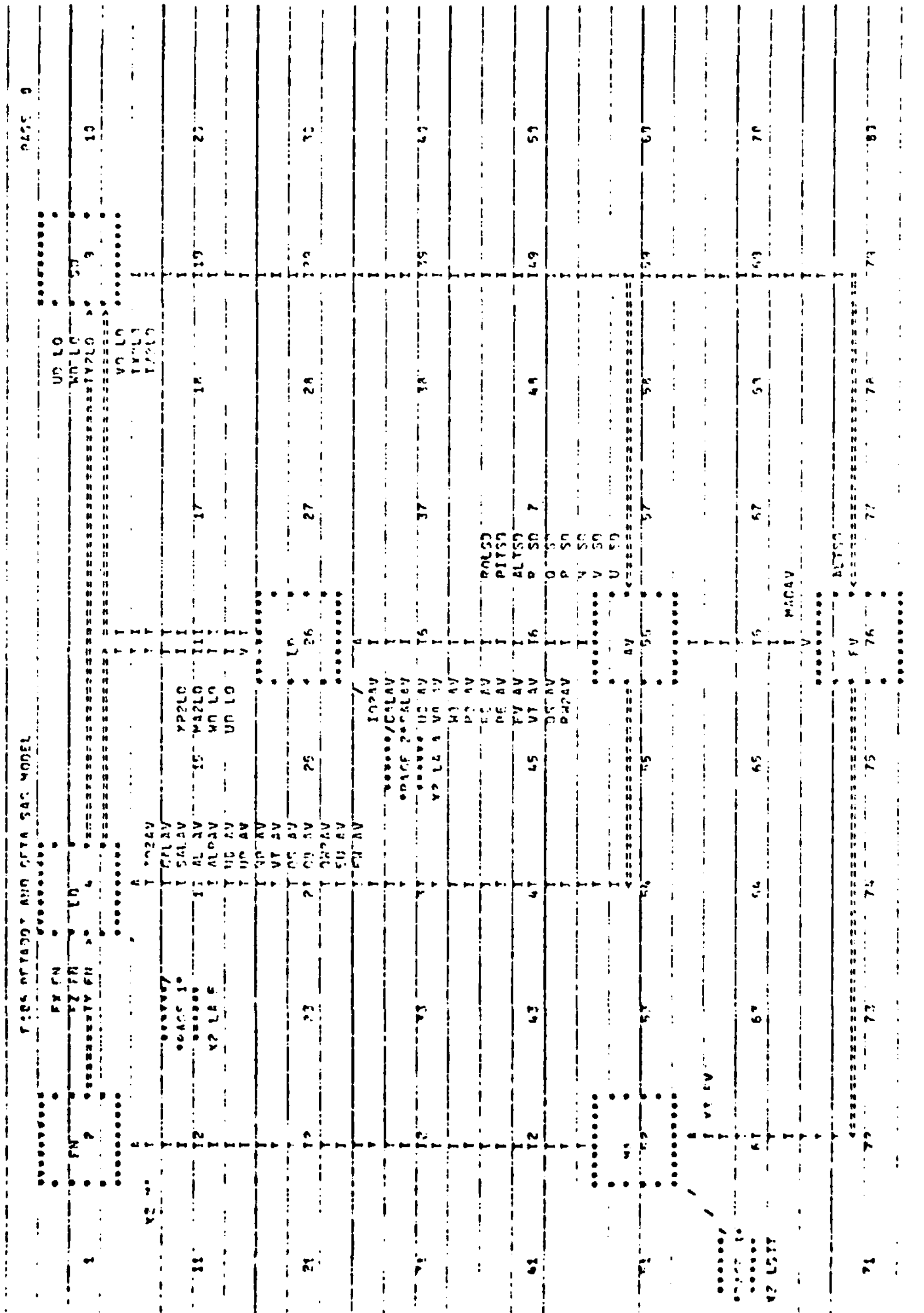


Figure C-1. (Cont'd)

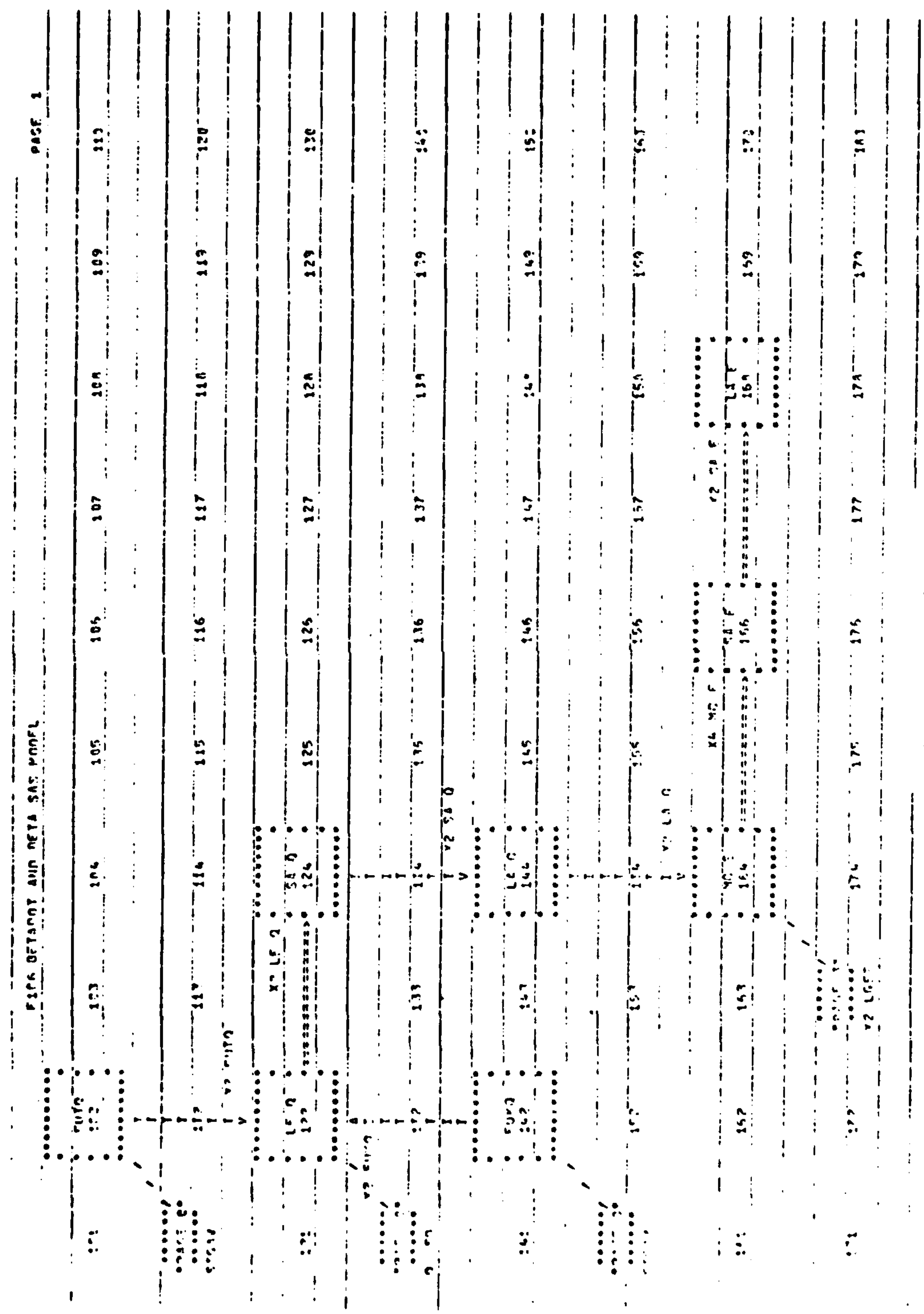


Figure C-1. (Cont'd)

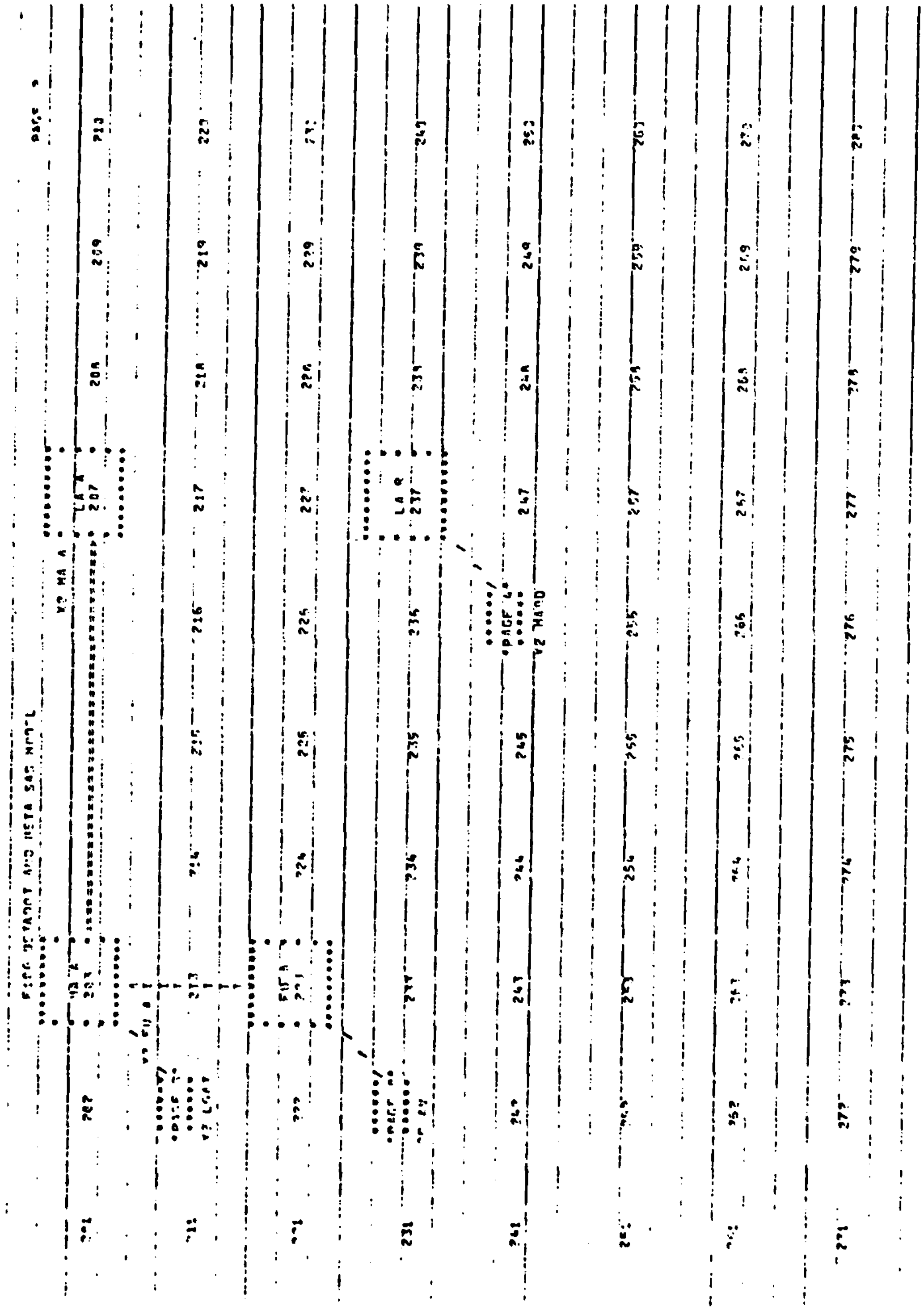


Figure C-1. (Cont'd)

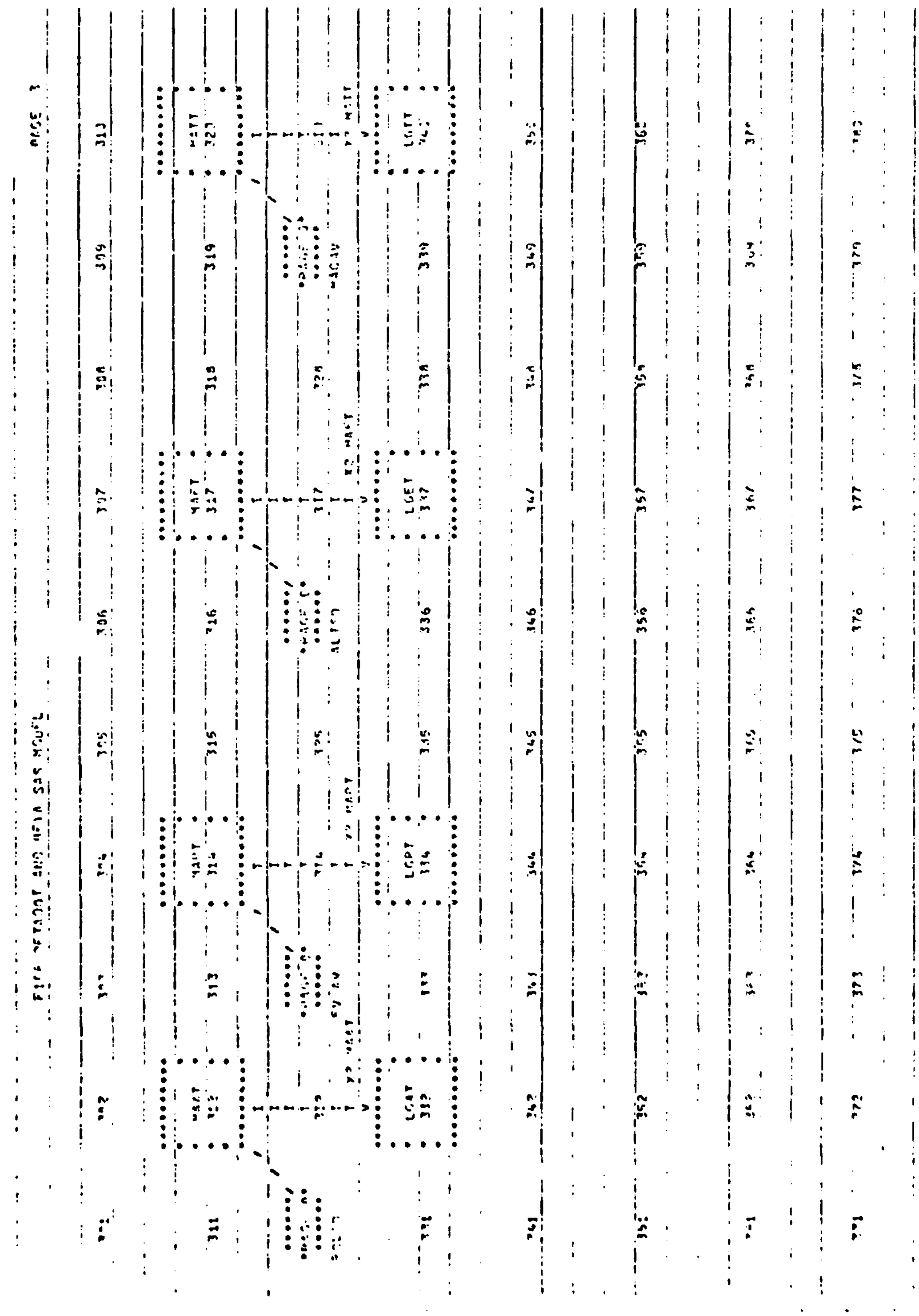


Figure C-1. (Cont'd)

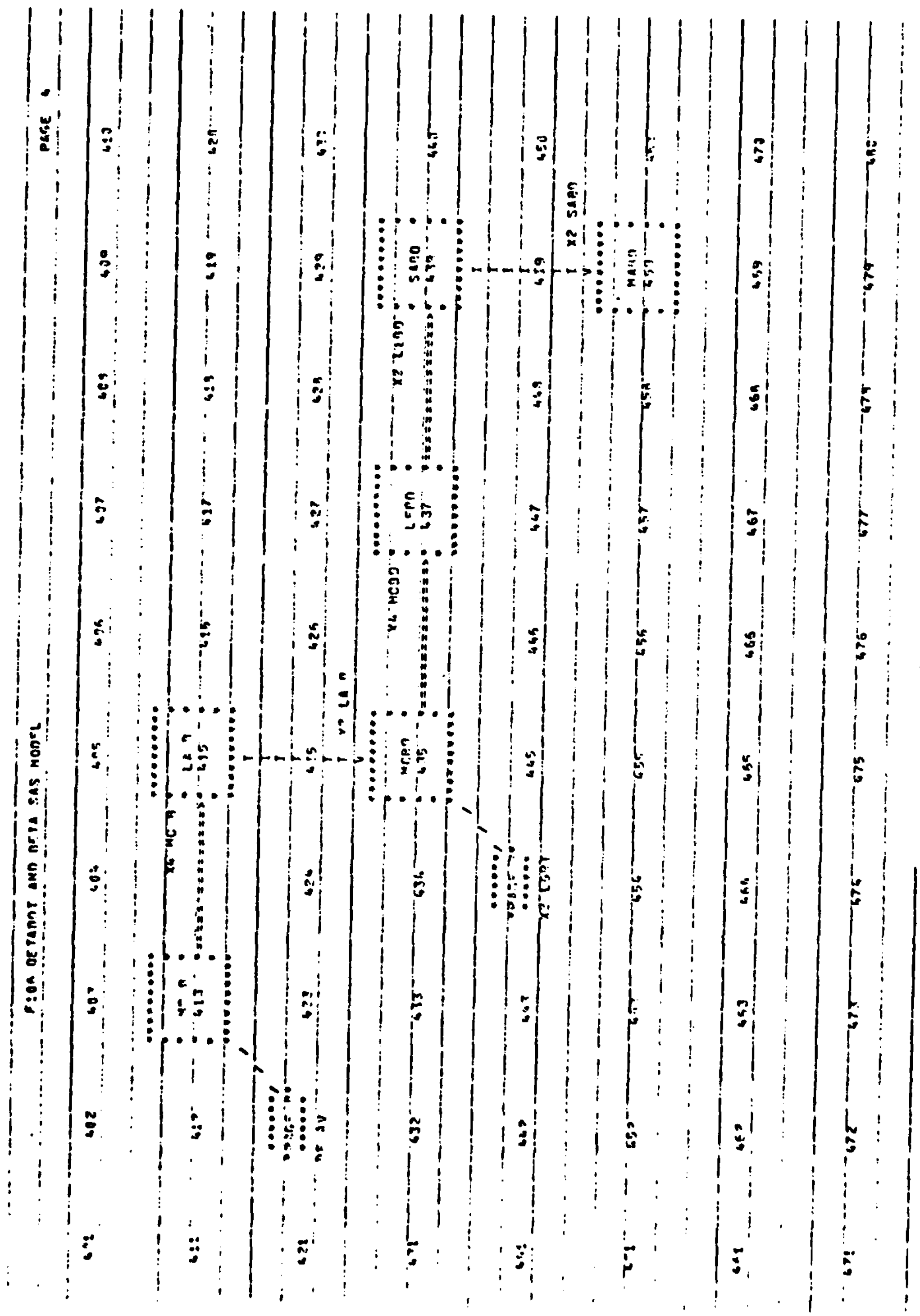


Figure C-1. (Concluded)

```
MODEL DESCRIPTION      F105 STANDARD SAS MODEL
ADD TABLES=CYBA,-53,CNBA,-53,CNDAA,-53,CNDADE,-53
ADD TABLES=CLZ,158,CL=,158,CLDA,115,CLDA2,153,CL30,158,CLDA,158,
CLDR,158,CLP,158,CLPA2,158,CLR,158,CLRA,158,CMDE,158,CMO,158,CMQ,158,
CNO,151,CNBA2,158,CN33,153,CNDA,158,CNDR,113,CNP,158,CNR,158,CYB,158,
CYBA2,155,CY33,153,CYDA,153,CYDR,158,CYP,153,CYR,158,CLA,153,CLDE,158,
TNP,151,CLPA,158,CD0,327,CD25,327,CD5,327,CD10,327,CD15,327
ADD PARAMETERS= ,XCG,YREF,YCG,ZREF,ZCG,RPD
ADD VARIABLES=AX,AY,AZ
LOCATION=56      AV      INPUTS=SD
LOCATION=75      FV      INPUTS=SD(ALT=X),AV(MAC=X)
LOCATION=52      MA      INPUTS=FJ(X=C1),LGTT,
LOCATION=2       EN      INPUTS=MA(X=THR)
FORTRAN STATEMENTS
C
C           COMPUTE ACCELERATIONS IN G'S
C
      G=32.2
      AX=EU AV/G
      AY=EV AV/G
      AZ=EW AV/G
CCCCCCCCC
C           COMPUTE LONGITUDINAL FORCE TERMS% FZ EN AND FX EN
CCCCCCCCC
C                  INTERPOLATE TO FIND LIFT COEFFICIENTS
C
      CL0= TBLU2(MACAV,ALTSD,CLZ(3),CLZ(4),CLZ(34),1,1,-25,-5,25,5)
      CLAO= TBLU2(MACAV,ALTSD,CLA(3),CLA(4),CLA(34),1,1,-25,-5,25,5)
      CLDEO=TBLU2(MACAV,ALTSD,CLDE(3),CLDE(4),CLDE(34),1,1,-25,-5,25,5)
C
C                  COMPUTE LIFT, DRAG COEFFICIENTS AND BODY-AXIS FORCES
      ELEV= X2 LA E*RPD
      ALPHA= AL AV*RPD
       CL1= CL0 + CLAO*ALPHA + CLDEO*ELEV
C
C              LINEAR INTERPOLATION OF DRAG BETWEEN ELEVATOR SETTINGS
      DE=-X2 LA E
      IF(DE.GT.2.5) GO TO 10
      DEL=0.
      DDE=.4
      CDL=TBLU2(CL1,MACAV,CD0(16),CD0(4),CD0(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CD25(16),CD25(4),CD25(40),1,1,24,12,24,12)
      GO TO 40
   10 IF(DE.GT.5.) GO TO 20
      DEL=2.5
      DDE=.4
      CDL=TBLU2(CL1,MACAV,CD25(16),CD25(4),CD25(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CD5(16),CD5(4),CD5(40),1,1,24,12,24,12)
      GO TO 40
   20 IF(DE.GT.10) GO TO 30
      DEL=5.
      DDE=.2
      CDL=TBLU2(CL1,MACAV,CD5(16),CD5(4),CD5(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CD10(16),CD10(4),CD10(40),1,1,24,12,24,12)
      GO TO 40
   30 DEL=10.
      DDE=.2
      CDL=TBLU2(CL1,MACAV,CD10(16),CD10(4),CD10(40),1,1,24,12,24,12)
      CDU=TBLU2(CL1,MACAV,CD15(16),CD15(4),CD15(40),1,1,24,12,24,12)
   40 CDO=CDL + (CDU - CDL)*DDE*(DE - DEL)
  200 CALP= COS(ALPHA)
      SALP= SIN(ALPHA)
```

Figure C-2. EASY Model Generation Data and Resulting Model for Standard SAS

```
      FXSAV= FX EN
      FZ EN=-QS AV*(CL1*SALP + CDO*SALP) + FZ EN
      FX EN= QS AV*(CL1*SALP - CDO*CALP) + FX EN
CCCCCCCCC
C        COMBINE LONGITUDINAL DYNAMICS IN "LO"
CCCCCCCCC
      IO LO= TBLU2(MACAV,ALTSD,CMO(9),CMO(4),CMO(34),1,1,-25,-5,25,5)
      IQ LO=2.*TBLU2(MACAV,ALTSD,CMQ(9),CMQ(4),CMQ(34),1,1,-25,-5,25,5)
      IADLO=IQ LO
      IDELO=TBLU2(MACAV,ALTSD,CMDE(9),CMDE(4),CMDE(34),1,1,-25,-5,25,5)
LOCATION=4       LO       INPUTS=AV,LA E(X=ELE),EN
FORTRAN STATEMENTS
CCCCCCCCC
C        ADJUST LONGITUDINAL MOMENTS FOR CG LOCATION
CCCCCCCCC
      INPC=TBLU2(MACAV,ALTSD,INP(9),INP(4),INP(34),1,1,-25,-5,25,5)
      TY2LO= TY2LO + (ZREF-ZCG)*(FX2LO-FXSAV) - (TNPO*C  LO-XCG)*
     1              (FZ2LO-FZSAV)
CCCCCCCCC
C        COMPUTE LATERAL DIRECTIONAL NONLINEAR TERMS FY1LO,TX1LO,TZ1LO
CCCCCCCCC
C                  INTERPOLATE TO FIND FY DERIVATIVES
C
      CYBA20= TBLU2(MACAV,ALTSD,CYBA2(9),CYBA2(4),CYBA2(34),1,1,
     1           -25,-5,25,5)
      CYBAO= TBLU1(MACAV,CYBA(4),CYBA(29),1,-25)
      CYBBO= TBLU2(MACAV,ALTSD,CYBB(9),CYBB(4),CYBB(34),1,1,
     1           -25,-5,25,5)
C
C                  COMPUTE NONLINEAR Y FORCES
      BETA = BE AV*RPD
      FY1LO= QS AV*(BETA*(ALPHA*
     1           (CYBA20*ALPHA + CYBAO) + CYBBO*ABS(BETA)))
C
C                  INTERPOLATE TO FIND L=TX DERIVATIVES
      CLBA20= TBLU2(MACAV,ALTSD,CLBA2(9),CLBA2(4),CLBA2(34),1,1,
     1           -25,-5,25,5)
      CLBAO=TBLU2(MACAV,ALTSD,CLBA(3),CLBA(4),CLBA(26),1,1,-17,-5,17,5)
      CLBBO=TBLU2(MACAV,ALTSD,CLBB(3),CLBB(4),CLBB(34),1,1,-25,-5,25,5)
      CLPA20= TBLU2(MACAV,ALTSD,CLPA2(9),CLPA2(4),CLPA2(34),1,1,
     1           -25,-5,25,5)
      CLPAO=TBLU2(MACAV,ALTSD,CLPA(3),CLPA(4),CLPA(34),1,1,-25,-5,25,5)
      CLRAO=TBLU2(MACAV,ALTSD,CLRA(9),CLRA(4),CLRA(34),1,1,-25,-5,25,5)
C
C                  COMPUTE NONLINEAR L=TX TORQUES
      CNOLIN= ((CLBA20*ABS(ALPHA) + CLBAO)*ALPHA + CLBBO*ABS(BETA))
     1           *BETA + ((CLPA20*ALPHA + CLPAO)*P  SD + CLRAO*R  SD)
     2           *ALPHA*B  /(2*RPD/(VT AV*VT AV))
       TX1LO=QS AV*B  LO*CNOLIN
C
C                  INTERPOLATE TO FIND N=TZ DERIVATIVES
      CNBA20= TBLU2(MACAV,ALTSD,CNBA2(9),CNBA2(4),CNBA2(34),1,1,
     1           -25,-5,25,5)
      CNBAO= TBLU1(MACAV,CNBA(4),CNBA(29),1,-25)
      CNBBO=TBLU2(MACAV,ALTSD,CNBB(3),CNBB(4),CNBB(34),1,1,-25,-5,25,5)
      CNDAAC= TBLU1(MACAV,CNDAA(4),CNDAA(29),1,-25)
      CDADEO= TBLU1(MACAV,CNDADE(4),CNDADE(29),1,-25)
C
C                  COMPUTE NONLINEAR N=TZ TORQUES
      AIL= X2 LA  *RPD
      CNONLI= ALPHA*(CNBA20*ALPHA + CNBAO) + BETA*CNBBO*ABS(BETA)
     1           + (CNDAAC*ALPHA + CDADEO*ELEV)*AIL
      TZ1LO= QS AV*B  LO*CNONLI
CCCCCCCCC
C        LOOK UP LATERAL-DIRECTIONAL LINEAR COEFFICIENTS FOR LO
CCCCCCCCC
```

Figure C-2. (Cont'd)

```
CCCCCC;CC
      YB LO=TBLU2(MACAV,ALTSO,CYB(3),CYB(4),CYB(34),1,1,-25,-5,25,5)
      YP LO=TBLU2(MACAV,ALTSO,CYP(9),CYP(4),CYP(34),1,1,-25,-5,25,5)
      YR LO=TBLU2(MACAV,ALTSO,CYR(9),CYR(4),CYR(34),1,1,-25,-5,25,5)
      YDALO=TBLU2(MACAV,ALTSO,CYDA(3),CYDA(4),CYDA(34),1,1,-25,-5,25,5)
      YDRLO=TBLU2(MACAV,ALTSO,CYDR(3),CYDR(4),CYDR(34),1,1,-25,-5,25,5)
      LP LO=TBLU2(MACAV,ALTSO,CLP(9),CLP(4),CLP(34),1,1,-25,-5,25,5)
      LR LO=TBLU2(MACAV,ALTSO,CLR(9),CLR(4),CLR(34),1,1,-25,-5,25,5)
      LB LO=TBLU2(MACAV,ALTSO,CLB(9),CLB(4),CLB(34),1,1,-25,-5,25,5)
      LDALO=TBLU2(MACAV,ALTSO,CLDA(3),CLDA(4),CLDA(34),1,1,-25,-5,25,5)
      LDRLO=TBLU2(MACAV,ALTSO,CLDR(9),CLDR(4),CLDR(34),1,1,-25,-5,25,5)
      NB LO=TBLU2(MACAV,ALTSO,CNB(3),CNB(4),CNB(34),1,1,-25,-5,25,5)
      NDALO=TBLU2(MACAV,ALTSO,CNDA(3),CNDA(4),CNDA(34),1,1,-25,-5,25,5)
      NDRLO=TBLU2(MACAV,ALTSO,CNDR(3),CNDR(4),CNDR(26),1,1,-17,-5,17,5)
      NP LO=TBLU2(MACAV,ALTSO,CNP(9),CNP(4),CNP(34),1,1,-25,-5,25,5)
      NR LO=TBLU2(MACAV,ALTSO,CNR(3),CNR(4),CNR(34),1,1,-25,-5,25,5)
LOCATION=26     LO      INPUTS=AV,LO,LA A(X=AIL),LA R(X=RUD)
FORTRAN STATEMENTS
CCCCCC;CC
C          ADJUST LATERAL MOMENTS FOR CG POSITION
CCCCCC;CC
      TX2LO= TX2LO + (YREF-YCG)*(FZ2LO-FZSAV) - (ZREF-ZCG)*FY2LD
      TZ2LO= TZ2LO +(TNPO*S   LO-XCG)*FY2LO -(YREF-YCG)*(FX2LO-FXSAV)
CCCCCC;CC
C          CONTROL SYSTEM MODEL
CCCCCC;CC
LOCATION=9        SO       INPUTS=LO,LO
LOCATION=102      FUTQ     INPUTS=AV(SIG=X)
LOCATION=142      FUKQ     INPUTS=AV(SIG=X)
LOCATION=122      LE Q     INPUTS=SO(Q=X),FUTQ(X=FO),FUKQ(X=GAI)
LOCATION=124      SA Q     INPUTS=LE Q,
LOCATION=144      LA Q     INPUTS=SA Q,
LOCATION=164      MC E     INPUTS=LA Q,,LGET(X=C4)
LOCATION=166      SA E     INPUTS=MC E,
LOCATION=163      LA E     INPUTS=SA E,
LOCATION=223      FU A     INPUTS=AV(QC=X)
LOCATION=203      MA A     INPUTS=FU A(X=GAI),LGAT,
LOCATION=207      LA A     INPUTS=MA A,
LOCATION=233      LE R     INPUTS=SO(R=X)
LOCATION=253      FU P     INPUTS=AV(QC=X)
LOCATION=255      LE P     INPUTS=SO(P=X),FU P(X=GAI)
LOCATION=235      MC R     INPUTS=MA A,LE R,LE P,LGRT(X=C4)
LOCATION=237      LA R     INPUTS=MC R,
C
C          OUTER LOOP FEEDBACKS FOR TRIM CALCULATIONS
C
LOCATION=312,MAAT,INPUTS=SO(ROL=X)
LOCATION=332,LGAT,INPUTS=MAAT,
LOCATION=314,MART,INPUTS=AV    (E/A=X)
LOCATION=334,LGRT,INPUTS=MART,
LOCATION=317,MAET,INPUTS=SO    (ALF=X)
LOCATION=337,LGET,INPUTS=MAET,
LOCATION=320,MATT,INPUTS=AV    (MAB=X)
LOCATION=340,LGTT,INPUTS=MATT,
END OF MODEL
PRINT
```

Figure C-2. (Cont'd)

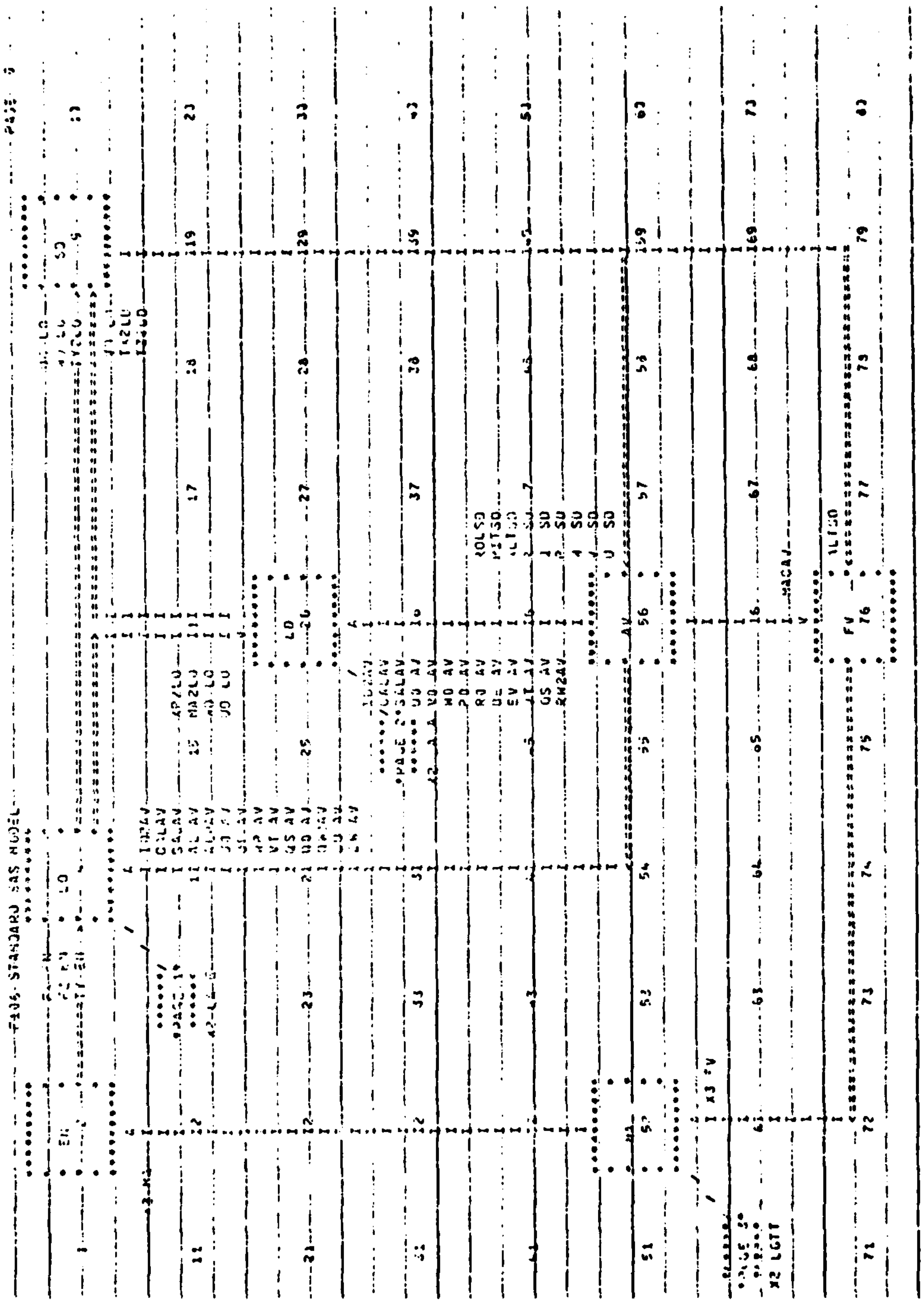


Figure C-2. (Cont'd)

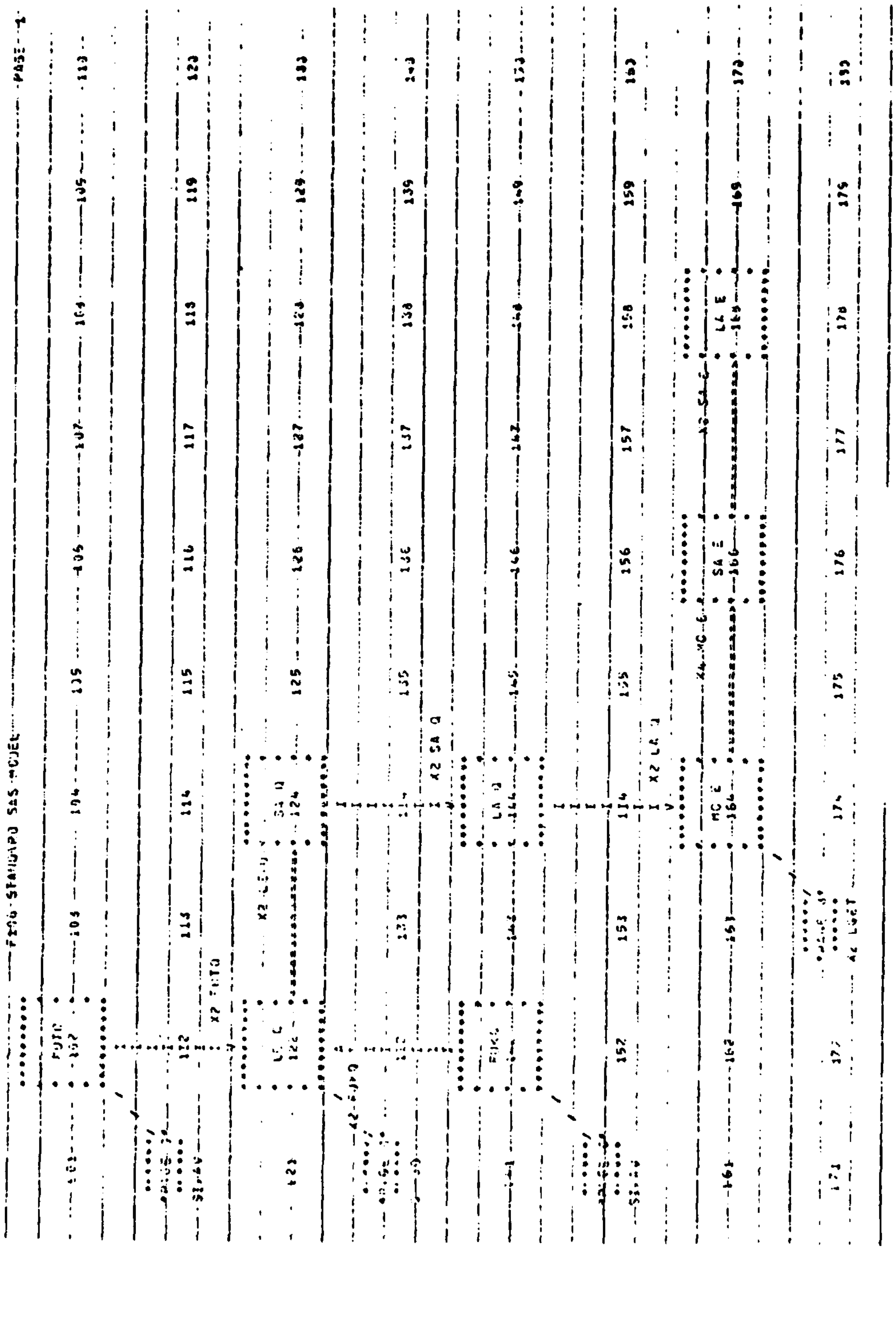


Figure C-2. (Cont'd)

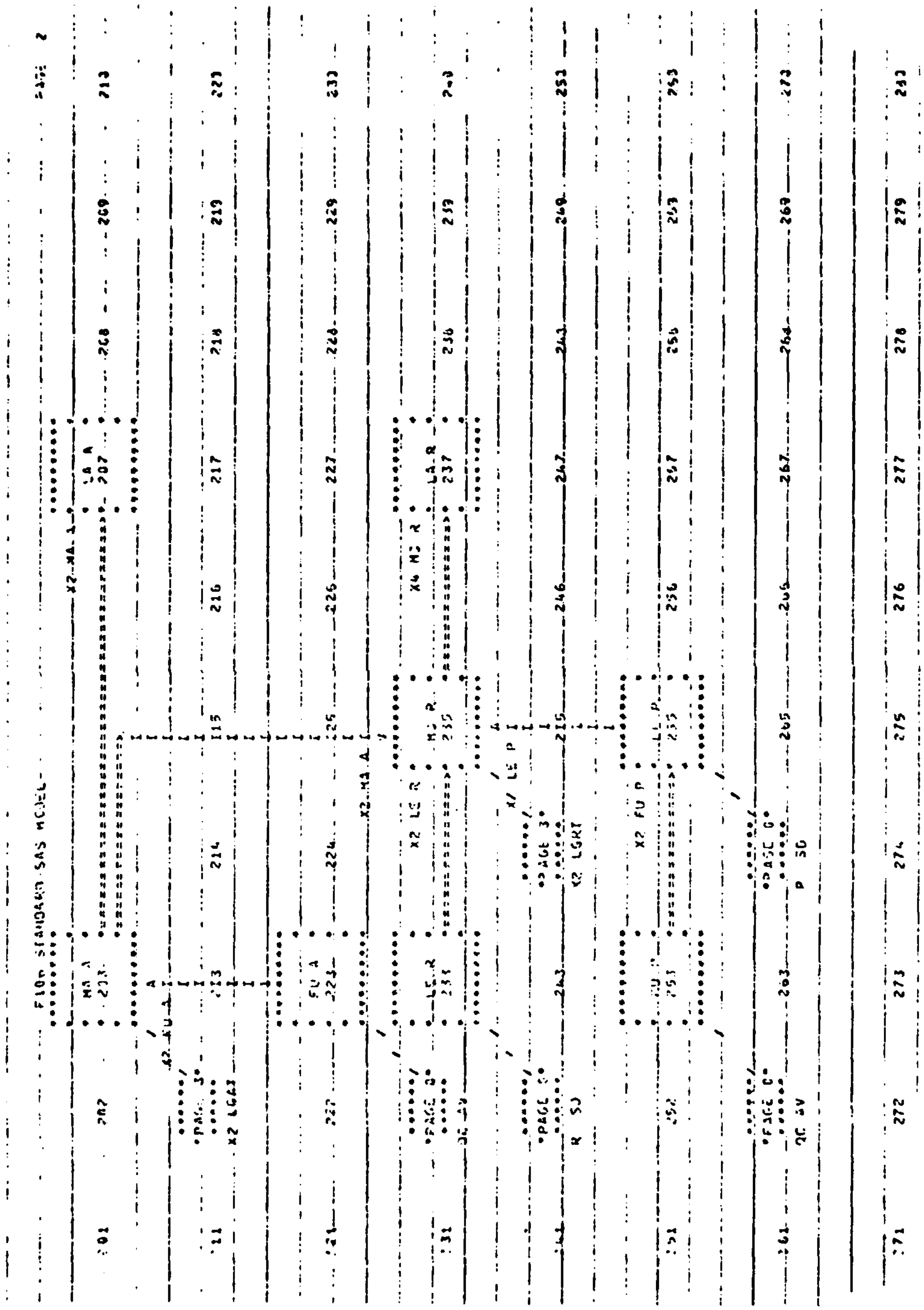


Figure C-2. (Cont'd)

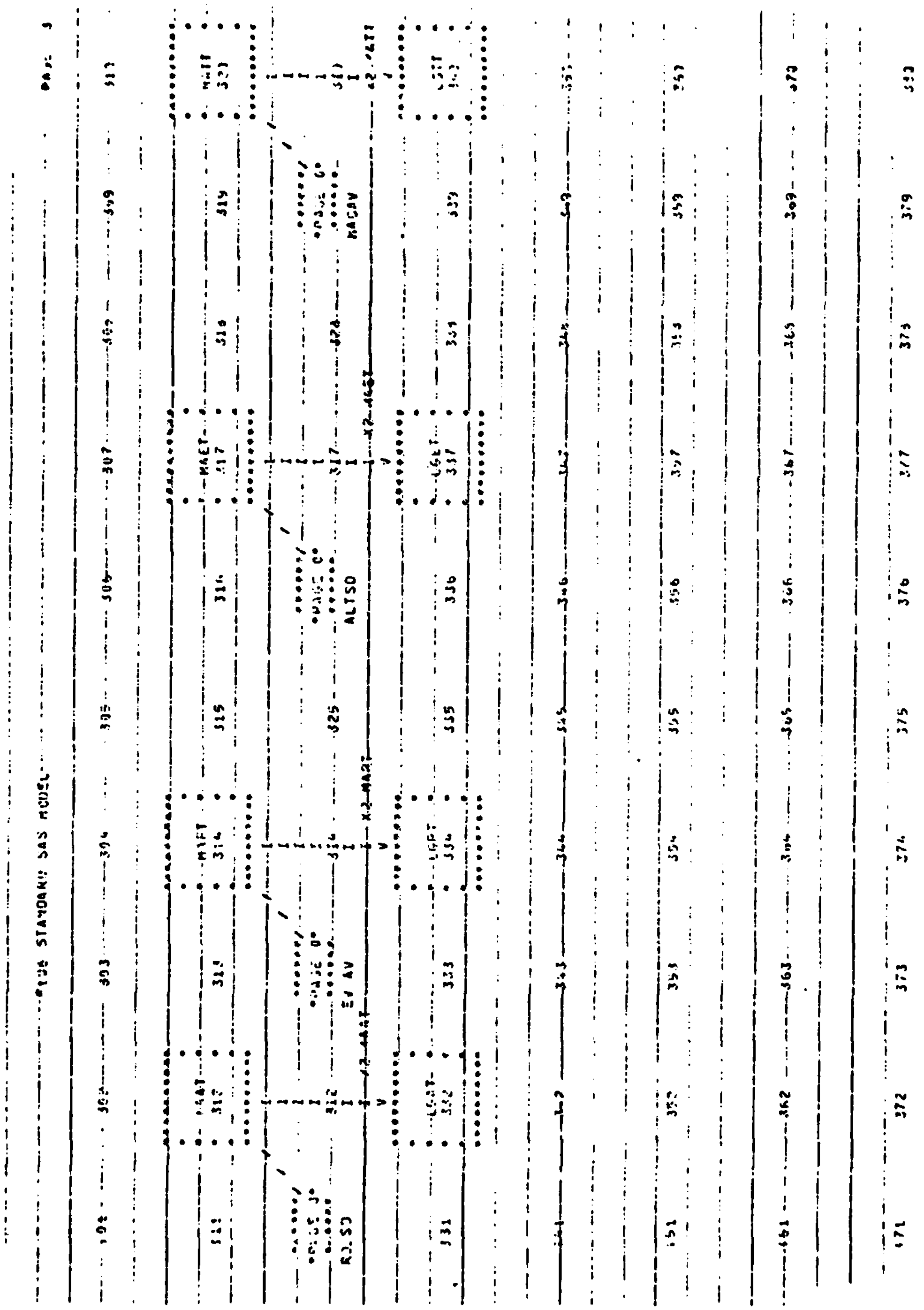


Figure C-2. (Cont'd)

```
.400, .450, .500, .550, .600, .650, .700, .750, .800, .825
.650, .875, .900, .925, .950, .975,1.000,1.025,1.050,1.075
1.100,1.125,1.150,1.175,1.200,
  .00157800,  .00160600,  .00163960,  .00167600,  .00172080
  .00178240,  .00184120,  .00139720,  .00200000,  .00205120
  .00210720,  .00219120,  .00231720,  .00253480,  .00279600
  .00320360,  .00337920,  .00370640,  .00378000,  .00374160
  .00359360,  .00331400,  .00311240,  .00301440,  .00295000
TITLE=F106 NONLINEAR 6 DOF TRIM ANALYSIS
PARAMETER VALUES
B  LO=38.13,C  LO=23.755,S  AV=695
TCOFM=1.,GAZEM=0,GAXEM=1.,XC EM=-11.8,ZC EM=0.
[illegible]
IO1AV=1.,ALSAV=0.
AM FUTO=-1,AM FUKO=-1,ZC LE Q=0
C1 SA Q=1,C2 SA Q=1.E-6,C3 SA Q=1,C4 SA Q=1,C5 SA Q=1.E-6,
GAILA Q=-1,TC LA Q=.07,C6 SA Q=-1
C1 MC E=1,C2 MC E=0,C3 MC E=0,X2 MC E=0,X3 MC E=0
C1 SA E=1,C2 SA E=1.E-6,C3 SA E=5
C4 SA E=1,C5 SA E=1.E-6,C6 SA E=-25
GAILA E=1,TC LA E=.07
PARAMETER VALUES
AM FV=-1,AM FV=1,C2 MA=0
C2 MA A=0,GAILA A=1,TC LA A=.17
GAILE R=-1,ZC LE R=0,PC LE R=1,ZC LE R=0,PC LE R=1
C1 MC R=1,C2 MC R=-1,C3 MC R=-1,
GAILA R=1,TC LA R=.07,AM FU R=-1,AM FU A=-1
C1 MAAT=-1.,PC LGAT=0.,ZC LGAT=.5,C1 MART=-1.,PC LGRT=0.,ZC LGRT=1.
C1 MAET=-1.,PC LGET=0.,ZC LGET=.01,C1 MATT=-1.,PC LGTT=0,ZC LGTT=.2
TABLE,FTAFU A=11
0,50,100,150,200,300,400,500,600,800,900
3,3,3,1.25,.6,-.2,-.7,-1.1,-1.25,-1.5,-1.5
TABLE,FTAFU R=11
0,50,100,150,200,300,400,500,600,800,900
.2,.2,.155,.105,.07,.055,.04,.04,.035,.035
TABLE,FTAFUTO=4
0,.07,.2,1
2,2,4,20
TABLE,FTAFUKO=4
0,.05,.35,1
-.4,-.4,-.2,-.1
PARAMETER VALUES
MAIL0=[illegible],IXXSO=15771.,IYYSO=1[illegible],IZZSO=[illegible],IXZSO=[illegible]
XCG=-6.34,VS AV=597.
C2 MAAT=0.,PC MART=[illegible],C2 MET=30000.,C2 MATT=.6
INITIAL CONDITIONS
ALTSO=30000.,POLSO=0.,U SO=500.
INT CONTROL=YAWSO=0.
TITLE=F106 LATERAL DYNAMICS FOR M=.6 AT 30K FT
PRINT CONTROL=3
STEADY STATE
XIC-X
NO-STATES
INT CONTROL=P  SO=1,Q  SO=1,R  SO=1,U  SO=1,V  SO=1,W  SO=1
PARAMETER VALUES=[illegible] LGET=0,PC LGAT=0,ZC LGRT=1,ZC LGTT=1
GAILA Q=0,GAXEN=0,GAILA A=0,GAILE R=0,GAILA R=0,GAILA E=0,GAZEN=0
INT CONTROL=PITSO=1
INT CONTROL=ROLSO=1
INT CONTROL=YAWSO=1
INT CONTROL=XI LE Q=1,X2 LA Q=1,X2 LA E=1
PARAMETER VALUES=GAILA E=1,GAILA Q=1
INT CONTROL=X2 LA A=1
PARAMETER VALUES=GAILA A=1
INT CONTROL=XI LE R=1,XI LE R=1,X2 LA R=1
PARAMETER VALUES=GAILE R=-1,GAILA R=1
INT CONTROL=ALTSO=1
```

Figure C-3. EASY β-$\dot{\beta}$ SAS Analysis Data

```
PARAMETER VALUES=GAILA R=1
INT CONTROL=X2 LA B=1,XI ...BO=1,X2 LA R=1
PARAMETER VALUES=GAILA B=1,GAILEBO=1,GAILA R=1
INT CONTROL=ALTSO=1
INT CONTROL=TH EN=1
PARAMETER VALUES=GAXEN=1
PLOT OT
TITLE=BETADOT SAS BETA/DELTA RUDDER .8,10000
TF INPUT=X2 LA R,TF OUTPUT=BE AV
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
TITLE=BETADOT SAS PHI/DELTA RUDDER .6,10000
TF INPUT=X2 LA R,TF OUTPUT=ROLSO
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
TITLE=BETADOT SAS BETA/DELTA AILERON .8,10000
TF INPUT=X2 LA A,TF OUTPUT=BE AV
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
```

Figure C-3. (Concluded)

```
TABLE,/MONACL,C3
 .400, .450, .500, .550, .600, .650, .700, .750, .800, .825
 .850, .875, .900, .925, .950, .975, 1.000,1.025,1.050,1.075
1.100,1.125,1.150,1.175,1.200,
  .00157650,  .00160600,  .00163960,  .00167500,  .00172330
  .00178240,  .00184120,  .00189720,  .00200030,  .00205120
  .00210720,  .00219120,  .00231720,  .00250150,  .00273600
  .00356360,  .00393200,  .00395540,  .00389030,  .00373160
  .00359950,  .00331400,  .00311240,  .00301440,  .00295300
TITLE=F106 NONLINEAR 6 DOF TRIM ANALYSIS
PARAMETER VALUES
B  LO=18.13,C  LO=23.755,S  AV=695
TCOEN=1.,GAZEN=0,SAXEN=1.,XC EN=-11.8,Z0 EN=0.
YREF=0.,ZREF=-.83,YCG=0.,ZCG=-.76,RPD=.01745329
IOLAV=1.,AESAV=0.
AN FUTQ=-1,AN FUKQ=-1,Z0 LE Q=0
C1 SA Q=1,C2 SA Q=1.E-6,C3 SA Q=1,C4 SA Q=1,C5 SA Q=1.E-6,
GAILA Q=-1,TC LA Q=.07,C6 SA Q=-1
C1 MC E=1,C2 MC E=0,C3 MC E=0,X2 MC E=0,X3 MC E=0
C1 SA E=1,C2 SA E=1.E-6,C3 SA E=8
C4 SA E=1,C5 SA E=1.E-6,C6 SA E=-25
GAILA E=1,TC LA E=.07
PARAMETER VALUES
AN FV=-1,BN FV=1,C2 MA=0
C2 MA A=0,GAILA A=1,TC LA A=.07
C1 MC B=2,C2 MC B=.01745329,C3 MC B=0,C4 MC B=0
GAILA B=1,TC LA B=2
C1 MC3D=-2.5,C2 MC3D=-6.5,C3 MC3D=0
GAILE3D=1,P0 LE3D=0,Z0 LE3D=.2
C6 SA3D=-.1047,C5 SA3D=.00001,C4 SA3D=1,C3 SA3D=.1047,
C2 SA3D=.00001,C1 SA3D=1
C1 MA3D=57.3,C2 MA3D=0
GAILA R=1,TC LA R=.07,AN FR A=-1
C1 MAAT=-1.,P0 LGAT=0.,Z0 LGAT=.5,C1 MART=-1.,P0 LGRT=0.,Z0 LGRT=1.
C1 MAET=-1.,P0 LGET=0.,Z0 LGET=.01,C1 MATT=-1.,P0 LGTT=0,Z0 LGTT=.2
TABLE,F TAFU A=11
0,50,100,150,200,300,400,500,600,800,900
3,3,3,1.25,.6,-.2,-.7,-1.1,-1.25,-1.5,-1.5
TABLE,F TAFUTQ=4
0,.07,.2,1
2,2,4,20
TABLE,F TAFUKQ=4
0,.05,.35,1
-.4,-.4,-.2,-.1
PARAMETER VALUES
MAILO=310.67,IXXSO=15771.,IYYSO=169040.,IZZSO=198310.,IXZSO=4073.
XCG=-6.34,VS AV=597.
C2 MAAT=0.,C2 MART=0.,C2 MAET=10000.,C2 MATT=.8
INITIAL CONDITIONS
ALTSO=10000.,ROLSO=0.,U  SO=862.
INT CONTROL=YAWSO=0,XI LE3D=0
TITLE=F106 LATERAL DYNAMICS FOR M=.8 AT 10K FT
PRINT CONTROL=3
STEADY STATE
XIC=X
NO STATES
INT CONTROL=P  SO=1,Q  SO=1,R  SO=1,U  SO=1,V  SO=1,W  SO=1
PARAMETER VALUES=Z0 LGET=0,Z0 LGAT=0,Z0 LGRT=0,Z0 LGTT=0
GAILA Q=0,SAXEN=0,GAILA A=1,GAILA B=0,GAILE3D=0,GAILA R=0,GAILA E=0,
GAZEN=1
INT CONTROL=PITSO=1
INT CONTROL=ROLSO=1
INT CONTROL=YAWSO=1
INT CONTROL=XI LE Q=1,X2 LA Q=1,X2 LA E=1
PARAMETER VALUES=GAILA E=1,GAILA Q=1
INT CONTROL=X2 LA A=1
```

Figure C-4. EASY Standard SAS Analysis Data

```
INT CONTROL=TH EN=1
PARAMETER VALUES=SAXEN=1
PLOT ON
TITLE=STANDARD SAS BETA/DELTA RUDDER .6,30000
TF INPUT=Y2 LA 7,TF OUTPUT=BE AV
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
TITLE=STANDARD SAS PHI/DELTA RUDDER .6,30000
TF INPUT=Y2 LA 7,TF OUTPUT=POLSO
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
TITLE=STANDARD SAS BETA/DELTA AILERON .6,30000
TF INPUT=Y2 LA 3,TF OUTPUT=BE AV
FREQ MIN=.01,FREQ MAX=100.
TRANSFER FUNCTION
```

Figure C-4. (Concluded)

APPENDIX D

DERIVATION OF SIDESLIP RATE

The β-$\dot{\beta}$ system uses as feedbacks both sideslip (β) and sideslip rate ($\dot{\beta}$). Sideslip can be measured with a vane attached to the aircraft. Sideslip rate, on the other hand, cannot be measured directly. The β signal is too noisy to differentiate, so $\dot{\beta}$ must come from some other source. The solution to this problem begins with the definition of β.

$$\beta = \arcsin v/U \qquad \text{(D-1)}$$

v and U are the side and total velocity of the aircraft in body axis coordinates differentiating with respect to time.

$$\dot{\beta} = \frac{U\dot{v}-v\dot{U}}{U^2+v^2} \qquad \text{(D-2)}$$

The terms in D-2 are normalized using total velocity, U.

$$\dot{\beta} = \frac{\frac{U}{U}\frac{\dot{v}}{U} - \frac{v}{U}\frac{\dot{U}}{U}}{\frac{U^2}{U^2} + \frac{v^2}{U^2}} \qquad \text{(D-3)}$$

An order of magnitude analysis is performed on Equation D-3 using the assumptions below.

$$\frac{\dot{v}}{U} << 1$$

$$\frac{v}{U} << 1$$

$$\frac{\dot{U}}{U} << 1$$

Using these assumptions, $\dot{\beta}$ is reduced to D-4.

$$\dot{\beta} = \frac{\dot{v}}{U} \qquad \text{(D-4)}$$

The $\dot{v}$ term in Equation D-4 is the side acceleration as seen by an observer in the body coordinate frame. This term cannot be measured; it must be synthesized from aircraft states which can be measured by sensors onboard the aircraft.

The total rate of change of the velocity in the inertial frame must be derived in order to get $\dot{v}$ in terms of measurable variables.

$$\dot{\bar{v}}_I = \dot{\bar{v}}_b + \bar{\omega} \times \bar{v}_b \tag{D-5}$$

$\dot{\bar{v}}_I = \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix}_i$ the inertial acceleration vector in body axis coordinates

$\dot{\bar{v}}_b = \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix}_b$ the acceleration vector observed in the body frame in body axis coordinates

$\bar{\omega} = \begin{bmatrix} p \\ q \\ r \end{bmatrix}$ the body angular rate vector in body axis coordinates

$\bar{v}_b = \begin{bmatrix} u \\ v \\ w \end{bmatrix}_b$ the body velocity vector in body axis coordinates

The y-coordinate scalar equation resulting from Equation D-5 is shown below.

$$\dot{v}_I = \dot{v} - pw + ur \tag{D-6}$$

The inertial side acceleration $\dot{v}_I$ is a measurable quantity consisting of lateral accelerometer output, $\left.A_y\right)_{acc}$, summed with the gravitational component in the y-direction.

$$\dot{v}_I = \left.A_y\right)_{acc} + g\cos\theta\sin\phi \tag{D-7}$$

Using Equation D-6 and Equation D-7, $\dot{v}$ is shown below.

$$\dot{v} = pw - ur + \left.A_y\right)_{acc} + g\cos\theta\sin\phi \tag{D-8}$$

Dividing by V.

$$\frac{\dot{v}}{V} = \frac{pw}{V} - \frac{ur}{V} + \frac{\left.A_y\right)_{acc}}{V} + \frac{g}{V}\cos\theta\sin\phi \tag{D-9}$$

Equation D-9 is further simplified by assuming $\frac{w}{V}$ equal to angle of attack and $\frac{u}{V}$ equal to one.

$$\frac{\dot{v}}{V} \doteq p\alpha - r + \frac{\left.A_y\right)_{acc}}{V} + \frac{g}{V}\cos\theta\sin\phi \tag{D-10}$$

Substituting, using Equation D-4,

$$\dot{\beta} \doteq p\alpha - r + \frac{\left.A_y\right)_{acc}}{V} + \frac{g}{V}\cos\theta\sin\phi \tag{D-11}$$

Equation D-11 represents a synthesis of sideslip rate based on measurable variables.

APPENDIX E

ANALYSIS OF VARIANCE OF TRACKING DATA

A three-way analysis of variance was conducted on azimuth error, elevation error, and total error. The three error sources considered were pilot, flight condition, and SAS. Since no replications were available, the error source interactions were not examined. The analysis is based on the method described by Miller and Freund.

The model used for the analysis is shown below.

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \varepsilon_{ijk}$$

α_i = Effect due to $i^{\underline{th}}$ pilot $i = 1, 2$

β_j = Effect due to $j^{\underline{th}}$ SAS $j = 1, 2, 3$

γ_k = Effect due to $k^{\underline{th}}$ flight condition $k = 1, 2, 3$

ε_{ijk} = Effect due to interactions and error

$$SSTO = \sum_i\sum_j\sum_k Y^2_{ijk} - C$$

$$SS(\text{Pilot}) = \frac{(\Sigma Y_{\text{pilot }1})^2 + (\Sigma Y_{\text{pilot }2})^2}{N_{\text{pilot}}} - C$$

$$SS(SAS) = \frac{(\Sigma Y_{SAS1})^2 + (\Sigma Y_{SAS2})^2 + (\Sigma Y_{SAS3})^2}{N_{SAS}} - C$$

$$SS(FC) = \frac{(\Sigma Y_{FC1})^2 + (\Sigma Y_{FC2})^2 + (\Sigma Y_{FC3})^3}{N_{FL}} - C$$

$$C = \frac{(\Sigma Y)^2}{N_{\text{total}}}$$

TABLE E-1

AZIMUTH ERROR ANOVA

Source	SS	DOF	MS	F	Level of Significance
Pilot	26.68	1	26.68	7.8	.0163
Flt Cond	188.6	2	94.3	27.6	.00003
SAS	39.66	2	19.83	5.8	.0173
Error	41.02	12	3.42		
Total	296	17			

TABLE E-2

ELEVATION ERROR ANOVA

Source	SS	DOF	MS	F	Level of Significance
Pilot	8.76	1	8.76	7.18	.0201
Flt Cond	157.6	2	78.8	64.55	.00001
SAS	10.08	2	5.01	4.1	.044
Error	14.65	12	1.22		
Total	191.09	17			

TABLE E-3

TOTAL ERROR ANOVA

Source	SS	DOF	MS	F	Level of Significance
Pilot	33.49	1	33.49	10.97	.0053
Flt Cond	317.28	2	158.6	52	.00001
SAS	38.45	2	19.23	6.3	.0135
Error	36.65	12	3.05		
Total	425.87	17			

APPENDIX F

ASSEMBLY LISTING OF FLIGHT TEST OPERATIONAL FLIGHT PROGRAM

This appendix contains an assembled listing of the IRAM computer program used to perform the SAS calculations and the built-in test. The Hughes-built IRAM (improved reliability and maintainability) computer is a fixed-point, two's compliment airborne digital computer in the F-106 fire control system.

```
                                   'SAS CHANNEL 40 C3043 01  28 JUN 1978'
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS            C3043                CHANNEL 40, BLOCK A  PAGE  1

                         10 ***      STABILITY AUGMENTATION SYSTEM (SAS)    C3043
                         11 ***          THIS PROGGRAM HAS REVISED SCALING INCORPORATED IN
                         12 ***          IT AS FOLLOWS, TRIM IS INCLUDED IN THE DIFF ELEVON
                         13 ***            AS (.5*TRIM)/40,  TRIM IN RUDDER EQ. IS 3*TRIM/160
                         14 ***      THE DATA LINK SWITCH IS USED TO DIFFERENTIATE BETWEEN
                         15 ***      TRIMING THE ELEVONS OR RUDDER... POS 1 = ELEVON TRIM,  POS 2 =
                         16 ***      RUDDER TRIM.
                         17 *      CYCLE TIME FOR THIS PROGRAM:
                         18 *          IN SSGC3        5.32 MS
                         19 *          NOT SSGC3      15.9 MS
                         20 *          ________________________________
                         30 **
                         40 ***
                         50 ***      THE MAIN PROGRAM STARTS AT SECTOR 0400
                         60 ***
                        500 **********************************************************
                        502 *                                                        *
                        504 *                    /ELVON                              *
                        506 *        CALC. DIFFERENTIAL ELEVON CMD                   *
                        508 *                                                        *
                        510 **********************************************************
                       1000            BLOCK    A
                       1010            ORG      0000
                       1299 *** CALCULATION OF DEL SUB AC
                       1300 *** DELAC = (KSURS*DELPS-KSURR*ROLL RATE + .5*TRIM)*FSUBT
                       1310 ***    FSUBT IS A ONE SEC FADER
0000      30 0000      1315 /ELVON TRA  $$
0001      04 1215      1320        CLA      /KSURR       ROLL RT VARIABLE GAIN K/.25
0002      40 0756      1330        MPY      /ROLRT       ROLL RT/160
0003      64 3006      1340        STO      D3           (KSURR*RR)40
0004      04 1214      1350        CLA      /KSURS       LSP VARIABLE GAIN K/4
0005      40 0762      1360        MPY      /DELPS       LSP/4.34 = 2.30*LSP/40
0006      10 3006      1370        SUB      D3
0007      06 0763      1375        ADD      /AILTM       ADD (.5*TRIM)/40
0010      64 3006      1380        STO      D3           (KS*2.30*DELPS-KRR*RR+.5*TRIM)/40
0011      42 0026      1390        DVP      /ELVNK       (1/40) LIMIT CMD TO +-1
0012      22 3006      1400        STQ      D3
0013      04 0512      1410        CLA      /FSUBT       FADER FOR ELEVON CMD
0014      42 0513      1420        DVP      /NOR1
0015      22 3007      1430        STQ      D4
0016      04 3007      1440        CLA      D4
0017      40 3006      1450        MPY      D3           +-1 DEG= +-1.0 IN ACCUM
0020      24 3001      1460        ARS      01           +-1 DEG = +-.5 IN ACCUM
0021      06 2762      1470        ADD      R17          +- 1 DEG = 0 TO 1 IN ACCUM
0022      64 3006      1480        STO      D3
0023      64 3705      1490        SAO      A55N         OUTPUT DIFFERENTIAL ELEVON CMD
0024      30 0000      1495        TRA      /ELVON       EXIT
                       3000 ***    DATA FOR ELEVON CALC.S
0025      23 6561      3020 /LSPK1 DEC      .62          6.2/10
0026      00 6315      3030 /ELVNK DEC      .182         1/40
                       4000 **********************************************************
                       4005 *                                                        *
                       4010 *                         /DSPL                          *
                       4015 *                  DISPLAY A RAM LOCATION                *
                       4020 *                                                        *
                       4025 **********************************************************
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS          C3043                 CHANNEL 40, BLOCK A  PAGE  2

  0027      30 0000       4030 /DSPL  TRA     $$
  0030      72 0021       4035        RDI     G87          D170,171,172,173
  0031      64 3750       4040        STO     TEMP2
  0032      72 0022       4045        RDI     G88          D180,181,182,183
  0033      02 2766       4050        ANA     B2T1
  0034      24 0004       4055        ALS     04
  0035      06 3750       4060        ADD     TEMP2
  0036      64 3750       4065        STO     TEMP2        D180,181,170,171,172,173
  0037      72 0020       4070        RDI     GA6          D165,166,167,168
  0040      02 2772       4075        ANA     B3T1
  0041      64 3010       4080        STO     D5           0,D166,167,168
  0042      10 2767       4085        SUB     B3A1         0101 = INPUT MSBS
  0043      32 0050       4090        TNZ     $+5          NOT INPUTING MSBS,TRY LSBS?
  0044      04 3750       4095        CLA     TEMP2        STORE THE MSBS OF THE
  0045      24 0006       4100        ALS     06             LOCATION THAT IS TO
  0046      64 3017       4105        STO     S2CC86             BE DISPLAYED.
  0047      30 0027       4110        TRA     /DSPL
  0050      06 2764       4115        ADD     B1           IS D5 = 0100?
  0051      32 0027       4120        TNZ     /DSPL        TRANSFR IF NOT 0100
  0052      04 3750       4125        CLA     TEMP2        INPUT LSBS
  0053      06 3017       4130        ADD     S2CC86       ADD MSBS
  0054      52 0055       4135        STA     $+1
  0055      56 0000       4140        DRL     0000         DISPLAY THE DUDE
  0056      30 0027       4145        TRA     /DSPL
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS          C3043              CHANNEL 40, BLOCK B  PAGE  3

                          10000          BLOCK   B
                          10005          ORG     0400
0400      04 3677         10015 /STRUP CLA     ZERO          ENTER HERE FROM MA=1 ROUTINE
0401      64 0512         10020          STO     /FSUBT         INITIALIZE FADER CONSTANT
0402      04 0410         10025          CLA     /CYTIM        CYCLE TIME = 20 MS/81.92
0403      64 3571         10030          STO     INC           USED IN SRWHEN
0404      76 1434         10035          RDB     3,ABC,26       LOAD CHNL 28 SUBROUTINES AND CONSTANTS
0405      76 4150         10037          RDB     0,A,40        LOAD SAS ADD ON (ELEVON CALC) STUFF
0406      50 0431         10040          TSR     /TRAKC        SET UP RETICLE AS A TRACKING CROSS
0407      30 0411         10045          TRA     /MAIN
0410      00 0040         10050 /CYTIM OCT     040           20MS/81.92SEC
                          10054 *
                          10055 * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                          10060 *                                                         *
                          10065 *  ****************************************************** *
                          10070 *  *                                                  *  *
                          10075 *  *                                                  *  *
                          10080 *        MAIN PROGRAM   MAIN PROGRAM                  *  *
                          10085 *  *                                                  *  *
                          10090 *  *                                                  *  *
                          10095 *  ****************************************************** *
                          10100 *                                                         *
                          10105 * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                          10110 ***    CHK IF GUNSIGHT(SAS) IS SELECTED,
0411      72 1023         10115 /MAIN  LXI     GA9           D185,186,187,188
0412      44 0416         10120          TXR     S+4,1
0413      50 2663         10125          TSR     SRDRUM              SAS NOT SELECTED, GOODBY
0414      76 0000         10130          RDB     0,ABC,0
0415      30 0000         10135          TRA     ORIGIN
                          10140 ***    SAS SELECTED, RUN THE MAIN PROGRAM
0416      50 0472         10145          TSR     /FADER        CALC FADER VALUE
0417      50 0514         10150          TSR     /SW3A4        CHK HUD SWS 3 AND 4, SET /KSW3 AND /KSW4
0420      50 0532         10155          TSR     /RADI         READ IN ALL DATA INPUTS
0421      50 1023         10160          TSR     /HOMPT        READ HOMING POINT FOR GAIN CONSTANTS
0422      50 1216         10165          TSR     /CALC          CALCULATE RUDDER CMD
0423      50 0000         10166          TSR     /ELVON        CALC DIFF ELEVON CMD
0424      50 1300         10170          TSR     /RNGDS        READ AND DISPLAY DIGITAL RNG (ON TARGET ALT )
0425      50 0027         10175          TSR     /DSPL         DISPLAY RAM LOCATION (FOR DEBUGGING)
0426      50 2636         10180          TSR     SRWHEN         FILL CYCLE TIME ( CHNL 28 )
0427      70 1000         10185          SNL
0430      30 0411         10190          TRA     /MAIN
                          10195 *
                          10200 ***********************************************************
                          10205 *                                                         *
                          10210 *                         /TRAKC                          *
                          10215 *           MAKE A 'TRACKING' CROSS FROM A RETICLE        *
                          10220 *                                                         *
                          10225 ***********************************************************
0431      30 0000         10230 /TRAKC TRA     $$
                          10235 ***
                          10240 ***    GROUND BORESIGHT CAL IS BASED ON 81V=WATER LINE, HENCE
                          10245 ***    A FACTOR OF 94 MILS IS ADDED IN ELEVATION. ( AZ IS ASSUMED
                          10250 ***    TO BE ZERO). THE DISPLAY CALIBRATION IS ASSUMED TO B
                          10255 ***    NOMINAL, IF ANY CHANGE IS DESIRED TO THE CROSS LOCATION,
                          10260 ***    SIMPLY CHANGE EITHER /BAZ, /BEL, OR /RETSZ AS DESIRED.
                          10265 *
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS          C3043              CHANNEL 40, BLOCK B  PAGE  4

                            10270 ***    CALC THE RETICLE A.O. S
                            10275 ***
                            10280 *      /HORZ = -3.31*AZ + .5     ( POS = RT )
                            10285 *      /VERT = 3.31*EL + .5      ( POS = UP )
                            10290 *      /RAD = 3.31*RETSZ
                            10295 *      SEE SNAPSHOOT PROGRAM FOR TERMINOLOGY
0432     04 0463            10300          CLA     /BAZ         5 MILS/1 RADIAN
0433     06 0466            10305          ADD     /TRAK1       GRND B.S. CAL , AZ
0434     40 0470            10310          MPY     /TRAK3       3.31/4 * (BAZ + CAL )
0435     24 0002            10315          ALS     02           *4
0436     06 2762            10320          ADD     B17          .5
0437     64 3730            10325          STO     A68          /HORIZ3
0440     04 0464            10330          CLA     /BEL         -50 MILS/1 RADIAN
0441     06 0467            10335          ADD     /TRAK2       GRND B. S. CAL   EL
0442     40 0470            10340          MPY     /TRAK3       3.31/4  *  (EL + CAL)
0443     24 0002            10345          ALS     02           *4
0444     06 2762            10350          ADD     B17          .5
0445     64 3746            10355          STO     A79          /VERT3
0446     04 0465            10360          CLA     /RETSZ       10 MILS/1 RADIAN
0447     40 0470            10365          MPY     /TRAK3
0450     64 3741            10370          STO     A67          /RAD3
                            10375 ***    SET OTHER RETICLES OFF THE HUD
0451     04 3677            10380          CLA     ZERO
0452     64 3724            10385          STO     A62          //VERT2
0453     64 3735            10390          STO     A57          /VERT3
0454     04 2762            10395          CLA     B17          .5
0455     64 3723            10400          STO     A61          /HORZ2
0456     64 3740            10405          STO     A56A          /HORZ1
0457     04 0471            10410          CLA     /TRAK4       .15
0460     64 3720            10415          STO     A58          /RAD2
0461     64 3713            10420          STO     A53A          /RAD1
0462     30 0431            10425          TRA     /TRAKC
0463     00 1217            10430 /BAZ     DEC     -.005        5 MILS/1 RADIAN
0464     74 7534            10435 /BEL     DEC     -.095        MINUS 95 MILS/1RADIAN
0465     00 7534            10440 /RETSZ   DEC     .030         10 MILS/1 RADIAN RETICLE WIDTH
0466     00 0000            10445 /TRAK1   DATA    00           GRND BS CAL    AZ
0467     03 0041            10450 /TRAK2   DEC     .094         GRND BS CAL    EL
0470     32 3656            10455 /TRAK3   OCT     3.31B2       3.31/4 = SNAPSHOOT DISPLAY GAIN V/R*4
0471     04 6315            10460 /TRAK4   DEC     .15
                            10465 ***********************************************************
                            10470 *                                                         *
                            10475 *                   /FADER                                *
                            10480 *           ONE SECOND FADER COMPUTATION                  *
                            10485 *                                                         *
                            10490 ***********************************************************
0472     30 0000            10495 /FADER   TRA     SS
0473     72 1006            10500          LXI     G71          D102,110,118,126
0474     04 0512            10505          CLA     /FSUBT
0475     44 4503            10510          TXB     S+6,2        XFER IF HUD SW 2 IS ON
0476     32 0500            10515          TNZ     S+2          SW OFF, FADE OUT IF NONZERO
0477     30 0472            10520          TRA     /FADER       LEAVE = 0
0500     10 2764            10525          SUB     B1           DECREMENT
0501     64 0512            10530          STO     /FSUBT
0502     30 0472            10535          TRA     /FADER       EXIT
0503     10 0513            10540          SUB     /NOB1        OCTAL NO OF B1 S IN A SEC
0504     34 0506            10545          TMI     S+2          TRANSFER IF F< 50  CYCLES
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS         C3043              CHANNEL 40, BLOCK B  PAGE  5

 0505      30 0472       10550          TRA     /FADER       TRANSFR IF F= 50  CYCLES
 0506      04 0512       10555          CLA     /FSUBT
 0507      06 2764       10560          ADD     B1
 0510      64 0512       10565          STO     /FSUBT
 0511      30 0472       10570          TRA     /FADER
 0512      00 0000       10575 /FSUBT DATA      00           ONE SEC FADER
 0513      00 0062       10580 /NOB1  OCT       000062       50  CYCLES (* 20MS/CYCLE)
                         10585 ***********************************************************
                         10590 *                                                         *
                         10595 *                     /SW3A4                              *
                         10600 *               CHK HUD SWITCHES 3 AND 4                  *
                         10605 *                                                         *
                         10610 ***********************************************************
                         10615 *       HUDSW # 3 IS  D120, /KSW3 USED IN /HOMPT
                         10620 *       HUD SW # 4 IS D141, /KSW4 USED IN /CALC
                         10625 *       (NOTE; SW # 1 IS READ IN /MAIN, #2 IS READ IN /FADER.)
 0514      30 0000       10630 /SW3A4 TRA       $$
 0515      04 2635       10635          CLA     Z18          ASSUME SW 3 IS ON
 0516      72 1010       10640          LXI     G73          D104,112,120,128
 0517      44 4521       10645          TXB     $+2,2          D120 HIGH?
 0520      04 3677       10650          CLA     ZERO         SW 3 IS OFF
 0521      64 0530       10655          STO     /KSW3
                         10660 *
 0522      04 2635       10665          CLA     Z18          ASSUME SW 4 IS ON
 0523      72 1002       10670          LXI     G80          D141,142,143,144
 0524      45 4526       10675          TXB     $+2,4         D141 HIGH?
 0525      04 3677       10680          CLA     ZERO
 0526      64 0531       10685          STO     /KSW4
 0527      30 0514       10690          TRA     /SW3A4
 0530      00 0000       10695 /KSW3  DATA      00           HUD SWITCH 3 ON/OFF MARKER
 0531      00 0000       10700 /KSW4  DATA      00           HUD SWITCH 4 MARKER
                         10705 ***********************************************************
                         10710 *                                                         *
                         10715 *                  /RADI                                  *
                         10720 *       READ ALL DATA INPUTS.                             *
                         10725 *             (OR INSERT FAKE DATA IF REQ'D)              *
                         10730 *                                                         *
                         10735 ***********************************************************
 0532      30 0000       10736 /RADI  TRA       $$           READ ALL DATA INPUTS
                         10737 *
                         10738 ***     SUMMARY OF PARAMETER SCALING FOLLOWS;
                         10739 *
                         10741 *PARAMETER       INPUT        INPUT        SCALING/RESOLUTION IN
                         10742 *                SCALING    RESOLUTION       CALCULATIONS
                         10744 *YAW RT          39.37      .0384 DEG/SEC     160/.0012 DEG/SEC
                         10745 *ROLL RT         196.8      .192 DEG/SEC      160/.0012 DEG/SEC
                         10746 *ASURY           200        .1953 FPS/S      500/.0038 FPS/S
                         10747 *TRIM            4.0        .0039 DEG         160/.0012 DEG
                         10748 *ALPHA           90         .0879             60/.00045 DEG
                         10753 *
                         10754 ***     CHK SSGC, IF SSGC=3 THEN USE FAKE DATA
 0533      72 0013       10755          RDI     G76          D107,115,123,131
 0534      24 3001       10760          ARS     01           0,D107,115,123
 0535      02 2760       10765          ANA     B372
 0536      64 3000       10770          STO     A            0,D107,115,0
 0537      72 0010       10775          RDI     G73          D104,112,120,128
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS         C3043               CHANNEL 40, BLOCK 8  PAGE  6

 0540     24 3003      10780          ARS     03
 0541     06 3000      10785          ADD     A              0,107,115,104
 0542     64 3573      10790          STO     SSGCDI
 0543     10 2766      10795          SUB     R2T1           SSGC3=011
 0544     32 0546      10800          TNZ     S+2            NOT SSGC3,READ IN REAL DATA
 0545     30 0764      10805          TRA     /FAKDA          GO INSERT FAKE DATA
                       10810 ***    READ DATA INPUTS, COS(THETA),SIN(PHI), VSUBI (FROM
                       10815 ***    MACH AND IMPACT TEMP.), ROLL RATE , YAW RATE ,ALPHA,
                       10820 ***    LATERAL ACCELERATION (ASUBY) , RUDDER PEDAL POS.,TRIM,
 0546     72 2045      10825          RAI     E19
 0547     10 2755      10830          SUB     B10            .5/2**7
 0550     24 0007      10835          ALS     7
 0551     64 3167      10840          STO     STHETA         .5SIN(THETA)
                       10845 *COMPUTE COSINE THETA
 0552     40 3167      10850          MPY     STHETA
 0553     64 3000      10855          STO     A
 0554     04 2752      10860          CLA     B16
 0555     10 3000      10865          SUB     A
 0556     50 2706      10870          TSR     SRSQRT
 0557     04 3000      10875          CLA     A
 0560     64 3170      10880          STO     CTHETA         .5 COS(THETA)
 0561     72 2047      10885          RAI     E21            (.5 SIN(PHI)+.5)/2**7
 0562     10 2755      10890          SUB     B10            .5/2**7
 0563     24 0007      10895          ALS     7
 0564     64 3171      10900          STO     SPHI           .5SIN(PHI)
 0565     72 2040      10905          RAI     E22            (.5 COS(PHI)+.5)/2**7
 0566     10 2755      10910          SUB     B10            .5/2**7
 0567     24 0007      10915          ALS     7
 0570     64 3172      10920          STO     CPHI           .5COS(PHI)
 0571     66 2764      10925          LXA     B1             INPUT ALTITUDE THEN MACH  *SIM*300046
                       10930 *INPUT MACH AND HSUBI
 0572     73 3056      10935 /RV      RDG*    D373           (1-(M-.13)/2.9091)/2**3 OR
                       10940 *                               (I-(H+1100)/81910)/2**3
 0573     64 3000      10945          STO     A
 0574     12 3000      10950          CLS     A
 0575     10 2760      10955          SUB     B1
 0576     02 0737      10960          ANA     /RVK17         MACH-.13/2.9091*2**3 OR H+1100/81910*2*
 0577     07 0721      10965          ADD*    /RVK5          0.13/(2.091*2**3) OR ZERO
 0600     43 0723      10970          DVP*    /RVK6          2**2/(2.091*2**3) OR FULL SCALE
 0601     22 3000      10975          STQ     A              MACH/2**2 OR HSUBI/81910*2**3 FEET
 0602     04 3000      10980          CLA     A
 0603     11 3135      10985          SUB*    MACH1          (LAST TIME)
 0604     64 3001      10990          STO     B
 0605     16 3001      10995          CAL     B
 0606     10 0725      11000          SUB     /RVK7           0.2M/2**2 OR 4095/81910*2**3 FT.
 0607     34 0611      11005          TMI     /RV1
                       11010 * NEW INPUT IS 5 PER CENT GREATER THAN LAST TIME ***DO-NOT-USE***
 0610     30 0612      11015          TRA     /RV2
 0611     23 3137      11020 /RV1     STQ*    MACH
 0612     23 3135      11025 /RV2     STQ*    MACH1
 0613     54 0572      11030          TIX     /RV
                       11290 * COMPUTE VSUBT/2**11
 0614     04 3137      11295 /VST     CLA     MACH           M/4
 0615     40 3137      11300          MPY     MACH           M**2/16
 0616     40 0741      11305          MPY     /KVA1          .2(4) YIELDS .2M**2/4
 0617     06 2752      11310          ADD     B16            1/4
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS        C3043                   CHANNEL 40, BLOCK B  PAGE  7

  0620     64 3005     11315          STO     D2            (1+.2M**2)/4
  0621     72 2022     11320          RAI     A10           (2=365.4)/414(2**7)
  0622     24 0004     11325          ALS     04
  0623     40 0742     11330          MPY     /KYA2          414/2**9
  0624     06 0743     11335          ADD     /KYA3          365.4/2**12
  0625     64 3001     11340          STO     B             ZIT/2**12
  0626     42 3005     11345          DVP     D2            ZIT/((1+.2M**2)*2**10
  0627     22 3004     11350          STO     D1            ZI/2**10
  0630     16 3004     11355          CAL     D1
  0631     50 2706     11360          TSR     SRSQRT
  0632     40 0744     11365          MPY     /KYA4          49.01/2**6
  0633     64 3415     11370          STO     VSUBS         VEL OF SOUND /2**11 FT/SEC
  0634     40 3137     11375          MPY     MACH          MI/4
  0635     42 2752     11380          DVP     B16           YIELDS VSUBI/2**11
  0636     22 3004     11382          STO     D1
  0637     04 3004     11384          CLA     D1
  0640     10 0740     11385          SUB     /RVK18         LIMIT VSUBI TO E/GT 300FPS
  0641     34 0645     11390          TMI     $+4
  0642     06 0740     11395          ADD     /RVK18
  0643     64 3413     11400          STO     VSUBI         V(I)/2**12
  0644     30 0647     11405          TRA     $+3           GO READ IN ALPHA
  0645     04 0740     11410          CLA     /RVK18
  0646     30 0643     11415          TRA     $-3
                       11420  ***   READ IN ANGLE OF ATTACK
                       11425  ***     +-5V = +- 45 DEGREES
  0647     72 2050     11430          RAI     E25           (.007794)ALPHA/90 + (.007794)/2
  0650     24 0007     11435          ALS     07            ALPHA/90 + .5
  0651     10 2762     11440          SUB     B17           ALPHA/90
  0652     42 0745     11445          DVP     /ALPK         60/90
  0653     22 0757     11450          STO     /ALPHA        ALPHA/60
                       11455  ***   READ IN ROLL AND YAW RATES
                       11460  ***     + - 5V = + - 50.0    ROLL RT
                       11462  ***     + - 5V = + - 19.685    YAW RT
  0654     72 2054     11470  /HERE   RAI     E18A          ROLL, (.007794)RR/100.00 +.007794/2
  0655     24 0007     11475          ALS     07
  0656     10 2762     11480          SUB     B17           YIELDS RR/100.00
  0657     40 0747     11485          MPY     /RTSCA+1       100/160
  0660     64 0756     11490          STO     /ROLRT
  0661     72 2052     11492          RAI     E16A          (.007794*YAW RT)/39.37 + .007794
  0662     24 0007     11494          ALS     07
  0663     10 2762     11496          SUB     B17           YIELDS YR/39.37
  0664     40 0746     11498          MPY     /RTSCA        39.37/160
  0665     64 0755     11500          STO     /YAWRT        YAW RT/160
                       11510  ***   READ IN LATERAL ACCELERATION, ASUBY
                       11515  ***     +- 5V = +- 100   FPS
  0666     72 2055     11520          RAI     E26           (.007794)AY/200 + (.007794)/2
  0667     24 0007     11525          ALS     07            ASUBY/200 + .5
  0670     10 2762     11530          SUB     B17           ASUBY/200
  0671     40 0753     11532          MPY     /AYK1         SCALE OVER 500
  0672     64 0754     11535          STO     /ASUBY         ASUBY/500
                       11540  ***   READ IN TRIM (A16)
                       11545  ***     0-100V = +- 2 DEGREES
  0673     72 2004     11550          RAI     A16           (.007794)T/4 + .007794/2
  0674     24 0007     11555          ALS     07            TRIM/4 + .5
  0675     10 2762     11560          SUB     B17           TRIM/4    ( +- 2)
  0676     72 1004     11561          LXI     GA2
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS         C3043              CHANNEL 40, BLOCK B  PAGE  8

0677    45 4703     11562           TXR     *+4,4         84 IS D156(PART OF DL STA SELECT)
0700    40 0750     11563           MPY     /TRIMK        STOR TRIM IN RUDDER LOCATION
0701    64 0761     11564           STO     /TRIM         YIELDS 3*TRIM/160
0702    30 0705     11565           TRA     *+3           GO READ IN RUDDER PED POS
0703    40 0751     11566           MPY     /TRMK2        SCALE FOR USE IN DIFF ELEVON CALC
0704    64 0763     11567           STO     /AILTM        YIELDS .5TRIM/40
                    11575 ***     READ IN RUDDER PEDAL POSITION
                    11580 ***       50V+-30V = +-3.25INCHES
0705    72 2025     11585           RAI     A22           (.007794)PP/10.833 + .007794/2
0706    24 0007     11590           ALS     07            PED POS/10.833 + .007794/2
0707    10 2762     11595           SUB     B17           PED POS/10.833
0710    42 0752     11600           DVP     /RDPOK        10/10.833=.923077
0711    22 0760     11605           STQ     /RDPOS        PEDAL POSITION/10
                    11606 ***     READ IN LAT STICK POSITION
                    11607 ***       0-100V = += 3.5 INCHES
0712    72 2024     11608           RAI     A21           (.007794)*LSP/7 + .007794/2
0713    24 0007     11609           ALS     07            LSP/7 + .5
0714    10 2762     11610           SUB     B17           LSP/7
0715    42 0025     11611           DVP     /LSPK1        6.2/10
0716    22 0762     11612           STQ     /DELPS        YIELDS LSP/4.32 ???
0717    30 0532     11613           TRA     /RADI
0720    04 0461     11615 /RVK2     DEC     .127324       .8/2PI
0721    00 1334     11620 /RVK5     DEC     .04468783     0.13/2.9091*2**3
0722    00 0000     11625           DEC     .0            ZERO
0723    05 4000     11630 /RVK6     DEC     1.37500B3     2**2/(2.9091*2**3)
0724    37 7777     11635           OCT     0377777
0725    01 4632     11640 /RVK7     DEC     .282          0.2M/2**2 OR 4095/81910*2**3
0726    01 6420     11645 /RVK8     DEC     .45608483     (36089+1100)/81913*2**3
0727    75 5221     11650 /RVK9     DEC     -.58487983         -20805.9/81910*2**3*.434294
0730    35 4257     11655 /RVK10    DEC     .923209       0.223362*2116.22*2**3/2**12
0731    22 0127     11660 /RVK11    DEC     .56316        81910/145.447
0732    04 0174     11665 /RVK12    DEC     .125949       (1 + 1100/145447)/2**3
0733    06 0551     11670 /RVK13    DEC     .190255       1/5.2561
0734    07 5740     11675 /RVK14    DEC     .24194        2**12/2116.22*2**3
0735    00 0334     11680 /RVK15    DEC     .01344283     1100/(81910*2**3)
0736    03 3262     11685 /RVK16    DEC     .85459783     70000/81910*2**3
0737    03 7776     11690 /RVK17    OCT     0037776
0740    04 5400     11695 /RVK18    DEC     300B11        300 FPS MIN VEL
0741    31 4632     11700 /KYA1     DEC     .8            .2*4
0742    31 7000     11705 /KYA2     DEC     81489
0743    02 6655     11710 /KYA3     DEC     365.4812
0744    30 4024     11715 /KYA4     DEC     49.0186
                    11720 ***     SOME SCALING FACTORS...
0745    25 2525     11725 /ALPK     DEC     .666667       60/90
0746    70 1014     11730 /RTSCA    DEC     -.2460        39.37/160    YAW RATE SCALING
0747    24 0000     11732           DEC     .62500         100/160
0750    02 3146     11735 /TRIMK    DEC     .075          12/160
0751    01 4632     11736 /TRMK2    DEC     .05           .05=.5/10 WHICH YIELDS .5*TRIM/40 ABOVE
0752    35 4236     11740 /RDPOK    DEC     .923077       10/10.8333
0753    14 6315     11742 /AYK1     DEC     .400          200/500      ASUBY SCALING
                    11745 ***     SOME DATA LOCATIONS...
0754    00 0000     11750 /ASUBY    DATA    00            LATERAL ACCEL/500
0755    00 0000     11755 /YAWRT    DATA    00            YAW RATE/160
0756    00 0000     11760 /ROLRT    DATA    00            ROLL RATE/160
0757    00 0000     11765 /ALPHA    DATA    00            ANGLE OF ATTACK/60
0760    00 0000     11770 /RDPOS    DATA    00            RUDDER POSITION/10
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS          C3043             CHANNEL 40, BLOCK B  PAGE  9

  0761      00 0000      11775 /TRIM   DATA    00           TRIM INPUT/160
  0762      00 0000      11776 /DELPS  DATA    00           LATERAL STICK POSITION
  0763      00 0000      11777 /AILTM  DATA    00           TRIM/4 FOR USE IN DIFF ELEVON CALC
  0764      04 1011      11780 /FAKDA  CLA     /F1
  0765      64 3170      11785         STO     CTHETA
  0766      04 1012      11790         CLA     /F2
  0767      64 3171      11795         STO     SPHI
  0770      04 1013      11800         CLA     /F3
  0771      64 3413      11805         STO     VSUBI
  0772      04 1014      11810         CLA     /F4
  0773      64 0756      11815         STO     /ROLRT
  0774      04 1015      11820         CLA     /F5
  0775      64 0755      11825         STO     /YAWRT
  0776      04 1016      11830         CLA     /F6
  0777      64 0757      11835         STO     /ALPHA
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS          C3043                 CHANNEL 40, BLOCK C  PAGE 10

  1000      04 1017     11840          CLA     /F7
  1001      64 0754     11845          STO     /ASUBY
  1002      04 1020     11850          CLA     /F8
  1003      64 0760     11855          STO     /RDPOS
  1004      04 1021     11860          CLA     /F9
  1005      64 0761     11865          STO     /TRIM
  1006      04 1022     11870          CLA     /F10
  1007      64 0762     11872          STO     /DFLPS
  1010      30 0532     11875          TRA     /RADI          EXIT
                        11880 ***    FAKE DATA FOLLOWS        ***
  1011      17 7406     11885 /F1      DEC     .49809         COS(THETA)/2,   =5 DEG
  1012      73 6676     11890 /F2      DEC     -.12941        SIN(PHI)/2,     =15 DEG
  1013      15 3600     11895 /F3      DEC     .420898        VSUBI/2**11,    862
  1014      01 0000     11900 /F4      DEC     .031250        ROLL RT/160     5 DEG/SEC
  1015      01 0000     11905 /F5      DEC     .031250        YAW RT/160      5 DEG/SEC
  1016      03 5674     11910 /F6      DEC     .116667        ALPHA/60,    7 DEG
  1017      77 6356     11915 /F7      DEC     -.0060         ASUBY/500       =3FPS/S
  1020      74 0000     11920 /F8      DEC     -.1250         RUDDER POS/10     =1.25 INCHES
  1021      00 0000     11925 /F9      DEC     00             TRIM/160,      ZERO
  1022      00 0000     11926 /F10     DEC     00             LAT STICK POS/10       ZERO
                        11930 ***********************************************************
                        11935 *                                                         *
                        11940 *              /HOMPT                                     *
                        11945 *      READ IN SYSTEM VARIABLE GAIN VALUES,               *
                        11950 *          (BASED ON HOMING POINT SELECT POSITION)        *
                        11955 *                                                         *
                        11960 *                                                         *
                        11965 ***********************************************************
  1023      30 0000     11970 /HOMPT TRA     SS
  1024      66 1210     11975          LXA     /B432          15 VALUES
  1025      72 0015     11980          RDI     G83               D176,177,178,175
  1026      64 3000     11985          STO     A
  1027      72 0014     11990          RDI     G77            D108,116,124,132
  1030      02 2770     11995          ANA     R3             D116 ALONE
  1031      24 0002     12000          ALS     02
  1032      06 3000     12005          ADD     A
  1033      11 1055     12010          SUB*    /HPDAT         MATCH STORED POS WITH SWITCH
  1034      32 1036     12015          TNZ     S+2            NOT A MATCH THIS TIME,TRY AGAIN
  1035      30 1040     12020          TRA     S+3            MATCHES SO LOAD THE CONSTANTS
  1036      54 1025     12025          TIX     /HOMPT+2       IF NO POS IS SATISFIED THEN POS
                        12030 *                                ITION A IS ASSUMED.
  1037      66 3677     12035          LXA     ZERO
  1040      05 1074     12040          CLA*    /KB             INDEXED BETA DOT VALUES
  1041      64 1212     12045          STO     /KSUBB                KSUB(BETA DOT) OVER 4
  1042      05 1113     12050          CLA*    /KP            INDEXED RUDR PETAL POS GAINS
  1043      40 0530     12055          MPY     /KSW3          IF SW 3 OFF, /KSUBP=0 (SEE /SW3A4)
  1044      64 1213     12060          STO     /KSURP                KSUB(RUDR POS) OVER 16
  1045      05 1132     12065          CLA*    /KALPH         ANGLE OF ATTACK BIAS VALUES
  1046      06 0757     12070          ADD     /ALPHA         ANGLE OF ATTACK
  1047      64 1211     12075          STO     /ALFAC          (ALPHA + ALPHA BIAS)/60
  1050      05 1171     12076          CLA*    /KRR
  1051      64 1215     12077          STO     /KSURR         ROLL RT VAR GAIN CONSTANT
  1052      05 1151     12078          CLA*    /KS
  1053      64 1214     12079          STO     /KSUBS         LAT STICK POS VARIABLE GAIN CONSTANT
  1054      30 1023     12080          TRA     /HOMPT
                        12085 ***    DATA TABLES FOR HOMING PT SWITCH FOLLOWS
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS         C3043                 CHANNEL 40, BLOCK C  PAGE 11

                         12090 *
                         12095 *                           INDEX  SW POS
  1055     00 0012       12100 /MPDAT OCT     012           0      A
  1056     00 0005       12105        OCT     005           1      B
  1057     00 0010       12110        OCT     010           2      C
  1060     00 0021       12115        OCT     021           3      D
  1061     00 0022       12120        OCT     022           4      E
  1062     00 0006       12125        OCT     006          5      F
  1063     00 0034       12130        OCT     034           6      G
  1064     00 0033       12135        OCT     033           7      H
  1065     00 0007       12140        OCT     007           8      J
  1066     00 0014       12145        OCT     014           9      K
  1067     00 0031       12150        OCT     031           10     L
  1070     00 0003       12155        OCT     003           11     M
  1071     00 0004       12160        OCT     004           12     N
  1072     00 0030       12165        OCT     030           13     O
  1073     00 0023       12170        OCT     023           14     P
                         12175 *
                         12180 *      BETA DOT CONSTANTS SCALED OVER 4
  1074     17 1463       12185 /KB    DEC     1.9B2         0      A
  1075     17 1463       12190        DEC     1.9B2         1      B
  1076     17 1463       12195        DEC     1.9B2         2      C
  1077     22 0000       12200        DEC     2.25B2        3      D
  1100     14 0000       12205        DEC     1.5B2         4      E
  1101     17 1463       12210        DEC     1.9B2         5      F
  1102     17 1463       12215        DEC     1.9B2         6      G
  1103     17 1463       12220        DEC     1.9B2         7      H
  1104     17 1463       12225        DEC     1.9B2         8      J
  1105     17 1463       12230        DEC     1.9B2         9      K
  1106     17 1463       12235        DEC     1.9B2         10     L
  1107     17 1463       12240        DEC     1.9B2         11     M
  1110     17 1463       12245        DEC     1.9B2         12     N
  1111     17 1463       12250        DEC     1.9B2         13     O
  1112     17 1463       12255        DEC     1.9B2         14     P
                         12260 *
                         12265 *      RUDDER POS CONSTANTS SCALED OVER 16
  1113     24 0000       12270 /KP    DEC     10B4          0      A
  1114     24 0000       12275        DEC     10B4          1      B
  1115     24 0000       12280        DEC     10B4          2      C
  1116     24 0000       12285        DEC     10B4          3      D
  1117     24 0000       12290        DEC     10B4          4      E
  1120     24 0000       12295        DEC     10B4          5      F
  1121     24 0000       12300        DEC     10B4          6      G
  1122     12 0000       12305        DEC     5B4           7      H
  1123     24 0000       12310        DEC     10B4          8      J
  1124     24 0000       12315        DEC     10B4          9      K
  1125     24 0000       12320        DEC     10B4          10     L
  1126     24 0000       12325        DEC     10B4          11     M
  1127     24 0000       12330        DEC     10B4          12     N
  1130     24 0000       12335        DEC     10B4          13     O
  1131     24 0000       12340        DEC     10B4          14     P
                         12345 *
                         12350 *      ALPHA CONSTANTS SCALED OVER 60
  1132     02 1042       12355 /KALPH DEC     .066667       0      A
  1133     00 4211       12360        DEC     .016667       1      B
  1134     02 1042       12365        DEC     .066667       2      C
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS          C3043                 CHANNEL 40, BLOCK C  PAGE 12

  1135      02 1042     12370          DEC     .066667      3       D
  1136      02 1042     12375          DEC     .066667      4       E
  1137      01 4632     12380          DEC     .050000      5       F
  1140      03 3106     12385          DEC     .10600       6       G
  1141      02 1042     12390          DEC     .066667      7       H
  1142      02 1042     12395          DEC     .066667      8       J
  1143      01 0421     12400          DEC     .033333      9       K
  1144      02 1042     12405          DEC     .066667      10      L
  1145      02 1042     12410          DEC     .066667      11      M
  1146      02 1042     12415          DEC     .066667      12      N
  1147      02 1042     12420          DEC     .066667      13      O
  1150      02 1042     12425          DEC     .066667      14      P
                        12498 *
                        12499 *        LATERAL STICK POSITION VARIABLE GAIN CONSTS/4
  1151      30 0000     12500 /KS      DEC     .750         0       A
  1152      30 0000     12505          DEC     .750         1       B
  1153      30 0000     12510          DEC     .750         2       C
  1154      30 0000     12511          DEC     .750         3       D
  1155      30 0000     12515          DEC     .750         4       E
  1156      30 0000     12517          DEC     .750         5       F
  1157      30 0000     12519          DEC     .750         6       G
  1160      30 0000     12521          DEC     .750         7       H
  1161      30 0000     12523          DEC     .750         8       J
  1162      30 0000     12525          DEC     .750         9       K
  1163      20 0000     12527          DEC     .500         10      L
  1164      37 7777     12529          OCT     0377777      11      M
  1165      30 0000     12531          DEC     .750         12      N
  1166      30 0000     12533          DEC     .750         13      O
  1167      30 0000     12535          DEC     .750         14      P
  1170      30 0000     12537          DEC     .750         1       B
                        12598 *
                        12599 *        ROLL RATE GAIN CONSTANTS SCALED OVER .250
  1171      23 1463     12600 /KRR     DEC     .600         0       A
  1172      23 1463     12605          DEC     .600         1       B
  1173      23 1463     12610          DEC     .600         2       C
  1174      23 1463     12615          DEC     .600         3       D
  1175      23 1463     12620          DEC     .600         4       E
  1176      23 1463     12625          DEC     .600         5       F
  1177      23 1463     12630          DEC     .600         6       G
  1200      23 1463     12635          DEC     .600         7       H
  1201      37 7777     12640          OCT     0377777      8       J
  1202      23 1463     12645          DEC     .600         9       K
  1203      23 1463     12650          DEC     .600         10      L
  1204      23 1463     12655          DEC     .600         11      M
  1205      14 6315     12660          DEC     .400         12      N
  1206      31 4632     12665          DEC     .800         13      O
  1207      23 1463     12670          DEC     .600         14      P
  1210      00 0016     20000 /B432    OCT     016              DEC 14
  1211      00 0000     20010 /ALFAC   DATA    00               CORRECTED ANGLE OF ATTACK
  1212      00 0000     20020 /KSURR   DATA    00               KSURR/4
  1213      00 0000     20030 /KSURP   DATA    00               KSURP/16
  1214      00 0000     20032 /KSUBS   DATA    00               LATERAL STICK POS VAR GAIN CONST/8
  1215      00 0000     20034 /KSURR   DATA    00               ROLL RATE GAIN CONST/.25
                        20040 ******************************************************
                        20050 *                                                    *
                        20060 *                 /CALC                              *
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS          C3043                CHANNEL 40, BLOCK C  PAGE 13

                          20070 *       CALCULATE RUDDER COMMAND                          *
                          20080 *                                                         *
                          20090 ***********************************************************
                          20100 ***   BETA DOT EQUATION    ***
                          20110 *
                          20120 * BDOT=P(ALPHA)/57.3 - YAW  RT +(57.3*ASUBY)(KSUBA)/VSUBI +
                          20130 *                                     (57.3*G*CTHETA*SPHI)/VSUBI
                          20140 *
                          20150 ***   FOR REFERENCE THE TERMS ARE DENOTED 1ST, 2ND, 3RD, 4TH BELOW
1216     30 0000          20160 /CALC  TRA     SS
                          20170 ***   SUBTRCT 2ND FROM 3RD
1217     04 1274          20180        CLA     /ASUBK        (57.3*500 )/(2048*160)=.087432
1220     42 3413          20190        DVP     VSUBI         V/2048       (MIN VALUE IS 300/2048=.14648)
1221     22 3000          20200        STQ     A
1222     04 3000          20210        CLA     A
1223     40 0754          20220        MPY     /ASUBY        (57.3*ASUBY)/(VSUBI*160)
                          20230 *                             ( /ASUBYSCALED OVER 500   )
1224     40 0531          20240        MPY     /KSWA          EITHER 0 OR 1 (SEE /SW3A4)
1225     10 0755          20250        SUB     /YAWRT         YAW RATE/160
1226     64 3000          20260        STO     A             ((57.3*ASUBY/VSUBI)-YR)/160
                          20270 ***  ADD 1ST TERM
1227     04 1211          20280        CLA     /ALFAC        /ALFAC/60
1230     40 0756          20290        MPY     /ROLRT        P/320    (ROLL RATE)
1231     42 1276          20300        DVP     /RRATK        57.3/60
1232     22 3001          20310        STQ     B
1233     04 3001          20320        CLA     B
                          20330 *    YIELDS (P*ALPHA)/(57.3*160)
1234     06 3000          20340        ADD     A
1235     64 3000          20350        STO     A             ( 1ST + 3RD - 2ND )/160
                          20360 ***   ADD 4TH TERM
1236     04 1277          20370        CLA     /GRAVK        (57.3*G)/(2048*20)=.045045
1237     42 3413          20380        DVP     VSUBI         V/2048      (MIN IS .14648)
1240     22 3001          20390        STQ     B             (57.3*G)/V    (MAX IS .307)
1241     04 3001          20400        CLA     B
1242     40 3170          20410        MPY     CTHETA        COS(PITCH)/2
1243     40 3171          20420        MPY     SPHI          SIN(ROLL)/2
                          20430 *    YIELDS  (57.3*G*COS(PITCH)*SIN(ROLL))/(VSUBI*80)
1244     24 3001          20440        ARS     01            SCALE OVER 160
1245     06 3000          20450        ADD     A             (1ST + 3RD - 2ND + 4TH )/160
1246     42 2752          20460        DVP     B16            SCALE AND LIMIT OVER 40
1247     22 3002          20470        STQ     C             TOTAL RATE/40
                          20480 ***   RUDDER CMD EQUATION      ***
                          20490 *
                          20500 *  RUDR CMD =(KSUBP*RUDDER POS. + 3*TRIM - KSUBB*BETADOT)
                          20510 *   THE RESULT IS MULTIPLIED*ONE SECOND FADER, /FSUBT
                          20520 *
1250     04 1212          20530 /RUDDR CLA     /KSUBB        KSUBB/4
1251     40 3002          20540        MPY     C
1252     64 3001          20550        STO     B             (KSUBB*BETA DOT )/160
1253     04 1213          20560        CLA     /KSUBP         /KSUBP/16
1254     40 0760          20570        MPY     /RDPOS        RUDDER POSITION FEEDBACK/10
1255     10 3001          20580        SUB     B             (KSUBP*/RDPOS - KSUBB*BETA DOT)/160
1256     06 0761          20590        ADD     /TRIM           3*TRIM/160
1257     64 3003          20600        STO     D0             TOTAL RUDDER CMD SIGNAL
1260     42 1275          20610        DVP     /RUDRK        6/160    RESCALE OVER 6
1261     22 3003          20620        STQ     D0
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS          C3043              CHANNEL 40, BLOCK C  PAGE 14

 1262     04 0512      20630          CLA     /FSUBT       FADER
 1263     42 0513      20640          DVP     /NOB1          000144
 1264     22 3004      20650          STQ     D1             ONE SEC = FULL SCALE
 1265     04 3004      20660          CLA     D1
 1266     40 3003      20670          MPY     D0
 1267     24 3001      20680          ARS     01           +-6DEG = +-.5
 1270     06 2762      20690          ADD     B17          ADD .5 YIELDS +-6DEG = 0 TO 1.0
 1271     64 3003      20700          STO     D0
 1272     64 3704      20710          SAO     A54N         OUTPUT RUDDER CMD
 1273     30 1216      20720          TRA     /CALC
 1274     02 6304      20730 /ASURK   DEC     .087432
 1275     01 1463      20740 /RUDRK   DEC     .03750
 1276     36 4366      20750 /RRATK   DEC     .95500
 1277     01 3420      20760 /GRAVK   DEC     .045045
                       20770 ***************************************************************
                       20780 *                                                             *
                       20790 *                         /RNGDS                              *
                       20800 *            READ DIGITAL RNG, DISPLAY ON TARGET ALT          *
                       20810 *                                                             *
                       20820 ***************************************************************
                       20830 *
 1300     30 0000      20840 /RNGDS   TRA     SS
                       20850 ***     FIRST DETERMINE DIG RNG CORRECT FACTORS
 1301     04 3777      20860 /K1K2    CLA     CALCON       LOC 3777
 1302     02 1333      20870          ANA     /B13T9
 1303     24 0004      20880          ALS     04           R CORR/787
 1304     40 1335      20890          MPY     /RNGK1       .786857 GIVES CORR/1000
 1305     06 2742      20900          ADD     B9           APPROX 2 FT...LSB ERROR AVE
 1306     24 2011      20910          LGR     011
 1307     64 1336      20920          STO     /RNGK2       RNG CORR/512000
 1310     04 3777      20930          CLA     CALCON
 1311     02 1334      20940          ANA     /R8T1        OSC CORR FACTOR   NOMINAL=0135
 1312     06 1337      20950          ADD     /MINK1       MIN VALUE OF K1/2
 1313     40 1335      20960          MPY     /RNGK1       /RNGK1*OSC CORR/2
 1314     24 0001      20970          ALS     01
 1315     64 1335      20980          STO     /RNGK1       RANGE SCALE FACTOR
                       20990 ***     NOW READ DIGITAL RANGE
 1316     72 0025      21000          RDI     D353         RANGE IN B14T1,B14=OVERFLOW
 1317     24 0003      21010          ALS     03           RNG/402870 FT
 1320     36 2770      21020          ADD     B3           12.3 FT
 1321     40 1335      21030          MPY     /RNGK1       .786857
 1322     10 1336      21040          SUB     /RNGK2       RANGE DELAY CONSTANT SET BY /K1K2 SUBRT
 1323     64 3750      21050          STO     TEMP2        RANGE/512000
 1324     42 1332      21060          DVP     /RNGK3       70/512=.136718
 1325     22 1331      21070          STQ     /RANGE
 1326     04 1331      21080          CLA     /RANGE       RANGE/70000
 1327     64 3725      21090          STO     A63N         TARGET ALTITUDE
 1330     30 1300      21100          TRA     /RNGDS
 1331     00 0000      21110 /RANGE   DATA    00           RANGE/70000
 1332     04 3000      21120 /RNGK3   DEC     .136718      70/512
 1333     01 7400      21130 /B13T9   OCT     017400
 1334     00 0377      21140 /R8T1    OCT     0377
 1335     31 1337      21150 /RNGK1   OCT     0311337      DEC .786857=402,870/512,000
 1336     00 0000      21160 /RNGK2   DATA    00
 1337     17 7643      21170 /MINK1   DATA    0177643      MIN VALUE OF K1/2
                       21480 *           THE END
```

```
LOCATION INSTRUCTION SEQUENCE LABEL  INST    OPERANDS          C3043                  CHANNEL 40, BLOCK C  PAGE 15

  1376      30 4350       21490         END      40
  1377      57 7616       21490
       529 DRUM LOCATIONS UTILIZED, 239 REMAIN AVAILABLE IN THIS CHANNEL
           TAPE SUM 0174776
```

GLOBAL SYMBOLS DEFINED BY AND/OR REFERENCED IN THIS CHANNEL   ***CHANNEL 40***

SYMBOL	DEF/REF
A	REF
A10	REF
A16	REF
A21	REF
A22	REF
A53A	REF
A54N	REF
A55N	REF
A56A	REF
A57	REF
A58	REF
A61	REF
A62	REF
A63N	REF
A67	REF
A68	REF
A79	REF
B	REF
B1	REF
B10	REF
B16	REF
B17	REF
B2T1	REF
B3	REF
B3A1	REF
B3T1	REF
B3T2	REF
B9	REF
C	REF
CALCON	REF
CPHI	REF
CTHETA	REF
D0	REF
D1	REF
D2	REF
D3	REF
D353	REF
D373	REF
D4	REF
D5	REF
E16A	REF
E18A	REF
E19	REF
E21	REF
E23	REF
E25	REF
E26	REF
G71	REF
G73	REF
G76	REF
G77	REF
G80	REF
G82	REF
G83	REF
G86	REF

```
***GLOBAL SYMBOLS DEFINED BY AND/OR REFERENCED IN THIS CHANNEL***      ***CHANNEL 40***

SYMBOL   DEF/REF

G87      REF
G88      REF
G89      REF
INC      REF
MACH     REF
MACH1    REF
ORIGIN   REF
SPHI     REF
SRDRUM   REF
SRSQRT   REF
SRWHEN   REF
SSGCDI   REF
STHETA   REF
S2CCA6   REF
TEMP2    REF
VSUBI    REF
VSUBS    REF
ZERO     REF
Z18      REF
```

```
IRAM ASSEMBLY SUMMARY INFORMATION:
    CHANNEL            STATUS
    =======   =======================
      40      ASSEMBLED WITHOUT ERROR
     ====
       1      CHANNELS ASSEMBLED
CHANNELS WITH ASSEMBLY ERRORS (IF ANY) HAVE BEEN WRITTEN TO C3043,PRINTER,DATA
```

REFERENCES

1. Blakelock, J.H., Automatic Control of Aircraft and Missiles, John Wiley and Sons, New York, 1965.

2. Burroughs, J.D., and A.W. Warren, Application of the EASY Dynamic Analysis Program to Aircraft Modeling Users Manual, Boeing Computer Services, Inc., Seattle, Washington, November 1976.

3. Campbell, A., and M. Abramovitz, Lateral-Directional Stability Augmentation Methods for the STOL Flight Regime, Douglas Paper 6373, McDonnell Douglas Corporation, August 1975.

4. D'Azzo, J.J., and C.H. Houpis, Linear Control System Analysis and Design Conventional and Modern, MdGraw-Hill, Inc., New York, 1975.

5. Etkin, B., Dynamics of Atmospheric Flight, John Wiley and Sons, Inc., New York, 1972.

6. Holt, R.L., F-102/F-106 Five Degree-of-Freedom Flight Response Program (P5474), GDCA-DFM-72-001, April 1972.

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

8. McRuer, D.T., C.L. Bates, and I.L. Ashkenas, Dynamics of the Airframe, Bureau of Aeronautics Navy Department Report AE-61-411, Sept 1952.

9. Roskam, Jan, Flight Dynamics of Rigid and Elastic Airplanes, Roskam Aviation and Engineering Corporation, Lawrence, Kansas, 1975.

*U.S.Government Printing Office: 1980 — 657-084/131