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MODEL 367-80 CONTRACT NAS1-4096

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ABSTRACT

Concerning the use of a large four-engine jet airplane, Boeing #367-80 (707 prototype), as an in-flight dynamic simulator for the simulation of other large transport type airplanes operating in the subsonic region, including the approach and landing phases of flight.

TABLE OF CONTENTS

INTRODUCTION

During 1965 the Airplane Division of The Boeing Company undertook a program utilizing the Boeing 367-80 airplane (707 prototype), which would provide in-flight dynamic simulation of large supersonic transport-type airplanes in their landing configurations. The bulk of this work was carried out under NASA Contract #NAS 1-4096.

The results of this program can be found in Boeing Document D6-10743, "Simulation of Three Supersonic Transport Configurations with the Boeing 367-80 In-Flight Dynamic Simulation Airplane". (Reference A)

The main purpose of this document is to describe the technique, hardware and operational procedures involved in this variable stability program.

Also included is a description of the SST configurations that were simulated and flight tested and a discussion of some of the problems encountered.

Although this document is limited to the supersonic transport type airplanes simulated under the above contract number, it should be noted that the system is valid for any large airplane operating at subsonic speeds and in fact has been used to simulate a large subsonic military transport airplane (C5A).

LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

V	Velocity
α	Angle of Attack
β	Angle of Sideslip - Wind from Right of Nose
θ	Pitch Angle - Nose Up
Q	Pitch Rate
ϕ	Roll Angle - Right Wing Down
P	Roll Rate
ψ	Yaw Angle - Nose Right
R	Yaw Rate
γ	Flight Path Angle - Climb
δ_E	Simulated SST Elevator
δ_{TH}	Simulated SST Thrust
δ_W	Simulated SST Wheel
δ_R	Simulated SST Rudder
δe_c	-80 Elevator Command
δth_c	-80 Thrust Command
δab_c	-80 Spoiler Command
$\delta \omega_c$	-80 Wheel Command
δr_c	-80 Rudder Command
C_L	Lift Coefficient
C_D	Drag Coefficient
C_m	Pitching Moment Coefficient - Nose Up
C_ℓ	Rolling Moment Coefficient - Right Wing Down
C_n	Yawing Moment Coefficient - Nose Right
C_Y	Side Force Coefficient - To Right

LIST OF SYMBOLS (Continued)

$\Delta C_m, \Delta C_L, \Delta C_D$	Additional Pitch, Lift & Drag Coefficients Due to Ground Effect
T	Engine Thrust
m	Airplane Mass
I_{xx}	Roll Axis Inertia
I_{yy}	Pitch Axis Inertia
I_{zz}	Yaw Axis Inertia

1.0 SUMMARY

1.1 CONFIGURATIONS TESTED

The Boeing 367-80 airplane (707 prototype) has been successfully modified to perform as an in-flight dynamic simulator for the simulation of large supersonic aircraft in the approach and landing phases of flight. Nearly 100 hours of flight time have been completed while simulating various proposed supersonic transport airplanes.

The basic SST configurations tested were:

- A variable-sweep-wing airplane with the wings in the fully forward position (20 degree sweep).
- The same airplane with the wings in the fully aft position (72 degree sweep).
- A delta-wing airplane.

In addition, the following departures from the basic configurations were simulated:

- The incorporation of a suitable longitudinal stability augmentation system (pitch quickening).
- The incorporation of a suitable lateral directional stability augmentation system.
- A variation in c.g. location.
- A configuration with degraded lateral directional handling qualities.

When the airplane was in the simulation mode, it was flown from the right-hand seat position by the "Evaluation Pilot".

The airplane performance was continuously monitored by the Safety Pilot in the left-hand seat, who could take command at any time and revert to the normal 367-80 control systems. The Safety Pilot could also override the Evaluation Pilot's inputs with his own controls without disengaging the simulation.

1.2 AIRCRAFT MODIFICATIONS

The modifications necessary to convert the 367-80 to a variable stability research airplane consisted of:

Conversion of the airplane to fully powered control surfaces by the addition of electrohydraulic actuators. This gave the capability of moving the control surfaces by either a mechanical input from the Safety Pilot through the normal airplane control cable systems, or by an electrical command input when in the simulation mode. In addition, provision was made for modulating the positions of the spoiler panels and the thrust reverser clam-shell doors with electrical commands.

1.2 CONTINUED

- The installation of a general purpose analog computer (Systron-Donner SD/80) which provided electrical command signals to the airplane control systems - elevators, ailerons, spoiler panels, rudder, and thrust reversers - to modify the response characteristics of the basic -80 airplane to conform to those of the SST configuration being simulated.

- The installation of a special set of Evaluation Pilot's controls for the right-hand seat position. These controls consisted of an instrumented column and wheel, a fake throttle lever and transducers on the existing rudder pedals, and provided electrical signals proportional to the Evaluation Pilot's control inputs. Electrical pitch and roll trim controls were also added.

- The installation of special sensors and wiring for the measurement of such parameters as angle-of-attack, sideslip angle, pitch, roll and yaw rates, roll angle and airspeed. A 17-foot streamlined boom was added to the nose of the airplane to carry the $\alpha\beta$ vane sensor. (See Fig.1).

- The installation of a rack of special test equipment, referred to as the interface, which provided:

a. Input and output connections to the computer.

b. Isolation and demodulation, where necessary, for the signals from the various airplane sensors, and proper scaling and biasing of the incoming and outgoing signals.

c. Electronic control for the electrohydraulic servo systems.

d. Logic circuitry for the mode selection control allowing the simulation mode to be selected from either the cockpit or the interface station. This function also included error detection and display circuitry and provisions for automatic disengagement in the event of a malfunction.

1.3 TECHNIQUE OF SIMULATION

The technique adopted for the simulation system was essentially an open loop, low-gain compensation technique in which the response of the airplane to any disturbance was modified by modulating the airplane control surfaces with electrical commands from the analog computer. Figure 15 shows a very simplified block diagram of the system.

The magnitudes of the electrical commands were obtained from the precalculated differences between the response of the basic 367-80 airplane and the response of the simulated SST to the same disturbance. They were based on the known stability and control derivatives of the 367-80 and the predicted derivatives of the simulated SST.

The accuracy of the simulation depended primarily upon the accuracy with which the control and stability derivatives of the basic 367-80 were known. For this reason, the initial calculations for the gains used in the analog computer were followed up with flight tests for the purpose of "fine tuning"

1.3 (CONTINUED)

the simulation system to compensate for any discrepancy between the published values of the airplane derivatives and the true values under dynamic conditions.

This technique, unlike a high gain, closed-loop feedback, or model following method, is not self-correcting and consequently has limitations regarding gross weight, c.g. location, etc., changes of which tend to affect the validity of the simulation.

Despite these drawbacks, the technique adopted was considered preferable to the model following method because of the high probability of structural bending modes coupling with a model system.

1.4 FACTORS AFFECTING THE ACCURACY OF THE SIMULATION

1.4.1 Linearization of the Equations of Motion

Because the computation system was based on linearized equations of motion for a rigid airframe, the validity of the simulation decreased as the airplane departed from the established trim condition. For this reason, the following limits were established to keep the simulation within the desired accuracy:

Airspeed	± 10 knots from trim speed.
Bank Angle	± 20 degrees
Sideslip Angle	± 10 degrees
Load Factor	± .6 g's

1.4.2 Knowledge of the Basic 367-80 Characteristics

The accuracy with which the basic 367-80 airplane could be simulated had a major effect on the overall simulation accuracy.

This factor became increasingly important if the airplane being simulated was radically different from the 367-80.

1.4.3 Accuracy of the Signals from Aircraft Sensors

The accuracy of the signals from the various aerodynamic sensors, i.e., angle-of-attack, sideslip angle, roll, yaw and pitch rates, roll angle and airspeed, was important since these signals fed directly into the computer to form the commands to the control surfaces.

1.4.4 Response Characteristics of the Control Surfaces

A further factor affecting the accuracy of the simulation was the response characteristics of the control surfaces. This included the frequency response of the servo systems plus any nonlinearities in the linkage and effects due to airloads.

1.4.5 Variations in Gross Weight and Center of Gravity Location

Because the simulation was based on calculations assuming a 367-80 airplane of fixed-gross weight and c.g. location any change in these two factors, due perhaps to fuel distribution before flight and consumption during flight, caused a deterioration in the simulation.

1.4.6 Atmospheric Conditions

The above paragraphs refer to factors which were more or less under the control of the test engineer.

The 367-80 aerodynamic derivatives could be improved by means of increased flight time and increased knowledge of the basic -80 airplane characteristics.

The signals from the aircraft sensors could be improved with careful calibration and compensation.

The discrepancies caused by using linear equations of motion can be calculated and limits set on the simulation to keep the accuracy within reasonable bounds. Similarly, the effects of change in gross weight and c.g. location could be calculated and allowed for.

However, the one factor which was out of the control of the test engineer was atmospheric turbulence. The major part of the problem with turbulence was caused by the production of erroneous angle-of-attack and sideslip angle readings due to local gusts at the $\alpha\beta$ vane. These signals were immediately fed into the computer resulting in commands to the control surfaces which caused erroneous motions of the airplane.

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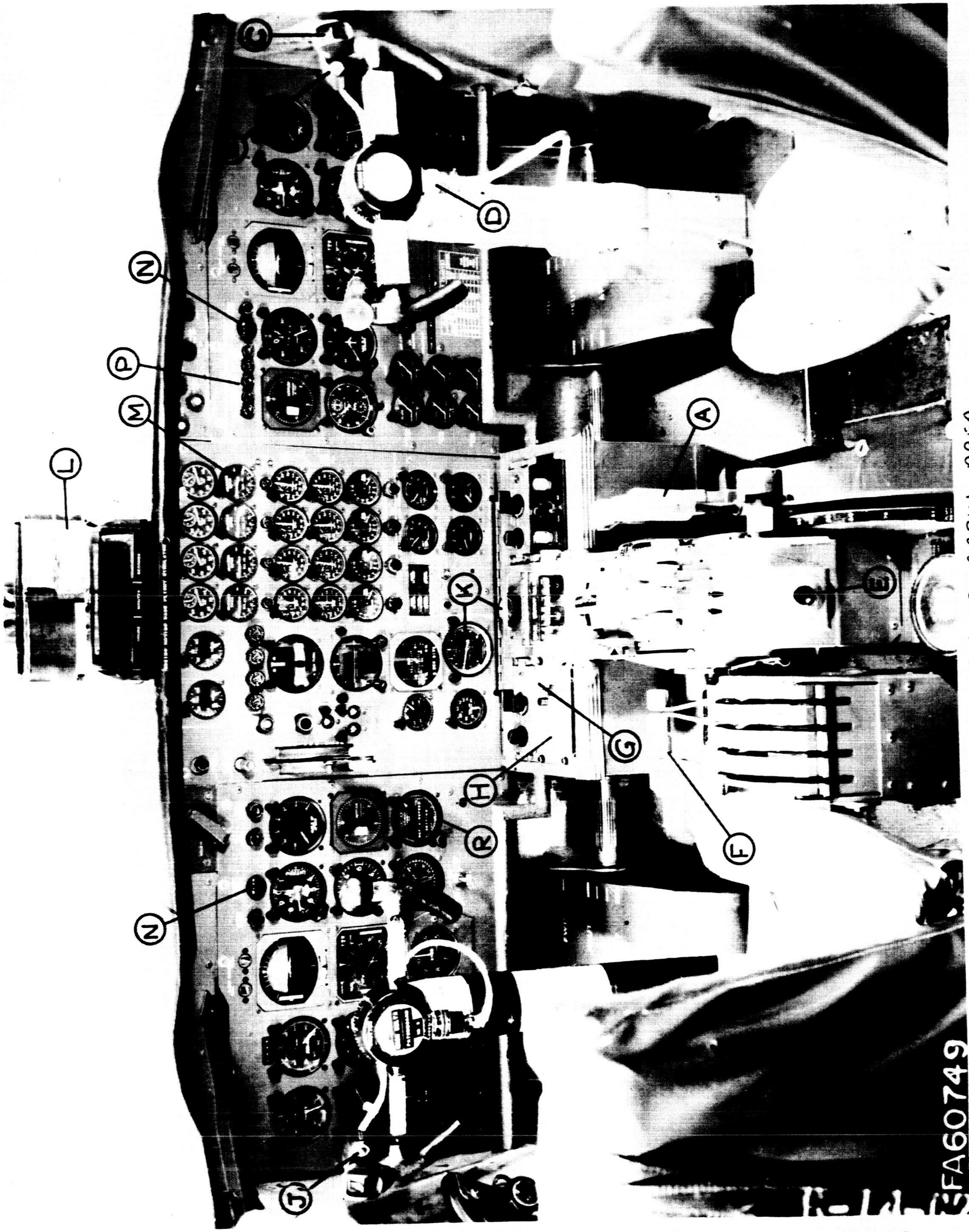
GENERAL VIEW OF 367-80 AIRPLANE



GENERAL VIEW OF CABIN AREA

FIG. 2

CLOSE-UP OF EVALUATION PILOT'S CONTROLS

TD 1546 L-R3

CLOSE-UP OF PILOT'S SIMULATION CONTROL PANEL

TD 1546 L-R3

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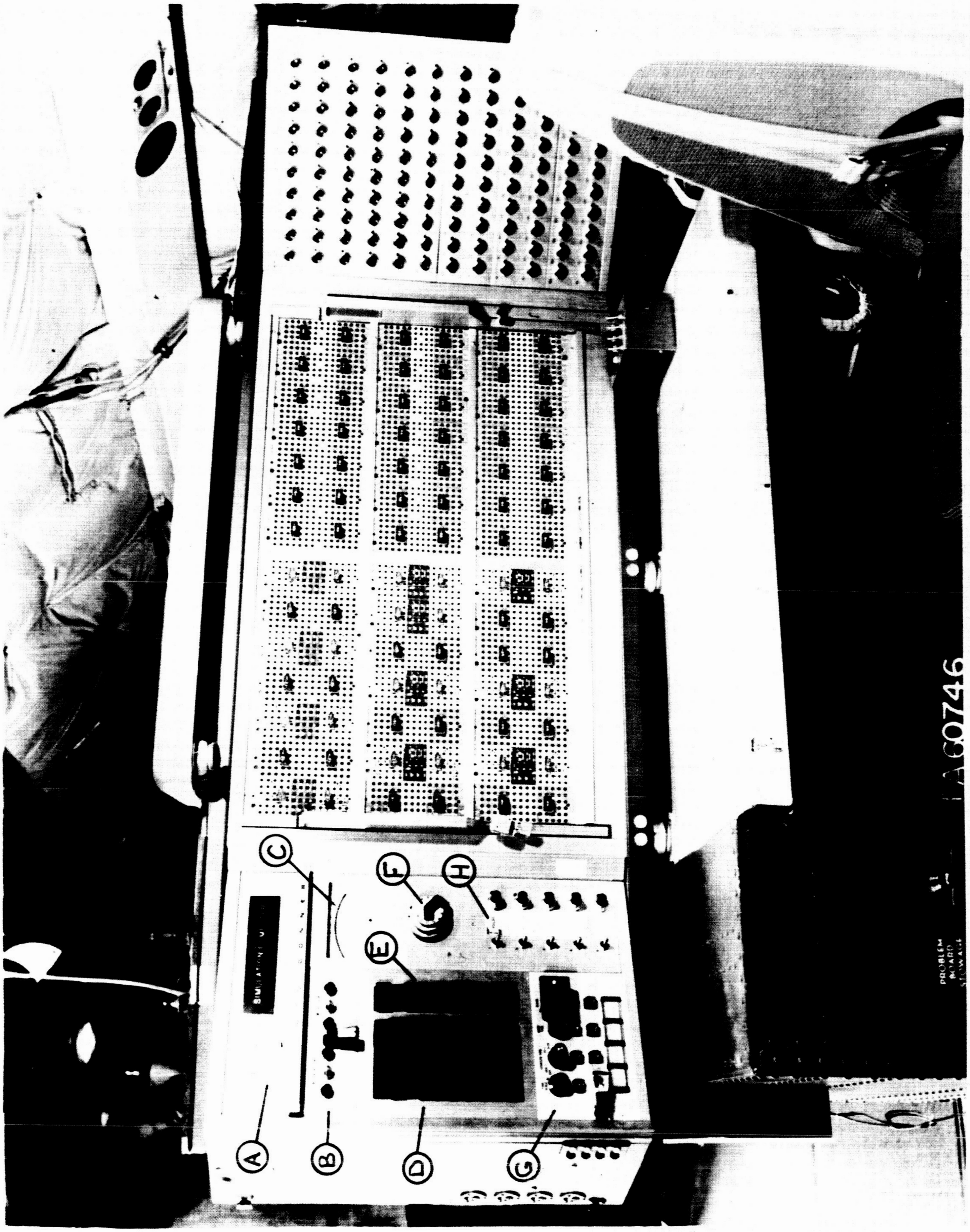
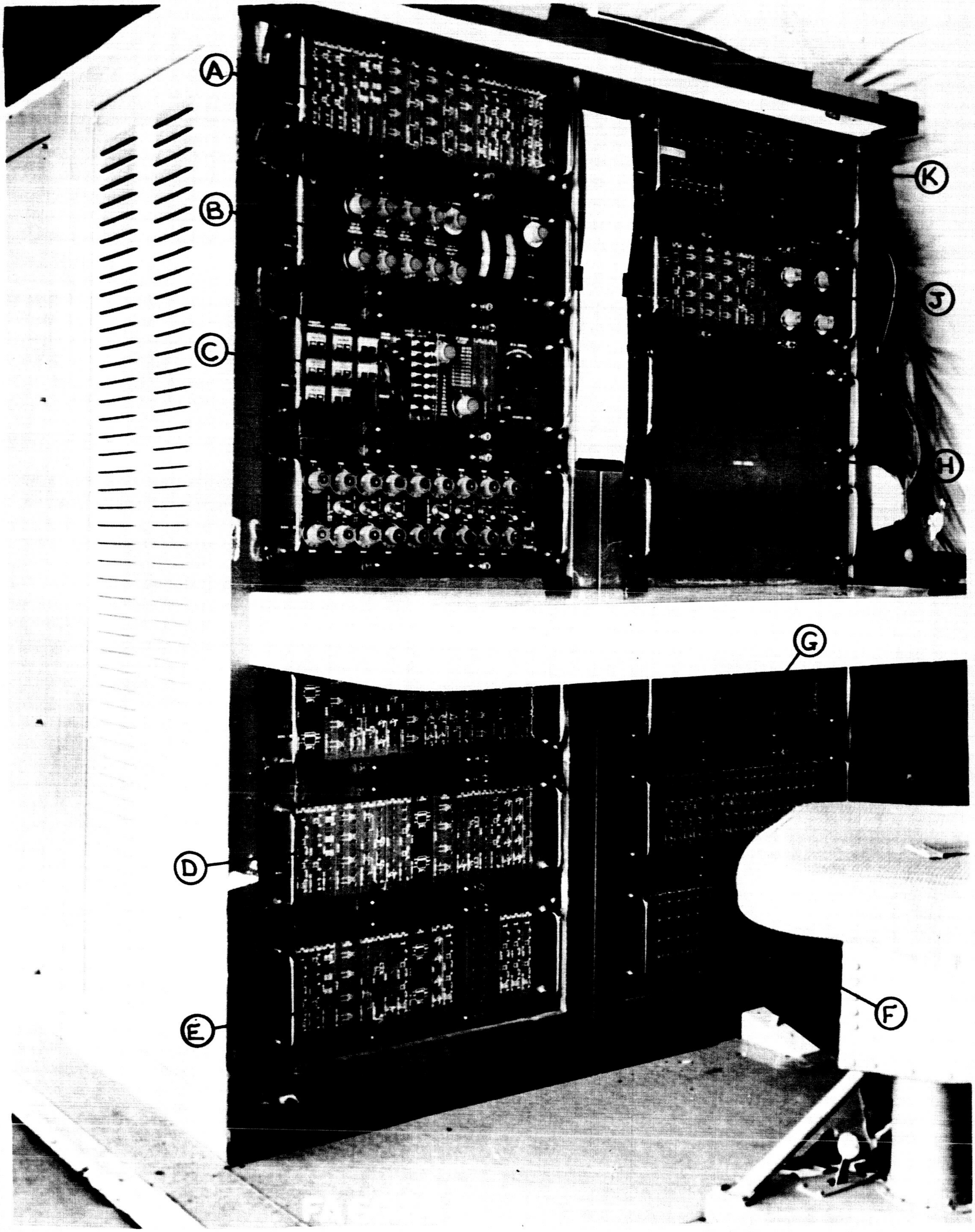


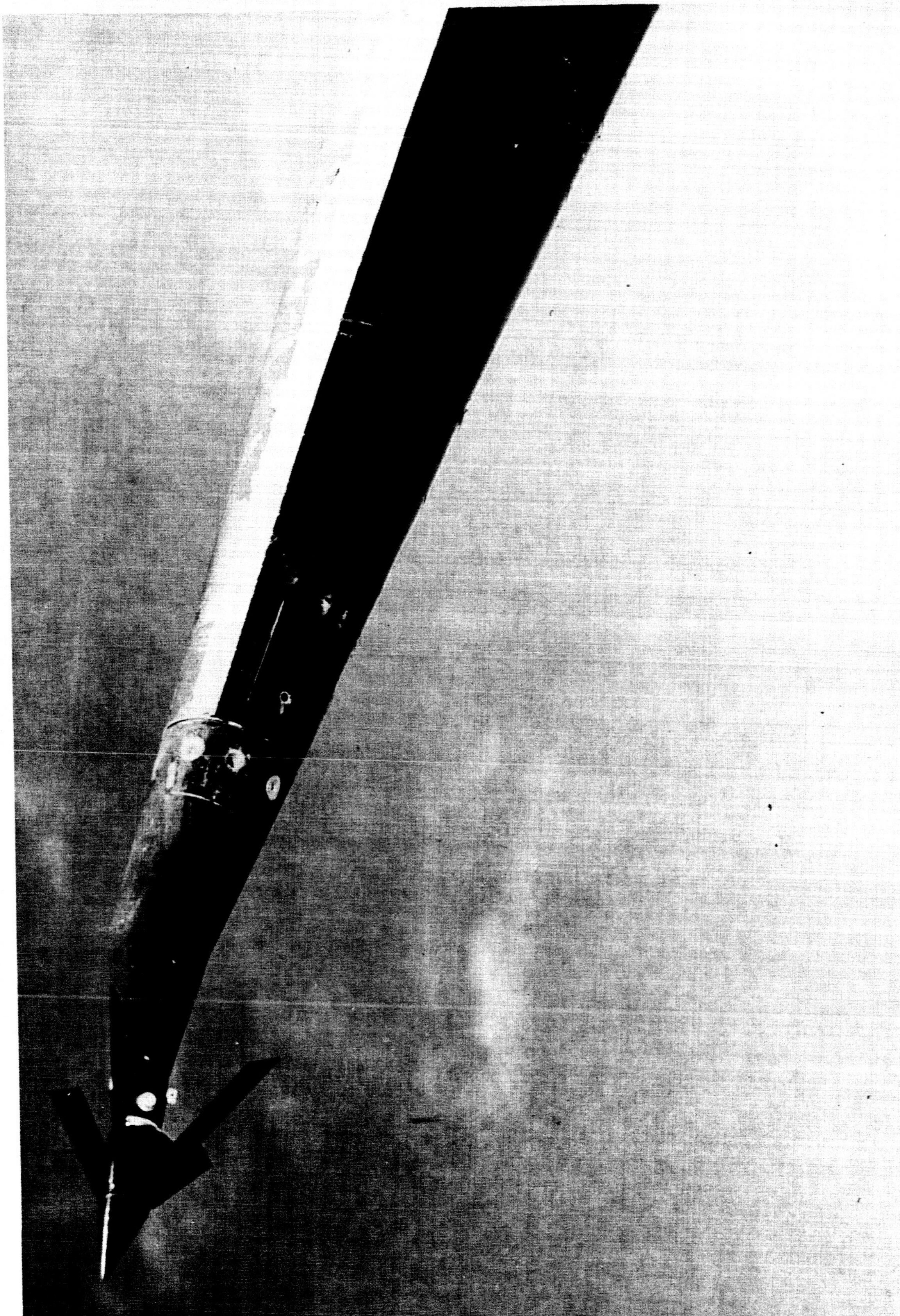
GENERAL VIEW OF AIRBORNE ANALOG COMPUTER

FIG. 5



GENERAL VIEW OF INTERFACE

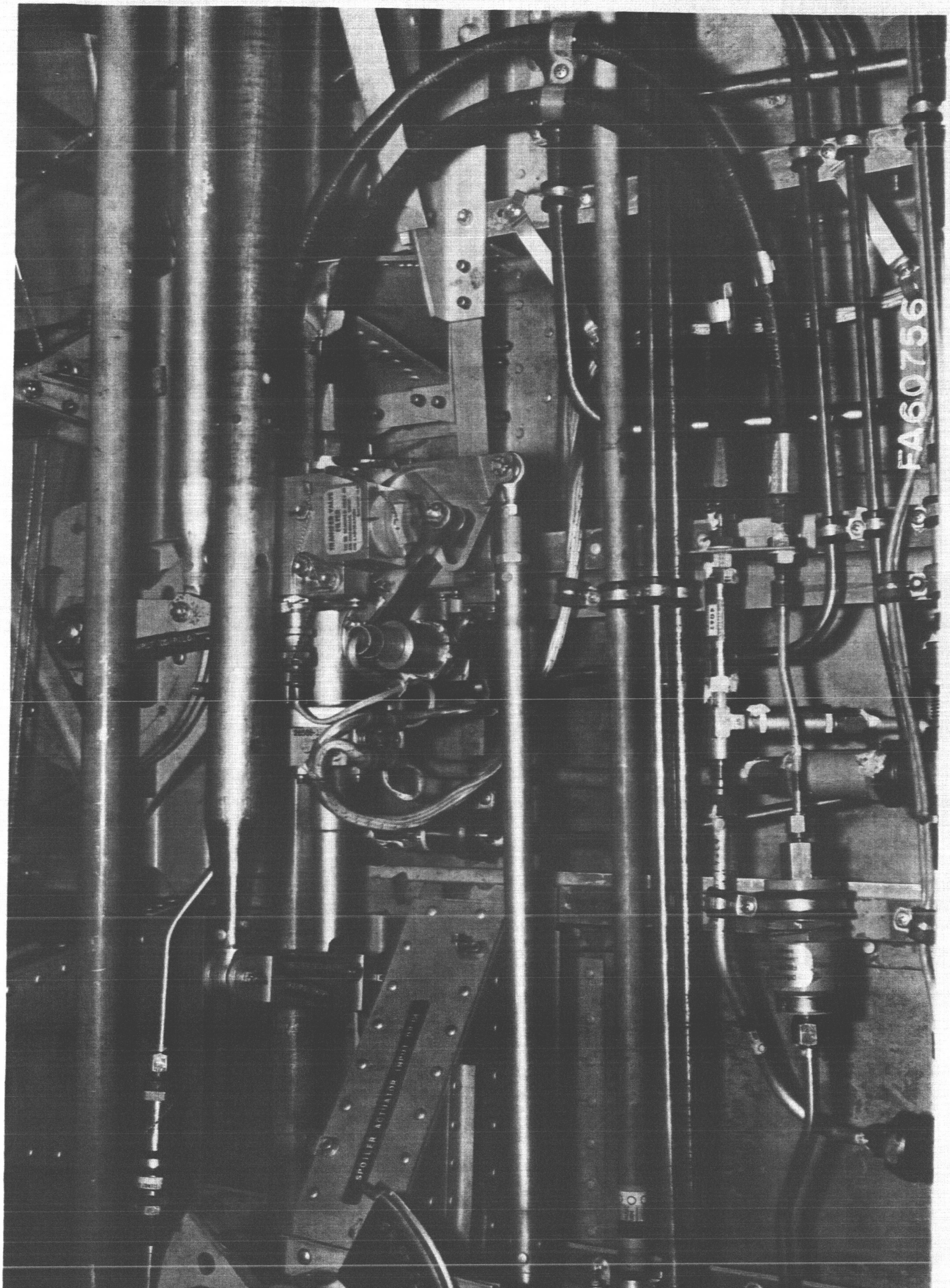
FIG. 6



CLOSE-UP OF αβ VANE

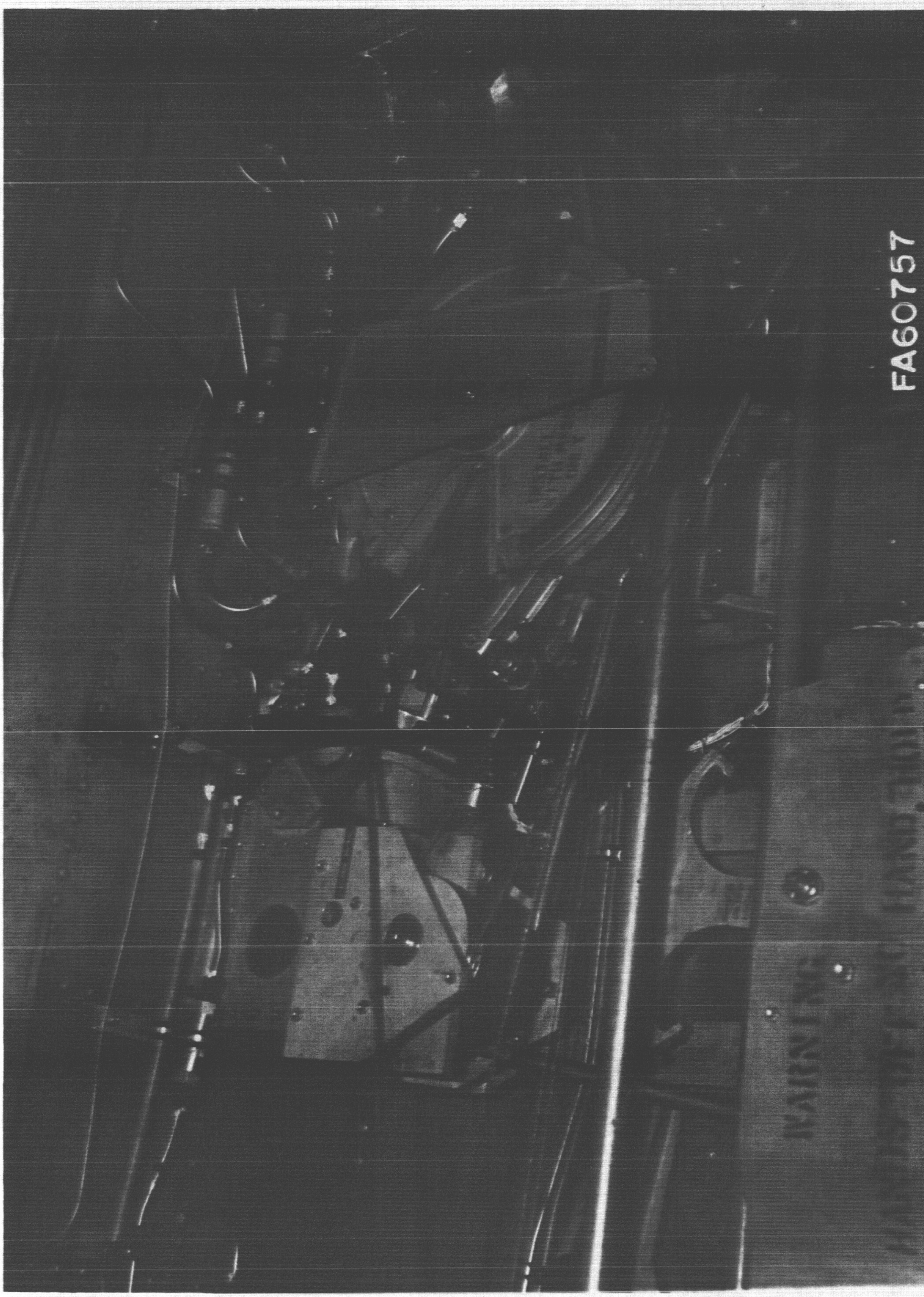
CLOSE-UP OF RATE GYROS

FIG. 8



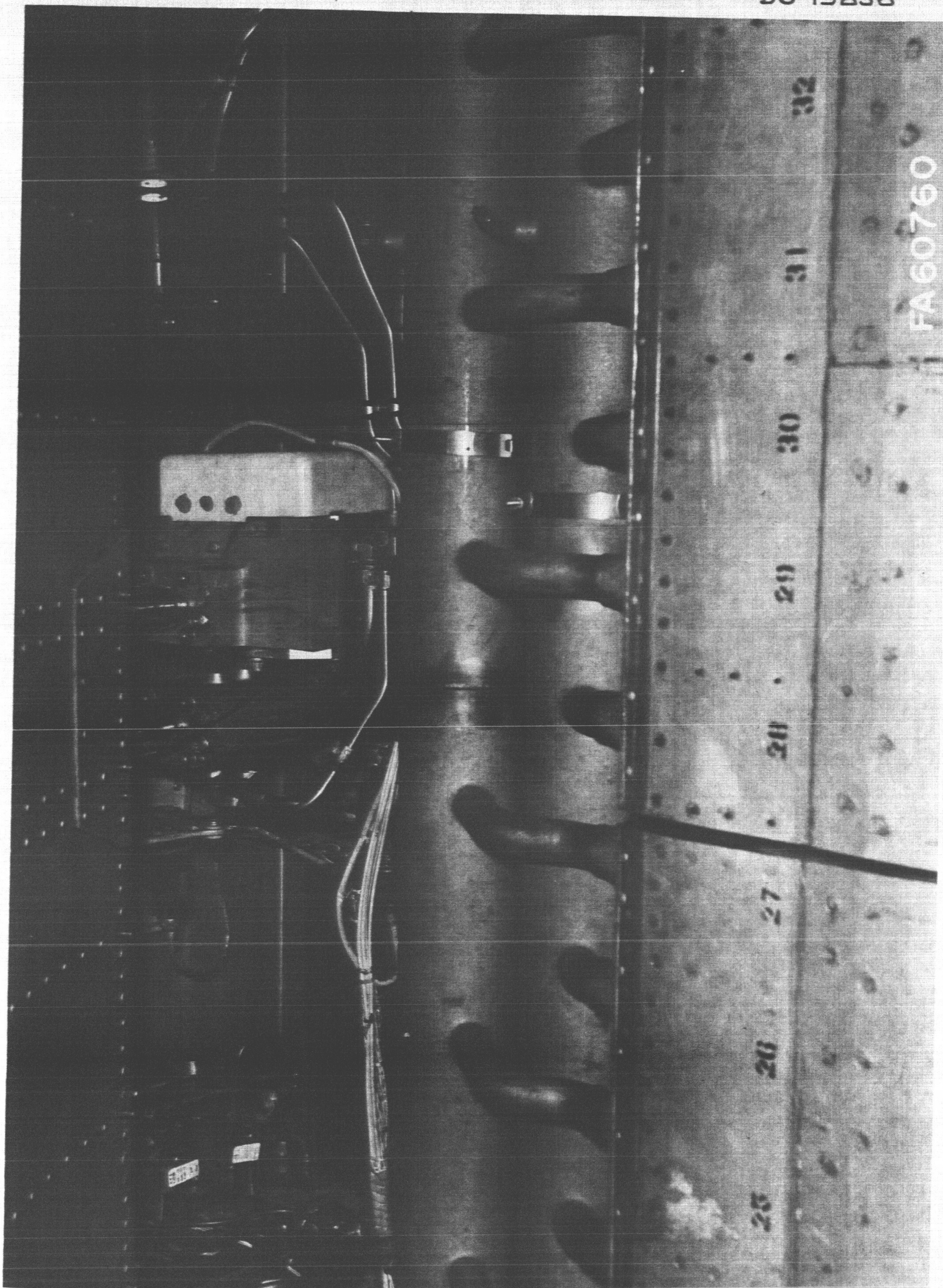
LATERAL CONTROL POWER UNIT (R.H. WHEEL WELL)

TD 1546 L-R3

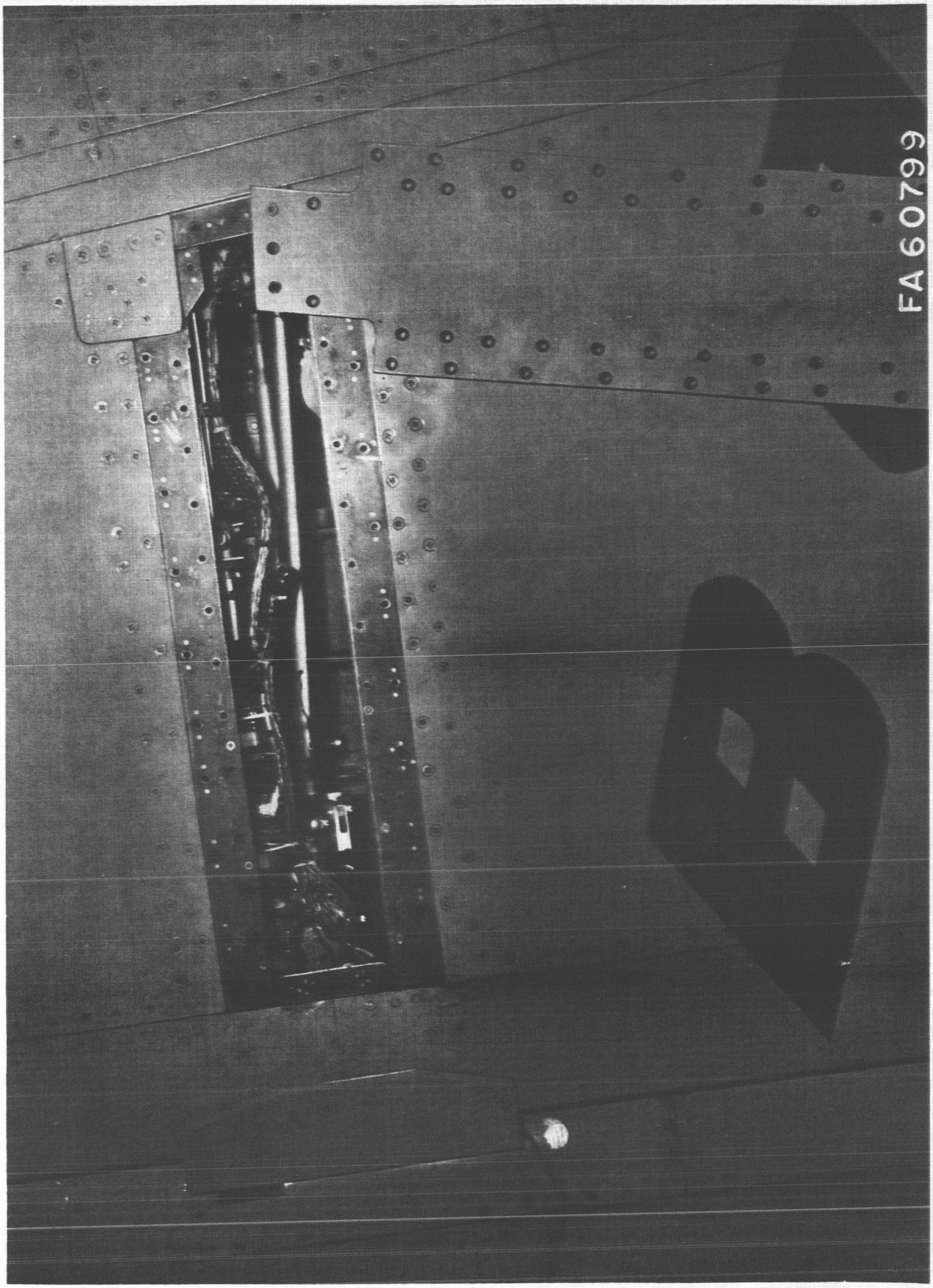


AILERON ACTUATOR (L.H. WHEEL WELL)

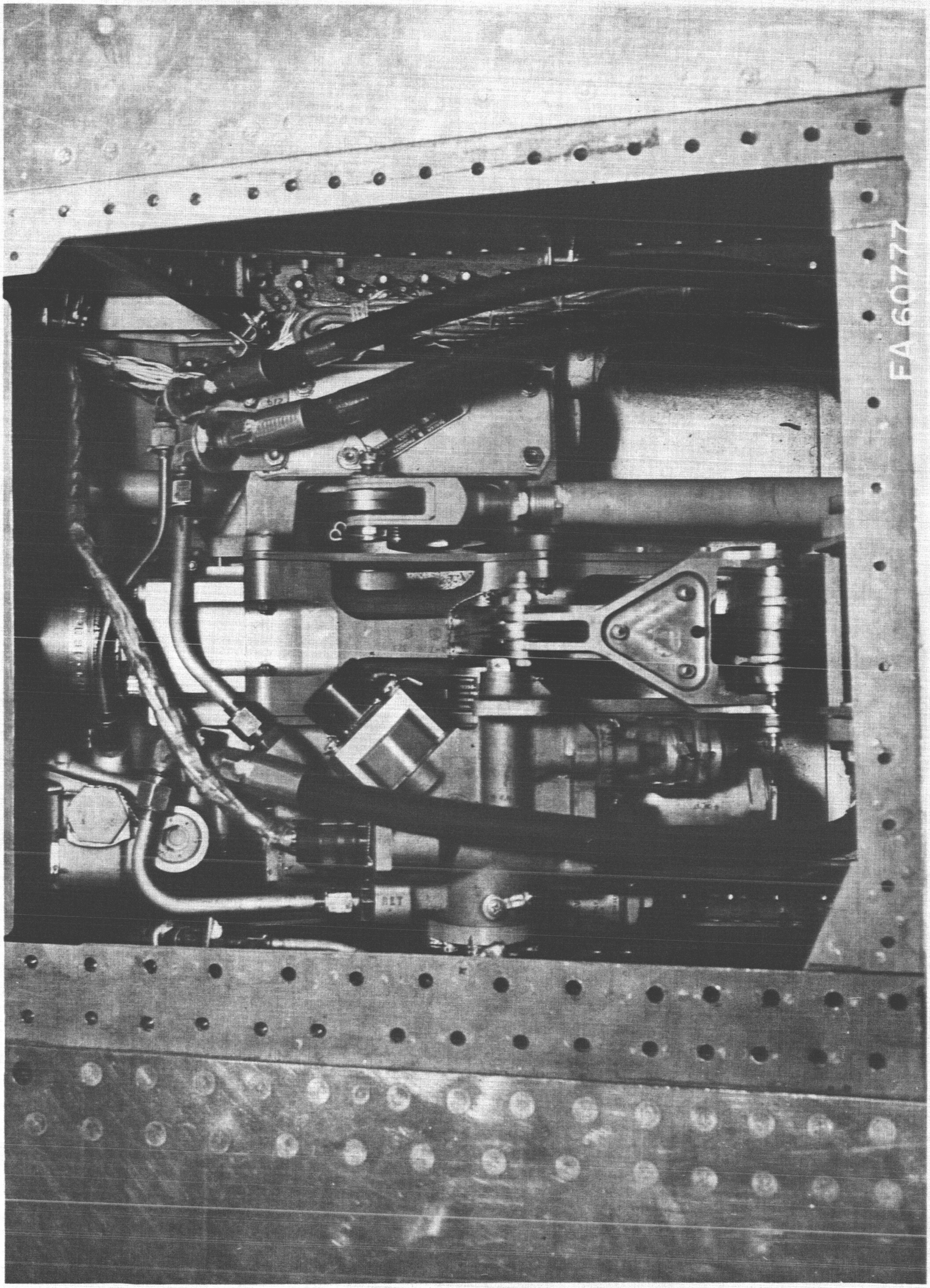
TD 1546 L-R3



HYDOMAT UNIT FOR SPOILER PANEL #6.



RUDDER ACTUATOR



R.H. ELEVATOR POWER CONTROL UNIT

TD 1546 L-R3

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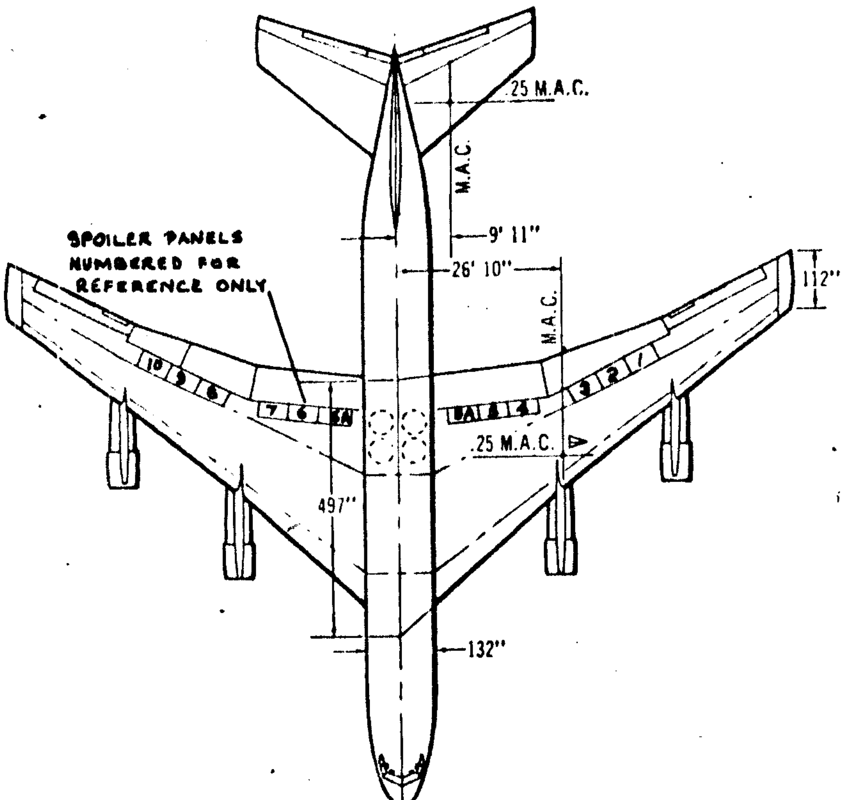
MODEL 367-80 CHARACTERISTICS



TOP VIEW

WING

Area	2,821.36 Ft^2
Aspect Ratio	6.00
Sweep (.25C)	35°
Dihedral	7°
Incidence	2°
M.A.C.	20.05 Ft

POWER PLANT

Four Pratt & Whitney Model JT3D 1 Turbofan Jet Engines

HORIZONTAL TAIL

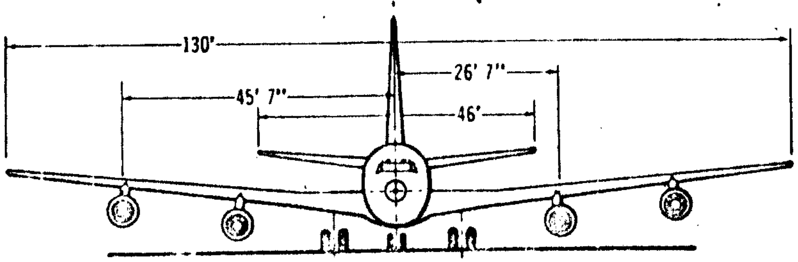
Area (Increased to)	625 Ft^2
Aspect Ratio	3.37
Taper Ratio	.421
Sweep (.25C)	35°
Dihedral	7°

VERTICAL TAIL

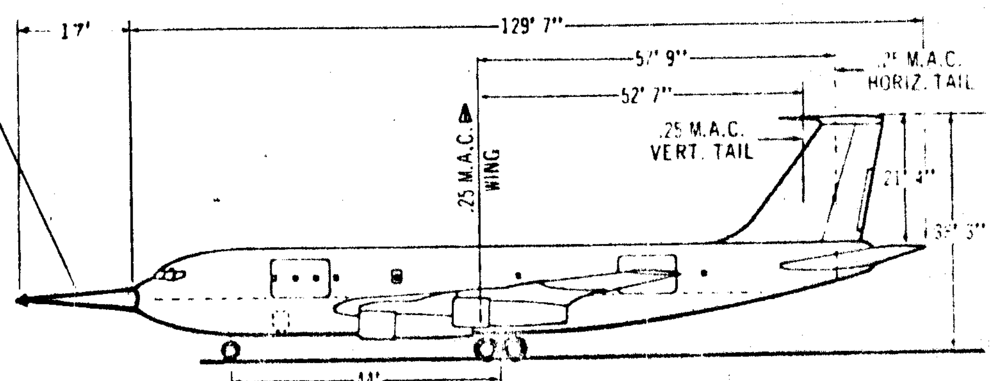
Area(excl.dorsal)	312 Ft^2
Aspect Ratio (excl.dorsal)	1.46
Taper Ratio (excl.dorsal)	.45
Sweep .25C	31°

Maximum Gross Weight = 180,000 Pounds

NOSE BOOM FOR α β SENSOR (NOT SHOWN IN TOP VIEW)

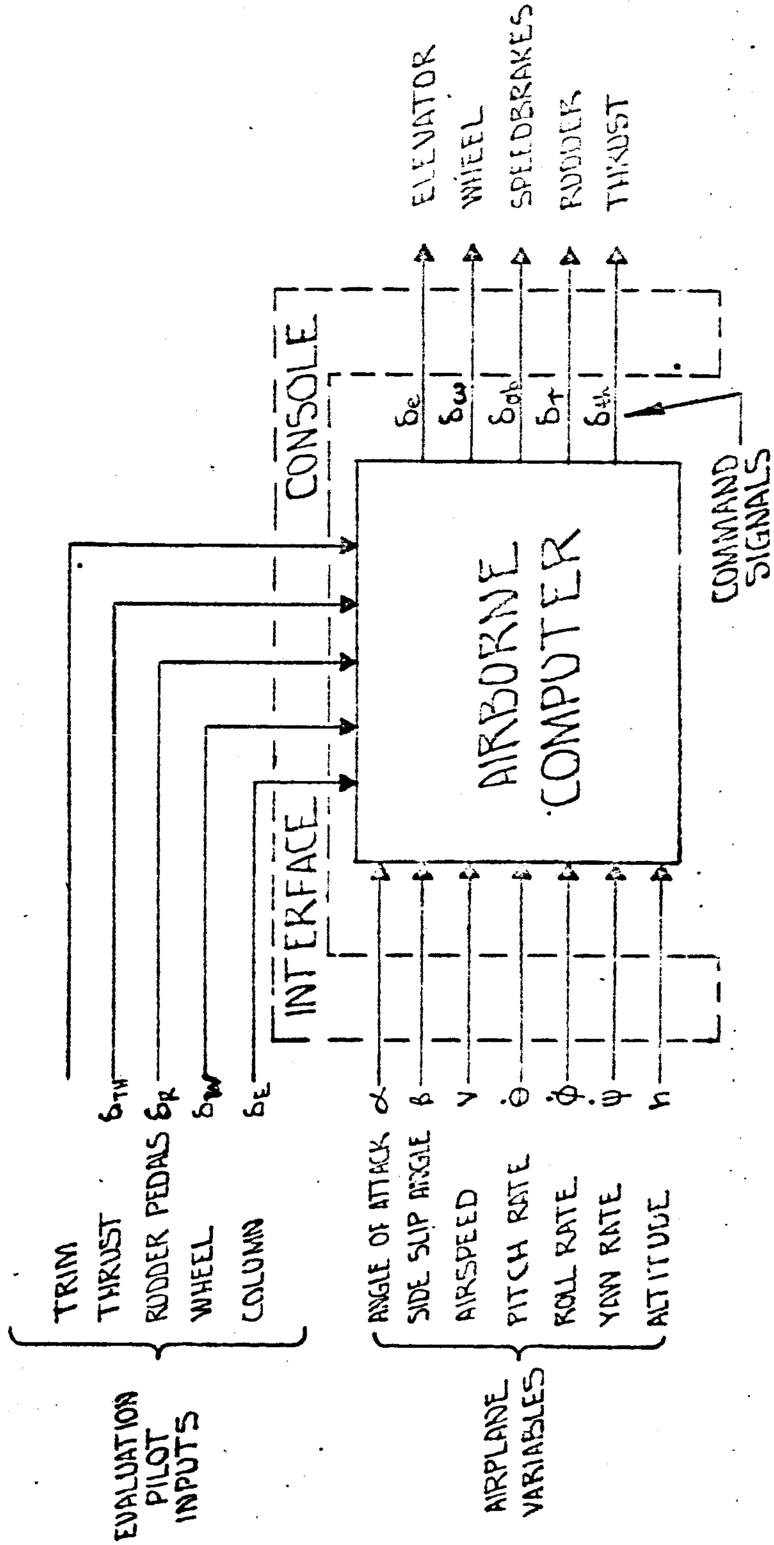


FRONT VIEW



SIDE VIEW

FIG 14



AIRBORNE COMPUTER
367-80 SST SIMULATION

TD 1546 L-R3

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2.0 DESCRIPTION AND OPERATION OF SIMULATION SYSTEM

2.1 BASIC THEORY

The 367-80 in-flight variable stability system provides a five-degree-of-freedom simulation of large jet aircraft operating at subsonic speeds.

The technique adopted (called response feedback) is to modulate the control surfaces of the 367-80 aircraft in such a manner as to cause the aircraft to behave in the manner predicted for the particular configuration being simulated.

The correct roll, yaw and pitch motions of the aircraft are produced by modulating the lateral controls, rudder and elevator respectively. The correct lift and normal acceleration characteristics are obtained by modulating the wing-mounted spoiler panels, and the correct drag by modulating the engine thrust reversers. There is no simulation of side force, but studies have shown that the errors introduced by this omission are small enough to be neglected.

The controls are moved by electrical commands to the appropriate actuators or servos. The commands are produced by a Systron Donner SD/80 general purpose analog computer which forms the heart of the simulation system. A brief step-by-step description and example of how these commands are generated follows:

a. The calculations are all based on the linearized equations of motion for a rigid airframe (see Appendices A, B, and C), e.g., the pitch axis equation is:

$$I_{YY}\dot{Q} = q_o S\bar{c}\left(C_{m_\alpha}\cdot\Delta\alpha + C_{m_{\dot{\alpha}}}\cdot\dot{\alpha} + C_{m_Q}\cdot Q + C_{m_{\delta_e}}\cdot\delta_e + C_{m_{\delta_{ab}}}\cdot\delta_{ab} + C_{m_{\Delta T}}\cdot\Delta T + C_{m_{\Delta V}}\cdot\Delta V\right)$$

b. The equations are used to mechanize a linearized simulation of the 367-80 airplane on the SD/80 computer; and as a basis for deriving the equations giving the summation of forces along, and the moments about, the X, Y, and Z axes. The equation for the linear acceleration experienced by the aircraft in the Z direction for example is:

$$\ddot{Z} = \frac{-T_o}{m}\Delta\alpha - \frac{\alpha_o}{m}\Delta T - g\left(\cos\Theta_W \cos\phi_W - 1\right) - 2\frac{q_o S}{m V_o} C_{L_{TRIM}}\Delta V - \frac{q_o S}{m}\left(C_{L_\alpha}\cdot\Delta\alpha + C_{L_{\delta_{ab}}}\cdot\delta_{ab}\right)$$

c. Now, if the 367-80 airplane is to simulate the behavior of an SST airplane, then the linear and angular accelerations that it experiences for any given conditions must be identical to those that would be experienced by this SST airplane under the same conditions.

2.1.c BASIC THEORY (Continued)

Thus, the equations derived in Step b. can be written down twice; once, using the known stability and control derivatives of the 367-80 (designated by the suffix -80) and; secondly, using the predicted derivatives of the SST configuration being simulated (designated by the suffix SST). Then, using the identities;

$$\ddot{X}_{-80} = \ddot{X}_{SST}$$
$$\ddot{Y}_{-80} = \ddot{Y}_{SST}$$
$$\ddot{Z}_{-80} = \ddot{Z}_{SST}$$
$$\dot{P}_{-80} = \dot{P}_{SST}$$
$$\dot{Q}_{-80} = \dot{Q}_{SST}$$
$$\dot{R}_{-80} = R_{SST}$$
$$V_{-80} = V_{SST}$$

these expressions can be equated, e.g., equating the pitch accelerations:

$$\dot{Q}_{-80} = \left(\frac{q_o S\bar{c}}{I_{YY}}\right)_{-80} \begin{bmatrix} (C_{m_{\Delta T}} \cdot \Delta T)_{-80} + (C_{m_\alpha})_{-80} \cdot \Delta\alpha \\ + (C_{m_{\dot{\alpha}}})_{-80} \cdot \dot{\alpha} + (C_{m_Q})_{-80} \cdot Q \\ + (C_{m_{\Delta V}})_{-80} \cdot \Delta V + (C_{m_{\delta e}} \cdot \delta e)_{-80} \\ + (C_{m_{\delta ab}} \cdot \delta_{ab})_{-80} \end{bmatrix} = \left(\frac{q_o S\bar{c}}{I_{YY}}\right)_{SST} \begin{bmatrix} (C_{m_{\Delta T}} \cdot \Delta T)_{SST} + (C_{m_\alpha})_{SST} \cdot \Delta\alpha \\ + (C_{m_{\dot{\alpha}}})_{SST} \cdot \dot{\alpha} + (C_{m_Q})_{SST} \cdot Q \\ + (C_{m_{\Delta V}})_{SST} \cdot \Delta V + (C_{m_{\delta E}} \cdot \delta_E)_{SST} \end{bmatrix} = \dot{Q}_{SST}$$

From the example given it can be seen that these expressions contain a mixture of control derivative and stability derivative terms. The aerodynamic variables in the stability terms ($\Delta\alpha$, Q, ΔV, etc., shown outside the brackets) are identical for both the -80 and the SST sides of the equation. The control variables (δe, δE etc., shown inside the brackets) are separate and distinct.

2.1 BASIC THEORY (Continued)

d. These expressions can now be solved for the control variable appropriate to the axis being considered. Thus, for the example given above, the correct pitch acceleration is maintained by modulating the 367-80 elevator, so the equation can be rewritten as follows:

$$\delta_{e_{-80}} = \frac{K(C_{m_{\delta_E}})_{SST}}{(C_{m_{\delta_e}})_{-80}} \cdot \delta_E + \frac{K(C_{m_{\Delta T}} \cdot \Delta T)_{SST}}{(C_{m_{\delta_e}})_{-80}} - \frac{(C_{m_{\Delta T}} \cdot \Delta T)_{-80}}{(C_{m_{\delta_e}})_{-80}}$$

$$- \frac{(C_{m_{\delta_{ab}}} \cdot \delta_{ab})_{-80}}{(C_{m_{\delta_e}})_{-80}} + \frac{K(C_{m_\alpha})_{SST} - (C_{m_\alpha})_{-80}}{(C_{m_{\delta_e}})_{-80}} \cdot \Delta\alpha$$

$$+ \frac{K(C_{m_{\dot\alpha}})_{SST} - (C_{m_{\dot\alpha}})_{-80}}{(C_{m_{\delta_e}})_{-80}} \cdot \dot\alpha + \frac{K(C_{m_Q})_{SST} - (C_{m_Q})_{-80}}{(C_{m_{\delta_e}})_{-80}} \cdot Q$$

$$+ \frac{K(C_{m_{\Delta V}})_{SST} - (C_{m_{\Delta V}})_{-80}}{(C_{m_{\delta_e}})_{-80}} \cdot \Delta V \;, \quad \text{WHERE} \quad K = \frac{\left(\frac{q_o S \bar{c}}{I_{YY}}\right)_{SST}}{\left(\frac{q_o S \bar{c}}{I_{YY}}\right)_{-80}}$$

This equation expresses the 367-80 elevator displacement (from trim position) as a function of simulated SST elevator input, SST and -80 thrust levels, -80 airbrake position, and aerodynamic variables, such that the 367-80 airplane will behave in pitch like the simulated SST.

Similar expressions can be derived for the 367-80 rudder, wheel, thrust and airbrake commands.

NOTE: The above example does not include the terms for simulated ground effect.

For the full equations and derivations see Appendices A, B, and C.

2.1 BASIC THEORY (Continued)

e. The correct numerical values for the derivatives can now be inserted into these expressions, resulting in a set of equations which, when properly scaled, can be mechanized on the SD/80 computer using only amplifiers and potentiometers. The outputs of these amplifiers are then used as command signals to the 367-80 control surfaces to produce the required simulation.

2.2 SST CONFIGURATIONS AND VARIATIONS TESTED

Two basic types of proposed supersonic transport airplanes were simulated. These were:

- A variable-sweep-wing airplane. This airplane was simulated in both the wings fully forward configuration (20-degree sweep angle) which is referred to as the NASA 20, and the wings fully aft configuration (72 degree sweep angle) referred to as the NASA 72.
- A delta-wing airplane, referred to as the NASA Delta (or NASA Δ).

Provisions were made for including the following variations from the basic airplane configuration.

2.2.1 NASA 20 Variations

- The addition of a longitudinal axis stability augmentation system (LONG. SAS). This LONG. SAS was developed using a ground-based computer program and, as finally used, consisted of increasing the SST elevator to column gearing by a factor of 4 over the basic SST and adding pitch rate (Q) and angle-of-attack ($\Delta\alpha$) feedbacks into the elevator command. The gains of these feedbacks were 1.46Q and 1.5 $\Delta\alpha$ in the unscaled equations. It should be noted that this is not intended to be an optimum solution but merely represents one possible approach.
- The addition of a Lateral Directional Axis Stability Augmentation System (LAT.SAS). This system changed the gain of the $\dot{\beta}$ contribution into the rudder control command to produce a dutch-roll damping ratio of .275
- Aft c.g. configuration (3 percent static margin). This variation was to simulate the NASA 20 airplane flying with the c.g. location at the maximum allowable aft position. It should be noted that the basic NASA 20 simulation is based on the assumption that the c.g. is at the nominally normal position (30% $\bar{c}$).

  The effect of an aft c.g. position was simulated by changing the value of $(C_{m_\alpha})_{SST}$ used in the calculations from -.4584 to - .141.
- Degraded lateral-directional axis characteristics. For this variation, the value of C_{n_p} (SST) was changed from -.0223 to - .076 to produce adverse yaw characteristics and $C_{n_{\dot{\beta}}}$ (SST) changed from 0 to -.1842 to reduce the dutch-roll damping ratio to .05.

2.2 SST CONFIGURATIONS AND VARIATIONS TESTED (Continued)

2.2.2 NASA Delta Variations

- The equations of Motion on which the simulation was based are written in the stability axis and describe the motions of the c.g. of the airplane. Because there is a large difference between the actual angle-of-attack of the -80 (α TRIM$_{wing}$ = 5.45 degree) and the angle-of-attack of the simulated NASA Δ(α TRIM$_{wing}$ ≅ 12 degrees) the resulting cockpit motion is not a true simulation of the NASA Δ. This effect manifests itself mainly as an apparent adverse yaw characteristic. To combat this the value of $C_{n\delta_w}$ (SST) was changed from the original value of .0229 to .0504. This change improved the pilot's visual cues in the yaw axis, and this variation was then adopted as the basic NASA Δ.

- Longitudinal Axis Stability Augmentation System. This system is identical to that used in the NASA 20 except that the gain of the $\Delta\alpha$ feedback into the elevator was 1.0.

- Lateral-Directional Stability Augmentation System. The roll damping was increased to a value expressed by $\delta w/p$ = .45 while keeping the roll power constant by changing C_{n_p} (SST) from -.0049 to -.0152 and C_{l_p} (SST) from -.0438 to -.0696.
It was not necessary to include a $\dot{\beta}$ damper as the dutch roll damping ratio of the basic NASAΔ was already adequate.

- Forward c.g. Configuration. The effect of moving the c.g. of the NASAΔ forward to produce a static margin of 7% instead of 3% of the basic airplane was simulated by changing C_{m_α} (SST) from -.0802 to -.229.

- Degraded lateral-directional characteristics. The value of $C_{n_{\dot{\beta}}}$ was changed from 0 to -.168 to produce a dutch roll damping ratio of .05.

- Improved speed stability. In its landing configuration the basic NASA Δ is operating on the backside of the power required curve, such that $\frac{T/W}{\Delta V}$ = -.00199.
To study the effect of changing this value to + .0006, the value of C_{D_α} (SST) was changed from 1.203 to .610.

2.2.3 NASA 72 Variation

The NASA 72 was simulated only in its basic configuration.

2.3 COMPUTER MECHANIZATION (See Appendixes A, B and C for Computer Diagrams)

2.3.1 Problem Boards

One Problem Board was allocated to each basic configuration, i.e., NASA 20, NASA Δ, and the NASA 72, and an additional board called the "-80 Checkout Board" was used to obtain in-flight information on the 367-80 stability and control derivatives. Each of the SST simulation boards contained the following sections.

- 367-80 Model

  This was a linearized six-degree-of-freedom analog representation of the 367-80 airplane in the configuration corresponding to the particular SST configuration.

- SST Matrix

  This was a network of amplifiers and potentiometers, derived from the equations described in Section 2.1, which generated the commands for the 367-80 control surfaces, as a result of control inputs from the pilot and aerodynamic feedbacks from the airplane sensors.

- Lateral and Longitudinal Modification Circuits

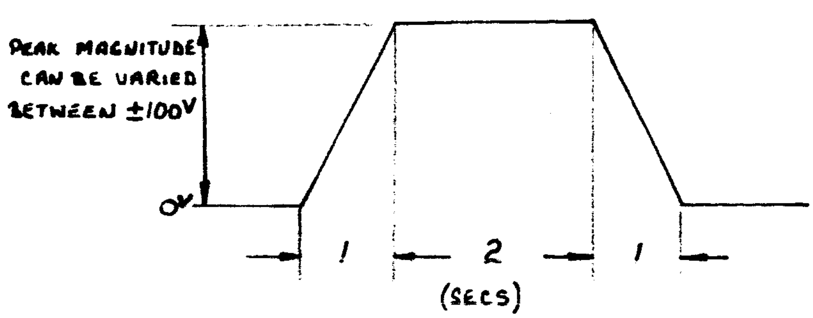
  These were relay switching networks which enabled the configuration being simulated to be changed quickly from the basic to any one of a number of possible variations; for example, to add a longitudinal stability augmentation system, or to degrade the lateral directional handling characteristics. It should be noted that the NASA 72 board did not have this feature since only the basic configuration was tested.

- Ground Effects

  In this section three diode function generators were used to generate lift, drag and pitching moment terms which provided as far as possible, the correct ground effect on the airplane from 100 ft. altitude to touchdown. The input for the function generators came from a radar altimeter. The NASA 72 board did not contain this feature due to lack of information about the ground effect characteristics of the NASA 72.

- Pulse Circuit

  This circuit produced a pulse of the shape shown below:



2.3.1 (Continued)

- Pulse Circuit (Continued)

The pulse was used as a standard forcing function into the elevator, rudder, or wheel either in the air or as part of the ground checkout. A separate circuit produced a step function which could be applied as a thrust command.

- Miscellaneous

The patchboards also contained a number of special circuits which are briefly described below.

- Synchronizing Circuits

There were two synchronizing circuits which were used to convert the absolute α and V signals respectively to incremental variations $\Delta\alpha$ and ΔV about a trim value. In addition, the $\Delta\alpha$ circuit had provisions to compensate for the nose boom sensor position. A third synchronizing circuit formed part of the thrust servo loop and was not an inherent part of the simulation.

- $\dot{\alpha}$ and $\dot{\beta}$ Generating Circuits

Since neither $\dot{\alpha}$ nor $\dot{\beta}$ signals were available directly as the outputs of sensors these two variables were generated at the computer.

$\dot{\alpha}$ was obtained by a pseudo-differentiation of $\Delta\alpha$ and $\dot{\beta}$ from a combination of roll angle and yaw rate ($\dot{\beta} = \frac{g\phi}{V_o} - R$).

- Control Input Circuits

These circuits provided the ability to apply either the Evaluation Pilot's command inputs from the instrumented controls, or the standard pulse from the pulse circuit, to the aircraft.

- Interlock Circuits

These circuits made it impossible to engage the simulation unless all the cables were correctly installed. In addition, one of the interlock circuits served to determine which elevator PCU (right or left) was to be used as the master. (See 2.4.1).

2.3.2 Interconnections Between Computer and Other Equipment

The SD/80 Computer had nine cable connectors on the back side. Two of these, J104 and J105 were for remote mode-selection control of the computer and connected to the interface.

2.3.2 Interconnections Between Computer and Other Equipment (Continued)

The next six, J1 thru J6, had the following functions:

J2 - Provided control command inputs to the -80 model and aerodynamic parameter outputs from the -80 analog model.

J4 - Provided aerodynamic and control inputs to the miscellaneous circuits listed in 2.3.1.6 and also the command outputs from the SST Matrix amplifiers to the -80 airplane control surfaces.

J3 - Provided connections between the various parameters being monitored and the in-flight C.E.C. oscillograph.

J5 - Provided simulation engaged signals for the synchronizing circuits and the System Engaged Light.

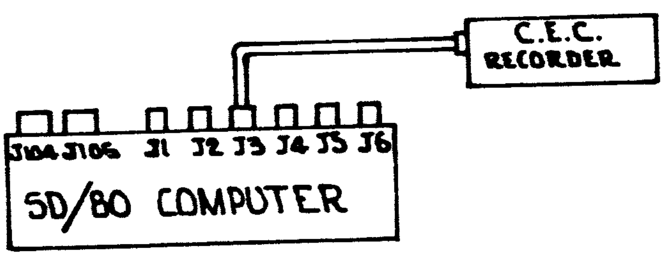
J1 - Provided engaged signal to the synchronizing circuits in ground checkout operation.

J6 - Spare

The ninth connector was for the main a.c. power supply.

The interconnecting cables could be hooked up in a number of different ways to produce different conditions.

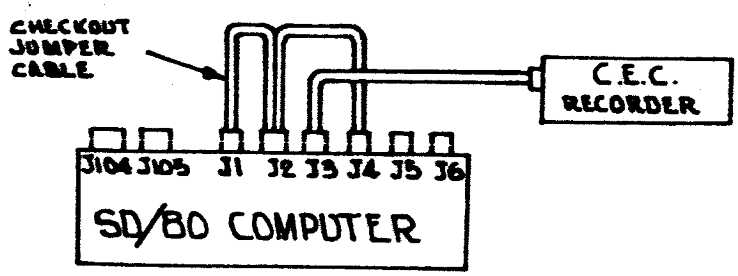
a. -80 Analog simulation ground check.



With only the connection as shown to the recorder the -80 analog model could be used by itself and the pulse circuit output plugged directly into the appropriate command channel δe , δr , etc.

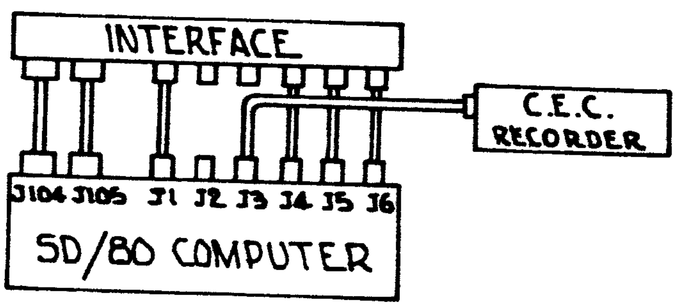
2.3.2 Interconnections Between Computer and Other Equipment (Continued)

b. SST Analog Simulation Ground Check:



With J1 and J4 connected to J2 by the "Checkout Jumper Cable" the SST Matrix was connected to the -80 analog model. In this condition the combined effect was that of an analog model of the SST configuration. It should be noted that if the SST Matrix gains were properly calculated then the same SST could be simulated with any values for the -80 derivatives. The Pulse Circuit was used to provide control inputs to the SST simulation; δ_E, δ_R, etc.

c. In-flight SST Simulation:



With J104, J105, J1, J4, J5 and J6 connected to the correct Interface connections the SST Matrix was connected, through the Interface to the 367-80 control systems. Now, if the basic 367-80 airplane characteristics were identical to those mechanized in the -80 analog model then the airplane would respond, in the air, in the same manner as the SST model did during ground checkout.

2.4 AIRPLANE CONTROL SERVO SYSTEMS

Figures 16 through 20 show block diagrams of the five primary control systems used in the SST simulation.

2.4.1 Elevator Control System (Figure 16)

The elevator system had two parallel type actuators, right hand and left hand, in which the feedback linkage moved the Safety Pilot's column. The two actuators had different authority limits and either could be selected as the master control and the other automatically slaved to it.

The motion of the Safety Pilot's column was transmitted through a system of cables and pulleys to provide a mechanical input to the control valve that controlled the actuator which moved the elevator.

The position transducer on the Evaluation Pilot's column produced an electrical signal (δ_{col}) that went to the computer. This signal was modified in the computer to provide the correct gain and summed with any contributions from the thrust command, air brake command, angle-of-attack, pitch rate, etc., to form an elevator command (δ_{e_c}). When the simulation was engaged, this signal was allowed to operate either the right hand or left hand transfer valve, whichever had been selected, and the resulting motion of the modulating piston operated the control valve of the actuator, causing the elevator to move.

2.4.2 Thrust Control System (Fig. 17)

The thrust reverser clamshell doors were moved by actuators, the control valves of which were supplied with mechanical inputs from the thrust reverser levers. If the simulation was not engaged the doors could be moved independently by moving the levers singly. However, as soon as the simulation was engaged the four levers were clamped together by an electro-mechanical clutch and moved as a unit by the thrust control servo. The transducer on the fake throttle produced an electrical signal (δ_{TH}) which went to the computer. Here it was modified to provide the correct gain and summed with any contributions from angle-of-attack, airspeed, air brake command, etc. to produce a thrust command (δth_c). This signal operated the electro-mechanical servo through the coupler.

2.4.3 Lateral Control System (Figure 18)

Lateral control of the airplane was obtained by differentially operating the ailerons and spoiler panels.

Moving the Safety Pilot's wheel put a mechanical input through the summing linkage into the control valve of the lateral control power unit and moved the actuator. The output of the actuator went to the spoiler mixer where it was summed with the mechanical output from the speed brake handle. The mechanical output of the spoiler mixer was connected to the Hydomat units which drove the spoiler panels.

2.4.3 Lateral Control System (Figure 18) (Continued)

The transducer on the Evaluation Pilot's wheel produced a signal (δw) which went to the SD/80 computer. Here it was modified to provide the correct gain and summed with any contributions from side-slip angle, yaw rate, roll rate, etc., to produce a wheel command ($\delta\omega_c$).

In simulation mode this command operated the transfer valve on the lateral control power unit. Since this power unit was a parallel-type actuator its output fed back to move the Safety Pilot's wheel.

2.4.4 Rudder Control System (Fig. 19)

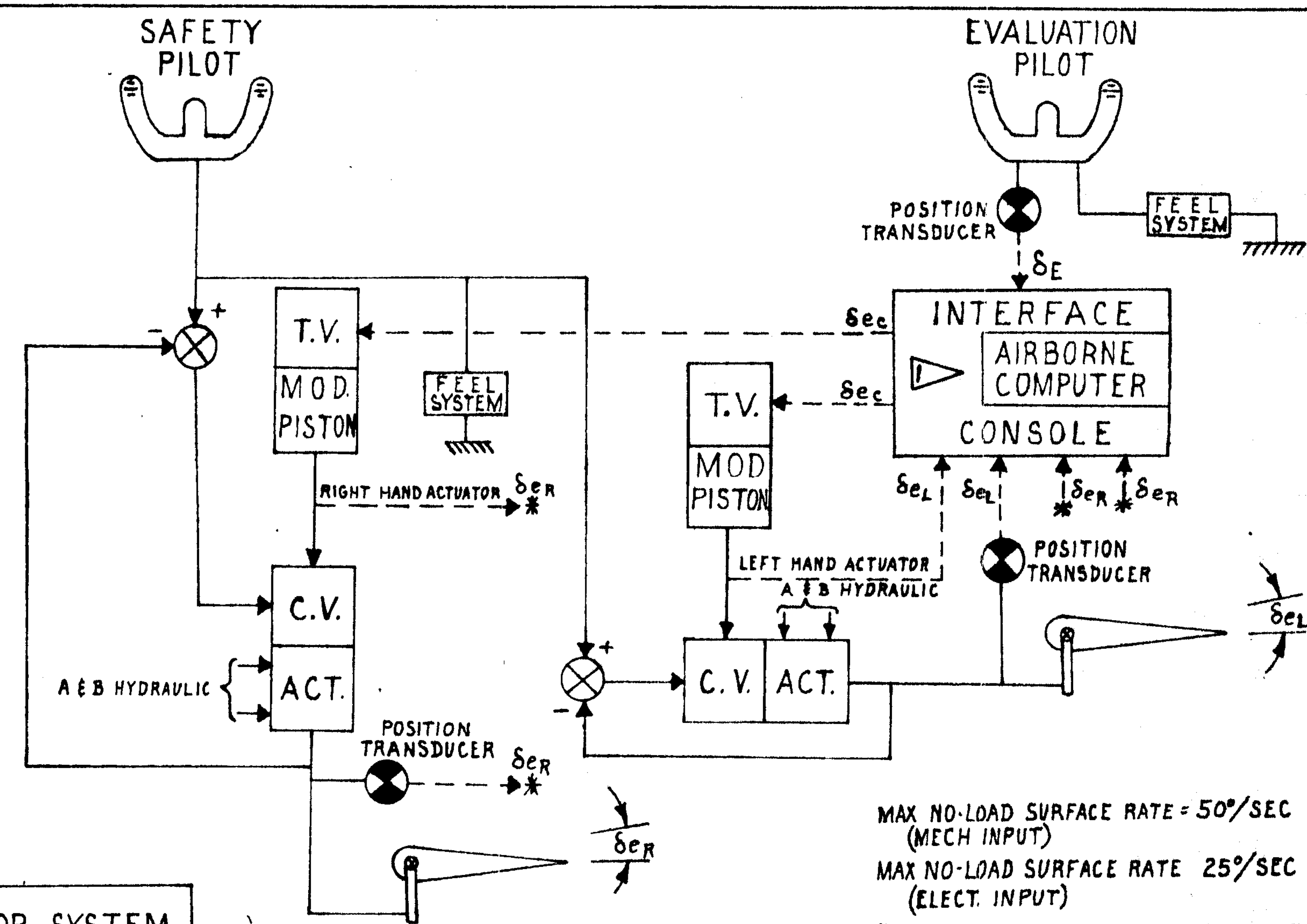
The Safety Pilot's and Evaluation Pilot's rudder pedals were coupled and provided a mechanical input through the summing linkage to the control valve on the rudder actuator. The output of the actuator moved the rudder and was also fed back to the summing linkage. In addition, the position transducer on the Evaluation Pilot's rudder pedals put out an electrical signal (δR) which went to the SD/80 computer. This signal was operated upon in the computer to provide the correct gain, and was summed together with any contributions from the wheel command, side slip angle, side slip rate, etc. to form the rudder command (δr_c). If the simulator was engaged, then this signal was allowed to operate the transfer valve causing the modulating piston to provide an additional input to the control valve. The modulating piston transducer provided rate feedback to the rudder command servo amplifier in the interface.

2.4.5 Lift Control System (Fig. 20)

Lift control during the simulation was obtained by modulating the spoiler panels on the upper wing surface. The positions of the spoilers are shown in Fig. 14 where they are numbered for clarity. For the simulations covered in this document, spoilers 1, 5A, 6A and 10 were not used. The spoilers were operated by electro-hydraulic Hydomat units. Spoilers #4,5, 6 and 7 each had a separate Hydomat Unit, but spoilers #8 and 9 were both driven by one unit and so were #2 and 3. Spoilers #2, 3, 8 and 9 are referred to as the outboard spoilers and #4, 5, 6 and 7 as the inboard spoilers.

The lift modulating signals (δab_c) were produced in the computer. Because of buffeting at high spoiler angles the inboard spoilers were electrically limited to + 10 degrees. Up to this point the spoilers all moved together but above 10 degrees the gain on the outboard spoilers was doubled, by a circuit in the computer, to keep the value of $C_{L_{\delta ab}}$ constant.

The mechanical input shown in Fig. 20 came from the spoiler mixer (see Fig. 18) and combined the initial trim setting from the speed brake handle and the lateral control input from the lateral control power unit.



MAX NO-LOAD SURFACE RATE = 50°/SEC (MECH INPUT)

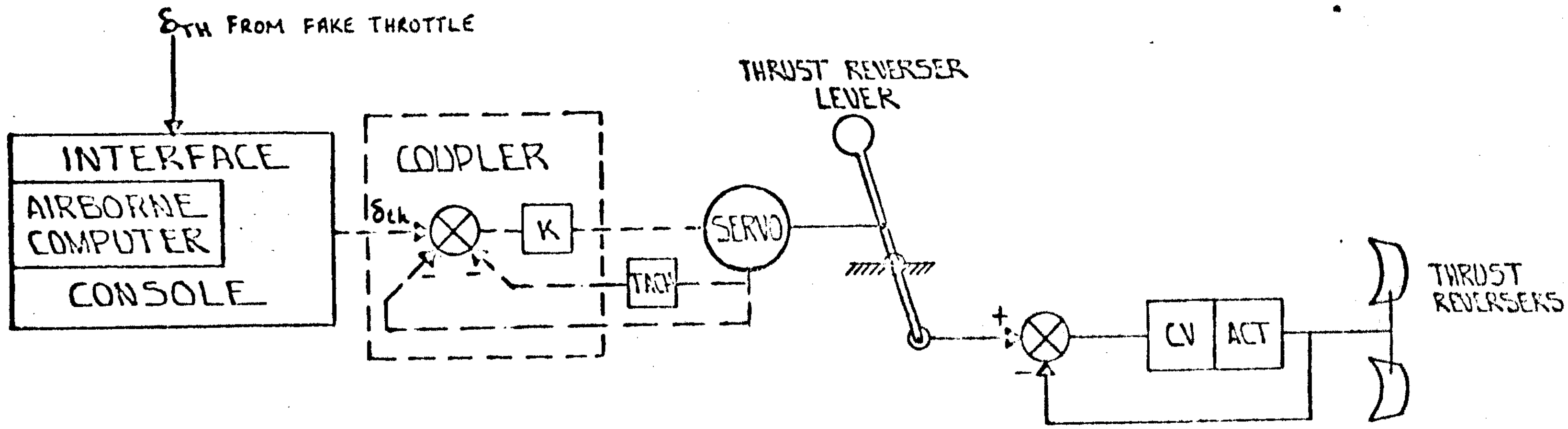
MAX NO-LOAD SURFACE RATE 25°/SEC (ELECT. INPUT)

ELEVATOR LIMIT = .5-1g MANEUVER

$$\frac{\delta_e}{e_{IN}} = KG(S) \approx \frac{K}{TS+1}, \quad T \leq .06$$

1 RIGHT OR LEFT SYSTEM SELECTED AS MASTER ON "FLY BY WIRE".

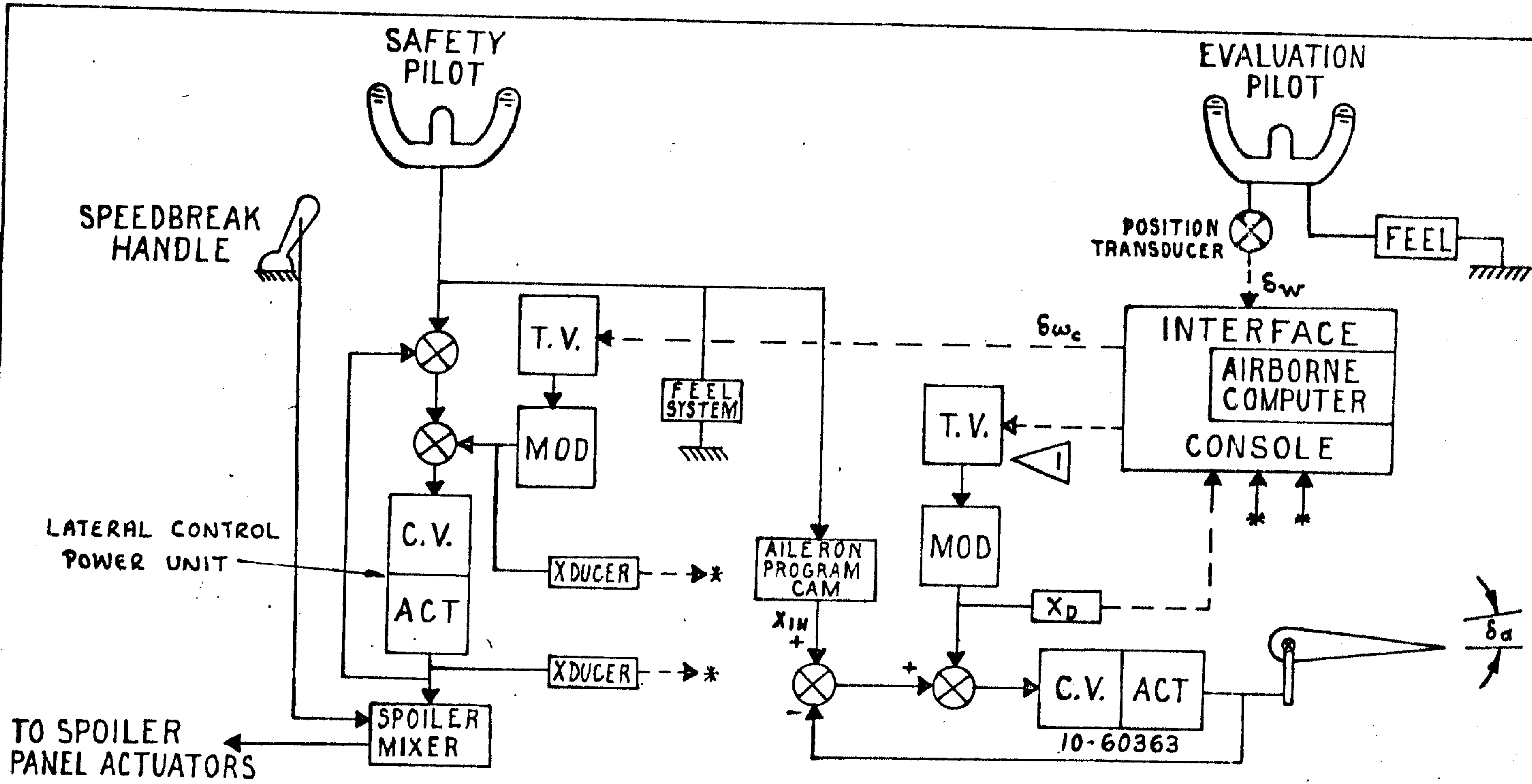
367-80 ELEVATOR SYSTEM FOR SST SIMULATION



CLAM SHELL RATE ≈ 14 $\frac{\text{DEG}}{\text{SEC}}$

$$\frac{\delta_{TH}}{e_{IN}} = KG(S) \approx \frac{K}{(T_1 S+1)(T_2 S+1)}, \quad T_1 \approx .19\,\text{SEC} \quad T_2 \approx .04\,\text{SEC}$$

367-80 THRUST CONTROL SYSTEM



δa MAX NO-LOAD RATE = 68°/SEC (MECH INPUT)

δa MAX NO-LOAD RATE = 68°/SEC

<u>MANUAL POWER</u>

$$\frac{\delta a}{X_{IN}} = KGS = \frac{183}{.05S+1}$$

ROLL STABILITY AUGMENTATION

$$\frac{\delta a}{e_{IN}} = \frac{K}{(.014S+1)(.05S+1)}$$

δ_{SP} NO-LOAD RATE = 50°/SEC

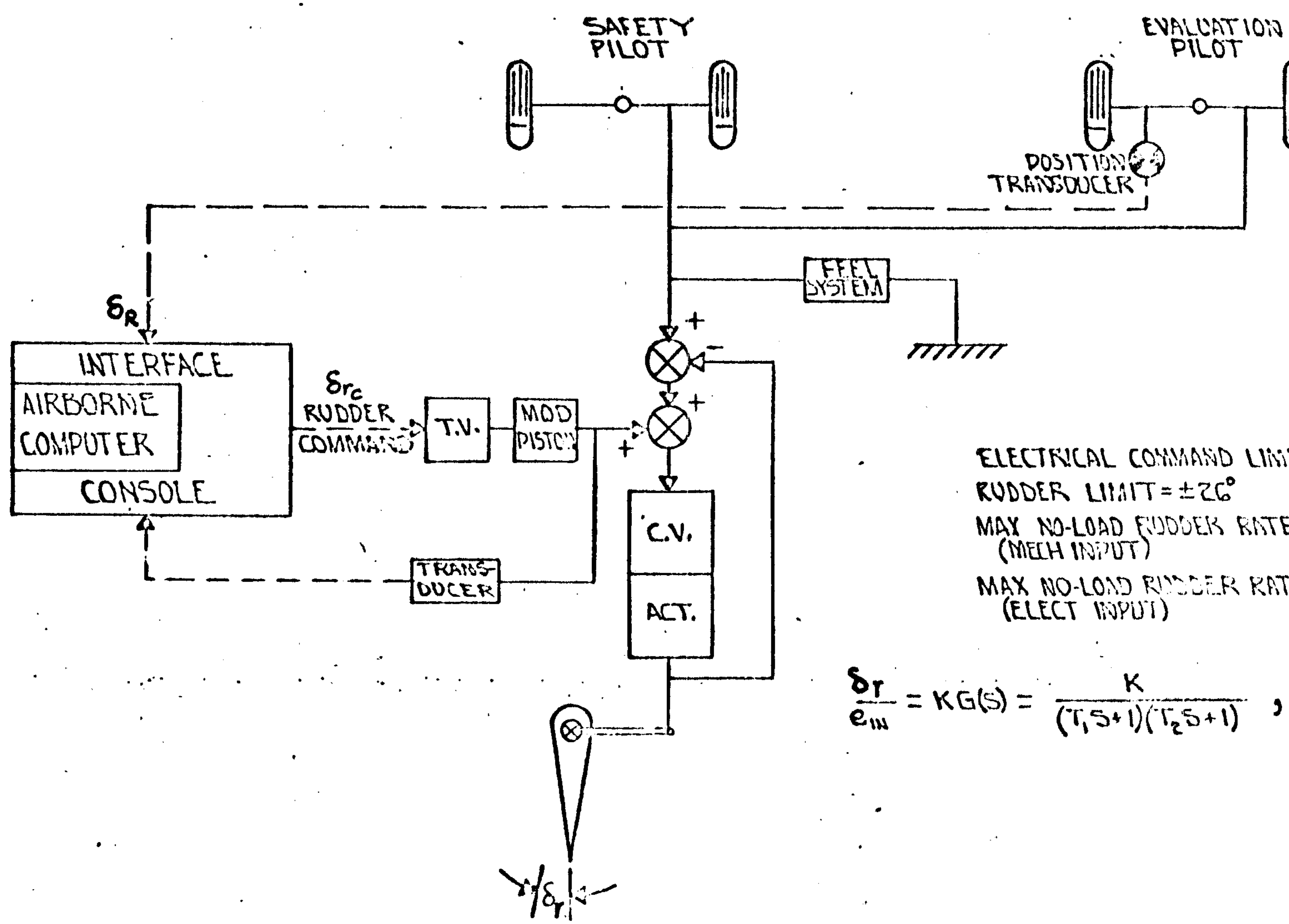
<u>MANUAL POWER</u>

$$\frac{\delta_{SP}}{INPUT} = KG(S) = \frac{K}{.06S+1}$$

<u>ELECTRICAL</u>

$$\frac{\delta_{SP}}{e_{IN}} = KG(S) = \frac{K(23)^2}{S^2 + (.7)(23)S + (23)^2}$$

367-80 LATERAL CONTROL SYSTEM FOR SST SIMULATION



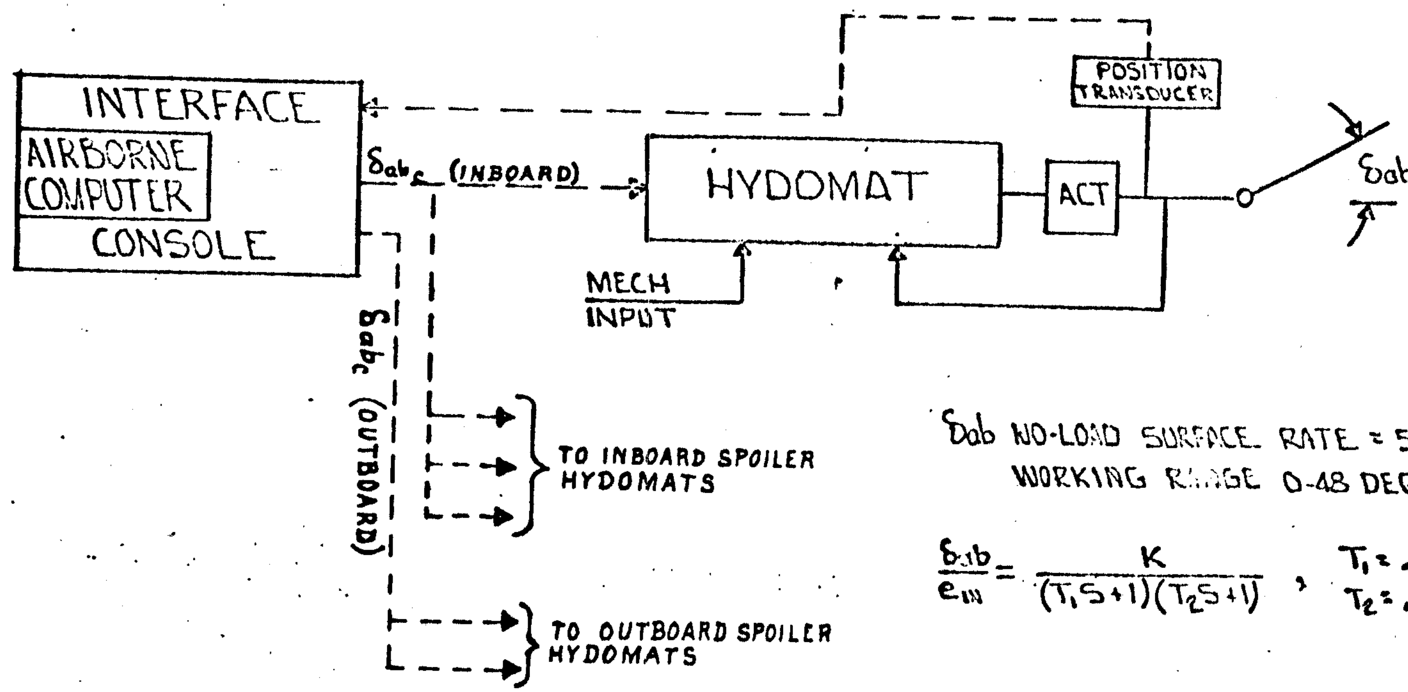
ELECTRICAL COMMAND LIMIT = ±10° δ_r
RUDDER LIMIT = ±26°
MAX NO-LOAD RUDDER RATE = 33 $\frac{DEG}{SEC}$ (MECH INPUT)
MAX NO-LOAD RUDDER RATE = 33 $\frac{DEG}{SEC}$ (ELECT INPUT)

$$\frac{\delta_r}{e_{in}} = KG(s) = \frac{K}{(T_1 s+1)(T_2 s+1)} \; , \quad T_1 = .063 \quad T_2 = .028$$

367-80 RUDDER CONTROL SYSTEM
FOR SST SIMULATION

TD 1546 L-R3

40



δ_{ab} NO-LOAD SURFACE RATE = 50°/SEC
WORKING RANGE 0-48 DEGREES

$$\frac{\delta_{ab}}{e_{in}} = \frac{K}{(T_1 S+1)(T_2 S+1)}, \quad T_1 = .1 \text{ SEC}, \quad T_2 = .03 \text{ SEC}$$

367-80 LIFT CONTROL SYSTEM

2.5 OPERATING PROCEDURES

2.5.1 Establishing the Basic 367-80 Characteristics

The first step in setting up a simulation was to establish a 367-80 configuration suitable for the airplane to be simulated. The factors to be considered were:

- The trimmed level flight airspeed of the 367-80 must match that required for the simulated airplane. This affected the trim thrust and flap setting.

  The 367-80 was equipped with a blown flap system using engine bleed air which could be used to increase the value of C_L. For the configurations described in this document it was not necessary to use this feature.

- The entire simulation was flown with the 367-80 engines at constant throttle settings and thrust and drag changes were achieved by modulating the thrust reverser position. This means that the clamshell doors had to be set initially at some partially closed position which allowed sufficient range of movement of opening and closing without limiting the simulation.

  This initial angle also had to be coordinated with the constant engine output to achieve the trimmed airspeed mentioned above.

- The changes in lift coefficient during simulation were achieved by modulating the spoiler panels on the upper wing surface. These therefore had to be set up at some angle for the trim condition so that they could be modulated in both directions during simulation.

- All simulation was performed with the landing gear down so that the approach could be continued down to touchdown.

The final configurations adopted for the 367-80 for simulating the supersonic transports were:

	367-80 CONFIGURATIONS AT TRIM						
	Airspeed	Angle of Attack Of Wing	Engine Settings (N2)	Clamshell Doors	Flaps	Spoilers	Gear
NASA 20	135 Knots	5.45°	96%	30°	30°	6°up	Down
NASA Δ	135 Knots	5.45°	96%	30°	30°	6°up	Down
NASA 72	150 Knots	5.3°	96%	30°	20°	6°up	Down

2.5.1 Establsihing the Basic 367-80 Characteristics (Continued)

These were the nominal settings. The aircraft was trimmed in level flight by the Safety Pilot at the desired airspeed and angle-of-attack, by use of the moveable stabilizer and small throttle adjustments, prior to engagement of the simulation. Once set, the stabilizer and throttles were not moved during simulation, as all pitch and thrust changes were made with the elevators and thrust reversers.

2.5.1.1 Flight Testing the Basic 367-80 Configuration

Once the trim configuration had been tentatively determined, the airplane was flight tested in order to obtain the following information:

a. Confirmation and adjustment, if necessary, of the basic trim configuration (proper stall margin and body landing attitude.)

b. Documentation of the airplane characteristics. This consisted of a series of maneuvers designed to facilitate the calculation of the airplane stability and control derivatives so that an accurate analog model of the 367-80 could be mechanized on a computer.

c. Recording of airplane responses to standard pulse inputs for confirmation and adjustment of the analog model. These recordings were used in the "overlay" technique described in Section 2.5.

The standard pulse inputs were performed using the -80 checkout board described below.

The -80 Checkout Board was a special patchboard used on the Systron Donner SD/80 Airborne Computer which contained: A six-degree-of-freedom linearized analog model of the basic 367-80; a special check pulse circuit (see 2.3.1); and provisions for connecting the Evaluation Pilot's controls through the SD/80 computer and the Interface to the airplane electro-hydraulic servo systems. The gains in the computer were selected so that the control derivatives remained identical to those of the basic airplane. Thus, the airplane characteristics were the same whether it was flown from the left-hand seat with the normal controls, or from the right-hand seat through the fly-by-wire system.

There was also provision for introducing the standard pulse into the system to simulate column, wheel, rudder or thrust commands. It should be noted that the input to the thrust was actually a step but for simplicity of writing it will be referred to as a standard pulse.

2.5.1 (Continued)

The aircraft checkout, using standard pulses, was as follows: The airplane was first trimmed in level flight at the correct airspeed and angle-of-attack by the Safety Pilot from the left-hand seat. When this condition had been achieved the simulation was engaged and the Evaluation Pilot then retrimmed the airplane, if necessary, to remove the effect of any engagement transients. When he was satisfied that the airplane was trimmed, he called for a standard pulse input from the computer. The input had already been selected to be applied to the elevator, wheel, rudder or thrust reversers. The pulse was initiated by operating a toggle switch.

The airplane response to this input was monitored by recording the following parameters on a CEC light beam oscillograph.

CHANNEL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
VARIABLE	δ_{ab}	P	Q	-R	ϕ	ΔV	$\Delta\alpha$	$-\beta$	$-\dot{\beta}$	δ_e	δ_ω	δ_r	PULSE	δ_{th}	δ_{CLAM}

If the input was an elevator or thrust command, the Evaluation Pilot would keep the wings level, being very careful not to initiate any longitudinal disturbances. Similarly during wheel and rudder pulses the Evaluation Pilot would maintain essentially the same pitch attitude without restraining the lateral degrees of freedom.

This technique enabled "hands-off" data to be obtained without the confusing cross-coupling effects between the longitudinal and lateral-directional axes.

The resulting airplane motion was allowed to continue sufficiently long to obtain several cycles of the phugoid mode for elevator inputs, or the Dutch Roll Mode for rudder and wheel inputs, or until the airspeed changed by 10 knots for the thrust steps.

The oscillograph records obtained during these tests were used to check the analog simulation of the basic 367-80.

2.5.1.2 Ground Support Programs (Basic 367-80 Only)

As soon as sufficient information had been received on the basic 367-80 control and stability derivatives from the Aerodynamics Group, the gains were calculated for the analog simulation of the basic airplane and the model was set up on the -80 checkout board.

The same standard pulse inputs that were applied to the actual airplane in-flight were applied to the analog model on the ground.

The response of the model was recorded using the same oscillograph to record the same variables with the same scalings.

- Ground Support Programs (Basic 367-80 Only) (Continued)

The accuracy of the simulation and hence the accuracy of the derivatives used were checked by directly comparing the results.

This was done partly by measurement and partly by comparing the various mode shapes by directly laying the flight test results over the ground test results.

The measured values were:

- o Phugoid period and damping ratio
- o Dutch roll period and damping ratio
- o Roll angle to side-slip-angle ratio
- o Spiral time constant (time to half amplitude)

The other characteristics, which did not lend themselves to direct measurement were:

- o Longitudinal short-period characteristics
- o Initial lateral-directional response to a control input
- o Pitching moment due to thrust changes.

These were compared by direct overlay.

By making adjustments to the appropriate gains on the computer simulation, the match between the flight and ground tests could be improved and the values of the basic 367-80 derivatives refined by calculating back from the corrected gain settings. This part of the program was backed up by an additional ground based computer simulation of the basic airplane as a check on the -80 checkout board model. It should be noted that this did not confirm the validity of the model but only served to demonstrate that the simulation, as patched-up, was functioning properly.

2.5.2 Setting Up the SST Simulation

Once the control and stability derivatives of the basic 367-80 had been reasonably well established the calculations for the SST matrix (see 2.3.1.) were performed. These calculations were based on the theory outlined in Section 2.1, and the full equations are given in Appendixes A, B, and C.

The calculations for the program covered in this document were initially done by hand using the tabulated forms shown in Appendixes A, B, and C, Pages A1 to A32, etc., but later a digital program was set up on an IBM 7090 computer to produce this information. The program was written in a Boeing-originated computer language called BLITZ. (Further information on this language can be obtained from Boeing Document D2-36343-1, "The BLITZ User's Manual" (See Ref. B).

The SST matrix was then patched up on the appropriate SST patchboard and the correct gains set in.

Once the particular SST patchboard under study was completed, a ground simulation of this SST configuration was produced by connecting the checkout jumper cable as shown in Section 2.3.2 (b).

The end result of combining the basic 367-80 analog model with the SST matrix was to produce a simulation identical to that which would result from a straight-forward simulation using the SST derivatives alone.

It should be noted here that, as long as the SST matrix calculations were correct the basic -80 derivatives which were used in the calculations were irrelevant, as far as the ability to produce an analog simulation of the SST is concerned. In other words, a ground simulation of the particular SST could be obtained by using an analog simulation of a Pi er Cub, for example, provided the SST matrix calculations were based on the Piper Cub derivatives. Naturally this would vastly effect the results obtained in the air when the real 367-80 characteristics were substituted for the analog model.

The output of the pulse circuit was then applied to the simulation to produce the responses of the SST to standard pulse inputs. The technique was similar to that described for testing the 367-80 analog model alone in Section 2.4.1 except that the pulses were applied at different terminals since it was commands to the SST elevator and rudder etc., that were required and not commands to the 367-80 elevator and rudder.

As before, the variables listed in Section 2.4.1 were recorded on the CEC Recorder, the results being checked against the results of the digital program described in the next section.

Two programs were used to support this phase of the overall program. One was an analog computer program that was set up on a PACE computer to duplicate the SD/80 simulation. This program was used as backup confirmation of the SD/80 mechanization and also as a tool for investigating the effects of some of the variations tested.

The other and most important program was a digital program using an IBM 7090 computer and the Boeing TL99 digital program to provide data concerning the dynamic response of the various SST configurations and variations.

This program was capable of solving simultaneous non-linear differential equations and lent itself to the solution of the equations of motion of an airplane. The equations could be expressed in a block diagram form that was very similar to the computer diagram for an analog simulation of an airplane.

This block dia ram was easily converted into a deck of punched cards for input to the digital computer.

Disturbing inputs, identical to the standard pulses, were introduced into the program and the resulting airplane responses became available as a time history of the aerodynamic variables whose values were tabulated at half-second intervals. The program was supplied with the calculated control and stability derivatives of the proposed SST configurations and the resulting tabulated data plotted on transparent mylar to the same vertical and horizontal scales as the outputs of the CEC Recorder. The master plots could be directly overlaid on the ground and flight recordings from the CEC recorder to determine the accuracy of the simulation.

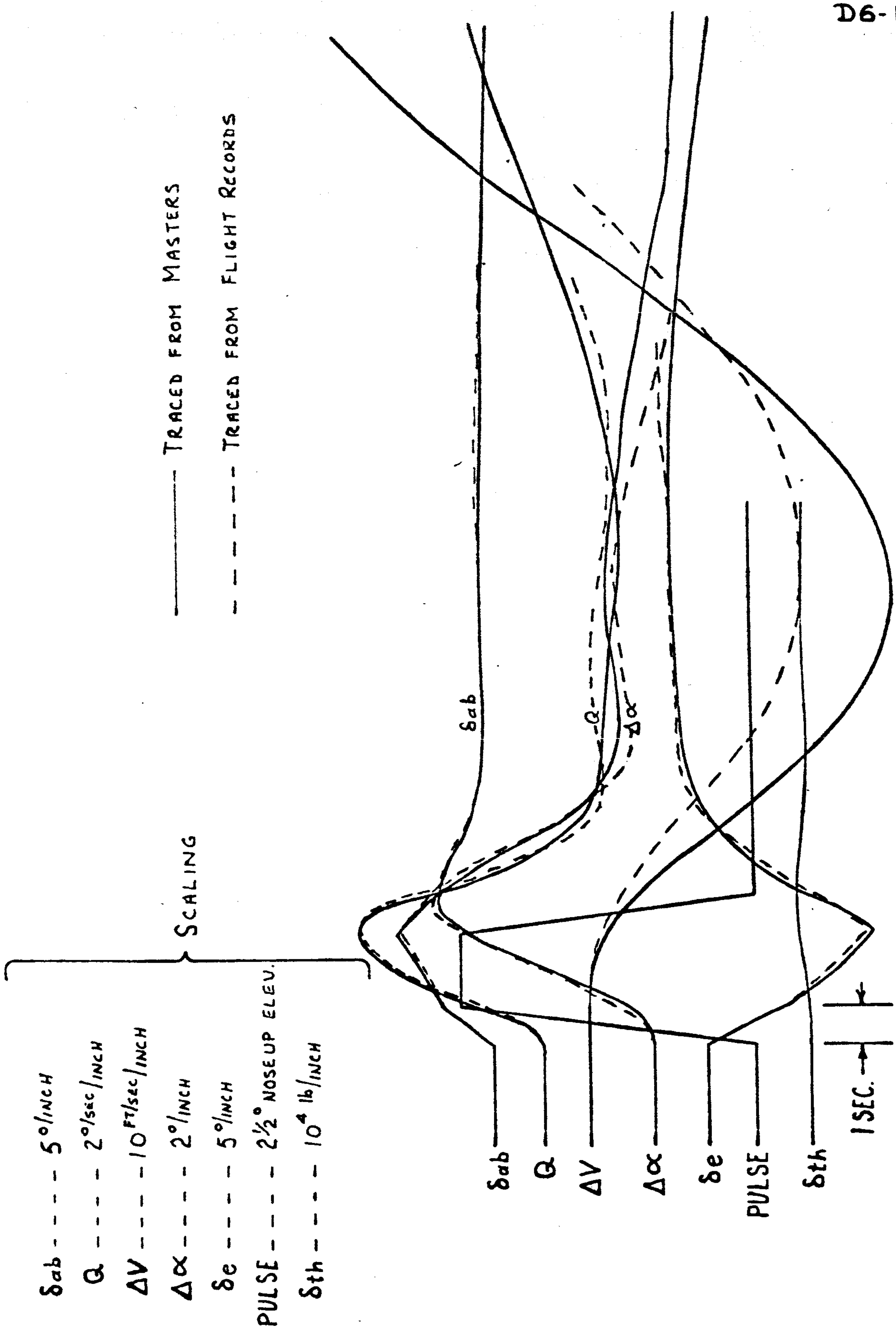
Figures 21 and 22 show prints from two typical master overlays obtained by this program with the flight data from the CEC Recorder for the same maneuvers superimposed on the master traces.

The Flight Tests of the SST Simulation were carried out with the SD/80 Computer-to-interface cable connections as shown in Section 2.3.2(c) Page 36. The procedure used for checking the accuracy of the simulation was identical to that already described in checking out a standard pulse.

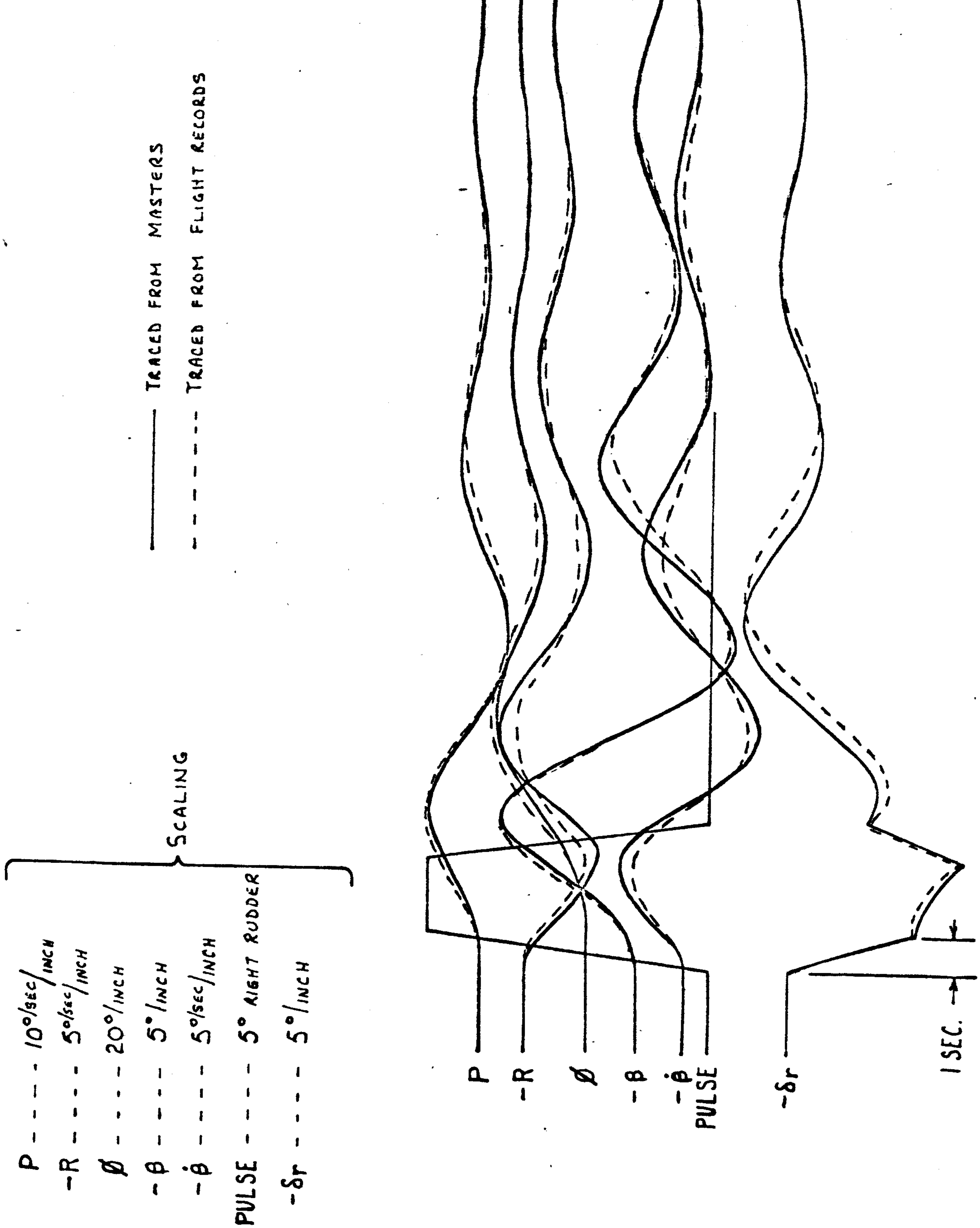
Immediately after each maneuver the in-flight recordings were checked to determine the accuracy of the simulation by direct measurement of phugoid and dutch roll periods, damping ratios, etc.; and by overlaying the master traces described in the above section.

In the initial or checkout phase of the flight test program, it was necessary to "fine tune" the simulation to improve its accuracy. This was done by changing the gains of the SST matrix and repeating the check pulses as required to improve the match between the flight and ground test results.

It should be noted that, since the SST derivatives were fixed, any changes made to the gains of the SST matrix during the checkout phase were equivalent to changing the basic 367-80 derivatives. The new 367-80 derivatives were obtained by calculating backwards from the SST Matrix gains and then cranked into the analog simulation of the basic 367-80.



ENGR.	PERSON	8-20-65	REVISED	DATE	NASA 20 NOSE UP ELEVATOR PULSE	FIG. 21
CHECK						
APR.					THE BOEING COMPANY RENTON, WASHINGTON	Page 48
APR						



ENGR.	PERSON	8-20-65	REVISED	DATE	NASA 20 RIGHT RUDDER PULSE	
CHECK						FIG. 22
APR					THE BOEING COMPANY RENTON, WASHINGTON	
APR						Page 49

Once the match was judged to be sufficiently good by the test engineer, the simulation was frozen and the test program proceeded to the documentation and pilot evaluation phases. From this point, the only changes made on the computer were those necessary to introduce the variations to the basic configuration which were to be tested, and the periodic adjustment of a special potentiometer which was varied according to the test altitude and outside air temperature to compensate for the variation in engine thrust.

During the documentation and evaluation phases, the airplane was subjected to the Standard Pulses at the beginning of each flight and the results were examined to confirm that the simulation was still valid, before proceeding with the tests.

2.5.3 Pre-Flight Checkout

The pre-flight checkout consisted of a series of ground tests that were performed as a standard procedure prior to each simulation flight.

Power was applied to the airplane and the system allowed to warm-up for at least 30 minutes before starting the pre-flight checkout.

The pre-flight checks were:

a. Computer voltage and amplifier balance checks. The computer power supplies were checked for the correct voltage and the amplifiers checked for balance and adjusted if necessary.

b. Potentiometer Setting Checks. All the potentiometers that were used in the simulation were checked for the correct settings by nulling them against the reference potentiometer.

c. Standard Pulse Checks. The computer cables were connected for SST ground checkout (See 2.3.2(b) Page 34) and the standard pulses applied to the elevator, thrust, wheel and rudder inputs. The resulting traces from the CEC recorder were checked against the SST masters to confirm that the computerwas functioning properly.

d. Instrumentation Zeros. At this point the command outputs from the computer were set to zero by shorting the outputs of the relevant amplifiers to the summing junctions. This was done so that the Instrumentation Engineer could record the zero references.

e. Simulation Logic Checks. The logic circuitry was checked to ensure that the "SELECT", "ENGAGE", "RESET" controls, disconnect buttons and error detectors were working properly.

f. System Functional ("Wiggle Tests"). These tests were to ensure, as far as was possible, that the entire system was working as programmed. The computer cables were connected for in-flight simulation (see 2.3.2 (C), Page 34).

To perform the tests, the airplane hydraulics were turned on and hydraulic power supplied to all the actuators; the spoiler panels set to 6°; and the clamshell doors set to 30°. The simulation was then engaged and the following tests performed:

TEST	CHECK THAT NOTE: The values depend on the SST Configuration and so are not quoted.
Move Evaluation Pilot's column fully forward and aft.	Safety Pilot's wheel and -80 elevator move the correct amount and direction. Computer elevator command output is correct.
Move the Evaluation Pilot's wheel right and left.	Safety Pilot's wheel and the -80 ailerons and spoiler panels move the correct amount and direction. Computer rudder command output is correct.
Move the Evaluation Pilot's rudder pedals right and left.	The -80 rudder moves the correct amount and direction. Computer rudder command output is correct.
Move the Fake Throttle forward and aft.	Clamshell doors and thrust reverser levers move the correct amount and direction. Computer output commands are correct.
Move nose boom vane $\pm\alpha$, keeping β at 0.	-80 elevators and spoilers move correct amount and direction. Computer output commands are correct.
Move nose boom vane $\pm\beta$, keeping α at 0.	-80 rudder and lateral controls move correct amount and direction. Computer output commands are correct.
Operate Evaluation Pilot's longitudinal trim control.	-80 Elevators move up and down the correct amount.
Unbolt rate gyros and move by hand. (Hydraulics OFF)	Computer signals from gyros are correct polarity.

2.6 SYSTEM HARDWARE DESCRIPTION

2.6.1 Cabin Controls

Figure 2 shows an overall picture of the airplane cabin. In addition to the normal airplane controls and instruments, the following are of special interest in the simulation.

The Evaluation Pilot's control column and wheel were not mechanically connected to the airplane control systems. Instead, stick and wheel position signals were obtained from potentiometers and these signals were fed through the interface to the SD/80 Computer.

NOTE: The arms of the wheel were also instrumented with strain gauges, the outputs of which were averaged to give a measure of stick force. This signal was available at the computer and could be used as the Evaluation Pilot's input, but for the simulations covered in this document stick position was used.

Feel force for the Evaluation Pilot's wheel was supplied by a spring cartridge mounted on the column directly behind the wheel. The force gradient characteristics could be changed by changing the cartridge. The stick feel force was supplied by a hydraulic system which was controlled pneumatically from a pressurized nitrogen bottle. The control knob for changing the force gradient and the indicator for showing the stick force in lb/degree of stick movement can be seen at (K) in Figure 2 and also in the close-up picture Figure 3.

The Evaluation Pilot's rudder pedals were connected mechanically to the Safety Pilot's and consequently moved the 367-80 rudder through the normal control system. However, in addition, a potentiometer provided an electrical signal proportioned to pedal displacement which was used in the computer to modify the rudder motion during simulation.

The following descriptions all refer to the letters on Figure 2.

a. Fake Throttle Lever. This lever was connected to a potentiometer which put out an electrical signal to the computer and provided the Evaluation Pilot with the means to make thrust changes. Figure 3 shows a close-up of the Fake Throttle Lever and its calibrated scale.

b. Evaluation Pilot's Disconnect Button. The Evaluation Pilot could disengage the simulation and return control to the Safety Pilot at any time by operating this button. If disconnect occurred, the two red blinking warning lights (N) came on and the RESET button on the control panel (Figure 3) had to be operated before the simulation could be re-engaged (See Section 2.6.1 (H)).

2.6.1 Cabin Controls (Continued)

c. Evaluation Pilot's Longitudinal Trim Control. This was a two position, center-off switch which supplied either ± 15 V to the computer, depending upon whether it was held in the nose-up or nose-down trim position. This voltage was integrated in the computer and the result applied as an elevator command to trim the airplane.

d. Signal Connector. This connector carried the signals from the strain gages mentioned above.

e. Evaluation Pilot's Lateral Trim Control. Lateral trim in simulation mode was obtained by a potentiometer which applied a bias voltage to the lateral control command signal. This signal did not go to the SD/80 computer but was added in the Interface.

f. Thrust Reverser Positioning Levers. The standard thrust reverse levers were used to set the clamshell doors to their trim positions (approximately 30°). The clamshell door positions for the four engines were shown by the four indicators at (M).

g. Speed Brake Handle. The normal speed brake positioning control was used to set the spoiler panels to their trim position (6° up). The position of spoiler panel No. 8 was monitored with a transducer and displayed on an indicator (L) mounted above the IRIG time display on the glareshield.

h. Simulation Control Panel. This panel contained the controls with which the safety pilot selected the mode of operation. A close-up of this panel can be seen in Figure 4.

The selector buttons marked "YAW RATE", "YAW RATE & TOP", "RUD III", "AILERON" refer to various stability augmentation systems available on the basic 367-80 and are outside the scope of this document. The selector button marked "NORMAL" refers to a condition whereby the basic "367-80" could be flown by a "fly-by-wire" system from the right-hand seat and is also outside the scope of this document, although it resulted as a direct offshoot of this program. The controls that are directly concerned with the simulation are:

SIMULATION - When the Safety Pilot pushed this button, the simulation was selected but not engaged, and a blue light illuminated the left-hand section marked "SEL". The Safety Pilot selected this condition prior to

h. (Continued)

trimming the airplane. In this condition the mode control logic in the Interface put the SD/80 computer into the "COMPUTE" mode (it was previously in "RESET") which allowed the synchronizing circuits for $\Delta\alpha$ and ΔV to start operating. The Evaluation Pilot's controls were still disconnected from the system. When the aircraft was trimmed the Safety Pilot pushed the "PUSH TO ENGAGE" button.

"PUSH TO ENGAGE" - This control engaged the simulation and activated the analog gates in the Interface allowing the command outputs from the SD/80 computer to be applied to the control surface actuators. Simultaneously the $\Delta\alpha$ and ΔV synchronizing circuits in the computer were put into the "HOLD" condition; the "ON" portion of the "SIMULATION" control button was illuminated with a green light and the "simulation engaged" light on the computer patchboard was turned on. The simulation could be disengaged by pulling up on the "PUSH TO ENGAGE" button but this feature was seldom used.

"RESET" - This control was used to reset the mode selection logic in the Interface if the simulation had been disengaged as a result of an error in the system or because the Evaluation Pilot had operated his disconnect button.

j. Safety Pilot's Disconnect Button. By operating this control the Safety Pilot could disengage the simulation at any time and regain control of the airplane. The simulation mode changed from "ON" to "SELECTED".

k. Evaluation Pilot's Stick Feel Force Control and Indicator. Described previously.

l. Spoiler Panel No. 8 Position Indicator. Described previously.

m. Thrust Reverser Clamshell Door Position Indicators. Described previously.

n. Simulation Disconnected Warning Lights. These were two large red blinking warning lights that came on if the simulation was disengaged either by an error in the system or by the Evaluation Pilot's disconnect button. These lights did not go out until the Safety Pilot's Disconnect Button was operated.

o. Simulation Limits Warning Lights. These five amber warning lights for the rudder, spoiler, elevator, lateral control and thrust servo systems indicated when the servo amplifier error signal had been exceeding a predetermined threshold value for more than half a second. This did not result in an automatic disconnect but indicated that the accuracy of the simulation was in doubt.

p. Reference Airspeed Setting Indicator. The airspeed signal to the computer was the difference between the value obtained from the Pitot-Static System and the value set into the reference airspeed indicator. The latter value was set to the normal trim speed, by means of the knob at the lower left corner of the indicator, to prevent over-loading of the ΔV synchronizing circuit.

2.6.2 Systron-Donner SD/80 Analog Computer

The Systron-Donner SD/80 computer used on this program was basically a production-line desk-top type computer (Figure 5, Page 16 shows the computer as it was mounted in the airplane). Certain modifications were made at the factory prior to shipment. These were:

a. The addition of special shock mounts designed for the vibration environment in the airplane.

b. The ruggedizing of the amplifier module mounting system.

c. The potting of the amplifier components on the printed circuit boards.

d. The addition of a heater and fan, controlled by a toggle switch so that the computer could be purged with warm air. This provision was added because of the possibility of moisture condensation in the computer when the airplane stood outside overnight.

e. The addition of warning lights to indicate an overtemperature condition. This provision was added because the computer was used on the ground at times when the airplane air-conditioning system was not operating.

f. Modification to the power supplies to enable the computer to be operated from a 400 cps supply instead of 60 cps.

The computer contained 84 solid state operational amplifiers which were mounted in pairs on removable modules directly behind the patchboard (see Fig. 5, Page 16).

The modules contained additional components which determined the type of operation for which they could be used; i.e., summing amplifiers, inverting amplifiers, or integrators.

As used for this program the computer had 44 summers, 18 inverters and 22 integrators. In addition, there were 18 double-pole, double-throw relays mounted in pairs on 9 of the modules.

The computer had two moveable wings on which the controls were mounted.

The left-hand wing contained: (Referring to Figure 5)

a. Fifteen diode function generators in removable modules mounted in a receptacle behind this panel.

b. The overheat warning lights and the heater toggle switch.

c. A voltmeter which could be used either as a direct reading instrument or as a nullmeter.

d. The address selector switches for monitoring the output of any particular amplifier or potentiometer on the panel meter.

e. The top six switches were for selecting one of six direct-reading panel meter scales (± 300V, ± 100V, ± 30V, ± 10V, ± 3V, ± 1V) to 2% of full scale accuracy. The two bottom switches selected either ± NULL for measuring any problem voltage with an accuracy of 0.01% of full scale by comparison with a reference voltage selected by the reference potentiometer.

f. Four-digit reference potentiometer.

g. Panel containing operating controls and indicators. These are: Four push-button/indicators for selecting HOLD, COMPUTE, RESET and REP-OP Modes.

- Time scale control (not used in this simulation).
- Slave switch for selecting either local control at the computer or external control through the Interface.
- Power-on switch.
- Indication for oven-power, amplifier overload, etc.

h. Five single-pole, double-throw toggle switches with center off position, and five potentiometers for gain adjustment.

The right-hand wing contained 120 more potentiometers for gain adjustment.

2.6.3 Interface

The Interface is shown in Figure 6 as it was mounted in the airplane. Some of the equipment in the interface was concerned with basic 367-80 stability augmentation systems and is outside the scope of this document. The equipment associated with the variable stability system is, referring to Figure 6:

a. Section containing the servo amplifiers and associated electronics for the spoiler panel servos.

2.6.3 (Continued)

b. Controls for monitoring the outputs of the various amplifiers in the Interface, and for selecting the panel meter full scale deflection values.

c. This panel contains duplicate simulation mode controls similar to the controls in the cabin and error-indicating lights.

d. Lateral control servo amplifiers and associated electronics.

e. Elevator servo amplifiers and associated electronics.

f. Rudder and aileron servo amplifiers and associated electronics.

g. Isolation networks, demodulation, etc.

h. This section contains the mode control logic digital circuits.

i. Isolation networks.

j. Power distribution and control circuits.

2.6.4 <u>Airplane Sensors</u>

The following sensors were used to provide aerodynamic data to the computer.

- Angle-of-Attack and Sideslip Sensor ($\alpha\beta$ Vane)

  Figure 7 shows the $\alpha\beta$ vane as it was mounted on the nose boom. This vane was specially designed by Giannini to have a very good low frequency response characteristic and a natural frequency of about 23 cps. The vane was supported on two gimballs whose angles were monitored by low friction potentiometers. The tip of the beam was bent down so that high angles of attack, up to 30° could be accommodated without reaching the mechanical limit of the vane.

- <u>Rate Gyros</u>

  Pitch, roll and yaw rate information was obtained from two rate gyro packages mounted in the lower 41 section of the airplane. The roll-rate gyro was the smaller package on the right in Figure 8. The larger package was a 3-axis gyro which was used for pitch and yaw rates.

- <u>Vertical Gyro</u>

  Not shown on Figure 8 but directly below the rate gyros was a vertical gyro which provided roll angle information.

2.6.4 Continued

- **Airspeed Sensor**

The airspeed signal was obtained from the pilot's pitot static system, the output of which fed the airspeed synchro.

The final output of the airspeed system that went to the computer was a voltage that indicated the incremental difference of the airspeed above or below the value set on the pilot's reference airspeed instrument.

- **Radio Altimeter**

The output of the radio altimeter was used to accurately determine the altitude of the airplane from + 100 feet down to touchdown. This signal, which was accurate to within 2 percent was used as the input to the three ground effect function generators.

3.0 PROBLEM AREAS

A certain number of problems were encountered in the program that are inherent to this type of simulation. They are briefly summarized below.

3.1 Derivatives

Because the simulation depended upon the calculated differences between the 367-80 derivatives and the simulated SST derivatives, it was more difficult to simulate airplanes that were radically different from the 367-80. The worst case of this effect occurred in the compensation for ground effect in the NASA Δ simulation, where the range of lift modulation available was insufficient to fully compensate for the lift due to ground effect on the NASA Δ. A compromise solution was adopted where the maximum possible lift modulation was used at the peak of the lift curve and the rest of the curve scaled accordingly. In addition, the drag compensation curve was also scaled down such that the lift/drag curve remained the same as for the full compensation curves.

3.2 Linearized Equations

The simulation was based on linearized equations of motion and consequently any variables that were actually non-linear over the range of the simulation affected the accuracy of the simulation. This situation could be improved by using function generations for the most non-linear variables, provided of course, that the functions could be accurately defined.

3.3 True Trim Condition

Since the simulation was based on perturbation equations and the variables were all incremental values about a trim condition it was extremely important that the trim condition be established as accurately as possible. Any variation from the true trim condition before the simulation was engaged affected the subsequent airplane behavior.

3.4 Turbulence

The effect of turbulence on the accuracy of the simulation was very marked. This was because the output of the $\alpha\beta$ vane fed directly into the computer and any output which was the result of a gust rather than a true change in the angle-of-attack of the wing produced an erroneous elevator command and effected the behavior of the airplane.

3.5 Stability Axes

The equations used in the simulation were written for the airplane stability axes and although they were correct for describing the motions of the c.g., they gave rise to erroneous cockpit motions for those cases where the angles-of-attack of the 367-80 and the simulated SST were greatly different.

The major effect was to produce apparent adverse yaw characteristics at the cockpit. This problem was alleviated by changing the derivatives of the SST simulation so that the body yaw axis characteristics were reproduced, rather than the stability yaw axis. This could be done without greatly changing the other lateral directional characteristics and appeared to be an adequate solution.

REFERENCES

A. Boeing Document D6-10743, "Simulation of Three Supersonic Transport Configurations with the Boeing 367-80 In-Flight Dynamic Simulation Airplane".

B. Boeing Document D2-36343-1, "The BLTTL User's Manual"

APPENDIX A

DESCRIPTION AND CALCULATION SHEETS FOR

NASA 20

LINEARIZED EQUATIONS OF MOTION

$$I_{xx}\dot{P} = q_o S b \left(C_{\ell_\beta} \times \beta + C_{\ell_P} \times P + C_{\ell_R} \times R + C_{\ell_{\delta\omega}} \times \delta\omega + C_{\ell_{\delta r}} \times \delta r \right)$$

$$I_{YY}\dot{Q} = q_o S \bar{c} \left(C_{m_\alpha} \times \Delta\alpha + C_{m_{\dot\alpha}} \times \dot\alpha + C_{m_Q} \times Q + C_{m_{\delta e}} \times \delta e + C_{m_{\delta ab}} \times \delta ab + C_{m_{\Delta T}} \times \Delta T + C_{m_{\Delta V}} \Delta V \right)$$

$$I_{ZZ}\dot{R} = q_o S b \left(C_{n_\beta} \times \beta + C_{n_P} \times P + C_{n_R} \times R + C_{n_{\delta\omega}} \times \delta\omega + C_{n_{\delta r}} \times \delta r \right)$$

$$\Delta\dot{V} = -\frac{\rho S}{m} V_o C_{D_{TRIM}} \Delta V + \frac{1}{m}\Delta T - \frac{\rho S}{m}\frac{V_o^2}{2}\left(C_{D_\alpha}\Delta\alpha + C_{D_{\delta ab}} \times \delta ab \right) - g\,\theta_W$$

$$Q_W = \left(\frac{2g}{V_o^2} - \frac{T_o \alpha_o}{m V_o^2} \right)\Delta V + \left(\frac{\rho S}{2m} V_o C_{L_\alpha} + \frac{T_o}{m V_o} \right)\Delta\alpha + \frac{\alpha_o}{m V_o}\Delta T + \frac{\rho S}{2m} V_o C_{L_{\delta ab}} \times \delta ab$$

$$R_W = \frac{\rho S}{m}\frac{V_o}{2}\left(C_{Y_\beta} \times \beta + C_{Y_P} \times P + C_{Y_R} \times R + C_{Y_{\delta\omega}} \times \delta\omega + C_{Y_{\delta r}} \times \delta r \right) + \frac{g}{V_o}\phi_W$$

$$\dot\alpha = Q - Q_W \quad ; \quad \Delta\alpha = \int \dot\alpha\, dt \quad ; \quad \theta_W = \int Q_W\, dt$$

$$\dot\beta = R_W - R \quad ; \quad \beta = \int \dot\beta\, dt \quad ; \quad \phi_W = \int P\, dt.$$

In these equations, the following variables are:

- in radians : $\Delta\alpha$, β, $\delta\omega$, δr, δe, δab, θ_W, ϕ_W
- in radians/sec : $\dot\alpha$, $\dot\beta$, P, Q, R, Q_W, R_W
- in feet/sec : ΔV
- in lbs : ΔT

These equations are derived from WADC, Technical Note 55-747 by R.M. Howe, JUNE 1956.

They are valid for small perturbations around the trimmed level flight condition.

			REVISED	DATE		
ENGR.	Jan. 65	HPC			-80 Variable Stability	NASA 20
CHECK			3-3-65	HPC.	AIRPLANE MODEL	
APR			4-7-65	HPC.	AIRBORNE COMPUTER	
APR			6-15-65	HPC.	THE BOEING COMPANY RENTON, WASHINGTON	A1

Eliminating R_W and changing the units of the variables to the following:

in degrees : $\Delta\alpha$, β, $\delta\omega$, δr, δe, δab, θ_W, ϕ_W.

in degrees/sec : $\dot{\alpha}$, $\dot{\beta}$, P, Q, R, Q_W.

in feet/sec : ΔV

in pounds : ΔT

$$\dot{P} = \frac{q_0 S b}{I_{xx}} C_{\ell_\beta}{}^{*}\beta + \frac{q_0 S b}{I_{xx}} C_{\ell_p}{}^{*}P + \frac{q_0 S b}{I_{xx}} C_{\ell_R}{}^{*}R + \frac{q_0 S b}{I_{xx}} C_{\ell_{\delta\omega}}{}^{*}\delta\omega + \frac{q_0 S b}{I_{xx}} C_{\ell_{\delta r}}{}^{*}\delta r$$

$$\dot{Q} = \frac{q_0 S \bar{c}}{I_{YY}} C_{m_\alpha}{}^{*}\Delta\alpha + \frac{q_0 S \bar{c}}{I_{YY}} C_{m_{\dot{\alpha}}}{}^{*}\dot{\alpha} + \frac{q_0 S \bar{c}}{I_{YY}} C_{m_Q}{}^{*}Q + \frac{q_0 S \bar{c}}{I_{YY}} C_{m_{\delta e}}{}^{*}\delta e + \frac{q_0 S \bar{c}}{I_{YY}} C_{m_{\delta ab}}{}^{*}\delta ab + 57.3\frac{q_0 S \bar{c}}{I_{YY}} C_{m_{\Delta T}}{}^{*}\Delta T + \frac{q_0 S \bar{c}}{I_{YY}} 57.3\, C_{m_{\Delta V}}{}^{*}\Delta V$$

$$\dot{R} = \frac{q_0 S b}{I_{zz}} C_{n_\beta}{}^{*}\beta + \frac{q_0 S b}{I_{zz}} C_{n_p}{}^{*}P + \frac{q_0 S b}{I_{zz}} C_{n_R}{}^{*}R + \frac{q_0 S b}{I_{zz}} C_{n_{\delta\omega}}{}^{*}\delta\omega + \frac{q_0 S b}{I_{zz}} C_{n_{\delta r}}{}^{*}\delta r.$$

$$\Delta\dot{V} = -\frac{\rho S}{m} V_0 C_{D_{TRIM}} \Delta V + \frac{1}{m}\Delta T - \frac{\rho S}{m}\frac{V_0^2}{2 * 57.3} C_{D_\alpha}{}^{*}\Delta\alpha - \frac{\rho S}{m}\frac{V_0^2}{2 * 57.3} C_{D_{\delta ab}}{}^{*}\delta ab - \frac{g}{57.3}\theta_W$$

$$Q_W = \left[57.3\left(\frac{2g}{V_0^2}\right) - \frac{T_0\alpha_0}{mV_0^2}\right]\Delta V + \frac{\alpha_0}{mV_0}\Delta T + \left(\frac{\rho S}{2m}V_0 C_{L_\alpha} + \frac{T_0}{mV_0}\right)\Delta\alpha + \frac{\rho S}{2m} V_0 C_{L_{\delta ab}}{}^{*}\delta ab \quad (\alpha_0 \text{ in degrees})$$

$$\dot{\beta} = \frac{\rho S}{m}\frac{V_0}{2} C_{Y_\beta}{}^{*}\beta + \frac{\rho S}{m}\frac{V_0}{2} C_{Y_P}{}^{*}P + \frac{\rho S}{m}\frac{V_0}{2} C_{Y_R}{}^{*}R + \frac{\rho S}{m}\frac{V_0}{2} C_{Y_{\delta\omega}}{}^{*}\delta\omega + \frac{\rho S V_0}{m 2} C_{Y_{\delta r}}{}^{*}\delta r + \frac{g}{V_0}\phi_W - R$$

$$\dot{\alpha} = Q - Q_W$$

$$\Delta\alpha = \int\dot{\alpha}\,dt \; ; \quad \beta = \int\dot{\beta}\,dt \; ; \quad \theta_W = \int Q_W\,dt \; ; \quad \phi_W = \int P\,dt.$$

In these equations, the aerodynamic and control coefficients have the following units:

/LB : $C_{m_{\Delta T}}$

/radian : C_{ℓ_β} ; $C_{\ell_{\delta\omega}}$; $C_{\ell_{\delta r}}$; C_{m_α} ; $C_{m_{\delta e}}$; $C_{m_{\delta ab}}$; C_{n_β} ; $C_{n_{\delta\omega}}$; $C_{n_{\delta r}}$; C_{D_α} ; $C_{D_{\delta ab}}$; C_{L_α} ; $C_{L_{\delta ab}}$; C_{Y_β} ; $C_{Y_{\delta\omega}}$; $C_{Y_{\delta r}}$.

sec/radian : C_{ℓ_p} ; C_{ℓ_R} ; $C_{m_{\dot{\alpha}}}$; C_{m_Q} ; C_{n_p} ; C_{n_R} ; C_{Y_P} ; C_{Y_R}

			REVISED	DATE		
ENGR.	Jan. 28	HPC			-80 Variable Stability AIRPLANE MODEL AIRBORNE COMPUTER	NASA 20
CHECK			3-3-65	HPC		
APR			3-27-65	HPC		
APR			6-16-65	HPC	THE BOEING COMPANY RENTON, WASHINGTON	A2

THE FOLLOWING SCALE-FACTORS WILL BE USED

Q ; $10\,Q_w$; $\dot{\alpha}$; $5\,\Delta\alpha$; $5\,\theta_w$; ΔV

$.5\,P$; $5\,\dot{\beta}$; $.5\,\beta$; ϕ_w ; R

$5\,\delta e$; $10\,\delta ab$; $10\,\delta r$; $2\,\delta\omega$; $3\,\delta th$ where $3\delta th = \dfrac{\Delta T}{278}$

δth in degrees

$$-10\,Q_w = -\left[573\left(\frac{2g}{V_o^2}\right) - \frac{10\,T_o\alpha_o}{mV_o^2}\right](\Delta V) + \left(\frac{\rho S}{m}V_o C_{L_\alpha} + \frac{2T_o}{mV_o}\right)(5\,\Delta\alpha)$$

$$+\frac{2780\,\alpha_o}{mV_o}(3\delta th) + \frac{\rho S}{2m}V_o\left(-C_{L_{\delta ab}}\right)(-10\,\delta_{ab})$$

$$\Delta V = -\int\Bigg[\frac{\rho S}{m}V_o C_{D_{TRIM}}(\Delta V) + \frac{278}{m}(-3\delta th) + \frac{\rho S}{m}\frac{V_o^2}{57.3}\frac{C_{D_\alpha}}{10}(5\,\Delta\alpha)$$

$$+\frac{\rho S}{m}\frac{V_o^2}{2\times 57.3}\frac{(-C_{D\delta ab})}{10}(-10\,\delta ab) + \frac{2g}{573}(5\,\theta_w)\Bigg]dt$$

$$Q = -\int\Bigg[\frac{q_oS\bar{c}}{I_{YY}}\left(-\frac{C_{m_\alpha}}{5}\right)(5\,\Delta\alpha) + \frac{q_oS\bar{c}}{I_{YY}}(-C_{m_{\dot{\alpha}}})(+\dot{\alpha}) + \frac{q_oS\bar{c}}{I_{YY}}(-C_{m_Q})(Q) + \frac{q_oS\bar{c}}{I_{YY}}\left(-\frac{C_{m_{\delta e}}}{5}\right)(5\,\delta e)$$

$$+\frac{q_oS\bar{c}}{I_{YY}}57.3\,C_{m_{\Delta V}}(\Delta V) + \frac{q_oS\bar{c}}{I_{YY}}\left(-\frac{C_{m_{ab}}}{10}\right)(10\,\delta ab) + \frac{q_oS\bar{c}}{I_{YY}}(57.3\times 278\,C_{m_{\Delta T}})(-3\delta th)\Bigg]dt$$

$$-\dot{\alpha} = -\left[Q + (.1)(-10\,Q_w)\right] \qquad 5\,\Delta\alpha = -\int\left[.5(10)(-\dot{\alpha})\right]dt$$

$$5\theta_w = -\int .5(-10Q_w)\,dt$$

ENGR.	Jan. 29 HPC.	REVISED	DATE	-80 Variable Stability AIRPLANE MODEL LONGITUDINAL SYST. OF. EQUATIONS	NASA 20
CHECK		3-3-65	HPC		
APR		3-27-65	HPC.		
APR		4-7-65	HPC.	THE BOEING COMPANY RENTON. WASHINGTON	A3
		6-16-65	HPC.		

$$-5P = -\int\Big[\frac{q_0 S b}{I_{xx}}(-C_{\ell_\beta})(-5\beta) + \frac{q_0 S b}{I_{xx}}(-C_{\ell_p})(-5P) + \frac{q_0 S b}{I_{xx}}\frac{C_{\ell_R}}{2}(10R) + \frac{q_0 S b}{I_{xx}} 2.5\, C_{\ell_{\delta\omega}}(2\delta\omega) + \frac{q_0 S b}{I_{xx}}\frac{C_{\ell_{\delta r}}}{2}(10\delta r)\Big]\, dt$$

$$-10R = -\int\Big[\frac{q_0 S b}{I_{zz}} 20 C_{n_\beta}(5\beta) + \frac{q_0 S b}{I_{zz}}(-2C_{n_p})(-5P) + \frac{q_0 S b}{I_{zz}}(-C_{n_R})(-10R) + \frac{q_0 S b}{I_{zz}}(-2C_{n_{\dot\beta}})(-5\dot\beta) + \frac{q_0 S b}{I_{zz}} 5\, C_{n_{\delta\omega}}(2\delta\omega) + \frac{q_0 S b}{I_{zz}}\left(-\frac{C_{n_{\delta r}}}{1}\right)(-10\delta r)\Big]\, dt$$

$$5\dot\beta = -\Big[\frac{\rho S}{m}\frac{V_0}{2}(-10C_{Y_\beta})(.5\beta) + \frac{\rho S}{m}\frac{V_0}{2}C_{Y_p}(-5P) + \left(\frac{1}{2} - \frac{\rho S}{m}\frac{V_0}{2}\frac{C_{Y_R}}{2}\right)(10R) + \frac{\rho S}{2m}\frac{V_0}{20}(-100\Delta C_Y) + \frac{\rho S}{m}\frac{V_0}{2}(-2.5C_{Y_{\delta\omega}})(2\delta\omega) + \frac{\rho S}{2m}\frac{V_0}{2}C_{Y_{\delta r}}(-10\delta r) + \frac{5g}{V_0}(-\phi_w)\Big]$$

$$-2\phi_w = -\int\big[.4(10)\,(.5P)\big]\, dt \qquad\qquad -5\beta = -\int(5\dot\beta)\, dt$$

ENGR	Jan. 29	HPE.	REVISED	DATE	-80 Variable Stability AIRPLANE MODEL LATERAL-DIR. SYST. OF EQUATIONS	NASA 20
CHECK			3-5-65	HPE.		
APR			3-27-65	HPE		
APR			5-17-65	D.E.G.	THE BOEING COMPANY RENTON, WASHINGTON	A4

ROTATIONS, BODY AXES

$$I_{xx}\dot{P} = (I_{YY} - I_{ZZ})QR + I_{XZ}(\dot{R} + PQ) + T_x + L$$

$$I_{YY}\dot{Q} = (I_{ZZ} - I_{XX})RP + I_{XZ}(R^2 - P^2) + T_Y + M$$

$$I_{ZZ}\dot{R} = (I_{XX} - I_{YY})PQ + I_{XZ}(\dot{P} - QR) + T_Z + N$$

ROTATIONS, STABILITY AXES

$$I'_{XX}\dot{P}_S = (I'_{YY} - I'_{ZZ})Q_S R_s + I'_{XZ}(\dot{R}_S + P_s Q_s) + T_X + L_S$$

$$I'_{YY}\dot{Q}_s = (I'_{ZZ} - I'_{XX})R_S P_S + I'_{XZ}(R_S^2 - P_S^2) + T_Y + M_S$$

$$I'_{ZZ}\dot{R}_S = (I'_{XX} - I'_{YY})P_S Q_S + I'_{XZ}(\dot{P}_S - \dot{Q}_S R_S) + T_Z + N_S$$

Where

$$P_S = P\cos\alpha + R\sin\alpha$$
$$Q_S = Q$$
$$R_S = -P\sin\alpha + R\cos\alpha$$

$$I'_{XX} = I_{XX}\cos^2\alpha + I_{ZZ}\sin^2\alpha - 2I_{XZ}\sin\alpha\cos\alpha$$

$$I'_{YY} = I_{YY}$$

$$I'_{ZZ} = I_{ZZ}\cos^2\alpha + I_{XX}\sin^2\alpha + 2I_{XZ}\sin\alpha\cos\alpha$$

$$I'_{XZ} = (I_{XX} - I_{ZZ})\sin\alpha\cos\alpha + I_{XZ}(\cos^2\alpha - \sin^2\alpha)$$

NEGLECTING THE NON-LINEAR TERMS:

P_sQ_s ; Q_sR_s ; R_sP_s ; P_s^2 ; R_s^2 :

ASSUMING SYMMETRICAL THRUST;

$T_x = 0$; $T_z = 0$

and SINCE THE TERM T_y IS ACCOUNTED FOR BY THE EQUIVALENT AERODYNAMIC COEFFICIENT $Cm_{\Delta T}$,

$$I'_{xx}\ \dot{P}_s = I'_{xz}\ \dot{R}_s + L_s$$

$$I_{YY}\ \dot{Q} = M$$

$$I'_{zz}\ \dot{R}_s = I'_{xz}\ \dot{P}_s + N_s$$

ISOLATING $\dot{P}_s$ and $\dot{R}_s$

$$\dot{P}_s = \frac{\frac{1}{I'_{xx}} L_s + \frac{I'_{xz}}{I'_{xx} I'_{zz}} N_s}{1 - \frac{I'^2_{xz}}{I'_{xx} I'_{zz}}} = \frac{1}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}} \left(L_s + \frac{I'_{xz}}{I'_{zz}} N_s \right)$$

$$\dot{R}_s = \frac{\frac{1}{I'_{zz}} N_s + \frac{I'_{xz}}{I'_{xx} I'_{zz}} L_s}{1 - \frac{I'^2_{xz}}{I'_{xx} I'_{zz}}} = \frac{1}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}} \left(N_s + \frac{I'_{xz}}{I'_{xx}} L_s \right)$$

IN ORDER TO INCLUDE IN THE SIMULATION THE EFFECT OF THE CROSS-PRODUCT OF INERTIA, I_{XZ}, THE FOLLOWING TECHNIQUE IS PROPOSED:

1. CONVERT THE MOMENTS OF INERTIA I_{XX}, I_{YY}, I_{ZZ}, I_{XZ} FROM BODY AXES TO STABILITY AXES I'_{XX}, I_{YY}, I'_{ZZ}, I'_{XZ} USING (α_{TRIM}) IN THE FORMULAE OF PAGE 1

   — FOR BOTH -80 AND SST AIRPLANES —

2. IN THE ROLL AND YAW EQUATIONS, REPLACE THE ROLLING AND YAWING MOMENTS OF INERTIA I_{xx} and I_{zz} by:

$$I'_{XX} - \frac{I'^{2}_{XZ}}{I'_{ZZ}} \quad \text{AND} \quad I'_{ZZ} - \frac{I'^{2}_{XZ}}{I'_{XX}}, \text{ respectively.}$$

   — FOR BOTH -80 AND SST AIRPLANES —

3. IN THE ROLL AND YAW EQUATIONS, REPLACE THE AERODYNAMIC AND CONTROL COEFFICIENTS AS FOLLOWS:

REPLACE	C_{ℓ_β}	BY	$C_{\ell_\beta} + \frac{I'_{XZ}}{I'_{ZZ}} C_{n_\beta}$
	C_{ℓ_p}	BY	$C_{\ell_p} + \frac{I'_{XZ}}{I'_{ZZ}} C_{n_p}$
	etc ...		
	C_{n_β}	BY	$C_{n_\beta} + \frac{I'_{XZ}}{I'_{XX}} C_{\ell_\beta}$
	C_{n_p}	BY	$C_{n_p} + \frac{I'_{XZ}}{I'_{XX}} C_{\ell_p}$
	etc....		

   — FOR BOTH -80 AND SST AIRPLANES —

4. CROSS-PRODUCTS OF INERTIA ARE NOT USED IN THE NASA 20 SIMULATION DUE TO RELATIVELY LOW ANGLE OF ATTACK WHICH MAKES THIS REFINEMENT UNNECESSARY

$$q_0 S = 174{,}500$$

$$q_0 S b = 174\,500 \times 130.8 = 22.8 \times 10^6$$
$$q_0 S \bar{c} = 174\,500 \times 20.1 = 3.51 \times 10^6$$

$$\frac{q_0 S b}{I_{xx}} = \frac{22.8 \times 10^6}{2.57 \times 10^6} = 8.88$$

$$\frac{q_0 S \bar{c}}{I_{YY}} = \frac{3.51 \times 10^6}{2.25 \times 10^6} = 1.56$$

$$\frac{q_0 S b}{I_{zz}} = \frac{22.8 \times 10^6}{4.73 \times 10^6} = 4.83$$

$$m V_0 = 4660 \times 228 = 1.063 \times 10^6$$

$$\frac{\alpha_0}{m V_0} = \frac{6 \times 10^{-6}}{1.063} = 5.65 \times 10^{-6}$$

$\alpha_0 = \alpha_{\text{WING, TRIM}}$ (DEGREES)

$$\frac{T_0 \alpha_0}{m V_0^2} = \frac{20\,300 \times 6}{1.063 \times 228 \times 10^6} = 5.03 \times 10^{-4}$$

$$\frac{T_0}{m V_0} = \frac{20{,}300}{1.063 \times 10^6} = .0191$$

$$\rho = .002378$$

$$\rho S = .002378 \times 2821 = 6.71$$

$$\frac{\rho S}{m} = \frac{6.71}{4660} = 1.44 \times 10^{-3}$$

$$\frac{\rho S}{m}\frac{V_0}{2} = \frac{1.44 \times 10^{-3} \times 228}{2} = .164$$

$$\frac{\rho S}{m}\frac{V_0^2}{2} = .164 \times 228 = 37.4$$

$$\frac{g}{V_0} = \frac{32.2}{228} = .1412$$

$$\frac{2g}{V_0^2} = \frac{2 \times .1412}{228} = 1.238 \times 10^{-3}$$

ENGR H. P-C	D.E.G. 3-18-65	-80 VARIABLE STABILITY AIRPLANE MODEL AIRBORNE COMPUTER	NASA 20
APR	H.P.C. 6-16-65	THE BOEING COMPANY RENTON WASHINGTON	A8
APR			

TD 1017 R6 6-7000

	POTENTIOMETER NO.	SETTING	VARIABLE	
ROLL AMPL. 17	22	$.1395^{10}$	-5β	$-C_{l_\beta}\frac{q_0Sb}{I_{xx}} = .1572 \times 8.88 = 1.395$
	23	.0795	$+10\delta_r$	$.5C_{l_{\delta r}}\frac{q_0Sb}{I_{xx}} = .5 \times .0179 \times 8.88 = .0795$
	24	$.145^{10}$	$+2\delta_w$	$2.5C_{l_{\delta w}}\frac{q_0Sb}{I_{xx}} = 2.5 \times .0653 \times 8.88 = 1.45$
	25	.3625	$+10R$	$\frac{C_{lR}}{2}\frac{q_0Sb}{I_{xx}} = .5 \times .0817 \times 8.88 = .3625$
	26	$.1391^{10}$	$-5P$	$-C_{lp}\frac{q_0Sb}{I_{xx}} = .1569 \times 8.88 = 1.391$
YAW AMPL. 21	27	.2171	$-5P$	$-2C_{np}\frac{q_0Sb}{I_{zz}} = 2 \times .0225 \times 4.83 = .2171$
	28	.198	$+2\delta_w$	$5C_{n\delta w}\frac{q_0Sb}{I_{zz}} = 5 \times .0082 \times 4.83 = .198$
	29	.350	$-10\delta_r$	$-C_{n\delta r}\frac{q_0Sb}{I_{zz}} = .0725 \times 4.83 = .350$
	30	$.770^{10}$	$+.5\beta$	$20C_{n\beta}\frac{q_0Sb}{I_{zz}} = 20 \times .0797 \times 4.83 = 7.70$
	19	.2075	$-10\dot{\beta}$	$-C_{n\dot{\beta}}\frac{q_0Sb}{I_{zz}} = .043 \times 4.83 = .2075$
	31	.2254	$-10R$	$-C_{nR}\frac{q_0Sb}{I_{zz}} = .0467 \times 4.83 = .2254$
SIDE FORCE AMPL. 23	32	$.1362^{10}$	$+.5\beta$	$-10C_{Y\beta}\frac{\rho S}{m}\frac{V_0}{2} = 10 \times .831 \times .164 = 1.362$
	33	.0244	$-5P$	$C_{Yp}\frac{\rho S}{m}\frac{V_0}{2} = .1492 \times .164 = .0244$
	34	.4929	$+10R$	$-\frac{C_{YR}}{2}\frac{\rho S}{m}\frac{V_0}{2} + \frac{1}{2} = .5 \times .0865 \times .164 + \frac{1}{2} = .4929$
	38	.0053	$+2\delta_w$	$-2.5C_{Y\delta w}\frac{\rho S}{m}\frac{V_0}{2} = 2.5 \times .0128 \times .164 = .0053$
	35	.014	$-10\delta_r$	$.5C_{Y\delta r}\frac{\rho S}{m}\frac{V_0}{2} = .5 \times .1712 \times .164 = .014$
	37	.3535	$-2\phi_w$	$2.5\frac{g}{V_0} = 2.5 \times .1412 = .3535$

ENGR H. P-C 6-16-65		VARIABLE STABILITY AIRPLANE MODEL AIRBORNE COMPUTER	NASA 20
CHECK	D.E.G. 3-10-65		
APR	D.E.G. 3-27-65		
APR	D.E.G. 3-30-65	THE BOEING COMPANY	A9
	D.E.G. 5-17-65	RENTON, WASHINGTON	

U3 1017-R6 6-7000

	POTENTIOMETER NO.	SETTING	VARIABLE	
LIFT AMPL. 33	43	.0157	$+3\delta_{th}$	$\frac{2780\,\alpha_0}{m\,V_0} = 2780 \times 5.65 \times 10^{-6} = .0157$
	44	.1127	$-10\delta_{ab}$	$\frac{\rho S}{m}\frac{V_0}{2}\left(-C_{L\delta_{ab}}\right) = .164 \times .688 = .1127$
	45	$.1648^{\underline{10}}$	$+5\Delta\alpha$	$\frac{\rho S\,V_0}{m} C_{L\alpha} + \frac{2T_0}{mV_0} = .328 \times 4.9 + .0382 = 1.648$
	46	.701	$+\Delta V$	$573\left(\frac{2g}{V_0^2}\right) - \frac{10T_0\alpha_0}{mV_0^2} = 573 \times 1.238 \times 10^{-3} - 5.03 \times 10^{-3} = .701$
				α_0 IN DEGREES
DRAG AMPL. 31	48	.0597	$-3\delta_{th}$	$\frac{278}{m} = \frac{278}{4660} = .0597$
	47	.0382	$+\Delta V$	$\frac{\rho S}{m} V_0 C_{D_{TRIM}} = .328 \times .1165 = .0382$
	49	.0672	$+5\Delta\alpha$	$\frac{\rho S}{m}\frac{V_0^2}{57.3}\frac{C_{D\alpha}}{10} = \frac{37.4 \times 2}{57.3} \times .0515 = .0672$
	50	.0004	$-10\delta_{ab}$	$\frac{\rho S}{m}\frac{V_0^2}{2 \times 573}\frac{(-C_{D\delta_{ab}})}{10} = \frac{37.4}{57.3} \times .000573 = .0004$
	51	.1122	$+5\theta_w$	$\frac{2g}{573} = \frac{64.4}{573} = .1122$
PITCH AMPL. 35	62	.314	$+5\Delta\alpha$	$-C_{m\alpha}\frac{q_0 S\bar{c}}{5I_{YY}} = 1.008 \times \frac{1.56}{5} = .314$
	53	.00*	$-3\delta_{th}$	$+C_{m\Delta T}\frac{q_0 S\bar{c}}{I_{YY}} 57.3 \times 278 = 2 \times 10^{-6} \times 1.56 \times 57.3 \times 278 = .0498$
	54	.0183	$+10\delta_{ab}$	$-C_{m\delta_{ab}}\frac{q_0 S\bar{c}}{10I_{YY}} = .0117 \times 1.56 = .0183$
	55	.260	$+5.25\delta_e$	$-\frac{C_{m\delta_e}}{5.25}\frac{q_0 S\bar{c}}{I_{YY}} = \frac{.85}{5.25} \times 1.56 = .260$
	56	.406	$+\dot{\alpha}$	$-C_{m\dot{\alpha}}\frac{q_0 S\bar{c}}{I_{YY}} = .261 \times 1.56 = .406$
	57	.925	$+Q$	$-C_{m_Q}\frac{q_0 S\bar{c}}{I_{YY}} = .594 \times 1.56 = .925$
	60	.045	$+\Delta V$	$-57.3\frac{q_0 S\bar{c}}{I_{YY}} C_{m_{\Delta V}} = 57.3 \times 1.56 \times .0005 = .045$

*EXPERIMENTALLY DERIVED VALUE DIFFERS FROM CALCULATED VALUE DUE TO NONLINEARITY of $C_{m_{\Delta T}}$

ENGR H. P-C 6-16-65

APR

APR

DEG 9-18-65
D.E.G. 3-27-65
H.P.C. 4-7-65
DE.G. 5-17-65

-80 VARIABLE STABILITY AIRPLANE MODEL AIRBORNE COMPUTER

THE BOEING COMPANY
RENTON WASHINGTON

NASA 20

POTENTIOMETER NO.	SETTING		VARIABLE	CALCULATED FROM
39	.1	A49	+ 10R	$\frac{R}{10R} = .1$
40	.4 ^{10}	A 18	+ .5P	$\frac{P}{.25P} = 4.0$
41	.1	A24	$-.5\beta$	$\frac{-.5\beta}{-5\beta} = .1$
58	.1	A 34	$-10Q_w$	$\frac{-Q_w}{-10Q_w} = .1$
59	.5 $\underline{10}$	A 36	$-\dot{\alpha}$	$\frac{-5\dot{\alpha}}{-\dot{\alpha}} = 5$
63	.5	A 32	$-10Q_w$	$\frac{-5Q_w}{-10Q_w} = .5$

DRAG AXIS ; UNITS : LBS

$$\Delta T_{-80_C} = \Delta T_{-80_{\Delta V}} \times \Delta V + \Delta T_{-80_{\Delta T_{SST}}} \times \Delta T_{SST} + \Delta T_{-80_{\delta ab}} \times \delta ab + \Delta T_{-80_{\Delta\alpha}} \times \Delta\alpha$$

LIFT AXIS ; UNITS : DEGREES

$$\delta ab_C = \delta ab_{\Delta\alpha} \times \Delta\alpha + \delta ab_{\Delta T_{SST}} \times \Delta T_{SST} + \delta ab_{\Delta T_{-80}} \times \Delta T_{-80} + \delta ab_{\delta E} \times \delta E + \delta ab_{\delta e} \times \delta e + \delta ab_{\Delta V} \times \Delta V$$

PITCH AXIS ; UNITS : DEGREES

$$\delta e_C = \delta e_{\Delta T_{SST}} \times \Delta T_{SST} + \delta e_{\Delta T_{-80}} \times \Delta T_{-80} + \delta e_{\Delta V} \times \Delta V + \delta e_{\Delta\alpha} \times \Delta\alpha + \delta e_{\dot\alpha} \times \dot\alpha$$
$$+ \delta e_Q \times Q + \delta e_{\delta ab} \times \delta ab + \delta e_{\delta E} \times \delta E$$

ROLL AXIS ; UNITS : DEGREES

$$\delta\omega_C = \delta\omega_\beta \times \beta + \delta\omega_P \times P + \delta\omega_R \times R + \delta\omega_{\delta w} \times \delta w + \delta\omega_{\delta R} \times \delta R + \delta\omega_{\delta r} \times \delta r$$

YAW AXIS ; UNITS : DEGREES

$$\delta r_C = \delta r_\beta \times \beta + \delta r_{\dot\beta} \times \dot\beta + \delta r_P \times P + \delta r_R \times R + \delta r_{\delta w} \times \delta w + \delta r_{\delta R} \times \delta R + \delta r_{\delta\omega} \times \delta\omega$$

SIDE FORCE AXIS ; UNITS : DIMENSIONLESS.

$$\Delta C_Y = \Delta C_{Y_\beta} \times \beta + \Delta C_{Y_P} \times P + \Delta C_{Y_R} \times R + \Delta C_{Y_{\delta w}} \times \delta w + \Delta C_{Y_{\delta R}} \times \delta R + \Delta C_{Y_{\delta\omega}} \times \delta\omega + \Delta C_{Y_{\delta r}} \times \delta r$$

THE FOLLOWING VARIABLES ARE IN DEGREES $\left\{ \begin{array}{l} \delta e \,;\, \delta r \,;\, \delta\omega \,;\, \delta ab \,;\, \Delta\alpha \,;\, \beta. \\ \delta E \,;\, \delta R \,;\, \delta w \,; \end{array} \right.$

IN DEGREES PER SECOND : P ; Q ; R ; $\dot\beta$; $\dot\alpha$

IN POUNDS : ΔT_{-80} ; ΔT_{SST}

IN FEET PER SECOND : ΔV

ENGR Jan. 65 WRC.		−80 Variable Stability	NASA 20
CHECK Apr. 5. 65 WRC.		DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS	
APR			
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SST AIRPLANE.

$$\frac{q_0 S \bar{c}}{I_{YY}} = \frac{.309 \times 10^6 \times 70}{17.57 \times 10^6} = 1.231$$

$$\frac{q_0 S b}{I_{XX}} = \frac{.309 \times 10^6 \times 85}{2.86 \times 10^6} = 9.184$$

$$\frac{q_0 S b}{I_{ZZ}} = \frac{.309 \times 10^6 \times 85}{20 \times 10^6} = 1.313$$

$$\frac{q_0 S}{m} = \frac{.309 \times 10^6}{8696} = 35.53$$

367 - 80 AIRPLANE

$$\frac{q_0 S \bar{c}}{I_{YY}} = \frac{.1745 \times 10^6 \times 20.1}{2.25 \times 10^6} = 1.56$$

$$\frac{q_0 S b}{I_{XX}} = \frac{.1745 \times 10^6 \times 130.8}{2.57 \times 10^6} = 8.88$$

$$\frac{q_0 S b}{I_{ZZ}} = \frac{.1745 \times 10^6 \times 130.8}{4.73 \times 10^6} = 4.83$$

$$\frac{q_0 S}{m} = \frac{.1745 \times 10^6}{4660} = 37.45$$

PITCH	$K_{PITCH} = \dfrac{\left.\dfrac{q_0 S \bar{c}}{I_{YY}}\right]_{SST}}{\left.\dfrac{q_0 S \bar{c}}{I_{YY}}\right]_{-80}} = .791$	ROLL	$K_{ROLL} = \dfrac{\left.\dfrac{q_0 S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}}\right]_{SST}}{\left.\dfrac{q_0 S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}}\right]_{-80}} = 1.035$
LIFT, DRAG	$K_{LIFT\ DRAG} = \dfrac{\left.\dfrac{q_0 S}{m}\right]_{SST}}{\left.\dfrac{q_0 S}{m}\right]_{-80}} = .95$	YAW	$K_{YAW} = \dfrac{\left.\dfrac{q_0 S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}}\right]_{SST}}{\left.\dfrac{q_0 S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}}\right]_{-80}} = .2725$

ENGR.	May 7.65	HPC.	REVISED	DATE	-80 Variable Stability DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS.	NASA 20
CHECK						
APR						
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		SST		-80	
$\delta\omega_\beta$	$C_{\ell\beta}$	-.1547	$C_{\ell\delta\omega}$ -80	-.1572	$\frac{(1.035)(-.1547)-(-.1572)}{.0653} = -.0444$
$\delta\omega_p$	$C_{\ell p}$	-.2269	$\boxed{+.0653}$	-.1569	$\frac{(1.035)(-.2269)-(-.1569)}{.0653} = 1.197$
$\delta\omega_R$	$C_{\ell R}$	+.0744	$K_{ROLL} = 1.035$	+.0817	-.072
$\delta\omega_{\delta w}$	$C_{\ell\delta w}$	.1146	ROLL	—	+1.816
$\delta\omega_{\delta R}$	$C_{\ell\delta R}$	0		—	0
$\delta\omega_{\delta r}$	$C_{\ell\delta r}$	—		+.0179	-.274
$\delta\omega_{\dot\beta}$	$C_{\ell\dot\beta}$	0		0	0
δr_β	$C_{n\beta}$	+.2006	$C_{n\delta r}$ -80	+.0797	$\frac{(.2725)(.2006)-(.0797)}{-.0725} = +.346$
δr_p	C_{np}	-.0223	$\boxed{-.0725}$	-.0225	-.227
δr_R	C_{nR}	-.0874	$K_{YAW} = .2725$	-.0467	-.316
$\delta r_{\delta w}$	$C_{n\delta w}$	+.0424	YAW	—	-.159
$\delta r_{\delta R}$	$C_{n\delta R}$	-.086		—	+.323
$\delta r_{\delta\omega}$	$C_{n\delta\omega}$	—		+.0082	+.113
$\delta r_{\dot\beta}$	$C_{n\dot\beta}$	0		-.043	-.593
$\Delta C_{Y\beta}$	$C_{Y\beta}$				
ΔC_{Yp}	C_{Yp}		$\boxed{57.3}$		
ΔC_{YR}	C_{YR}		SIDE FORCE		
$\Delta C_{Y\delta w}$	$C_{Y\delta w}$				
$\Delta C_{Y\delta R}$	$C_{Y\delta R}$				
$\Delta C_{Y\delta\omega}$	$C_{Y\delta\omega}$				
$\Delta C_{Y\delta r}$	$C_{Y\delta r}$				

-80 Variable Stability
DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS.

NASA 20
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		SST		-80	
$\delta e_{\Delta\alpha}$	C_{m_α}	-.4584	$C_{m_{\delta e}}$ -80	-1.008	$\frac{(.791)(-.4584)-(-1.008)}{-.85} = -.761$
$\delta e_{\dot\alpha}$	$C_{m_{\dot\alpha}}$	-.1335	$\boxed{-.85}$	-.261	-.183
δe_{Q}	C_{m_Q}	-.2149		-.594	-.498
$\delta e_{\Delta V}$	$57.3 C_{m_{\Delta V}}$	0	PITCH	-.0287	-.0337
δe_{δ_E}	$C_{m_{\delta_E}}$	-.7163		—	+.666
$\delta e_{\Delta T_{SST}}$	$57.3 C_{m_{\Delta T_{SST}}}$	$+13.24 \times 10^{-6}$		—	-.0000122
$\delta e_{\Delta h}$	$57.3\ \Delta C_m$	f(h)		f(h)	f(h)
$\delta e_{\Delta T_{-80}}$	$57.3 C_{m_{\Delta T_{-80}}}$	—		0	0
$\delta e_{\delta ab}$	$C_{m_{\delta ab}}$	—		-.117	-.138

$$\delta e_{\Delta h} = 57.3 \left[\frac{\left(\frac{q_0 S \bar c}{I_{YY}} \Delta C_m\right)_{SST} - \left(\frac{q_0 S \bar c}{I_{YY}} \Delta C_m\right)_{-80}}{\left(\frac{q_0 S \bar c}{I_{YY}} C_{m_{\delta e}}\right)_{-80}} \right] = f(h)$$

$$\delta e_c = \underset{\delta e_{\Delta\alpha}}{-.761}\ \Delta\alpha\ \underset{\delta e_{\dot\alpha}}{-.183}\ \dot\alpha\ \underset{\delta e_{Q}}{-.498}\ Q\ \underset{\delta e_{\Delta V}}{-.0337}\ \Delta V$$

$$\underset{\delta e_{\delta E}}{+.666}\ \delta_E\ \underset{\delta e_{\Delta T_{SST}}}{-.0000122}\ \Delta T_{SST}\ \underset{\delta e_{\Delta h}}{\text{FUNCTION}}\ \underset{\delta e_{\Delta T_{-80}}}{0}\ \Delta T_{-80}\ \underset{\delta e_{\delta ab}}{-.138}\ \delta ab$$

	April 5.65	[illegible]		-80 Variable Stability DERIVATION OF AIRBORNE COMP. COEFFICIENTS	NASA 20
					PITCH
					A16

$$\frac{m_{-80}}{m_{SST}} = \frac{4660}{8696} = .536$$

$$\left(2\frac{q_0 S}{V_0} C_{D_{TRIM}}\right)_{-80} - \left(2\frac{q_0 S}{V_0} C_{D_{TRIM}} + q_0 S C_{D_{\Delta V}}\right)_{SST} \frac{m_{-80}}{m_{SST}}$$

$$\Delta T_{-80_{\Delta V}} = \left(2\,\frac{174500}{228}\,.1165\right)_{-80} - \left(2\,\frac{309{,}000}{228}\,.115 + 309{,}000\times 0\right)_{SST} .536 = +11.3$$

$$\Delta T_{-80_{\Delta T_{SST}}} = \frac{m_{-80}}{m_{SST}}\left(1 - q_0 S C_{D_{\Delta T}}\right)_{SST} = .536(1-0) = .536$$

$$\Delta T_{-80_{\delta_{ab}}} = q_0 S \frac{C_{D_{\delta ab}}}{57.3} = 174{,}500 \times \frac{-.00573}{57.3} = -17.4$$

$$\Delta T_{-80_{\Delta\alpha}} = \left(q_0 S \frac{C_{D_\alpha}}{57.3}\right)_{-80} - \left[\left(q_0 S \frac{C_{D_\alpha}}{57.3}\right)_{SST} \frac{m_{-80}}{m_{SST}}\right] = \left(174500\,\frac{.515}{57.3}\right)_{-80} - \left[\left(309{,}000\,\frac{.418}{57.3}\right)_{SST} \times .536\right] = +360$$

$$\Delta T_{-80\Delta h} = \left(q_0 S \Delta C_D\right)_{-80} - \left(\frac{m_{-80}}{m_{SST}}\right)\left(q_0 S \Delta C_D\right)_{SST} = f(h)$$

$$\Delta T_{-80_{\Delta V}} \times \Delta V + \Delta T_{-80_{\Delta T_{SST}}} \times \Delta T_{SST} + \Delta T_{-80_{\delta_{ab}}} \times \delta_{ab} + \Delta T_{-80_{\Delta\alpha}} \times \Delta\alpha$$

$$\Delta T_{-80} = 11.3\ \Delta V + .536\ \Delta T_{SST} - 17.4\ \delta_{ab} + 360\ \Delta\alpha$$

			REVISED	DATE		
ENGR.	Dec. 64	HPC.			-80 Variable Stability DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS	NASA 20
CHECK	March. 30.65	HPC.				DRAG
APR	April 5.65	HPC.			THE BOEING COMPANY RENTON, WASHINGTON	A17
APR						

$$\delta ab_{\Delta\alpha} = \frac{\left(\frac{q_0 S}{m} C_{L_\alpha} + \frac{T_0}{m}\right)_{SST} - \left(\frac{q_0 S}{m} C_{L_\alpha} + \frac{T_0}{m}\right)_{-80}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{\left(35.53 \times 4.7 + \frac{35540}{8696}\right)_{SST} - \left(37.45 \times 4.9 + \frac{20{,}300}{4660}\right)_{-80}}{\left(37.45 \times -.688\right)_{-80}} = +.67$$

$$\delta ab_{\Delta T_{SST}} = \frac{\left(\frac{\alpha_0}{m}\right)_{SST} + 57.3\left(\frac{q_0 S}{m} C_{L_{\Delta T}}\right)_{SST}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{\frac{6.6}{8696} + 57.3(35.53 \times 0)}{-25.8} = -2.95 \times 10^{-5}$$

α_0 in degrees

$$\delta ab_{\Delta T_{-80}} = \frac{-\left(\frac{\alpha_0}{m}\right)_{-80}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{-\left(\frac{6}{4660}\right)_{-80}}{\left(-25.8\right)_{-80}} = 5 \times 10^{-5}$$

$\alpha_0 = \alpha_{TRIM,\ WING}$ in degrees

$$\delta ab_{\Delta V} = \frac{57.3\left[\left(\frac{q_0 S}{m} C_{L_{\Delta V}}\right)_{SST} + \left(\frac{2g}{V_0}\right)_{SST} - \left(\frac{2g}{V_0}\right)_{-80}\right]}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{57.3 \times 35.53 \times 0}{-25.8} = 0$$

$$\delta ab_{\delta_E} = \frac{\left(\frac{q_0 S}{m} C_{L_{\delta_E}}\right)_{SST}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{\left(35.53 \times .487\right)_{SST}}{\left(-25.8\right)_{-80}} = -.67$$

$$\delta ab_{\delta_e} = -\left(\frac{C_{L_{\delta_e}}}{C_{L_{ab}}}\right)_{-80} = -\left(\frac{0}{-.688}\right)_{-80} = 0$$

$$\delta ab_{\Delta h} = 57.3\left[\frac{\left(\frac{q_0 S}{m}\Delta C_L\right)_{SST} - \left(\frac{q_0 S}{m}\Delta C_L\right)_{-80}}{\left(\frac{q_0 S}{m} C_{L_{\delta ab}}\right)_{-80}}\right] = f(h)$$

$$\delta ab_c = \underset{\delta ab_{\Delta\alpha}}{+.67}\ \Delta\alpha \ \underset{\delta ab_{\Delta T_{SST}}}{-2.95 \times 10^{-5}}\ \Delta T_{SST} \ \underset{\delta ab_{\Delta T_{-80}}}{+5 \times 10^{-5}}\ \Delta T_{-80} + \underset{\delta ab_{\Delta V}}{0}\ \Delta V$$

$$\underset{\delta ab_{\delta_E}}{-.67}\ \delta_E + \underset{\delta ab_{\delta_e}}{0}\ \delta_e + \underset{\delta ab_{\Delta h}}{\text{function } \Delta h}$$

			REVISED	DATE		
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ΔT_{-80}	δ_{ab}	δ_e	VARIABLE	VARIABLE	δ_w	δ_r
360	+ .67	-.761	$\Delta\alpha$	β	-.0444	+.346
0	0	-.183	$\dot{\alpha}$	$\dot{\beta}$	0	-.593
0	0	-.498	Q	P	-1.197	-.227
+11.3	0	-.0337	ΔV	R	-.072	-.316
+.536	-2.95×10^{-5}	-12.2×10^{-6}	ΔT_{SST}	δ_W	+1.816	-.159
—	5.0×10^{-5}	0	ΔT_{-80}	δ_ω	—	+.113
-17.4	—	-.138	δ_{ab}	δ_R	0	+.323
0	-.67	+.666	δ_E	δ_r	-.274	—
0	0	—	δ_e			
function	—	—	Δh			
—	function	—	Δh			
—	—	function	Δh			

Example: if $\underbrace{\quad}$, then the following equations apply:

ΔT_{-80}	δ_{ab}	δ_e	
+217	+2.1	-.63	$\Delta\alpha$
-33	+.07	-.007	ΔV
+.25	$-3\cdot10^{-6}$	$+4.6\cdot10^{-5}$	ΔT_{SST}
—	$+1.7\cdot10^{-5}$	$+2\cdot10^{-4}$	ΔT_{-80}
0	-.09	+.38	δ_E

$$\Delta T_{-80} = 217\,\Delta\alpha - 33\,\Delta V + .25\,\Delta T_{SST}$$

$$\delta_{ab} = 2.1\,\Delta\alpha + .07\,\Delta V - 3\times10^{-6}\,\Delta T_{SST} + 1.7\times10^{-5}\,\Delta T_{-80} - .09\,\delta_E$$

$$\delta_e = -.63\,\Delta\alpha - .007\,\Delta V + 4.6\times10^{-5}\,\Delta T_{SST} + 2\times10^{-4}\,\Delta T_{-80} + .38\,\delta_E$$

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CHECK						
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LONGITUDINAL

	POTENTIOMETER NO	SETTING		VARIABLE	CALCULATED FROM
PITCH	18	.262	A44	$+20\,\delta e_{TRIM}$	1.05 (.25)
	64	.1922	A44	$-5\dot{\alpha}$	$1.05(-\delta e_{\dot{\alpha}})$
	65	.2615[10]	A43	$+Q$	$1.05 \times (-5\,\delta e_Q)$
	66	.798	A43	$+5\Delta\alpha$	$1.05(-\delta e_{\Delta\alpha})$
	67	.177	A43	$+\Delta V$	$1.05 \times (-5\,\delta e_{\Delta V})$
	68	.064	A44	$-.001\,\Delta T_{SST}$	$1.05 \times (-5000\,\delta e_{\Delta T_{SST}})$
	69	.0725	A43	$+10\,\delta ab_c$	$1.05 \times (-5\,\delta e_{\delta ab})$
	70	0	A44	$+.005\,\Delta T_{-80}$	$1.05 \times (+1000\,\delta e_{\Delta T-80})\ \left[\frac{1}{TS+1}\right]$
	71	.350[10]	A43	$-\delta_E'$	$1.05 \times (+5\,\delta e_{\delta E'})$
	DIRECT INPUT		A43	h	FUNCTION
DRAG	72	.360	A45	$+5\Delta\alpha$	$-.001\,\Delta T_{\Delta\alpha}$
	73	.2678[10]	A46	$-.001\,\Delta T_{SST}$	$+5\,\Delta T_{\Delta T_{SST}}$
	74	.0565	A45	$+\Delta V$	$-.005\,\Delta T_{\Delta V}$
	75	.0087	A46	$+10\,\delta ab$	$-.0005\,\Delta T_{\delta ab}$
	DIRECT INPUT		A45	h	FUNCTION
	80	.697	A50	$-.005\,\Delta T_{-80}$	$\frac{\delta_{th}}{\Delta T_{-80}}(600) = \frac{600}{861} = .697$ $\left(\frac{\delta_{CLAM}}{\delta_{THC}} = .266\right)$ (861 based on $\Delta T/_{DEG}$ clam $= 1080$)
LIFT	76	.100	A47	$-.005\,\Delta T_{-80}$	$+2000\,\delta ab_{\Delta T-80}$
	77	.295	A48	$-.001\,\Delta T_{SST}$	$-10\,000\,\delta ab_{\Delta T_{SST}}$
	78	.670[10]	A48	$-\delta_E'$	$-10\,\delta ab_{\delta_E}$
	79	.134[10]	A48	$+5\Delta\alpha$	$-2\,\delta ab_{\Delta\alpha}$
	13	0	A47	$-\Delta V$	$+10\,\delta ab_{\Delta V}$
	DIRECT INPUT		A48	h	FUNCTION

Note: the factor of 1.05 in the pitch axis computations arises from the inability of the elevator to respond to a command in a one to one ratio.

			REVISED	DATE			
CALC	March 30.65	HPC			-80 Variable Stability	LONG.	NASA 20
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APR	4-25-65		BASKA	4-25-65	POTENTIOMETER SETTINGS		
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	POTENTIOMETER NO	SETTING		VARIABLE	CALCULATED FROM
ROLL	106	.144	A72	$-R$	$+2\,\delta\omega_R$
	107	.4788[10]	A71	$+.5P$	$+4\,\delta\omega_P$
	108	.0178	A72	-5β	$-.4\,\delta\omega_\beta$
	109	.363[10]	A71	$-\delta w$	$+2\,\delta\omega_{\delta w}$
	110	0	A72	$+\delta R$	$+2\,\delta\omega_{\delta R}$
	111	.0548	A71	$+10\delta r$	$-.2\,\delta\omega_{\delta r}$
	90	.600	—	$+2\delta_{\omega_c}$	ROLL CONTROL EFFECTIVENESS
YAW	112	.593	A73	$-10\dot\beta$	$-\delta r_{\dot\beta}$
	113	.454[10]	A74	$+.5P$	$+20\,\delta r_P$
	114	.316[10]	A73	$-R$	$+10\,\delta r_R$
	115	.692	A74	-5β	$-2\,\delta r_\beta$
	116	.677[10]	A74	$+\delta R$	$+10(\delta r_{\delta R}-1)$
	117	.159[10]	A73	$-\delta w$	$+10\,\delta r_{\delta w}$
	118	.565	A73	$+2\delta\omega$	$+5\,\delta r_{\delta\omega}$

LATERAL

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CALC	March 30.65	14:C			-80 Variable Stability	LATERAL	NASA 20
CHECK			D.E.G	4-19-65	NUMERICAL VALUES OF	DIRECT	
APR					POTENTIOMETER SETTINGS		
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1. Control Column

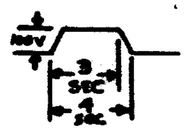
$$\boxed{\delta_E = K_E\,\delta_{CP} + K_{82}\,\text{Pulse}}$$

where δ_E = Simulated SST elevator position

K_E = SST Column to elevator gearing

δ_{CP} = Eval. Pilot's column position.

K_{82} = ELEVATOR PULSE -SCALE FACTOR (USED ONLY FOR CHECKOUT)

PULSE = 

2. Pitch Trim

$$\boxed{\delta_{ETRIM} = \frac{K_{TR}}{S}\,(\text{TRIM})}$$

where δ_{ETRIM} = Fake trim signal to -80 elevator

K_{TR} = Gain factor, to simulate SST trim rate.

(TRIM) = Eval. Pilot trim signal (-15V; 0V; +15V)

$$K_{TR} = \frac{\left(\dfrac{q_o S\bar{c}}{I_{YY}} \times C_{m_{i_H}} \times \text{Stabilizer trim rate}\right)_{SST}}{\left(\dfrac{q_o S\bar{c}}{I_{YY}}\, C_{m_{\delta_e}}\right)_{-80}}$$

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P3

3. Control Wheel

$$\boxed{\delta_W = \delta_{W_E} + K_{87}(\text{Pulse})}$$

where δ_W = Simulated SST Wheel Position

δ_{W_E} = Eval. Pilot Wheel Position

K_{87} = Wheel Pulse Scale Factor

4. Rudder Pedals and Rudder

$$\boxed{\delta_R = K_P \, \delta_P}$$

where δ_R = Simulated SST Rudder Position

K_P = SST Pedal to Rudder gearing

δ_P = Rudder Pedal Position.

Rudder Pulse circuit

$$\boxed{\delta_{R_{Pulse}} = \frac{1}{6.67}(\text{Pulse})}$$ Used only for Checkout.

where $\delta_{R_{Pulse}} = 15°$ Simulated SST Rudder Position, under control of a computer derived pulse

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5. Fake Throttle

$$\boxed{\Delta T_{SST} = K_{TH}\,\delta_{TH} \begin{array}{l} + K_{84}(\text{Pulse}) \ \text{AFT} \\ \text{or} \\ - K_{8}(\text{Pulse}) \ \text{FWD} \end{array}}$$

Where

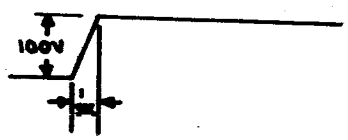
ΔT_{SST} = Simulated SST Thrust Increment.

K_{TH} = SST Thrust to Throttle ratio

δ_{TH} = Eval. Pilot Fake Throttle lever Position

K_{84} = AFT THRUST PULSE SCALE FACTOR

K_{8} = FWD " " " "

PULSE = 

SCALED EQUATIONS

$$+\ \delta E = -\left[(-2K_E)(+.5\,\delta_{CP}) + K_{82}(\text{Pulse})\right]$$

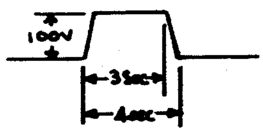
$$+\ 20\,\delta e_{TRIM} = -\int\left[\frac{20}{15}K_{TR}(\text{TRIM})\right]dt$$

$$-\ \delta w = -\left[10(.1\,\delta w_E) + K_{87}(\text{Pulse})\right]$$

$$\delta R = -\left[\frac{K_P}{2.5}(-2.5\,\delta_{PED})\right]$$

$$6.67\,\delta R_{Pulse} = \text{Pulse (15° SST RUDDER)}$$

$$-\frac{\Delta T_{SST}}{1000} = -\left[\left(\frac{K_{TH}}{1000\times.3}\right)(.3\,\delta_{TH}) \begin{matrix} +\ K_8\ \text{PULSE} \\ -\ K_{84}\ \text{PULSE}\end{matrix}\right]$$

FOR THE 367-80	FOR NASA Δ SST
$K_E = -2.2$ degree/degree	$K_E = -1.3$ degree/degree
$K_{TR} = 1.385$ degree/sec	$K_{TR} = 1.20$ degree/sec
$K_P = 6.25$ degree/inch	$K_P = 6.25$ degree/inch
$K_{th} = 1080$ lbs/degree ([illegible])	Pulse = 
THRUST RATE LIMIT ≃ 14,000 lb/SEC	
	$K_{TH} = \frac{170\,000}{57.3} \cong 3000$ lbs/degree [illegible] throttle

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POTENTIOMETER NO.	SETTING		VARIABLE	CALCULATED FROM
8	.150	A7	FWD THRUST STEP (-100V)	$\frac{3\delta_{TH}}{100} = \frac{3\times 5}{100} = .15$
61	.160[10]	A41	TRIM	$\frac{20}{15} K_{TR} = \frac{20}{15}(1.2) = 1.6$
81	.250[10]	A84	$-2.5\delta_p$	$\frac{K_P}{2.5} = 2.5$
82	.025	A78	ELEV. PULSE (+100V)	$\frac{\delta_E}{100} = .01 \times 2.5 = .025$
84	.300	A8	AFT THRUST STEP (-100V)	$\frac{3\delta_{TH}}{100} = \frac{3\times 10}{100} = .30$
85*	.484	A74	$6.67\delta_R$ PULSE	$10\frac{\delta_{r}\delta_{R}}{6.67} = \frac{10}{6.67}(.323) = .484$
87	.100	A77	WHEEL PULSE	$\frac{\delta_W}{100} = \frac{10}{100} = .10$
88	.260[10]	A78	$+.5\delta_{C_P}$	$-2K_E = -2(-1.3) = +2.6$
DIRECT INPUT	g_{10}	A77	$+.1\delta_{W_E}$	$10\frac{\delta_W}{\delta_{W_E}} = 10$

* SET TO PRODUCE A 15° SST PULSE

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1. Change in Angle of Attack $\Delta\alpha$

$$\Delta\alpha = \alpha_{-80} - \alpha_{TRIM}$$

$$\alpha_{-80} = \alpha_{VANE,\,CALM\ AIR} + Q\frac{\ell}{V} + \Delta\alpha_{VANE,\,TURBULENCE}\ e^{-s\frac{\ell}{V}}$$

$$\alpha_{-80} \cong Q\frac{\ell}{V_o} + \alpha_{V,C} + \Delta\alpha_{V,T}\left(1 - s\frac{\ell}{V_o}\right)$$

by definition $\alpha_V = \alpha_{V,C} + \Delta\alpha_{V,T}$

Replacing $s\frac{\ell}{V_o}\Delta\alpha_{V,T}$ by $s\frac{\ell}{V_o}\alpha_V$

since no $\Delta\alpha_{V,T}$ signal is available,

approximating $\left(1 - s\frac{\ell}{V_o}\right)$ with $\frac{1}{1+s\frac{\ell}{V_o}}$ -, and replacing αV by $1.4\alpha_V$ since the electrical scale factor of α_V is 1.4,

$$\boxed{\Delta\alpha \cong Q\frac{\ell}{V_o} + \frac{1.4\alpha_V}{1+s\frac{\ell}{V_o}} - \alpha_{TRIM}}$$

2. Rate of change of angle of attack $\dot{\alpha}$

The $\dot{\alpha}$ signal will be derived from the $\Delta\alpha$ signal, using a pseudo-differentiating circuit having the following transfer function

$$\boxed{\frac{\dot{\alpha}}{\Delta\alpha} \cong \frac{s}{1 + .1s}}$$

3. Angle of Sideslip β

$$\beta = \beta_{VANE,\ CALM} - R\frac{\ell}{V} + \Delta\beta_{VANE,\ TURBULENCE}\ e^{-s\frac{\ell}{V}}$$

Following steps similar to those of page 1 — derivation of the simplified $\Delta\alpha$ formula — results in:

$$\boxed{\beta \cong -R\frac{\ell}{V_o} + \frac{\beta_V}{1+s\frac{\ell}{V_o}}}$$

4. Rate of change of angle of sideslip $\dot{\beta}$

The $\dot{\beta}$ signal will be derived from a roll gyro signal (ϕ) and a yaw rate gyro signal (R), using the following equation:

$$\boxed{\dot{\beta} = \phi\frac{g}{V_o} - R}$$

5. Change in True Airspeed ΔV

$$\boxed{\Delta V = V - V_{TRIM}}$$

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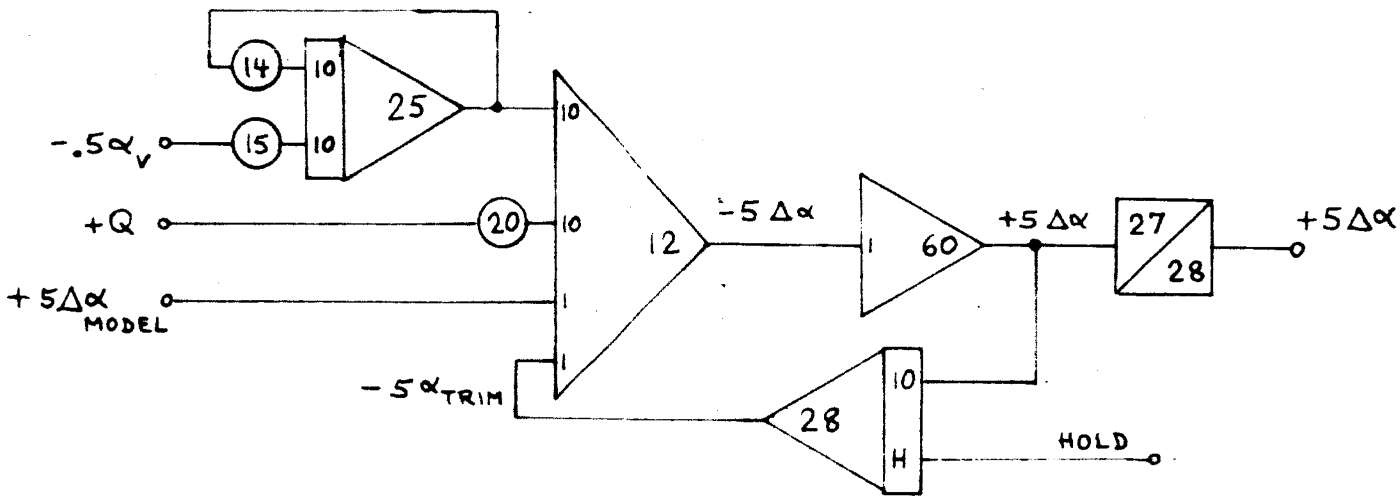
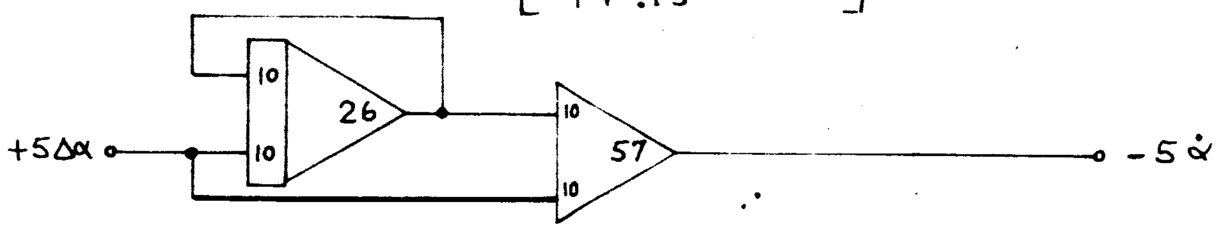
SCALED EQUATIONS

$$-5\,\Delta\alpha = -\left[\frac{5\ell}{V_0}(+Q) - 10\left(-\frac{.5\times 1.4\alpha_V}{1+\frac{\ell}{V_0}s}\right) + \left(5\alpha_{TRIM}\right)\right]$$



$$-5\,\dot{\alpha} = -\left[\frac{s}{1+.1s}\left(5\,\Delta\alpha\right)\right]$$



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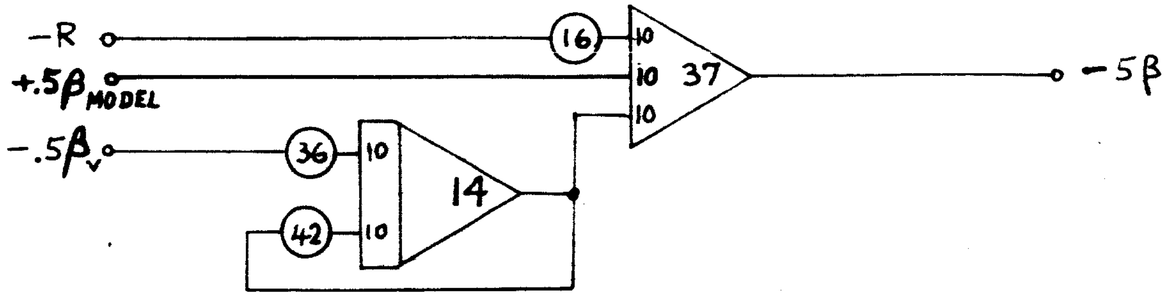
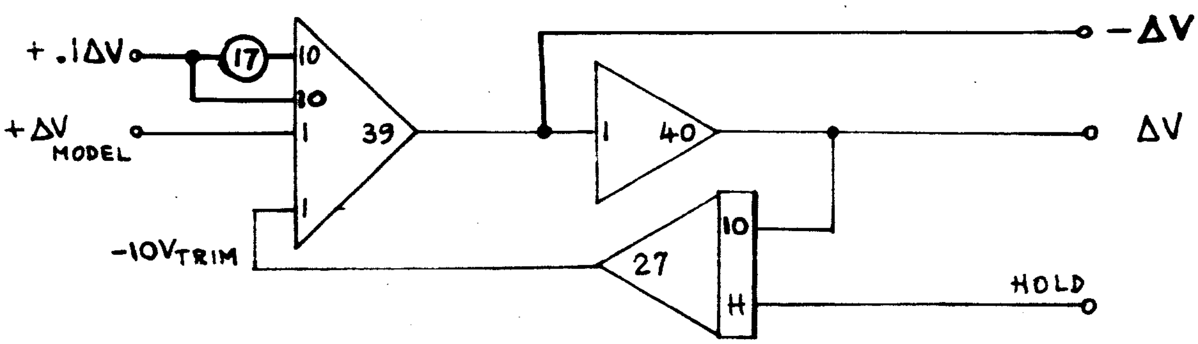
SCALED EQUATIONS.

$$-5\beta = -\left[\frac{5\ell}{V_o}(-R) + 10\left(+\frac{.5\beta_V}{1+\frac{\ell}{V_o}s}\right)\right]$$



$$-10\dot{\beta} = -\left[\frac{10g}{V_o}(+\phi) + 10(-R)\right]$$

$$-\Delta V = -\left[10K\left(+\frac{.1\Delta V}{K}\right) + (-V_{TRIM})\right]$$



K = 1.06 DERIVED FROM IN-FLT calibration

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POTENTIOMETER NO.	SETTING		VARIABLE	CALCULATED FROM
14	1.00^{10}	A 25	$+\frac{.5\alpha_v}{1+\frac{\ell}{V_0}s}$	$\tau = .1$, $K_{14} = \frac{1}{\tau} = 10$
15	$.700^{10}$	A 25	$-.5(1.4\alpha_v)$	$\lvert G\rvert = \frac{K_{15}}{K_{14}} = \frac{.5}{.5(1.4)}$; $\therefore K_{15} = \frac{10}{1.4} \approx 7.0$
20	$.160^{10}$	A 12	$+Q$	$\frac{5\ell}{V_0} = 1.60$
42	$.313^{10}$	A 14	$+\frac{.5\beta_v}{1+\frac{\ell}{V_0}s}$	$\frac{V_0}{\ell} = \frac{1}{\tau} = 3.13$
36	$.313^{10}$	A 14	$-.5\beta_v$	$\frac{V_0}{\ell} = \lvert G\rvert = \frac{K_{36}}{K_{42}} = 1$; $\therefore K_{36} = 3.13$
16	$.160^{10}$	A 37	$-R$	$\frac{5\ell}{V_0} = 1.60$
120	.707	A 76	$.2\phi$	$\frac{10g}{.2V_0} = \frac{322}{.2 \times 225} = 7.07$
17	$10+.06^{10}$	A39	$+\frac{.1}{K}\Delta V$	RESULT OF IN-FLT CALIBRATION

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	POTENTIOMETER NO.	POTENTIOMETER SETTING	VARIABLE		CALCULATED FROM
LONG.	119	$.146^{10}$	A79	$+Q$	$\frac{\delta_E'}{Q}$
	122	$.300^{10}$	A79	$+\delta_E$	$\left(\frac{\delta_E'}{\delta_E} - 1.0\right) = 4 - 1 = 3$
	123	.300	A79	$+5\Delta\alpha$	$\frac{1}{5}\left(\frac{\delta_E'}{\Delta\alpha}\right) = \frac{1.5}{5} = .30$
LATERAL	3	.323	A73	$-10\dot{\beta}$	TO MATCH DIGITAL DATA
DEGRADED LATERAL	21	.497	A74	$+.5P$	RESULT OF IN-FLIGHT ADJUSTING
	124	.0995	A74	$-10\dot{\beta}$	" " " "
AFT C.G.	83	.070 + 1	A43	$+5\Delta\alpha$	" " " "

ENGR			-80 VARIABLE STABILITY COMPUTER EQUATIONS FOR STAB. AUG.
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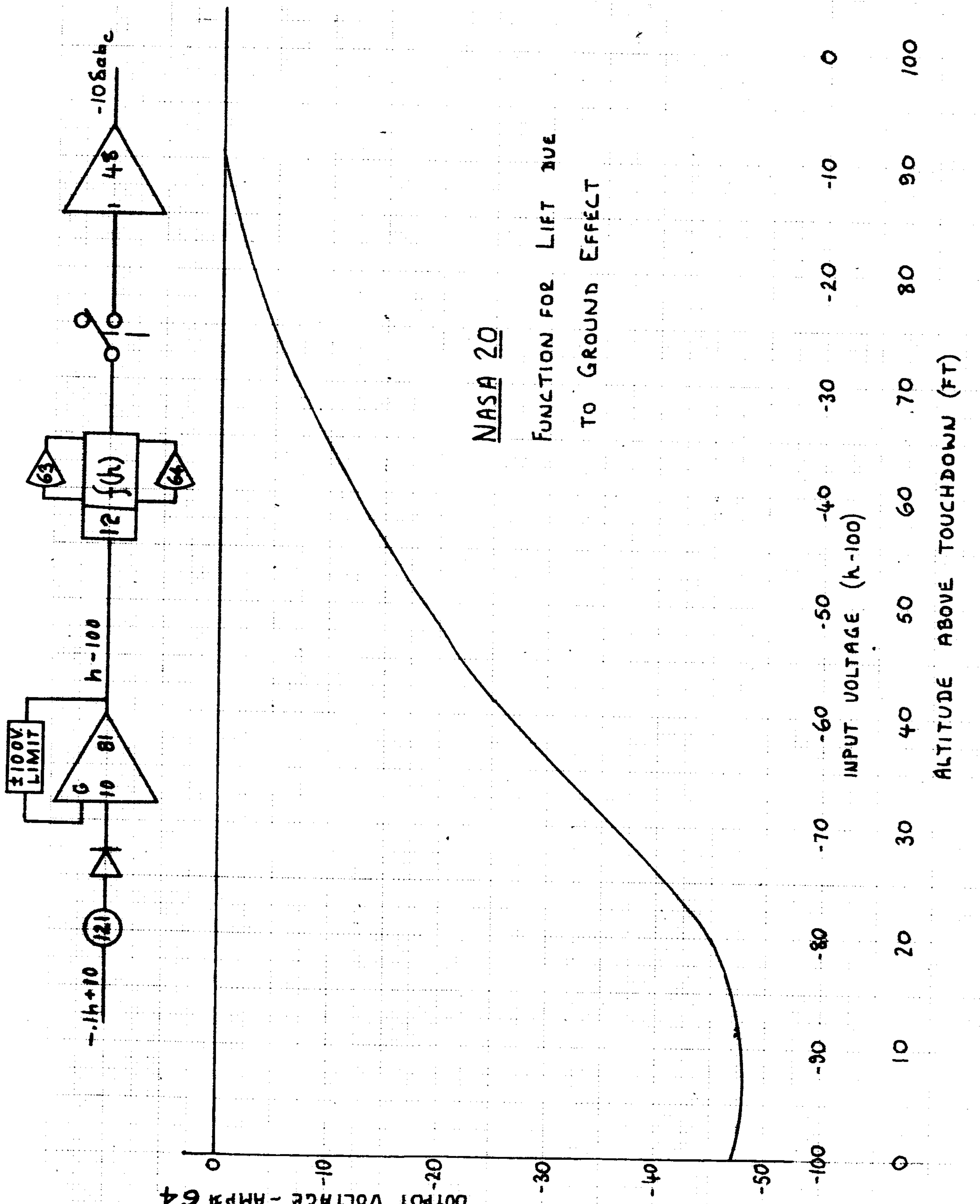
NASA 20°

POT #	SETTING
3	.323
6	.3333
8	.150
9	
10	
11	
12	
13	.000
14	1.000 [10]
15	.700 [10]
16	.160 [10]
17	.06 [10]
18	.262
19	.2075
20	.160 [10]
21	.497
22	.1395 [10]
23	.0795
24	.145 [10]
25	.3625
26	.1391 [10]
27	.2171
28	.198
29	.350
30	.770 [10]
31	.2254
32	.1362 [10]
33	.0244
34	.3929
35	.014
36	.313 [10]
37	.3535
38	.0053
39	.100
40	.400 [10]
41	.100
42	.313 [10]
43	.0157
44	.1127
45	.1648 [10]
46	.701
47	.0382
48	.0597
49	.0672
50	.0004
51	.1122
52	
53	.000
54	.0183
55	.260
56	.406
57	.925
58	.100
59	.500 [10]
60	.045
61	.160 [10]
62	.314
63	.500
64	.1922
65	.2615 [10]

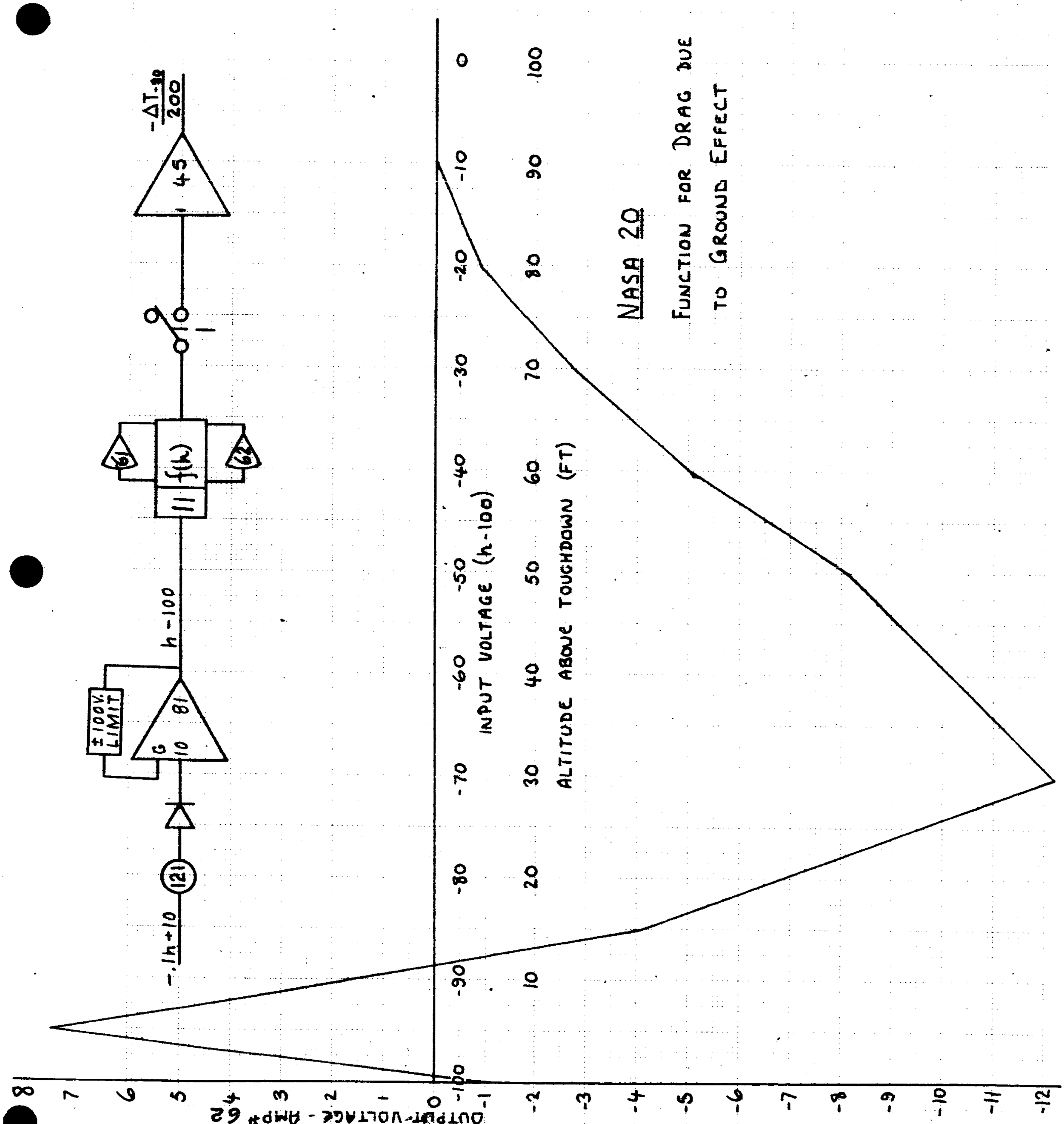
POT #	SETTING	
66	.798	
67	.177	.089*
68	.064	
69	.0725	
70	.000	
71	.350 [10]	
72	.360	
73	.2678 [10]	
74	.0565	
75	.0087	
76	.100	
77	.295	
78	.670 [10]	
79	.134 [10]	
80	.697	
81	.250 [10]	
82	.025	
83	.070	
84	.300	
85	.484	
86	.010	
87	.100	
88	.260 [10]	
89*	4.0 Volts	(LIMIT ON IUBD SPOILERS)
90	.60	with cable #4.14
91	.0166	RECORDER POTS
92	.1627	
93	.4610	
94	.1638	
95	.2263	
96	.9229	
97	.9046	
98	.3252	
99	.1875	
100	.3767	
101	.2234	
102	.1843	
103	.1841	
104	.0134	
105	.1861	
106	.144	
107	.4788 [10]	
108	.0178	
109	.363 [10]	
110	.000	
111	.0548	
112	.593	
113	.454 [10]	
114	.316 [10]	
115	.692	
116	.677 [10]	
117	.159 [10]	
118	.565	
119	.146 [10]	
120	.707 [10]	
121	1.00 [10]	
122	.30 [10]	
123	.30 [10]	
124	.0995	
125		

* SETTING REQUIRED FOR MATCHING



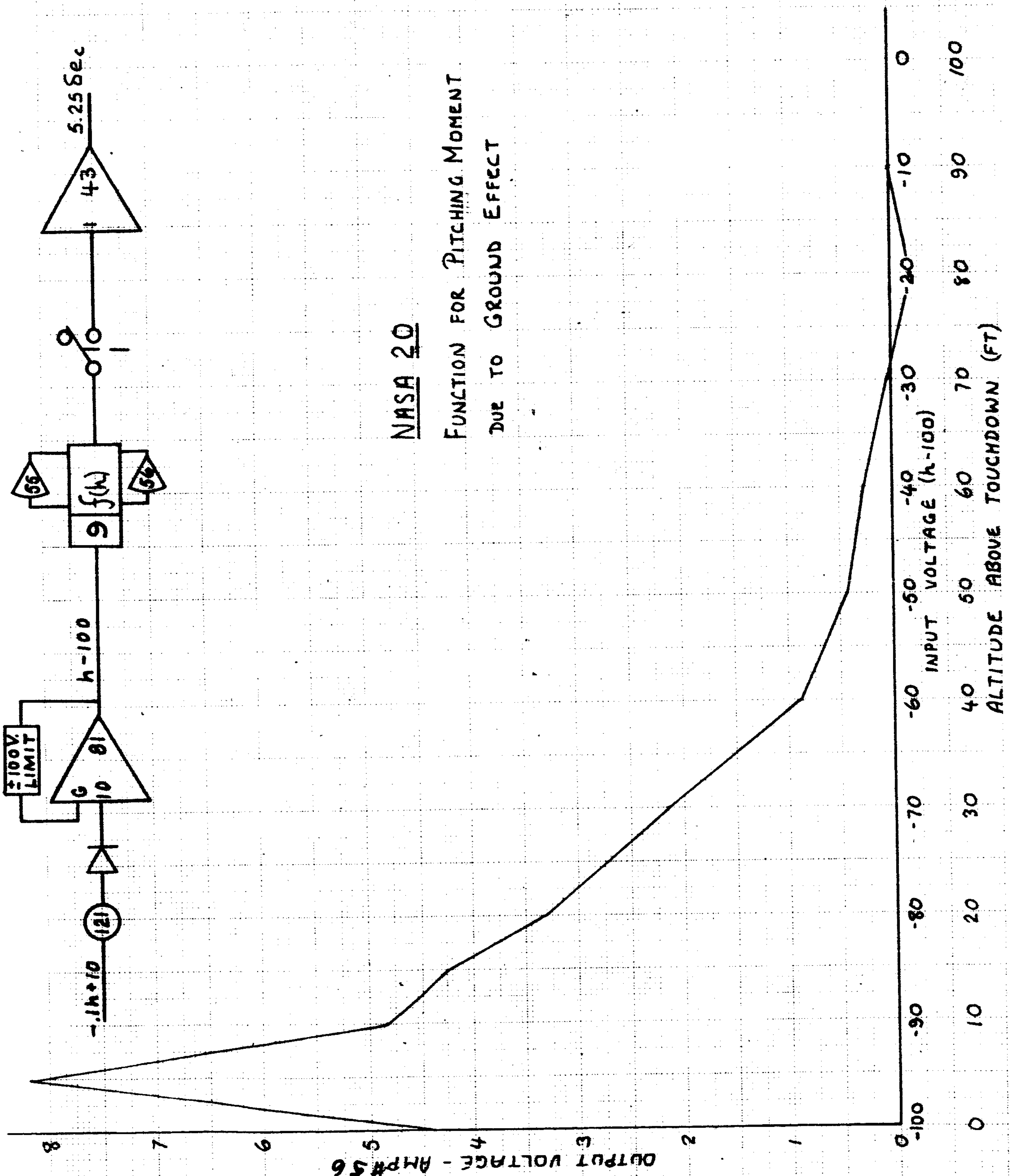
CALC			REVISED	DATE	NASA 20 - FUNCTION FOR LIFT DUE TO GROUND EFFECT	
CHECK						
APR						
APR					THE BOEING COMPANY	PAGE A34

TD 461 D



CALC		REVISED	DATE	NASA 20 - FUNCTION FOR DRAG DUE TO GROUND EFFECT	
CHECK					
APR					
APR				THE BOEING COMPANY	PAGE A35

TD 461 0



			REVISED	DATE		
CALC					NASA 20 - FUNCTION FOR PITCHING MOMENT DUE TO GROUND EFFECT	
CHECK						
APR						
APR					THE BOEING COMPANY	PAGE A36

		UNAUGMENTED			
			UNITS		
DRAG	$C_{D_{TRIM}}$	+.1165			
	C_{D_α}	+.515	/RAD		
	$C_{D_{\delta SAB}}$	−.00573	/RAD		
LIFT	$C_{L_{TRIM}}$	+.849			
	C_{L_α}	+4.9	/RAD		
	$C_{L_{\delta SAB}}$	−.688	/RAD		
PITCH	C_{m_α}	−1.008	/RAD		$C_{m_{\Delta T}}$
	$C_{m_{\dot\alpha}}$	−.261	/RAD/SEC		$C_{m_{\Delta V}}$
	C_{m_Q}	−.594	/RAD/SEC		
	$C_{m_{\delta e}}$	−.85	/RAD		
	$C_{m_{\delta SAB}}$	−.117	/RAD		
ROLL	C_{l_β}	−.1572	/RAD		
	C_{l_p}	−.1569	/RAD/SEC		
	C_{l_R}	+.0817	/RAD/SEC		
	$C_{l_{\delta a}}$	+.0809	/RAD		
	$C_{l_{\delta SP}}$	+.0468	/RAD		
	$C_{l_{\delta r}}$	+.0179	/RAD		
YAW	C_{n_β}	+.0797	/RAD		
	C_{n_p}	−.0225	/RAD/SEC		
	C_{n_R}	−.0467	/RAD/SEC		
	$C_{n_{\delta a}}$	+.0023	/RAD		
	$C_{n_{\delta SP}}$	+.0245	/RAD		
	$C_{n_{\delta r}}$	−.0725	/RAD		
	$C_{n_{\dot\beta}}$	−.043	/RAD/SEC		
SIDE FORCE	C_{Y_β}	−.831	/RAD		
	C_{Y_p}	+.1492	/RAD/SEC		
	C_{Y_R}	+.0865	/RAD/SEC		
	$C_{Y_{\delta a}}$	0			
	$C_{Y_{\delta SP}}$	−.039	/RAD		
	$C_{Y_{\delta r}}$	+.1712	/RAD		
	C_{Y_ϕ}	+.860	/RAD		

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SIMULATING NASA 20 — -80

WEIGHT 150,000 lbs
C.G. LOCATION 30% $\bar{c}$
ALTITUDE SEA LEVEL

DEPENDENT VARIABLES

q_{TRIM}	61.8
$q_{TRIM}S$	174,500
$THRUST_{TRIM}$	20,300 lbs
MASS	4660 SLUGS

MOMENTS OF INERTIA IN BODY AXES

$I_{xx} = 2.57 \times 10^6$ SLUG ft^2
$I_{yy} = 2.25 \times 10^6$ SLUG ft^2
$I_{zz} = 4.73 \times 10^6$ SLUG ft^2
$I_{xz} = 0.160 \times 10^6$ SLUG ft^2

FLIGHT CONDITION

FLAP SETTING 30°
BLOWING PRESSURE RATIO 1
SPEED BRAKE SETTING 6°
GEAR DOWN

$\frac{\Delta T}{\delta_{th}} = 861 \times 57.3 = 49300$ LB/RAD @ $\delta_{CLAM} = 30°$

$C_{\ell_{\delta w}} = +.0653$/RAD
$C_{n_{\delta w}} = +.0082$/RAD
$C_{Y_{\delta w}} = -.0128$/RAD

GEOMETRY

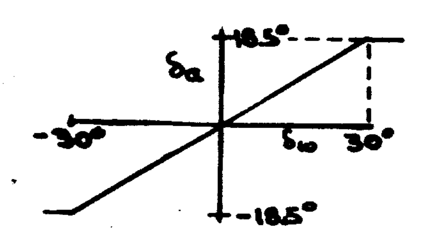
$S = 2821\ ft^2$
$\bar{c} = 20.1$ ft
$b = 130.8$ ft

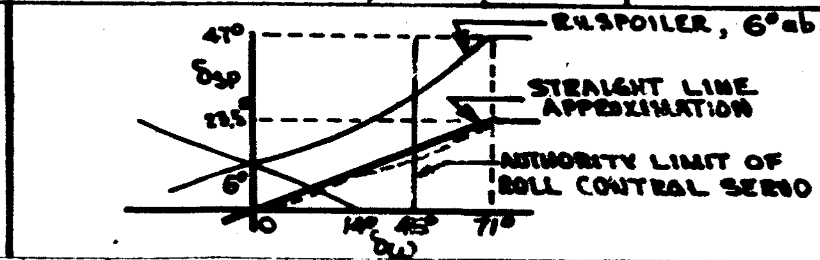
MODE SHAPES

SHORT PERIOD	$\omega_n =$ $\omega_D =$ $\zeta =$	RAD/SEC RAD/SEC
PHUGOID	$\omega_n =$ $\omega_D =$ $\zeta =$	RAD/SEC RAD/SEC
DUTCH ROLL	$\omega_n =$ $\omega_D =$ $\zeta =$	RAD/SEC RAD/SEC
ROLL T.C.		SEC
SPIRAL DIV. T.C.		SEC

TRIM

SPEED 135 Kts (228 ft/sec)
$\alpha_{TRIM_{BODY}} = 3.45°$ (.06 rad)
$\alpha_{TRIM_{WING}} = 5.45°$ (.095 rad)





CALC	12-4-4	REVISED	DATE
CHECK		BB	1-22-5
APR		D.E.G.	2-15-65
APR		D.E.G.	5-6-65
		D.E.G.	5-11-65

D.E.G. 5-14-65 B.B. 6-1-65
D.E.G. 5-16-65 B.B. 8-17-65
H.P.C. 5-21-65

VARIABLE STABILITY AIRPLANE DESCRIPTION

THE BOEING COMPANY

		UNAUGMENTED		AUGMENTED	
			UNITS		UNITS
DRAG	$C_{D_{TRIM}}$	+.115			
	C_{D_α}	+.418	/RAD		
LIFT	$C_{L_{TRIM}}$	+.893			
	C_{L_α}	+4.7	/RAD		
	$C_{L_{\delta E}}$	+.487	/RAD		
PITCH	C_{m_α}	−.4584	/RAD		
	$C_{m_{\dot\alpha}}$	−.1335	/RAD/SEC		
	C_{m_Q}	−.2149	/RAD/SEC	−.752	/RAD/SEC.
	$C_{m_{\delta E}}$	−.7163	/RAD		
	$C_{m_{\Delta T}}$	$+.231 \times 10^{-6}$	/LB		
ROLL	C_{l_β}	−.1547	/RAD		
	C_{l_p}	−.2269	/RAD/SEC	−.398	/RAD/SEC
	C_{l_R}	+.0744	/RAD/SEC		
	$C_{l_{\delta W}}$	+.1146	/RAD		
	$C_{l_{\dots}}$	0			
	$C_{l_{\delta R}}$	0			
YAW	C_{n_β}	+.2006	/RAD		
	C_{n_p}	−.0223	/RAD/SEC		
	C_{n_R}	−.0874	/RAD/SEC	−.24	/RAD/SEC
	$C_{n_{\delta W}}$	+.0424	/RAD		
	$C_{n_{\dot\beta}}$	0			
	$C_{n_{\delta R}}$	−.086	/RAD		
SIDE FORCE	C_{Y_β}	−.573	/RAD		
	C_{Y_p}	+.0253	/RAD/SEC		
	C_{Y_R}	+.093	/RAD/SEC		
	$C_{Y_{\delta W}}$	0			
	$C_{Y_{\dots}}$	0			
	$C_{Y_{\delta R}}$	+.1146	/RAD		

U3 4038 9000

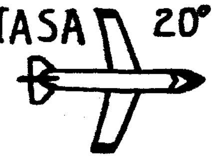
SOURCES:

367-80 CONFIGURATION FOR SIMULATION of NASA 20

-80 AERO # 96, UPDATED BY -80AERO # 131
-80 AERO # 132 (GR. EFF.)

SOURCES: NASA. AND C/S 733-AERO-217.

NASA 20°



WEIGHT	280,000
C.G. LOCATION	.46$\bar{c}$ (WINGS SWEPT)
ALTITUDE	SEA LEVEL

MOMENTS OF INERTIA IN BODY AXES

I_{xx}	2.86×10^6	SLUG FT^2
I_{YY}	17.57×10^6	SLUG FT^2
I_{zz}	20.00×10^6	SLUG FT^2
I_{xz}	0	

FLIGHT CONDITION

FLAP SETTING

WING SWEEP ANGLE $\Lambda_{L.E.} = 20°$

NOSE POSITION	UP
GEAR	DOWN

GEOMETRY

S 5,000 FT^2 (SWEPT REFERENCES)

$\bar{c}$ 70 FT

b 85 FT

TRIM

SPEED	135 KT	(228 FT/SEC)
α_{TRIM}	6.6 DEG	(.115 RAD)

ENGINE CHAR.

$$\frac{\Delta T}{\delta_{TH}} = \frac{170{,}000}{1 + S\tau_E} \quad LB/RAD$$

DEPENDENT VARIABLES

q_{TRIM} + 61.8

$q_{TRIM}S$ 309,000

$THRUST_{TRIM}$ 35,540 lbs.

MASS 8,696 SLUGS

(UNAUGMENTED) MODE SHAPES

SHORT PERIOD	ω_u = .886 RAD/SEC ω_D = .657 RAD/SEC ζ = +.672
PHUGOID	ω_u = .170 RAD/SEC ω_D = .170 RAD/SEC ζ = +.0193
DUTCH ROLL	ω_u = .628 RAD/SEC ω_D = .618 RAD/SEC ζ = +.186
ROLL T.C.	.48 SEC
SPIRAL DIV. T.C.	(D.A. = 254 SEC)

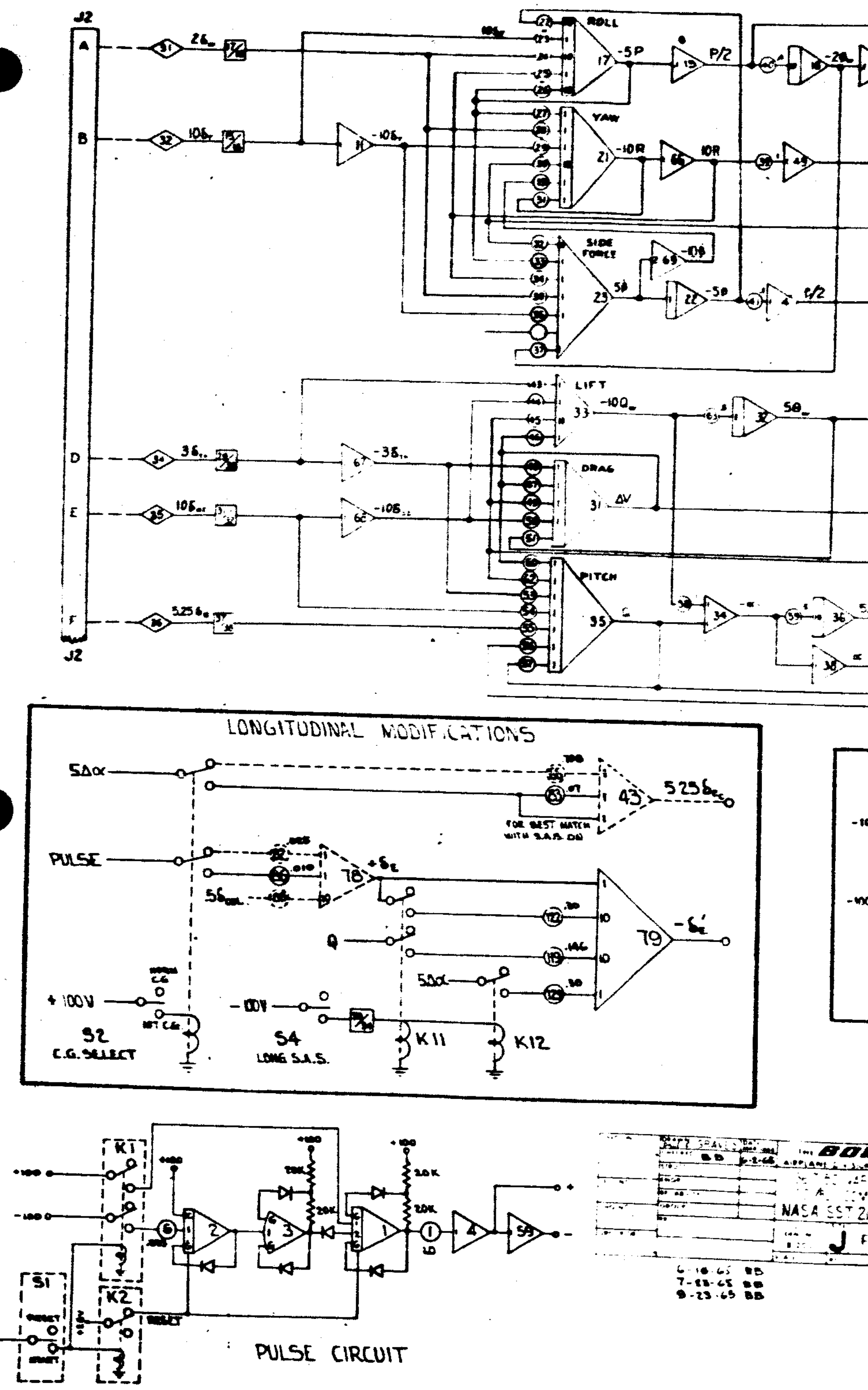
			REVISED	DATE
CALC	D.E.G.	2-3-65		
CHECK			D.E.G.	3-18-65
APR			H.P.C.	4-14-5
APR				

VARIABLE STABILITY AIRPLANE DESCRIPTION

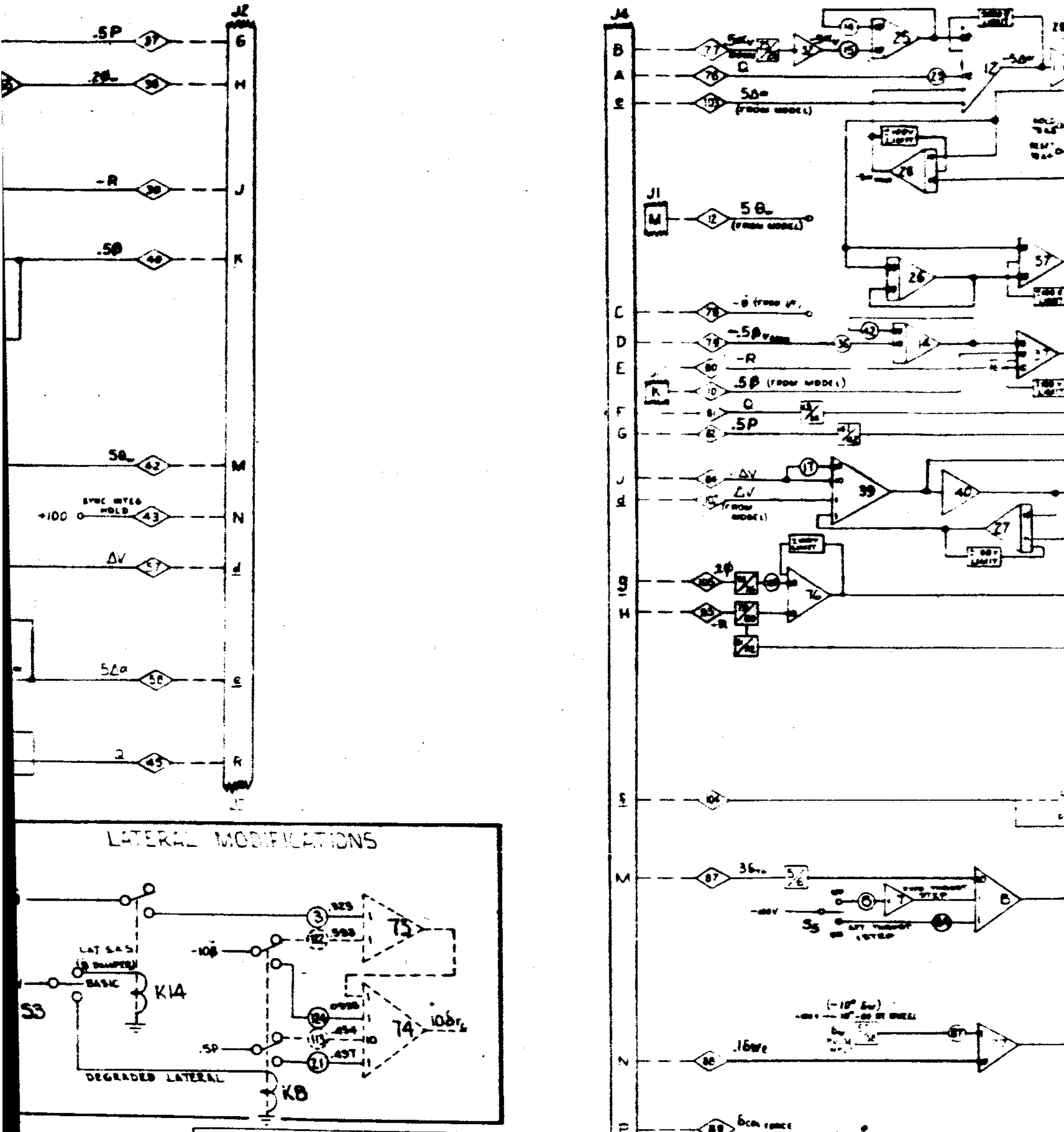
THE BOEING COMPANY

2

-80 MODEL



A-39-1

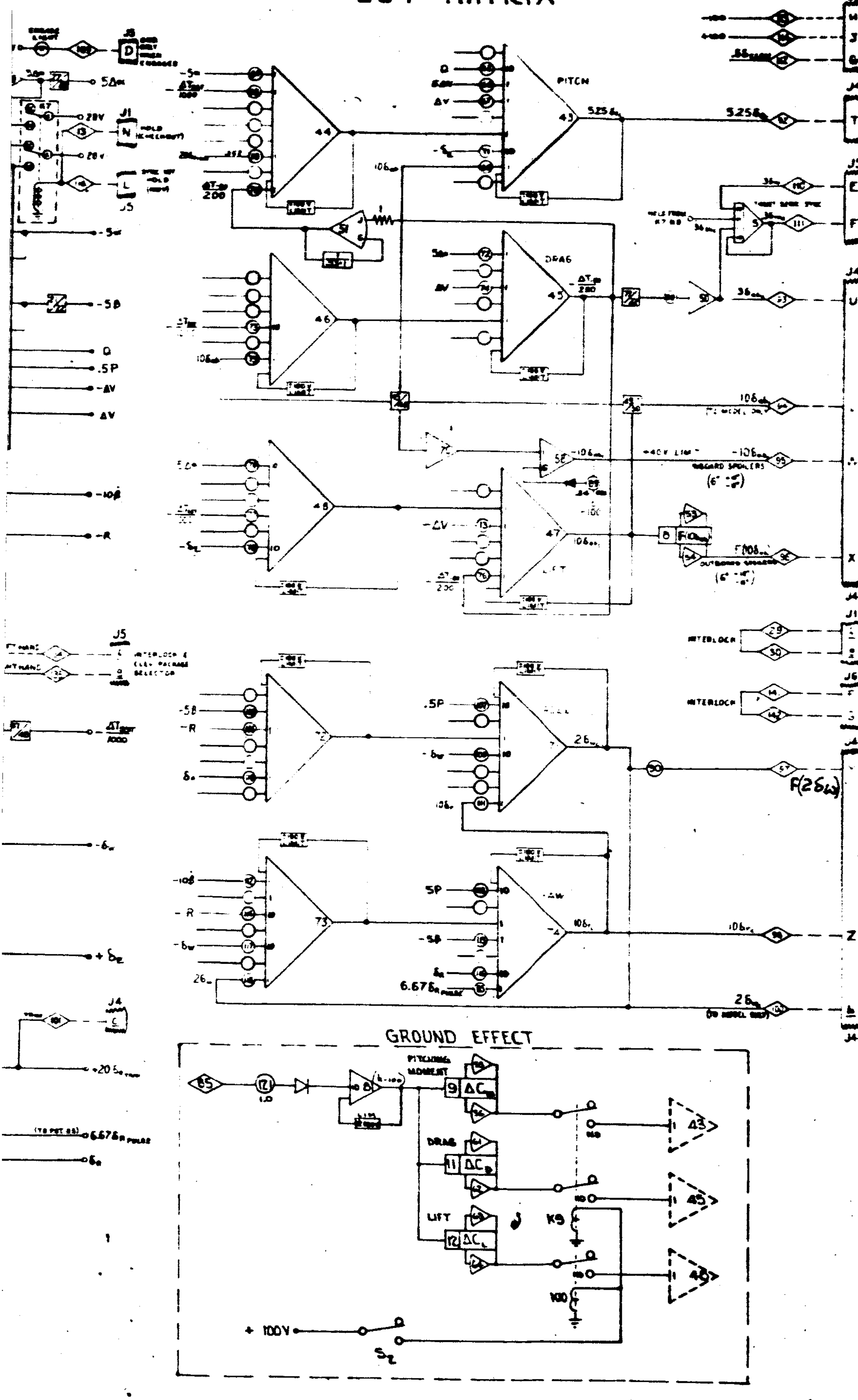


RECORDER								
VARIABLE	RANGE	SENSITIVITY	CHANNEL	POT NUMBER	POT SETTING	INPUT MODEL	INPUT SST	PULSE INPUTS
LONGITUDINAL								
[illegible]	[illegible]	[illegible]		91	.81[illegible]	A 47	A 4[illegible]	
Q	±4V	[illegible]/sec/in	3	93	.4610	A 35	13/14	
ΔV	±20V	[illegible]	6	96	.9507	A 31	A 40	
Δα	±20V	2°/in	7	97	.9086	A 36	27/28	
δ_e	±50V	5°/in	10	100	.3767	37/38	A 43	
[illegible]	±100V	[illegible]	[illegible]	[illegible]	.0104	29/30	A [illegible]	
[illegible]	±10V	10°/in	15	105	.1861	—	[illegible]	
LATERAL								
P	±10V	[illegible]/sec/in	2	[illegible]	[illegible]27	A [illegible]	[illegible]	
-R	±10V	5°/sec/in	4	[illegible]	.1633	A 40	[illegible]	
β	±8V	2.0°/in	5	95	.2263	A 44	75/76	
-φ	±50V	5°/in	8	[illegible]	.3252	A 22	21/22	
-φ̇	±100V	5°/sec/in	9	[illegible]	.1875	A [illegible]	A 75	
[illegible]	±50V	[illegible]/in	11	101	.2250	17/18	A 71	
[illegible]	±100V	5°/in	12	102	.048[illegible]	15/16	A 74	
PULSE	±100V		13	103	.1861	A 4(+) , A 5(-)		

A-39-2

SST MATRIX

D6-19856



NASA 20

APPENDIX B

DESCRIPTION AND CALCULATION SHEETS FOR

NASA Δ

~~LINEARIZED~~ EQUATIONS OF MOTION

$$I_{xx}\dot{P} = q_0 S b \left(C_{l_\beta} \times \beta + C_{l_P} \times P + C_{l_R} \times R + C_{l_{\delta\omega}} \times \delta\omega + C_{l_{\delta r}} \times \delta r\right)$$

$$I_{YY}\dot{Q} = q_0 S \bar{c} \left(C_{m_\alpha} \times \Delta\alpha + C_{m_{\dot{\alpha}}} \times \dot{\alpha} + C_{m_Q} \times Q + C_{m_{\delta e}} \times \delta e + C_{m_{\delta ab}} \times \delta ab + C_{m_{\Delta T}} \times \Delta T + C_{m_{\Delta V}} \times \Delta V\right)$$

$$I_{ZZ}\dot{R} = q_0 S b \left(C_{n_\beta} \times \beta + C_{n_P} \times P + C_{n_R} \times R + C_{n_{\delta\omega}} \times \delta\omega + C_{n_{\delta r}} \times \delta r\right)$$

$$\Delta\dot{V} = -\frac{\rho S}{m} V_0 C_{D_{TRIM}} \Delta V + \frac{1}{m}\Delta T - \frac{\rho S}{m}\frac{V_0^2}{2}\left(C_{D_\alpha}\Delta\alpha + C_{D_{\delta ab}} \times \delta ab\right) - g\,\theta_W$$

$$Q_W = \left(\frac{2g}{V_0^2} - \frac{T_0\alpha_0}{mV_0^2}\right)\Delta V + \left(\frac{\rho S}{2m} V_0 C_{L_\alpha} + \frac{T_0}{mV_0}\right)\Delta\alpha + \frac{\alpha_0}{mV_0}\Delta T + \frac{\rho S}{2m} V_0 C_{L_{\delta ab}} \times \delta_{ab}$$

$$R_W = \frac{\rho S}{m}\frac{V_0}{2}\left(C_{Y_\beta} \times \beta + C_{Y_P} \times P + C_{Y_R} \times R + C_{Y_{\delta\omega}} \times \delta\omega + C_{Y_{\delta r}} \times \delta r\right) + \frac{g}{V_0}\phi_W$$

$$\dot{\alpha} = Q - Q_W \quad ; \quad \Delta\alpha = \int \dot{\alpha}\, dt \quad ; \quad \theta_W = \int Q_W\, dt$$

$$\dot{\beta} = R_W - R \quad ; \quad \beta = \int \dot{\beta}\, dt \quad ; \quad \phi_W = \int P\, dt.$$

In these equations, the following variables are:

- in radians : $\Delta\alpha$, β, $\delta\omega$, δr, δe, δab, θ_W, ϕ_W
- in radians/sec : $\dot{\alpha}$, $\dot{\beta}$, P, Q, R, Q_W, R_W
- in feet/sec : ΔV
- in lbs : ΔT

These equations are derived from WADC, Technical Note 55-747 by R.M. Howe, June 1956.

They are valid for small perturbations around the trimmed level flight condition.

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Eliminating R_W and changing the units of the variables to the following:

in degrees : $\Delta\alpha$, β, $\delta\omega$, δr, δe, δab, θ_W, ϕ_W.

in degrees/sec : $\dot{\alpha}$, $\dot{\beta}$, P, Q, R, Q_W.

in feet/sec : ΔV

in pounds : ΔT

$$\dot{P} = \frac{q_0 S b}{I_{xx}} C_{\ell_\beta} * \beta + \frac{q_0 S b}{I_{xx}} C_{\ell_p} * P + \frac{q_0 S b}{I_{xx}} C_{\ell_R} * R + \frac{q_0 S b}{I_{xx}} C_{\ell_{\delta\omega}} * \delta\omega + \frac{q_0 S b}{I_{xx}} C_{\ell_{\delta r}} * \delta r$$

$$\dot{Q} = \frac{q_0 S \bar{c}}{I_{YY}} C_{m_\alpha} * \Delta\alpha + \frac{q_0 S \bar{c}}{I_{YY}} C_{m_{\dot{\alpha}}} * \dot{\alpha} + \frac{q_0 S \bar{c}}{I_{YY}} C_{m_Q} * Q + \frac{q_0 S \bar{c}}{I_{YY}} C_{m_{\delta e}} * \delta e + \frac{q_0 S \bar{c}}{I_{YY}} C_{m_{\delta ab}} * \delta ab + 57.3 \frac{q_0 S \bar{c}}{I_{YY}} C_{m_{\Delta T}} * \Delta T + \frac{q_0 S \bar{c}}{I_{YY}} 57.3\, C_{m_{\Delta V}} * \Delta V$$

$$\dot{R} = \frac{q_0 S b}{I_{zz}} C_{n_\beta} * \beta + \frac{q_0 S b}{I_{zz}} C_{n_p} * P + \frac{q_0 S b}{I_{zz}} C_{n_R} * R + \frac{q_0 S b}{I_{zz}} C_{n_{\delta\omega}} * \delta\omega + \frac{q_0 S b}{I_{zz}} C_{n_{\delta r}} * \delta r.$$

$$\Delta\dot{V} = -\frac{\rho S}{m} V_0 C_{D_{TRIM}} \Delta V + \frac{1}{m} \Delta T - \frac{\rho S}{m} \frac{V_0^2}{2 * 57.3} C_{D_\alpha} * \Delta\alpha - \frac{\rho S}{m} \frac{V_0^2}{2 * 57.3} C_{D_{\delta ab}} * \delta ab - \frac{g}{57.3} \theta_W$$

$$Q_W = \left[57.3 \left(\frac{2g}{V_0^2}\right) - \frac{T_0 \alpha_0}{m V_0^2}\right] \Delta V + \frac{\alpha_0}{m V_0} \Delta T + \left(\frac{\rho S}{2m} V_0 C_{L_\alpha} + \frac{T_0}{m V_0}\right) \Delta\alpha + \frac{\rho S}{2m} V_0 C_{L_{\delta ab}} * \delta ab$$

(α_0 in degrees)

$$\dot{\beta} = \frac{\rho S}{m} \frac{V_0}{2} C_{Y_\beta} * \beta + \frac{\rho S}{m} \frac{V_0}{2} C_{Y_P} * P + \frac{\rho S}{m} \frac{V_0}{2} C_{Y_R} * R + \frac{\rho S}{m} \frac{V_0}{2} C_{Y_{\delta\omega}} * \delta\omega + \frac{\rho S V_0}{m 2} C_{Y_{\delta r}} * \delta r + \frac{g}{V_0} \phi_W - R$$

$$\dot{\alpha} = Q - Q_W$$

$$\Delta\alpha = \int \dot{\alpha}\, dt \; ; \quad \beta = \int \dot{\beta}\, dt \; ; \quad \theta_W = \int Q_W\, dt \; ; \quad \phi_W = \int P\, dt.$$

In these equations, the aerodynamic and control coefficients have the following units:

/LB : $C_{m_{\Delta T}}$

/radian : C_{ℓ_β} ; $C_{\ell_{\delta\omega}}$; $C_{\ell_{\delta r}}$; C_{m_α} ; $C_{m_{\delta e}}$; $C_{m_{\delta ab}}$; C_{n_β} ; $C_{n_{\delta\omega}}$; $C_{n_{\delta r}}$; C_{D_α} ; $C_{D_{\delta ab}}$; C_{L_α} ; $C_{L_{\delta ab}}$; C_{Y_β} ; $C_{Y_{\delta\omega}}$; $C_{Y_{\delta r}}$.

sec/radian : C_{ℓ_p} ; C_{ℓ_R} ; $C_{m_{\dot{\alpha}}}$; C_{m_Q} ; C_{n_p} ; C_{n_R} ; C_{Y_P} ; C_{Y_R}

THE FOLLOWING SCALE FACTORS WILL BE USED

$$Q \;;\; 10\,Q_w \;;\; \dot{\alpha} \;;\; 5\,\Delta\alpha \;;\; 5\,\theta_w \;;\; \Delta V$$

$$.5\,P \;;\; 5\,\dot{\beta} \;;\; .5\,\beta \;;\; \phi_w \;;\; R$$

$$5\,\delta e \;;\; 10\,\delta ab \;;\; 10\,\delta r \;;\; 2\,\delta\omega \;;\; 3\,\delta th \quad \text{where } 3\delta th = \frac{\Delta T}{278}$$

δth in degrees

$$-10\,Q_w = -\left[573\left(\frac{2g}{V_o^2}\right) - \frac{10\,T_o\alpha_o}{mV_o^2}\right](\Delta V) + \left(\frac{\rho S}{m}V_o C_{L_\alpha} + \frac{2T_o}{mV_o}\right)(5\,\Delta\alpha)$$
$$+ \frac{2780\,\alpha_o}{mV_o}(3\delta th) + \frac{\rho S}{2m}V_o\left(-C_{L_{\delta ab}}\right)(-10\,\delta_{ab})$$

$$\Delta V = -\int\left[\frac{\rho S}{m}V_o C_{D_{TRIM}}(\Delta V) + \frac{278}{m}(-3\delta th) + \frac{\rho S}{m}\frac{V_o^2}{57.3}\frac{C_{D_\alpha}}{10}(5\,\Delta\alpha)\right.$$
$$\left. + \frac{\rho S}{m}\frac{V_o^2}{2\times 57.3}\frac{(-C_{D_{\delta ab}})}{10}(-10\,\delta ab) + \frac{2g}{573}(5\,\theta_w)\right]dt$$

$$Q = -\int\left[\frac{q_o S\bar{c}}{I_{YY}}\left(-\frac{C_{m_\alpha}}{5}\right)(5\,\Delta\alpha) + \frac{q_o S\bar{c}}{I_{YY}}(-C_{m_{\dot{\alpha}}})(+\dot{\alpha}) + \frac{q_o S\bar{c}}{I_{YY}}(-C_{m_Q})(Q) + \frac{q_o S\bar{c}}{I_{YY}}\left(-\frac{C_{m_{\delta e}}}{5}\right)(5\,\delta e)\right.$$
$$\left. + \frac{q_o S\bar{c}}{I_{YY}}57.3\,C_{m_{\Delta V}}(\Delta V) + \frac{q_o S\bar{c}}{I_{YY}}\left(-\frac{C_{m_{ab}}}{10}\right)(10\,\delta ab) + \frac{q_o S\bar{c}}{I_{YY}}(57.3\times 278\,C_{m_{\Delta T}})(-3\delta th)\right]dt$$

$$-\dot{\alpha} = -\left[Q + (.1)(-10\,Q_w)\right] \qquad 5\,\Delta\alpha = -\int\left[.5(10)(-\dot{\alpha})\right]dt$$

$$5\,\theta_w = -\int .5(-10\,Q_w)\,dt$$

ENGR	Jan. 29 HPC.	REVISED	DATE	-80 Variable Stability AIRPLANE MODEL	NASA Δ
CHECK		3-3-65	HPC.		
APR		3-27-65	HPC.	LONGITUDINAL SYST. OF EQUATIONS	
APR		4-7-65	HPC.		
		6-16-65	HPC.	THE BOEING COMPANY RENTON, WASHINGTON	B 3

TD 1017-R6

ROTATIONS, BODY AXES

$$I_{xx}\dot{P} = (I_{YY} - I_{ZZ})QR + I_{XZ}(\dot{R} + PQ) + T_x + L$$

$$I_{YY}\dot{Q} = (I_{ZZ} - I_{xx})RP + I_{XZ}(R^2 - P^2) + T_Y + M$$

$$I_{ZZ}\dot{R} = (I_{xx} - I_{YY})PQ + I_{xz}(\dot{P} - QR) + T_Z + N$$

ROTATIONS, STABILITY AXES

$$I'_{xx}\dot{P}_s = (I'_{YY} - I'_{ZZ})Q_sR_s + I'_{xz}(\dot{R}_s + P_sQ_s) + T_x + L_s$$

$$I'_{YY}\dot{Q}_s = (I'_{ZZ} - I'_{xx})R_sP_s + I'_{xz}(R_s^2 - P_s^2) + T_Y + M_s$$

$$I'_{ZZ}\dot{R}_s = (I'_{xx} - I'_{YY})P_sQ_s + I'_{xz}(\dot{P}_s - Q_sR_s) + T_Z + N_s$$

Where

$$P_s = P\cos\alpha + R\sin\alpha$$
$$Q_s = Q$$
$$R_s = -P\sin\alpha + R\cos\alpha$$

$$I'_{xx} = I_{xx}\cos^2\alpha + I_{ZZ}\sin^2\alpha - 2I_{xz}\sin\alpha\cos\alpha$$

$$I'_{YY} = I_{YY}$$

$$I'_{ZZ} = I_{ZZ}\cos^2\alpha + I_{xy}\sin^2\alpha + 2I_{xz}\sin\alpha\cos\alpha$$

$$I'_{xz} = (I_{xx} - I_{ZZ})\sin\alpha\cos\alpha + I_{xz}(\cos^2\alpha - \sin^2\alpha)$$

NEGLECTING THE NON-LINEAR TERMS:

$P_s Q_s$; $Q_s R_s$; $R_s P_s$; P_s^2 ; R_s^2 ;

ASSUMING SYMMETRICAL THRUST;

$T_x = 0$; $T_z = 0$

and SINCE THE TERM T_y IS ACCOUNTED FOR BY THE EQUIVALENT AERODYNAMIC COEFFICIENT $C_{m_{\Delta T}}$:

$$I'_{xx} \dot{P}_s = I'_{xz} \dot{R}_s + L_s$$

$$I_{YY} \dot{Q} = M$$

$$I'_{zz} \dot{R}_s = I'_{xz} \dot{P}_s + N_s$$

ISOLATING $\dot{P}_s$ and $\dot{R}_s$

$$\dot{P}_s = \frac{\frac{1}{I'_{xx}} L_s + \frac{I'_{xz}}{I'_{xx} I'_{zz}} N_s}{1 - \frac{I'^2_{xz}}{I'_{xx} I'_{zz}}} = \frac{1}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}} \left(L_s + \frac{I'_{xz}}{I'_{zz}} N_s \right)$$

$$\dot{R}_s = \frac{\frac{1}{I'_{zz}} N_s + \frac{I'_{xz}}{I'_{xx} I'_{zz}} L_s}{1 - \frac{I'^2_{xz}}{I'_{xx} I'_{zz}}} = \frac{1}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}} \left(N_s + \frac{I'_{xz}}{I'_{xx}} L_s \right)$$

IN ORDER TO INCLUDE IN THE SIMULATION THE EFFECT OF THE CROSS-PRODUCT OF INERTIA, I_{xz}, THE FOLLOWING TECHNIQUE IS PROPOSED:

1. CONVERT THE MOMENTS OF INERTIA I_{xx}, I_{yy}, I_{zz}, I_{xz} FROM BODY AXES TO STABILITY AXES I'_{xx}, I_{yy}, I'_{zz}, I'_{xz} USING (α_{TRIM}) IN THE FORMULAE OF PAGE 1

   — FOR BOTH -80 AND SST AIRPLANES —

2. IN THE ROLL AND YAW EQUATIONS, REPLACE THE ROLLING AND YAWING MOMENTS OF INERTIA I_{xx} and I_{zz} by:

$$I'_{xx} - \frac{{I'_{xz}}^2}{I'_{zz}} \quad \text{AND} \quad I'_{zz} - \frac{{I'_{xz}}^2}{I'_{xx}} \text{, respectively.}$$

   — FOR BOTH -80 AND SST AIRPLANES —

3. IN THE ROLL AND YAW EQUATIONS, REPLACE THE AERODYNAMIC AND CONTROL COEFFICIENTS AS FOLLOWS:

REPLACE C_{ℓ_β} BY $C_{\ell_\beta} + \frac{I'_{xz}}{I'_{zz}} C_{n_\beta}$

C_{ℓ_p} BY $C_{\ell_p} + \frac{I'_{xz}}{I'_{zz}} C_{n_p}$

etc...

C_{n_β} BY $C_{n_\beta} + \frac{I'_{xz}}{I'_{xx}} C_{\ell_\beta}$

C_{n_p} BY $C_{n_p} + \frac{I'_{xz}}{I'_{xx}} C_{\ell_p}$

etc....

— FOR BOTH -80 AND SST AIRPLANES —

$q_o S = 174{,}500$

$q_o S b = (61.8)(2821)(130.8) = 2.28 \times 10^7$

$q_o S \bar{c} = (61.8)(2821)(20.0) = 3.52 \times 10^6$

$$\frac{q_o S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}} = 8.92$$

$$\frac{q_o S \bar{c}}{I_{YY}} = \frac{3.52 \times 10^6}{2.25 \times 10^6} = 1.565$$

$$\frac{q_o S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}} = 4.83$$

$m V_o =$

$$\frac{\alpha_o}{m V_o} = \frac{5.45}{(4660)(228)} = 5.12 \times 10^{-6}$$

$\alpha_o = \alpha_{WING,TRIM}$ (DEGREES)

$$\frac{T_o \alpha_o}{m V_o^2} = \frac{(20{,}300)(5.45)}{(4660)(228)(228)} = 4.56 \times 10^{-4}$$

$$\frac{T_o}{m V_o} = \frac{20{,}300}{(4660)(228)} = .0191$$

$\rho = .002378$ SLUGS/ft^3

$\rho S = (.002378)(2821) = 6.71$

$$\frac{\rho S}{m} = \frac{6.71}{4660} = .001438$$

$$\frac{\rho S}{m}\frac{V_o}{2} = \frac{(.00144)(228)}{2} = .1642$$

$$\frac{\rho S}{m}\frac{V_o^2}{2} = (.1642)(228) = 37.4$$

$$\frac{g}{V_o} = \frac{32.2}{228} = .1413$$

$$\frac{2g}{V_o^2} = \frac{.1413}{228} = .00062$$

ENGR H. P-C	D.E.G. 3-18-65 / H.P.C. 6-16-65	-80 VARIABLE STABILITY AIRPLANE MODEL AIRBORNE COMPUTER	NASA Δ
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6-7000

	POTENTIOMETER NO.	SETTING	VARIABLE	For work in STABILITY AXES, change ROLL and YAW terms below to: $-\frac{q_o S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}}\left(C_{l_\beta} + \frac{I'_{xz}}{I'_{zz}} C_{n_\beta}\right)$ * ← Typical
ROLL AMPL. 17	22	$.1397^{10}$	-5β	$-C_{l_\beta}\frac{q_o S b}{I'_{xx}} = (-)(-.1566)(8.92) = 1.397$
	23	.0798	$+10\delta_r$	$.5\,C_{l_{\delta_r}}\frac{q_o S b}{I'_{xx}} = (.5)(.0179)(8.92) = .07983$
	24	$.1458^{10}$	$+2\delta_w$	$2.5\,C_{l_{\delta_w}}\frac{q_o S b}{I'_{xx}} = (2.5)(.0654)(8.92) = 1.4584$
	25	.0968	$+10R$	$\frac{C_{l_R}}{2}\frac{q_o S b}{I'_{xx}} = (.5)(.0217)(8.92) = .0968$
	26	$.1399^{10}$	$-5P$	$-C_{l_P}\frac{q_o S b}{I'_{xx}} = (-)(-.1568)(8.92) = 1.3987$
YAW AMPL. 21	27	.2347	$-5P$	$-2C_{n_P}\frac{q_o S b}{I'_{zz}} = (-)(2)(.0243)(4.83) = .2347$
	28	.2149	$+2\delta_w$	$5C_{n_{\delta_w}}\frac{q_o S b}{I'_{zz}} = (5)(.0089)(4.83) = .2149$
	29	.3492	$-10\delta_r$	$-C_{n_{\delta_r}}\frac{q_o S b}{I'_{zz}} = (-)(-.0723)(4.83) = .3492$
	30	$.9061^{10}$	$+.5\beta$	$20C_{n_\beta}\frac{q_o S b}{I'_{zz}} = (20)(.0938)(4.83) = 9.061$
	19	.1662	$-10\dot{\beta}$	$-C_{n_{\dot\beta}}\frac{q_o S b}{I'_{zz}} = (-)(-.0344)(4.83) = .1662$
	31	.2241	$-10R$	$-C_{n_R}\frac{q_o S b}{I'_{zz}} = (-)(-.0464)(4.83) = .2241$
SIDE FORCE AMPL. 23	32	$.1365^{10}$	$+.5\beta$	$-10C_{Y_\beta}\frac{\rho S}{m}\frac{V_o}{2} =$
	33	.0245	$-5P$	$C_{Y_P}\frac{\rho S}{m}\frac{V_o}{2} =$
	34	.4929	$+10R$	$-\frac{C_{Y_R}}{2}\frac{\rho S}{m}\frac{V_o}{2} + \frac{1}{2} =$
	38	.0053	$+2\delta_w$	$-2.5C_{Y_{\delta_w}}\frac{\rho S}{m}\frac{V_o}{2} =$
	35	.0141	$-10\delta_r$	$.5C_{Y_{\delta_r}}\frac{\rho S}{m}\frac{V_o}{2} =$
	37	.3535	$-2\phi_w$	$2.5\frac{g}{V_o} =$

* SEE PAGE 15 FOR OTHER DERIVATIONS

	H. P-C	6-16-65			-80 VARIABLE STABILITY AIRPLANE MODEL AIRBORNE COMPUTER
			D.E.G.	9-10-65	NASA Δ
			D.E.G.	3-27-65	
			D.E.G.	3-30-65	THE BOEING COMPANY RENTON, WASHINGTON
			D.E.G.	5-17-65	B9

TD 1017-R6 6-7000

	POTENTIOMETER NO.	POTENTIOMETER SETTING	VARIABLE	
LIFT AMPL. 33	43	.0142	$+3\delta_{th}$	$\frac{2780\,\alpha_0}{m\,V_0} = \frac{(2780)(5.45)}{(4660)(228)} = .0142$
	44	.1130	$-10\delta_{ab}$	$\frac{\rho S}{m}\frac{V_0}{2}(-C_{L\delta_{ab}}) = (-)(.1642)(-.688) = .113$
	45	$.1648^{10}$	$+5\Delta\alpha$	$\frac{\rho S}{m}V_0\,C_{L\alpha} + \frac{2T_0}{mV_0} = (.1642)(2)(4.9)+2(.0191) = 1.648$
	46	.7004	$+\Delta V$	$573\left(\frac{2g}{V_0^2}\right) - \frac{10T_0\alpha_0}{mV_0^2} = 573[(.00072)(.849)+.00062]-.00456$
				$= .705 - .00456 = .7004$
				α_0 IN DEGREES
DRAG AMPL. 31	48	.0597	$-3\delta_{th}$	$\frac{278}{m} = \frac{278}{4660} = .0597$
	47	.0383	$+\Delta V$	$\frac{\rho S}{m}V_0\,C_{D_{TRIM}} = (.1642)(2)(.1165) = .0383$
	49	.0673	$+5\Delta\alpha$	$\frac{\rho S}{m}\frac{V_0^2}{57.3}\frac{C_{D\alpha}}{10} = \frac{(37.4)(2)(.515)}{573} = .06725$
	50	.0004	$-10\delta_{ab}$	$\frac{\rho S}{m}\frac{V_0^2}{2\times573}\frac{(-C_{D\delta_{ab}})}{10} = \frac{-(-.00573)(37.4)}{573} = .000374$
	51	.1125	$+5\theta_w$	$\frac{2g}{573} = \frac{64.4}{573} = .1125$
PITCH AMPL. 35	62	.3155	$+5\Delta\alpha$	$-C_{m\alpha}\frac{q_0S\bar{c}}{5I_{YY}} = (-)(-1.008)(.2)(1.565) = .3155$
	53	.0107	$-3\delta_{th}$	$+C_{m_{\Delta T}}\frac{q_0S\bar{c}}{I_{YY}}57.3\times278 = (278)(57.3)(4.29\times10^{-7})(1.565) = .0107$
	54	.0183	$+10\delta_{ab}$	$-C_{m\delta_{ab}}\frac{q_0S\bar{c}}{10I_{YY}} = (-)(-.117)(.1565) = .0183$
	55	.2535	$+5.25\delta_e$	$-\frac{C_{m\delta_e}}{5.25}\frac{q_0S\bar{c}}{I_{YY}} = -\frac{(-.85)(1.565)}{5.25} = .2535$
	56	.4080	$+\dot\alpha$	$-C_{m\dot\alpha}\frac{q_0S\bar{c}}{I_{YY}} = -(-.261)(1.565) = .4080$
	57	.820	$+Q$	$-C_{mQ}\frac{q_0S\bar{c}}{I_{YY}} = -(-.524)(1.565) = .820$
	60	.0225	$+\Delta V$	$-57.3\frac{q_0S\bar{c}}{I_{YY}}C_{m_{\Delta V}} = -(-.00025)(57.3)(1.565) = .0225$

		REVISED	DATE		
ENGR	H. P. C 6-16-65	D.E.G	9-18-65	-80 VARIABLE STABILITY AIRPLANE MODEL AIRBORNE COMPUTER	NASA Δ
CHECK		D.E.G.	3-27-66		
APR		H.P.C.	4-7-66	THE BOEING COMPANY RENTON, WASHINGTON	B 10
APR		D.E.G.	5-17-66		

POTENTIOMETER NO.	SETTING		VARIABLE	CALCULATED FROM
39	.1	A49	$+10R$	$\frac{R}{10R} = .1$
40	~~.4~~ 10	A18	$+.5P$	$\frac{P}{.25P} = 4$
41	.1	A24	-5β	$\frac{-.5\beta}{-5\beta} = .1$
58	.1	A34	$-10Q_w$	$\frac{-Q_w}{-10Q_w} = .1$
59	~~.5~~ 10	A36	$-\dot{\alpha}$	$\frac{-5\dot{\alpha}}{-\dot{\alpha}} = 5$
63	.5	A32	$-10Q_w$	$\frac{-5Q_w}{-10Q_w} = .5$
12	1.0	A34	$+Q$	SCALE

DRAG AXIS ; UNITS : LBS

$$\Delta T_{-80} = \Delta T_{-80_{\Delta V}} \times \Delta V + \Delta T_{-80_{\Delta T_{SST}}} \times \Delta T_{SST} + \Delta T_{-80_{\delta ab}} \times \delta ab + \Delta T_{-80_{\Delta\alpha}} \times \Delta\alpha$$

LIFT AXIS ; UNITS : DEGREES

$$\delta ab = \delta ab_{\Delta\alpha} \times \Delta\alpha + \delta ab_{\Delta T_{SST}} \times \Delta T_{SST} + \delta ab_{\Delta T_{-80}} \times \Delta T_{-80} + \delta ab_{\delta E} \times \delta E + \delta ab_{\delta e} \times \delta e + \delta ab_{\Delta V} \times \Delta V$$

PITCH AXIS ; UNITS : DEGREES

$$\delta e = \delta e_{\Delta T_{SST}} \times \Delta T_{SST} + \delta e_{\Delta T_{-80}} \times \Delta T_{-80} + \delta e_{\Delta V} \times \Delta V + \delta e_{\Delta\alpha} \times \Delta\alpha + \delta e_{\dot\alpha} \times \dot\alpha$$
$$+ \delta e_{Q} \times Q + \delta e_{\delta ab} \times \delta ab + \delta e_{\delta E} \times \delta E$$

ROLL AXIS ; UNITS : DEGREES

$$\delta\omega = \delta\omega_{\beta} \times \beta + \delta\omega_{P} \times P + \delta\omega_{R} \times R + \delta\omega_{\delta W} \times \delta W + \delta\omega_{\delta R} \times \delta R + \delta\omega_{\delta r} \times \delta r$$

YAW AXIS ; UNITS : DEGREES

$$\delta r = \delta r_{\beta} \times \beta + \delta r_{\dot\beta} \times \dot\beta + \delta r_{P} \times P + \delta r_{R} \times R + \delta r_{\delta W} \times \delta W + \delta r_{\delta R} \times \delta R + \delta r_{\delta\omega} \times \delta\omega$$

SIDE FORCE AXIS ; UNITS : DIMENSIONLESS.

$$\Delta C_Y = \Delta C_{Y_\beta} \times \beta + \Delta C_{Y_P} \times P + \Delta C_{Y_R} \times R + \Delta C_{Y_{\delta W}} \times \delta W + \Delta C_{Y_{\delta R}} \times \delta R + \Delta C_{Y_{\delta\omega}} \times \delta\omega + \Delta C_{Y_{\delta r}} \times \delta r$$

THE FOLLOWING VARIABLES ARE IN DEGREES $\left\{ \begin{array}{l} \delta e ; \delta r ; \delta\omega ; \delta ab ; \Delta\alpha ; \beta . \\ \delta E ; \delta R ; \delta W ; \end{array} \right.$

IN DEGREES PER SECOND : $P ; Q ; R ; \dot\beta ; \dot\alpha$

IN POUNDS : $\Delta T_{-80} ; \Delta T_{SST}$

IN FEET PER SECOND : ΔV

			REVISED	DATE		
ENGR	Jan. 65	HPC.			-80 Variable Stability	NASA Δ
CHECK	Apr. 5. 65	HPC			DEFINITION OF AIRBORNE COMPUTER	
APR					COEFFICIENTS	
APR						
					THE BOEING COMPANY RENTON, WASHINGTON	B 12

SST AIRPLANE.

$$I'_{xx} = I_{xx}\cos^2\alpha + I_{zz}\sin^2\alpha - 2I_{xz}\sin\alpha\cos\alpha$$

$$I'_{xx} = (2.222\times10^6)(.978^2) + (20\times10^6)(.208^2) - 0 = 2.125\times10^6 + 0.865\times10^6 = \underline{\underline{2.99\times10^6}}$$

$$I'_{zz} = I_{zz}\cos^2\alpha + I_{xx}\sin^2\alpha + 2I_{xz}\sin\alpha\cos\alpha$$

$$I'_{zz} = (20\times10^6)(.978^2) + (2.222\times10^6)(.208^2) + 0 = 19.14\times10^6 + .0963\times10^6 = \underline{\underline{19.236\times10^6}}$$

$$I'_{xz} = (I_{xx} - I_{zz})\sin\alpha\cos\alpha + I_{xz}(\cos^2\alpha - \sin^2\alpha)$$

$$I'_{xz} = (2.222-20)(10^6)(.208)(.978) + 0 = (-17.778)(.208)(.978)(10^6) = \underline{\underline{-3.615\times10^6}}$$

$\alpha = \alpha_{TRIM,\,BODY} = 12^\circ$

$$\frac{q_o S\bar{c}}{I_{yy}} = \frac{(494{,}472)(89)}{18.11\times10^6} = \frac{4.41\times10^7}{18.11\times10^6} = \underline{\underline{2.433}}$$

$$\frac{q_o S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}} = \frac{(494{,}472)(111)}{\left(2.99 - \frac{13.08}{19.236}\right)\times10^6} = \frac{5.495\times10^7}{(2.995-.679)\times10^6} = \frac{54.9\times10^6}{2.316\times10^6} = \underline{\underline{23.7}}$$

$$\frac{q_o S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}} = \frac{54.95\times10^6}{\left(19.236 - \frac{13.08}{2.99}\right)\times10^6} = \frac{54.95\times10^6}{14.866\times10^6} = 3.695$$

$$\frac{q_o S}{m} = \frac{494{,}472}{8696} = 56.9$$

$$\left(\frac{I'_{xz}}{I'_{zz}}\right)_{SST} = \frac{-3.615\times10^6}{19.236\times10^6} = -.1878$$

$$\left(\frac{I'_{xz}}{I'_{xx}}\right)_{SST} = \frac{-3.615\times10^6}{2.99\times10^6} = -1.21$$

-80 AIRPLANE

$$\left(\frac{I'_{xz}}{I'_{zz}}\right)_{-80} = \frac{+.0294\times10^6}{4.739\times10^6} = +.0062$$

$$\left(\frac{I'_{xz}}{I'_{xx}}\right)_{-80} = \frac{+.0294\times10^6}{2.558\times10^6} \quad +.0115$$

			REVISED	DATE		
ENGR.	May 7 65	HPC.			-80 Variable Stability DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS	NASA Δ
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367-80 AIRPLANE

$$I'_{xx} = I_{xx}\cos^2\alpha + I_{zz}\sin^2\alpha - 2\,I_{xz}\sin\alpha\cos\alpha$$

$$I'_{xx} = (2.57\times10^6)(.9982^2) + (4.73\times10^6)(.0602^2) - 2(.160\times10^6)(.0602)(.9982) =$$
$$(2.57\times10^6)(.9964) + .01713\times10^6 - 2(.00961\times10^6) = 2.57813^{\times10^6} - .01922^{\times10^6} = \underline{\underline{2.5589\times10^6}}$$

$$I'_{zz} = I_{zz}\cos^2\alpha + I_{xx}\sin^2\alpha + 2\,I_{xz}\sin\alpha\cos\alpha$$

$$I'_{zz} = (4.73\times10^6)(.9964) + (2.57\times10^6)(.0036) + 2(.160\times10^6)(.0602)(.9982) =$$
$$(4.7129\times10^6) + (.00925\times10^6) + (.01923\times10^6) = \underline{\underline{4.7414\times10^6}}$$

$$I'_{xz} = (I_{xx} - I_{zz})\sin\alpha\cos\alpha + I_{xz}(\cos^2\alpha - \sin^2\alpha)$$

$$I'_{xz} = (-2.16\times10^6)(.0602)(.9982) + .160\times10^6(.9982^2 - .0602^2) =$$
$$(-.1298\times10^6) + (.1588\times10^6) = \underline{\underline{+.0290\times10^6}}$$

$\alpha = \alpha_{TRIM,\,BODY} = 3.45^\circ$

$$\frac{q_0 S\bar{c}}{I_{YY}} = \frac{(61.8)(2821)(20.1)}{2.25\times10^6} = \underline{\underline{1.56}}$$

$$\frac{q_0 S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}} = \frac{(61.8)(2821)(130.8)}{\left(2.5589 - \frac{.00084}{4.7414}\right)\times10^6} = \frac{22.8\times10^6}{2.5587\times10^6} = \underline{\underline{8.91}}$$

$$\frac{q_0 S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}} = \frac{(61.8)(2821)(130.8)}{\left(4.7414 - \frac{.00084}{2.5589}\right)\times10^6} = \frac{22.8\times10^6}{4.74107\times10^6} = \underline{\underline{4.809}}$$

$$\frac{q_0 S}{m} = \frac{(61.8)(2821)}{4660} = \underline{\underline{37.45}}$$

PITCH	$K_{PITCH} = \dfrac{\left.\frac{q_0 S\bar{c}}{I_{YY}}\right]_{SST}}{\left.\frac{q_0 S\bar{c}}{I_{YY}}\right]_{-80}} = \dfrac{2.433}{1.56} = 1.5596$	ROLL	$K_{ROLL} = \dfrac{\left.\frac{q_0 S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}}\right]_{SST}}{\left.\frac{q_0 S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}}\right]_{-80}} = \dfrac{23.7}{8.91} = 2.66$
LIFT, DRAG	$K_{LIFT\,DRAG} = \dfrac{\left.\frac{q_0 S}{m}\right]_{SST}}{\left.\frac{q_0 S}{m}\right]_{-80}} = \dfrac{56.9}{37.45} = 1.519$	YAW	$K_{YAW} = \dfrac{\left.\frac{q_0 S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}}\right]_{SST}}{\left.\frac{q_0 S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}}\right]_{-80}} = \dfrac{3.695}{4.809} = .768$

ENGR.	May 7.65	HPC.	REVISED	DATE	-80 Variable Stability DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS	NASA Δ
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		SST NASA Δ		-80	
$\delta\omega_\beta$	$C_{l_\beta} + \frac{I'_{xz}}{I'_{zz}} C_{n_\beta}$	$-.1071$	$C_{l_{\delta w}} + \frac{I'_{xz}}{I'_{zz}} C_{n_{\delta w}}$	$-.1566$	$\frac{(-.1071)(2.66)-(-.1566)}{.0654} = -1.965$
$\delta\omega_p$	$C_{l_p} + \frac{I'_{xz}}{I'_{zz}} C_{n_p}$	$-.0429$	$\boxed{+.0654}$	$-.1568$	$\frac{(-.0429)(2.66)-(-.1568)}{.0654} = +.6537$
$\delta\omega_R$	$C_{l_R} + \frac{I'_{xz}}{I'_{zz}} C_{n_R}$	$+.0921$	K = 2.66	$+.0217$	$\frac{(.0921)(2.66)-.0217}{.0654} = +3.419$
$\delta\omega_{\delta w}$	$C_{l_{\delta w}} + \frac{I'_{xz}}{I'_{zz}} C_{n_{\delta w}}$	$+.0530$	ROLL	—	$\frac{(.053)(2.66)}{.0654} = 2.159$
$\delta\omega_{\delta R}$	$C_{l_{\delta R}} + \frac{I'_{xz}}{I'_{zz}} C_{n_{\delta R}}$	$+.0312$	$\left(\frac{I'_{xz}}{I'_{zz}}\right)^*_{SST}$	—	$\frac{(.0312)(2.66)}{.0654} = 1.27$
$\delta\omega_{\delta r}$	$C_{l_{\delta r}} + \frac{I'_{xz}}{I'_{zz}} C_{n_{\delta r}}$	—	$\left(\frac{I'_{xz}}{I'_{zz}}\right)^*_{-80}$	$+.0175$	$\frac{-(+.0175)}{.0654} = -.268$
$\delta\omega_{\dot\beta}$	$C_{l_{\dot\beta}} + \frac{I'_{xz}}{I'_{zz}} C_{n_{\dot\beta}}$				
δr_β	$C_{n_\beta} + \frac{I'_{xz}}{I'_{xx}} C_{l_\beta}$	$+.231$	$C_{n_{\delta r}} + \frac{I'_{xz}}{I'_{xx}} C_{l_{\delta r}}$	$+.0938$	$\frac{(+.231)(.768)-.0938}{-.0724} = -1.153$
δr_p	$C_{n_p} + \frac{I'_{xz}}{I'_{xx}} C_{l_p}$	$+.0481$	$\boxed{-.0724}$	$-.0243$	$\frac{(+.0481)(.768)-(-.0243)}{-.0724} = -.845$
δr_R	$C_{n_R} + \frac{I'_{xz}}{I'_{xx}} C_{l_R}$	$-.1903$	K = .768	$-.0464$	$\frac{(-.1903)(.768)-(-.0464)}{-.0724} = +1.376$
$\delta r_{\delta w}$	$C_{n_{\delta w}} + \frac{I'_{xz}}{I'_{xx}} C_{l_{\delta w}}$	$-.0464$	YAW	—	$\frac{(-.0464)(.768)}{-.0724} = +.492$
$\delta r_{\delta R}$	$C_{n_{\delta R}} + \frac{I'_{xz}}{I'_{xx}} C_{l_{\delta R}}$	$-.0953$	$\left(\frac{I'_{xz}}{I'_{xx}}\right)^*_{SST}$	—	$\frac{(-.0953)(.768)}{-.0724} = +1.0119$
$\delta r_{\delta \omega}$	$C_{n_{\delta w}} + \frac{I'_{xz}}{I'_{xx}} C_{l_{\delta w}}$		$\left(\frac{I'_{xz}}{I'_{xx}}\right)^*_{-80}$	$+.0089$	$\frac{-(+.0089)}{-.0724} = +.123$
$\delta r_{\dot\beta}$	$C_{n_{\dot\beta}} + \frac{I'_{xz}}{I'_{xx}} C_{l_{\dot\beta}}$			$-.0344$	$\frac{-(-.0344)}{-.0724} = -.474$
ΔC_{Y_β}	C_{Y_β}	$-.5272$		$-.831$	
ΔC_{Y_p}	C_{Y_p}	$+.0487$	$\boxed{57.3}$	$+.1492$	
ΔC_{Y_R}	C_{Y_R}	$+.146$		$+.0865$	NOT USED IN PRESENT SIMULATION
$\Delta C_{Y_{\delta w}}$	$C_{Y_{\delta w}}$		SIDE FORCE		
$\Delta C_{Y_{\delta R}}$	$C_{Y_{\delta R}}$	$+.1146$			
$\Delta C_{Y_{\delta \omega}}$	$C_{Y_{\delta \omega}}$			$-.0128$	
$\Delta C_{Y_{\delta r}}$	$C_{Y_{\delta r}}$			$+.1712$	

-80 Variable Stability

DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS.

		SST		-80	
$\delta e_{\Delta\alpha}$	C_{m_α}	$-.0802$	$C_{m_{\delta e_{-80}}}$	-1.008	$\frac{1.56(-.0802)-(-1.008)}{-.85} = -1.04$
$\delta e_{\dot\alpha}$	$C_{m_{\dot\alpha}}$	0.0	$\boxed{-.85}$	$-.261$	$\frac{-(-.261)}{-.85} = -.307$
δe_Q	C_{m_Q}	$-.1757$	K=1.56	$-.524$	$\frac{1.56(-.1757)-(-.524)}{-.85} = -.2941$
$\delta e_{\Delta V}$	$57.3\,C_{m_{\Delta V}}$	0.0	P	$(57.3)(-.00025)$	$\frac{-(57.3)(-.00025)}{-.85} = -.0169$
δe_{δ_E}	$C_{m_{\delta_E}}$	$-.287$	I	—	$\frac{1.56(-.287)}{-.85} = +.527$
$\delta e_{\Delta T_{SST}}$	$57.3\,C_{m_{\Delta T_{SST}}}$	$57.3(.045\times10^{-6})$	T	—	$\frac{(1.56)(57.3)(.045\times10^{-6})}{-.85} = -4.73\times10^{-6}$
$\delta e_{\Delta h}$	$57.3\,\Delta C_m$	—	C		
$\delta e_{\Delta T_{-80}}$	$57.3\,C_{m_{\Delta T_{-80}}}$		H	$(57.3)(4.238\times10^{-7})$	$\frac{-(57.3)(4.238\times10^{-7})}{-.85} = 2.857\times10^{-5}$
$\delta e_{\delta ab}$	$C_{m_{\delta ab}}$			$-.117$	$\frac{-(-.117)}{-.85} = .1376$

$$\delta e_{\Delta h} = 57.3\left[\frac{\left(\frac{q_0 S\bar c}{I_{YY}}\Delta C_m\right)_{SST} - \left(\frac{q_0 S\bar c}{I_{YY}}\Delta C_m\right)_{-80}}{\left(\frac{q_0 S\bar c}{I_{YY}} C_{m_{\delta e}}\right)_{-80}}\right]$$

$$\delta e_c = \underset{\delta e_{\Delta\alpha}}{-1.04}\,\Delta\alpha\ \underset{\delta e_{\dot\alpha}}{-.307}\,\dot\alpha\ \underset{\delta e_Q}{-.2941}\,Q\ \underset{\delta e_{\Delta V}}{-.0169}\,\Delta V$$

$$\underset{\delta e_{\delta E}}{+.527}\,\delta_E\ \underset{\delta e_{\Delta T_{SST}}}{-4.73\times10^{-6}}\,\Delta T_{SST}\ \underset{\delta e_{\Delta h}}{\text{function}}\ \underset{\delta e_{\Delta T_{-80}}}{2.857\times10^{-5}}\,\Delta T_{-80}\ \underset{\delta e_{\delta ab}}{-.1376}\,\delta ab$$

ENGR	April 5.65 / HAC	REVISED	DATE	-80 Variable Stability DERIVATION OF AIRBORNE COMP. COEFFICIENTS.	NASA Δ
CHECK					PITCH
APR				THE BOEING COMPANY RENTON, WASHINGTON	B16
APR					

$$\frac{m_{-80}}{m_{SST}} = \frac{4660}{8696} = \underline{\underline{0.536}}$$

$$\left(2\frac{q_0 S}{V_0} C_{D_{TRIM}}\right)_{-80} - \left(2\frac{q_0 S}{V_0} C_{D_{TRIM}} + q_0 S C_{D_{\Delta V}}\right)_{SST} \frac{m_{-80}}{m_{SST}}$$

$$\Delta T_{-80_{\Delta V}} = \Big(\overbrace{2\frac{(61.8)(2821)}{228} \times .1165}^{+178.3}\Big)_{-80} - \Big(\overbrace{2\frac{(61.8)(8000)}{228} \times .125}^{+290.6} + 0\Big)_{SST} \times .536 = \underline{\underline{-112.3}}$$

$$\Delta T_{-80_{\Delta T_{SST}}} = \frac{m_{-80}}{m_{SST}}\left(1 - q_0 S C_{D_{\Delta T}}\right)_{SST} = 0.536\ [1-(61.8)(8000)(0.0)] = \underline{\underline{0.536}}$$

$$\Delta T_{-80_{\delta_{ab}}} = q_0 S \frac{C_{D_{ab}}}{57.3} = 174{,}500 \times \frac{-.00573}{57.3} = \underline{\underline{-17.45}}$$

$$\Delta T_{-80_{\Delta\alpha}} = \left(q_0 S \frac{C_{D_\alpha}}{57.3}\right)_{-80} - \left[\left(q_0 S \frac{C_{D_\alpha}}{57.3}\right)_{SST} \frac{m_{-80}}{m_{SST}}\right] = \left(174{,}500\ \frac{.515}{57.3}\right)_{-80} - \left[\left(494{,}472 \frac{1.203}{57.3}\right)_{SST} \times .536\right] = -3996$$

$$1568.0 - (10{,}400)(.536) = 1568 - 5564 = -3996$$

$$\Delta T_{-80\Delta h} = \left(q_0 S \Delta C_D\right)_{-80} - \left(\frac{m_{-80}}{m_{SST}}\right)\left(q_0 S \Delta C_D\right)_{SST}$$

$$\Delta T_{-80\,\Delta V} \times \Delta V + \Delta T_{-80_{\Delta T_{SST}}} \times \Delta T_{SST} + \Delta T_{-80\,\delta_{ab}} \times \delta_{ab} + \Delta T_{-80\,\Delta\alpha} \times \Delta\alpha + \Delta T_{-80h} \times \Delta h$$

$$\Delta T_{-80} = -112.3\ \Delta V + 0.536\ \Delta T_{SST} - 17.45\ \delta_{ab} - 3996.0\,\Delta\alpha + \qquad \Delta h$$

ENGR.	Dec. 64	HPL.	REVISED	DATE	−80 Variable Stability DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS	NASA Δ
CHECK	March. 30.65	HPL.				DRAG
APR	April 5.65	HPL.			THE BOEING COMPANY RENTON, WASHINGTON	B17
APR						

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$$\delta ab_{\Delta\alpha} = \frac{\left(\frac{q_0 S}{m} C_{L_\alpha} + \frac{T_0}{m}\right)_{SST} - \left(\frac{q_0 S}{m} C_{L_\alpha} + \frac{T_0}{m}\right)_{-80}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{\underbrace{\left(56.9 \times 3.266 + \frac{61{,}809}{8696}\right)_{SST}}_{192.94} - \underbrace{\left(37.45 \times 4.9 + \frac{20{,}300}{4660}\right)_{-80}}_{187.86}}{\underbrace{\left(37.45 \times -.688\right)_{-80}}_{-25.77}} = \frac{5.08}{-25.77} = \underline{\underline{-.197}}$$

$$\delta ab_{\Delta T_{SST}} = \frac{\left(\frac{\alpha_0}{m}\right)_{SST} + 57.3\left(\frac{q_0 S}{m} C_{L_{\Delta T}}\right)_{SST}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{\frac{12}{8696} + 57.3(56.9 \times 0.0)}{-25.77} = \frac{.00138}{-25.77} = \underline{\underline{-5.35 \times 10^{-5}}}$$

α_0 in degrees

$$\delta ab_{\Delta T_{-80}} = \frac{-\left(\frac{\alpha_0}{m}\right)_{-80}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{-\left(\frac{5.45}{4660}\right)_{-80}}{\left(-25.77\right)_{-80}} = \frac{-.001169}{-25.77} = 4.53 \times 10^{-5}$$

$\alpha_0 = \alpha_{TRIM, WING}$ in degrees

$$\delta ab_{\Delta V} = \frac{57.3\left[\left(\frac{q_0 S}{m} C_{L_{\Delta V}}\right)_{SST} + \left(\frac{2g}{V_0}\right)_{SST} - \left(\frac{2g}{V_0}\right)_{-80}\right]}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \text{———} = 0.0$$

$$\delta ab_{\delta E} = \frac{\left(\frac{q_0 S}{m} C_{L_{\delta E}}\right)_{SST}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{\left(56.9 \times .8022\right)_{SST}}{\left(37.45 \times -.688\right)_{-80}} = \frac{45.645}{-25.766} = -1.772$$

$$\delta ab_{\delta e} = -\left(\frac{C_{L_{\delta e}}}{C_{L_{ab}}}\right)_{-80} = -\left(\frac{0}{-.688}\right)_{-80} = 0.0$$

$$\delta ab_{\Delta h} = 57.3\left[\frac{\left(\frac{q_0 S}{m}\Delta C_L\right)_{SST} - \left(\frac{q_0 S}{m}\Delta C_L\right)_{-80}}{\left(\frac{q_0 S}{m} C_{L_{\delta ab}}\right)_{-80}}\right]$$

$$\delta ab_c = \underset{\delta ab_{\Delta\alpha}}{-.197}\ \Delta\alpha \ \underset{\delta ab_{\Delta T_{SST}}}{-5.35 \times 10^{-5}}\ \Delta T_{SST} + \underset{\delta ab_{\Delta T_{-80}}}{4.53 \times 10^{-5}}\ \Delta T_{-80}\ \underset{\delta ab_{\Delta V}}{0.0}\ \Delta V$$

$$\underset{\delta ab_{\delta E}}{-1.772}\ \delta_E \quad \underset{\delta ab_{\delta e}}{0.0}\ \delta e \quad \underset{\delta ab_{\Delta h}}{\text{function } \Delta h}$$

CALC	March 30.65	HPC	REVISED	DATE	−80 Variable Stability	NASA Δ
CHECK	April 5.65	HPC			DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS	LIFT
APR						
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ΔT_{-80}	δ_{ab}	δ_e	VARIABLE		δ_ω	δ_r
−3996.0	−.197	−1.04	$\Delta\alpha$	β	−1.965	−1.153
		−.307	$\dot{\alpha}$	$\dot{\beta}$	—	−.474
		−.2941	Q	P	+.6537	−.845
−112.3	0.0	−.0169	ΔV	R	+3.419	+1.376
+0.536	-5.35×10^{-5}	-4.73×10^{-6}	ΔT_{SST}	δ_W	+2.159	+.492
	$+4.53\times10^{-5}$	2.857×10^{-5}	ΔT_{-80}	δ_ω	—	+.123
−17.45		−.1376	δ_{ab}	δ_R	+1.27	+1.01
	−1.772	+.527	δ_E	δ_r	−.268	—
	0.0		δ_e			
function			Δh			
	function		Δh			
		function	Δh			

Example: if $\underbrace{\ }$, then the following equations apply:

ΔT_{-80}	δ_{ab}	δ_e	
+217	+2.1	−.63	$\Delta\alpha$
−33	+.07	−.007	ΔV
+.25	$-3\cdot10^{-6}$	$+4.6\cdot10^{-5}$	ΔT_{SST}
—	$+1.7\cdot10^{-5}$	$+2\cdot10^{-4}$	ΔT_{-80}
0	−.09	+.38	δ_E

$$\Delta T_{-80} = 217\,\Delta\alpha - 33\,\Delta V + .25\,\Delta T_{SST}$$

$$\delta_{ab} = 2.1\,\Delta\alpha + .07\,\Delta V - 3\times10^{-6}\,\Delta T_{SST} + 1.7\times10^{-5}\,\Delta T_{-80} - .09\,\delta_E$$

$$\delta_e = -.63\,\Delta\alpha - .007\,\Delta V + 4.6\times10^{-5}\,\Delta T_{SST} + 2\times10^{-4}\,\Delta T_{-80} + .38\,\delta_E$$

CALC	March 30 65 HPC	REVISED	DATE	−80 Variable Stability NUMERICAL VALUES OF AIRBORNE COMPUTER COEFFICIENTS	NASA Δ
CHECK					
APR					
APR				THE BOEING COMPANY RENTON WASHINGTON	PAGE B19

Note: the factor of 1.05 in the pitch axis computations arises from the inability of the elevator to respond to a command in a one to one ratio.

	POTENTIOMETER NO	POTENTIOMETER SETTING		VARIABLE	CALCULATED FROM
PITCH	18	.2620	A 44	$-20\,\delta e_{TRIM}$	
	64	.3222	A 44	$-5\dot{\alpha}$	$1.05(-\delta e_{\dot{\alpha}})$
	65	$.1544^{10}$	A 43	$+Q$	$1.05 \times (-5\,\delta e_Q)$
	66	$.1092^{10}$	A 43	$+5\,\Delta\alpha$	$1.05(-\delta e_{\Delta\alpha})$
	67	.0888	A 43	$+\Delta V$	$1.05 \times (-5\,\delta e_{\Delta V})$
	68	.0248	A 44	$-.001\,\Delta T_{SST}$	$1.05 \times (-5000\,\delta e_{\Delta T_{SST}})$
	69	.0722	A 43	$+10\,\delta ab_c$	$1.05 \cdot (-.5\,\delta e_{\delta ab})$
	70	.0300	A 44	$+.005\,\Delta T_{-80}$	$1.05 \times (+1000\,\delta e_{\Delta T-80})\ \left[\frac{1}{TS+1}\right]$
	71	$.2770^{10}$	A 43	$-\delta_E'$	$1.05 \times (+5\,\delta e_{\delta E'})$
	DIRECT INPUT		A 43	h	function
DRAG	72	$.3996^{10}$	A 46	$+5\,\Delta\alpha$	$-.001\,\Delta T_{\Delta\alpha}$
	73	$.2680^{10}$	A 46	$-.001\,\Delta T_{SST}$	$+5\,\Delta T_{\Delta T_{SST}}$
	74	.5615	A 46	$+\Delta V$	$-.005\,\Delta T_{\Delta V}$
	75	.0087	A 46	$+10\,\delta ab$	$-.0005\,\Delta T_{\delta ab}$
	DIRECT INPUT		A 45	h	function
	80	.6970	A 50	$-.005\,\Delta T_{-80}$	$\frac{\delta th}{\Delta T-80}(600) = \frac{600}{861} = .697$ (861 based on ΔT/sec o/e/m = 1080)
LIFT	76	.0906	A 47	$-.005\,\Delta T_{-80}$	$+2000\,\delta ab_{\Delta T-80}$
	77	.5350	A 48	$-.001\,\Delta T_{SST}$	$-10\,000\,\delta ab_{\Delta T_{SST}}$
	78	$.772^{10} + 10$	A 48	$-\delta_E'$	$-10\,\delta ab_{\delta_E}$
	79	.3940	A 47	$+5\,\Delta\alpha$	$-2\,\delta ab_{\Delta\alpha}$
	13	0.0	A 47	$-\Delta V$	$+10\,\delta ab_{\Delta V}$
	DIRECT INPUT		A 48	h	function

LONGITUDINAL

			REVISED	DATE		
CALC	March 30 '65	[illegible]	D.E.G.	4-19-65	80 Variable Stability	LONG.
CHECK	3-31-65	[illegible]	BAOKA	[illegible]	NUMERICAL VALUES OF POTENTIOMETER SETTINGS	NASA Δ
APR	[illegible]		D.E.G.	[illegible]		
APR					THE BOEING COMPANY RENTON, WASHINGTON	PAGE B20

	POTENTIOMETER NO	POTENTIOMETER SETTING		VARIABLE	CALCULATED FROM
ROLL	106	$.6838^{10}$	A 71	$-R$	$+2\,\delta\omega_R$
	107	$.2615^{10}$	A 72	$+.5P$	$+4\,\delta\omega_P$
	108	.7860	A 72	-5β	$-.4\,\delta\omega_\beta$
	109	$.4318^{10}$	A 71	$-\delta w$	$+2\,\delta\omega_{\delta w}$
	110	$.2540^{10}$	A 72	$+\delta R$	$+2\,\delta\omega_{\delta R}$
	111	.0536	A 71	$+10\,\delta r$	$-.2\,\delta\omega_{\delta r}$
	90	.600		$+2\delta_{\omega_c}$	ROLL CONTROL EFFECTIVENESS
YAW	112	.474	A 73	$-10\dot\beta$	$-\delta r_{\dot\beta}$
	113	$.690^{10}+10$	A 74	$+.5P$	$+20\,\delta r_P$
	114	$.376^{10}+10$	A 74	$-R$	$+10\,\delta r_R$
	115	$.2306^{10}$	A 73	-5β	$-2\,\delta r_\beta$
	116	.1190	A 73	$+\delta R$	$+10(\delta r_{\delta R}-1)$?
	117	$.492^{10}$	A 74	$-\delta w$	$+10\,\delta r_{\delta w}$?
	118	.6150	A 73	$+2\,\delta\omega$	$+5\,\delta r_{\delta\omega}$

LATERAL

CALC March 30 '65	REVISED	DATE	80 Variable stability	LATERAL DIRECT
CHECK	D.E.G	4-19-65	NUMERICAL VALUES OF POTENTIOMETER SETTINGS	NASA Δ
APR				
APR			THE BOEING COMPANY RENTON WASHINGTON	PAGE B21

1. Control Column

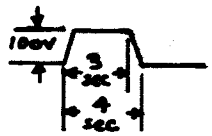
$$\delta_E = K_E \, \delta_{CP} + K_{82} \text{ Pulse}$$

Where δ_E = simulated SST elevator position

K_E = SST column to elevator gearing

δ_{CP} = Eval. Pilot's column position

K_{82} = ELEVATOR SCALE FACTOR

PULSE = 

2. Pitch Trim

$$\delta_{eTRIM} = \frac{K_{TR}}{S} \text{ TRIM}$$

Where δ_{eTRIM} = Fake trim signal to -80 elevator

K_{TR} = gain factor to simulate SST trim rate

TRIM = Eval Pilot trim signal (-15V; 0V; +15V)

$$K_{TR} = \frac{\left(\frac{q_0 S \bar{c}}{I_{YY}} \times C_{m_{iH}} \times \text{Stabilizer trim rate}\right)_{SST}}{\left(\frac{q_0 S \bar{c}}{I_{YY}} C_{m_{\delta e}}\right)_{-80}} =$$

CALC	March 29 65	HPK	REVISED	DATE	-80 Variable stability COMPUTER EQUATIONS FOR EVALUATION PILOT'S CONTROLS
CHECK					NASA 4
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APR					PAGE B22

3. Control Wheel

$$\boxed{\delta_W = \delta_{W_E} + K_{87}(100V\ Pulse)}$$

where δ_W = Simulated SST Wheel Position

δ_{W_E} = Eval. Pilot Wheel Position

$\left.\begin{matrix} K_{87} \\ Pulse \end{matrix}\right\}$ Used only for checkout.

4. Rudder Pedals and Rudder

$$\boxed{\delta_R = K_P \delta_P}$$

where δ_R = Simulated SST Rudder Position

K_P = SST Pedal to Rudder gearing

δ_P = Rudder Pedal Position.

Rudder Pulse circuit

$$\boxed{\delta_{R_{Pulse}} = .6 \times Pulse}$$ Used only for Checkout.

where $\delta_{R_{Pulse}}$ = Simulated SST Rudder Position, under control of a computer derived pulse

5. Fake Throttle

$$\boxed{\Delta T_{SST} = K_{TH}\,\delta_{TH} \begin{array}{l} + K_{84}(\text{Pulse}) \ \text{AFT} \\ \text{or} \\ - K_{8}\,(\text{Pulse}) \ \text{FWD} \end{array}}$$

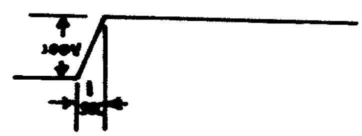
Where ΔT_{SST} = Simulated SST Thrust Increment.

K_{TH} = SST Thrust to Throttle ratio

δ_{TH} = Eval. Pilot Fake Throttle lever Position

K_{84} = AFT THRUST PULSE SCALE FACTOR

K_{8} = FWD " " " "

PULSE = 

SCALED EQUATIONS

$$+\ \delta E = -\left[(-2K_E)(+.5\,\delta_{CP}) + K_{82}(\text{Pulse})\right]$$

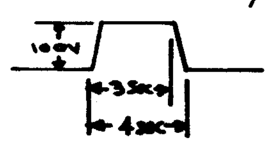
$$+\ 20\,\delta e_{TRIM} = -\int\left[\frac{20}{15}K_{TR}(\text{TRIM})\right]dt$$

$$-\ \delta w = -\left[10(.1\,\delta w_E) + K_{87}(\text{Pulse})\right]$$

$$\delta R = -\left[\frac{K_P}{2.5}\left(-2.5\,\delta_{PED}\right)\right]$$

$$16.67\,\delta R_{Pulse} = \text{Pulse (6° SST RUDDER)}$$

$$-\frac{\Delta T_{SST}}{1000} = -\left[\left(\frac{K_{TH}}{1000 \times 3}\right)(.3\,\delta_{TH}) \begin{array}{l} + K_8\ \text{PULSE} \\ - K_{84}\ \text{PULSE} \end{array}\right]$$

FOR THE 367-80	FOR NASA Δ SST
K_E = − 2.2 degree/degree	K_E = −1.0 degree/degree
K_{TR} = 1.385 degree/sec	K_{TR} = 1.20 degree/sec
K_p = 6.25 degree/inch	K_p = 6.25 degree/inch
K_{th} = 1080 lbs/degree (~~don~~)	Pulse = 
THRUST RATE LIMIT ≃ 14,000 lb/SEC	
	$K_{TH} = \frac{170\,000}{57.3} \cong 3000$ lbs/degree fake throttle

ENGR May 65 WRC	REVISED	DATE	80 Variable Stability COMPUTER EQUATIONS FOR EVALUATION PILOT'S CONTROLS	NASA Δ
CHECK				
APR				
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POTENTIOMETER NO.	SETTING		VARIABLE	CALCULATED FROM
8	.150	A7	FWD THRUST STEP	
10	1.0^{10}	A19	$.3\delta_{TH}$	$\frac{K_{TH}}{300} = \frac{3000}{300} = 10$
61	$.160^{10}$	A41	TRIM	$\frac{20}{15} K_{TR} = \frac{20}{15}(1.2) = 1.6$
81	$.250^{10}$	A84	$-2.5\delta_P$	$\frac{K_P}{2.5} = 2.5$
82	.010	A78	ELEV. PULSE	
83*	.1524	A72	$16.67\delta_R$ PULSE	$2 \frac{\delta_{W_{SR}}}{16.67} = \frac{2}{16.67}(1.27) = .1524$
84	.150	A19	AFT THRUST STEP	
85*	$.0606^{10}$	A73	$16.67\delta_R$ PULSE	$10 \frac{\delta_{r_{SR}}}{16.67} = \frac{10}{16.67}(1.01) = .606$
87	.100	A77	WHEEL PULSE	
88	$.200^{10}$	A78	$+.5\delta_{C_P}$	$-2K_E = -2(-1.0) = +2.0$
DIRECT INPUT	g_{10}	A77	$+.1\delta_W$	$10 \frac{\delta_W}{\delta_{W_E}} = 10$

* SET TO PRODUCE A 6° SST PULSE

ENGR		-80 VARIABLE STABILITY COMPUTER EQUATIONS FOR EVALUATION PILOT'S CONTROLS	NASA Δ
	BB 8-24-65		
APR			
APR		THE BOEING COMPANY RENTON WASHINGTON	B 26

TD 1017 R6

1. Change in Angle of Attack $\Delta\alpha$

$$\Delta\alpha = \alpha_{-80} - \alpha_{TRIM}$$

$$\alpha_{-80} = \alpha_{VANE,\,CALM\ AIR} + Q\frac{\ell}{V} + \Delta\alpha_{VANE,\,TURBULENCE}\ e^{-s\frac{\ell}{V}}$$

$$\alpha_{-80} \cong Q\frac{\ell}{V_o} + \alpha_{V,C} + \Delta\alpha_{V,T}\left(1 - s\frac{\ell}{V_o}\right)$$

by definition $\alpha_V = \alpha_{V,C} + \Delta\alpha_{V,T}$

Replacing $s\frac{\ell}{V_o}\Delta\alpha_{V,T}$ by $s\frac{\ell}{V_o}\alpha_V$

since no $\Delta\alpha_{V,T}$ signal is available,

and approximating $\left(1 - s\frac{\ell}{V_o}\right)$ with $\dfrac{1}{1 + s\frac{\ell}{V_o}}$

$$\boxed{\Delta\alpha \cong Q\frac{\ell}{V_o} + \frac{\alpha_V}{1 + s\frac{\ell}{V_o}} - \alpha_{TRIM}}$$

2. Rate of change of angle of attack $\dot{\alpha}$

The $\dot{\alpha}$ signal will be derived from the $\Delta\alpha$ signal, using a pseudo-differentiating circuit having the following transfer function

$$\boxed{\frac{\dot{\alpha}}{\Delta\alpha} \cong \frac{s}{1 + .1s}}$$

CALC	March 29	WPC	REVISED	DATE	-80 Variable Stability COMPUTER EQUATIONS FOR AIR DATA VARIABLES	NASA Δ
CHECK						
APR						
APR						
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3. Angle of Sideslip β

$$\beta = \beta_{VANE,\,CALM} - R\,\frac{\ell}{V} + \Delta\beta_{VANE,\,TURBULENCE}\; e^{-s\frac{\ell}{V}}$$

Following steps similar to those of page 1 — derivation of the simplified $\Delta\alpha$ formula — results in:

$$\boxed{\beta \cong -R\,\frac{\ell}{V_0} + \frac{\beta_V}{1 + s\,\frac{\ell}{V_0}}}$$

4. Rate of change of angle of sideslip $\dot\beta$

The $\dot\beta$ signal will be derived from a roll gyro signal (ϕ) and a yaw rate gyro signal (R), using the following equation:

$$\boxed{\dot\beta = \phi\,\frac{g}{V_0} - R}$$

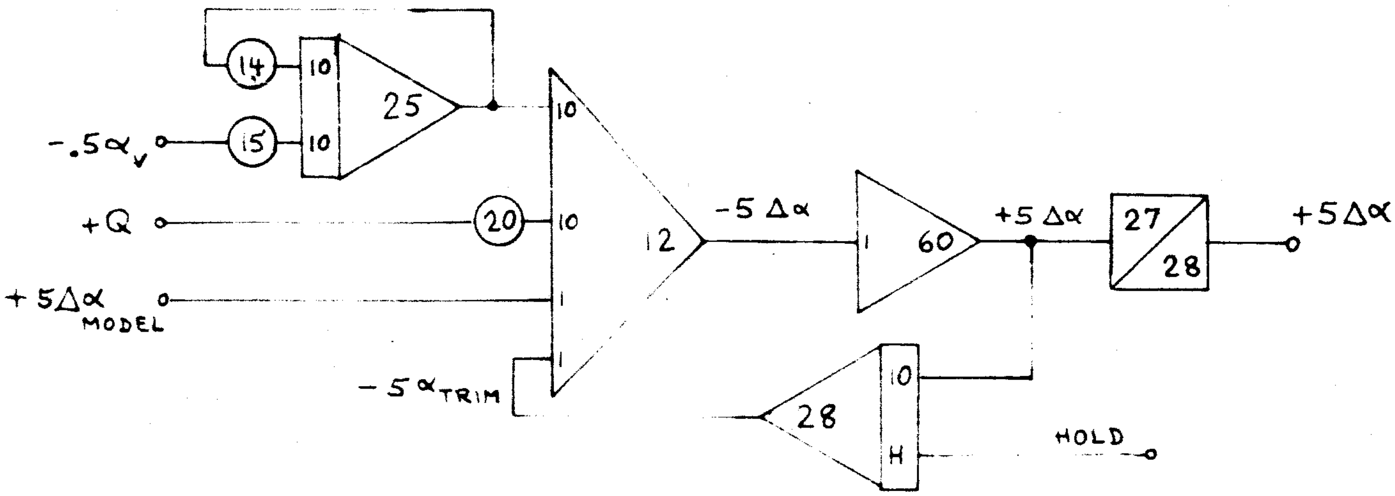
5. Change in True Airspeed ΔV

$$\boxed{\Delta V = V - V_{TRIM}}$$

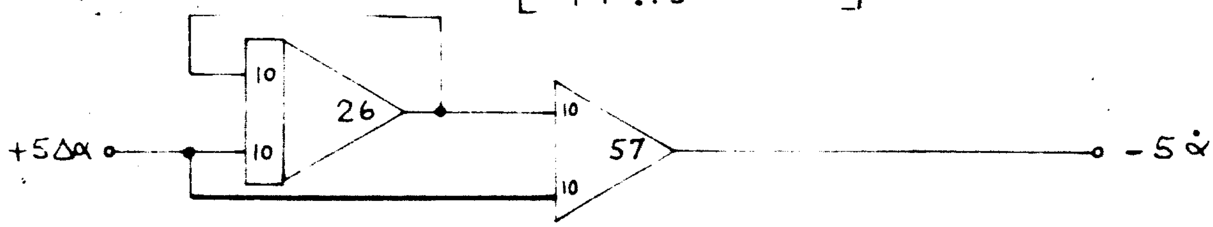
69

SCALED EQUATIONS

$$-5\,\Delta\alpha = -\left[\frac{5\ell}{V_o}(+Q) - 10\left(-\frac{.5\alpha_V}{1+\frac{\ell}{V_o}s}\right) + \left(5\,\alpha_{TRIM}\right)\right]$$

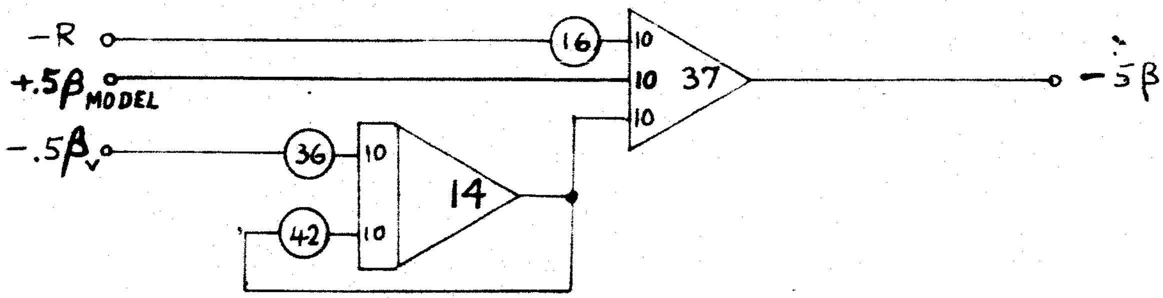


$$-5\,\dot{\alpha} = -\left[\frac{s}{1+.1s}\left(5\,\Delta\alpha\right)\right]$$

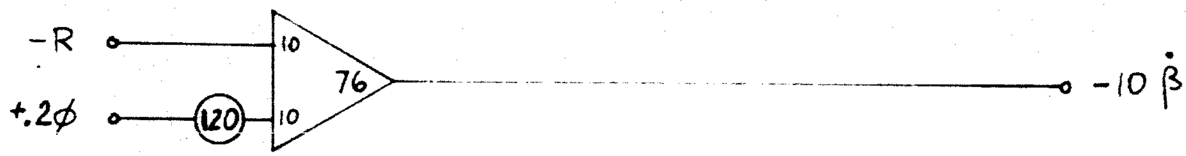


SCALED EQUATIONS

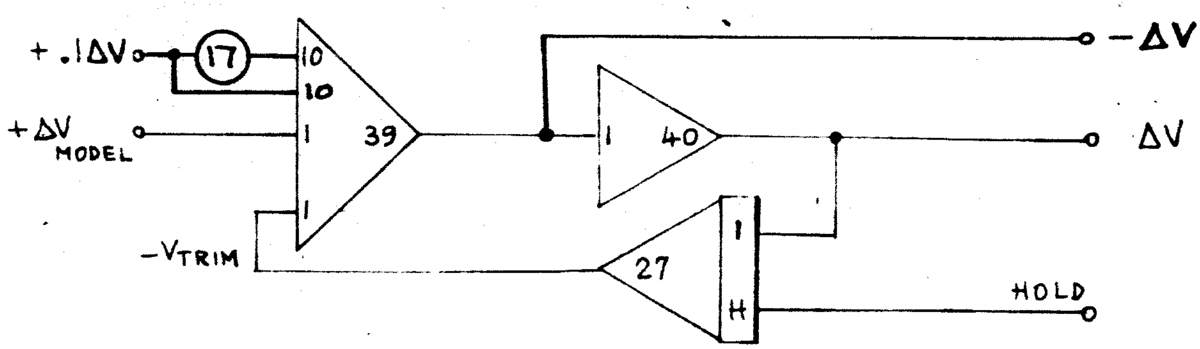
$$-5\beta = -\left[\frac{5\ell}{V_o}(-R) + 10\left(+\frac{.5\beta_V}{1+\frac{\ell}{V_o}s}\right)\right]$$



$$-10\dot{\beta} = -\left[\frac{10g}{V_o}(+\phi) + 10(-R)\right]$$



$$-\Delta V = -\left[10K\left(+\frac{.1\Delta V}{K}\right) + (-V_{TRIM})\right]$$



K = 1.06 determined from in-flight calibration

CALC	March 29 65	HPC	REVISED	DATE	−80 Variable Stability COMPUTER EQUATIONS FOR AIR DATA VARIABLES
CHECK	3.31.65	HPC.	D.E.G.	5-6-65	
APR					THE BOEING COMPANY RENTON WASHINGTON
APR					NASA Δ PAGE B30

POTENTIOMETER NO.	SETTING		VARIABLE	CALCULATED FROM
14	1.00^{10}	A 25	$+\frac{.5\alpha_v}{1+\frac{\ell}{V_0}s}$	$\frac{V_0}{\ell} = {}^{*}K(3.13)$
15	$.800^{10}$	A 25	$-.5\alpha_v$	$\frac{V_0}{\ell} = {}^{*}K(3.13)$
20	$.160^{10}$	A 12	$+Q$	$\frac{5\ell}{V_0} = 1.60$
42	$.313^{10}$	A 14	$+\frac{.5\beta_v}{1+\frac{\ell}{V_0}s}$	$\frac{V_0}{\ell} = 3.13$
36	$.313^{10}$	A 14	$-.5\beta_v$	$\frac{V_0}{\ell} = 3.13$
16	$.160^{10}$	A 37	$-R$	$\frac{5\ell}{V_0} = 1.60$
17	$10+.06^{10}$	A39	$+\frac{.1}{K}\Delta V$	Result of in-flight calibration

* ADJUSTED TO MATCH GROUNDWORK

			REVISED	DATE		
CALC	March 29. 65	HPC.			-80 Variable Stability COMPUTER EQUATIONS FOR AIR DATA VARIABLES	NASA Δ
CHECK	3. 31. 65	HPC.	D. E. G.	5-6-65		
APR						
APR					THE BOEING COMPANY RENTON, WASHINGTON	PAGE B 31

TB 1017 R8 — 6-7000

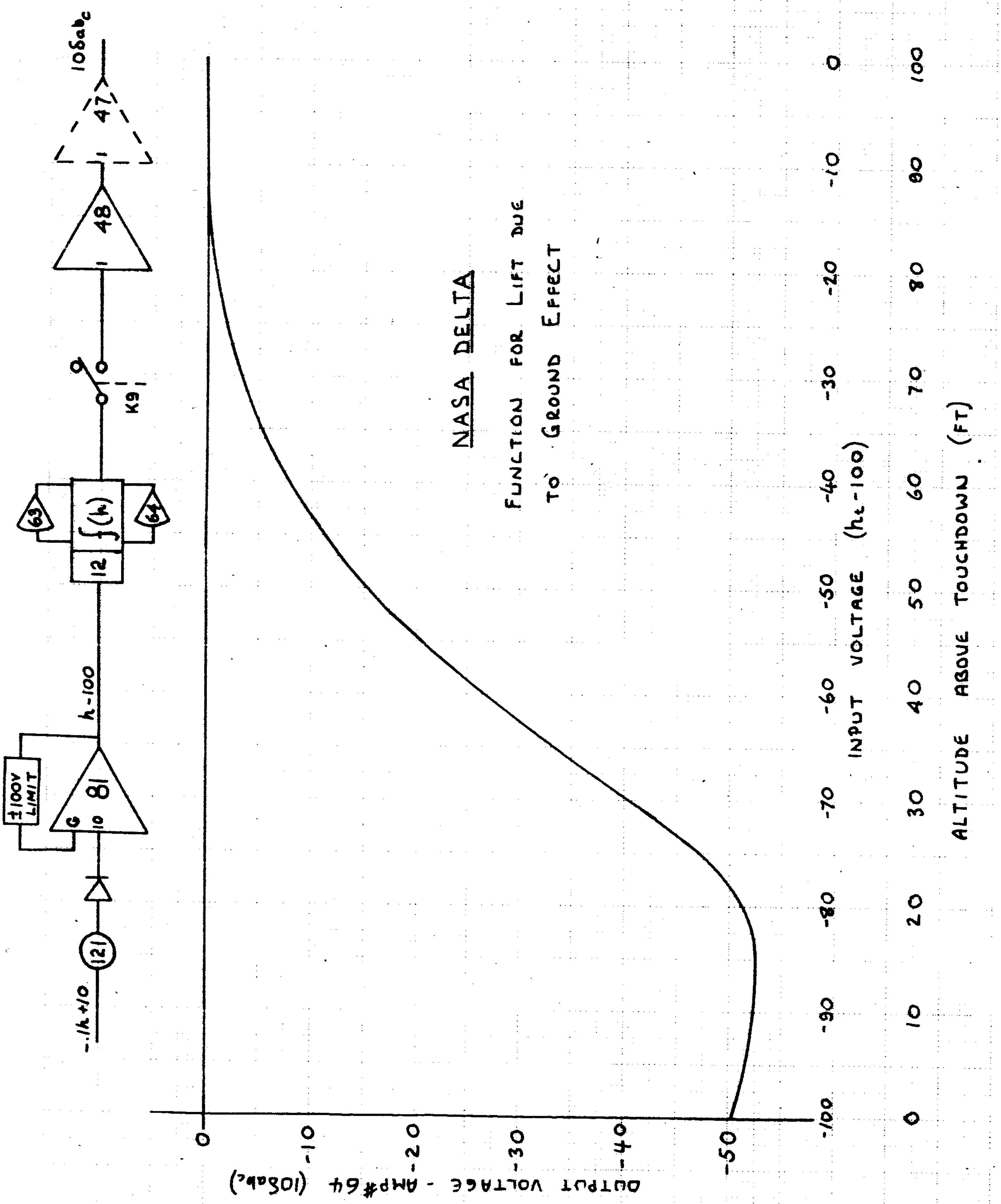
	POTENTIOMETER NO.	POTENTIOMETER SETTING		VARIABLE	CALCULATED FROM
LONG.	119	$.146^{10}$	A79	$+Q$	$\frac{\delta_E'}{Q}$
	122	$.300^{10}$	A79	$+\delta_E$	$\left(\frac{\delta_E'}{\delta_{COL}}+1.0\right)$
	123	.200	A79	$+5\Delta\alpha$	$\frac{1}{5}\left(\frac{\delta_E'}{\Delta\alpha}\right)$
LATERAL	86	.090	A77	$-5P$	$\frac{1}{5}\left(\frac{\delta_W}{P}\right)$
DEGRADED LATERAL	113	$.054^{10}+10$	A74	$+.5P$	$-20\delta_{r_P}$
	117	$.200^{10}$	A74	$-\delta_W$	RESULT OF INFLIGHT ADJUSTING
	124	$.1362^{10}$	A74	$-10\dot{\beta}$	" " " "

1.1.3. POTENTIOMETER CHECK.

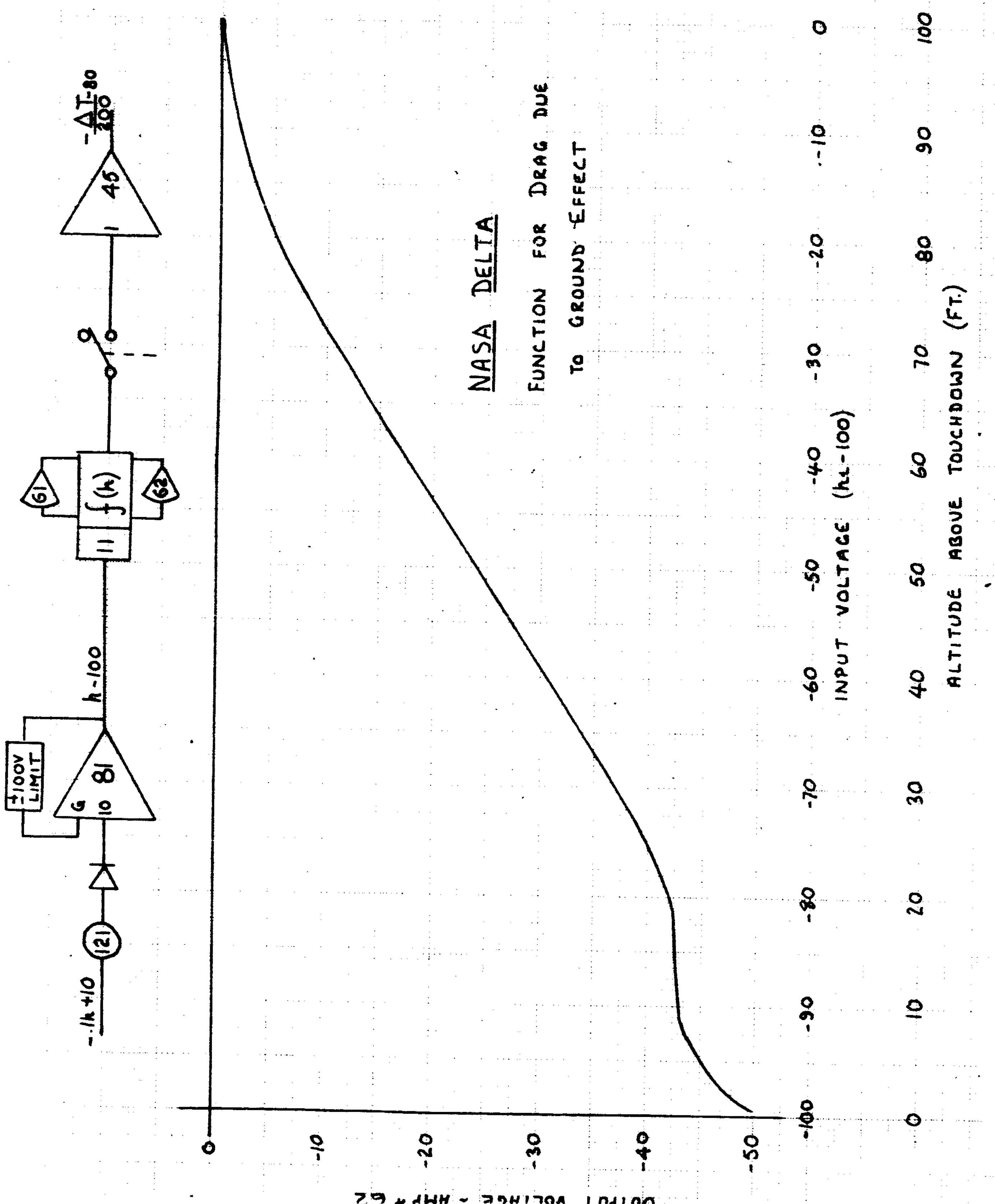
NASA Δ

Updated after FLT 671-6

POT #	SETTING		POT #	SETTING	
6	.333		66	.1092[10]	
7	.01		67	.0888	
8	.150		68	.0248	
9	.8042		69	.0722	
10	1.00		70	.030	
11	.1252		71	.2770[10]	
12	1.00		72	.4007[10]	
13	0.00		73	.268[10]	
14	1.00[10]		74	.5625	
15	.800[10]		75	.0087	
16	.160[10]		76	.0906	
17	.06		77	.535	
18	.262		78	.768[10]	
19	.166		79	.407	
20	.160[10]		80	.697	
21			81	.250[10]	
22	.1425[10]		82	.010	
23	.0807		83	.1524	
24	.1455[10]		84	.1500	
25	.100		85	.0606	
26	.1395[10]		86	.090	
27	.1412		87	.100	
28	.1175		88	.200[10]	
29	.3545		89	+40 volts	(LIMIT ON [illegible] SPOILERS)
30	.9220[10]		90	.600	WITH CABLE #4 IN
31	.246		91	.0166	
32	.1365[10]		92	.1627	
33	.0245		93	.4610	
34	.4929		94	.1633	
35	.0141		95	.2263	
36	.313[10]		96	.9229	
37	.3535		97	.9046	
38	.0053	RECORDER POTS	98	.3252	
39	.100		99	.1875	
40	.400[10]		100	.3767	
41	.100		101	.2234	
42	.313[10]		102	.1843	
43	.0142		103	.1841	
44	.1130		104	.0184	
45	.1648[10]		105	.1861	
46	.7004		106	.6820[10]	
47	.0383		107	.262[10]	
48	.0597		108	.7860	
49	.0673		109	.431[10]	
50	.0004		110	.254[10]	
51	.1125		111	.0536	
52			112	.476	
53	.0107		113	.692[10]	
54	.0183		114	.380[10]	
55	.2535		115	.2276[10]	
56	.4080		116	.119	
57	.820		117	.200	.492 FOR PRE-FLT
58	.100		118	.615	
59	.500[10]		119	.146[10]	
60	.0225		120	.707[10]	
61	.160[10]		121	1.00	
62	.3155		122	.300[10]	
63	.500		123	.200	
64	.3222		124	.1355	
65	.1344[10]		125		

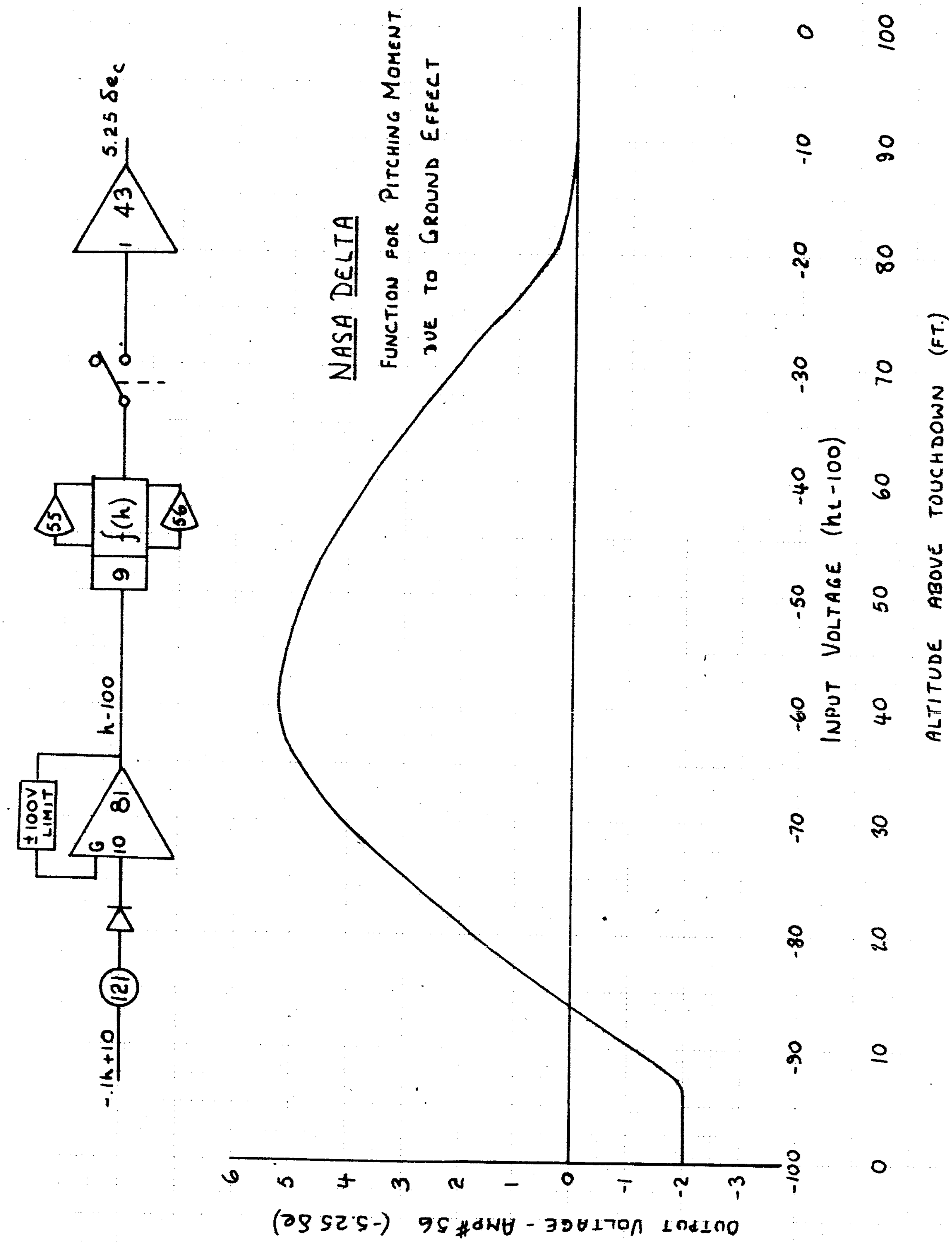


CALC			REVISED	DATE	NASA Δ ~ FUNCTION FOR LIFT DUE TO GROUND EFFECT	
CHECK						
APR						
APR						
					THE BOEING COMPANY	PAGE B34



CALC			REVISED	DATE	NASA Δ - FUNCTION FOR DRAG DUE TO GROUND EFFECT	
CHECK						
APR						
APR						
					THE BOEING COMPANY	PAGE B35

TO 461 D



CALC			REVISED	DATE	NASA Δ - FUNCTION FOR PITCHING MOMENT DUE TO GND. EFFECT	
CHECK						
APR						
APR					THE BOEING COMPANY	PAGE B36

DERIVATIVES FOR NASA Δ-80 *(CALC FROM FLT 671-6 8-9-65)

		UNAUGMENTED	UNITS
DRAG	$C_{D_{TRIM}}$	+.1165	
	C_{D_α}	+.515	/RAD
	$C_{D_{\delta AB}}$	-.00573	/RAD
LIFT	$C_{L_{TRIM}}$	+.849	
	C_{L_α}	+4.9	/RAD
	$C_{L_{\delta AB}}$	-.688	/RAD
PITCH	C_{m_α}	-1.008	/RAD
	$C_{m_{\dot\alpha}}$	-.261	/RAD/SEC
	C_{m_Q}	-.524*	/RAD/SEC
	$C_{m_{\delta e}}$	-.85	/RAD
	$C_{m_{\delta AB}}$	-.117	/RAD
ROLL	C_{l_β}	-.1572	/RAD
	C_{l_p}	-.1569	/RAD/SEC
	C_{l_R}	+.0225	/RAD/SEC
	$C_{l_{\delta a}}$	+.0809	/RAD
	$C_{l_{\delta SP}}$	+.0468	/RAD
	$C_{l_{\delta r}}$	+.0179	/RAD
YAW	C_{n_β}	+.0956	/RAD
	C_{n_p}	-.0225	/RAD/SEC
	C_{n_R}	-.0467	/RAD/SEC
	$C_{n_{\delta a}}$	+.0023	/RAD
	$C_{n_{\delta SP}}$	+.0245	/RAD
	$C_{n_{\delta r}}$	-.0725	/RAD
	$C_{n_{\dot\beta}}$	-.0344	/RAD/SEC
SIDE FORCE	C_{Y_β}	-.831	/RAD
	C_{Y_p}	+.1492	/RAD/SEC
	C_{Y_R}	+.0865	/RAD/SEC
	$C_{Y_{\delta a}}$	0	
	$C_{Y_{\delta SP}}$	-.039	/RAD
	$C_{Y_{\delta r}}$	+.1712	/RAD
	C_{Y_ϕ}	+.860	/RAD

$C_{m_{\Delta T}}$	*4.238×10^{-7} /
$C_{m_{\Delta V}}$	*-.00025 /

B-37-1

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SIMULATING NASA Δ — -80

LB.
FT/SEC

WEIGHT	150,000 lbs
C.G LOCATION	30% $\bar{c}$
ALTITUDE	SEA LEVEL

MOMENTS OF INERTIA IN BODY AXES

$I_{xx} = 2.57 \times 10^6$ SLUG ft^2
$I_{yy} = 2.25 \times 10^6$ SLUG ft^2
$I_{zz} = 4.73 \times 10^6$ SLUG ft^2
$I_{xz} = 0.160 \times 10^6$ SLUG ft^2

FLIGHT CONDITION

FLAP SETTING	30°
BLOWING PRESSURE RATIO	1
SPEED BRAKE SETTING	6°
GEAR	DOWN

$\frac{\Delta T}{\delta_{th}} = 861 \times 57.3 = 49300$ LB/RAD @ $\delta_{CLAM} = 30°$

GEOMETRY

$S = 2821$ ft^2
$\bar{c} = 20.1$ ft
$b = 130.8$ ft

TRIM

SPEED 135 Kts (228 ft/sec)
$\alpha_{TRIM_{BODY}} = 3.45°$ (.06 rad)
$\alpha_{TRIM_{WING}} = 5.45°$ (.095 rad)

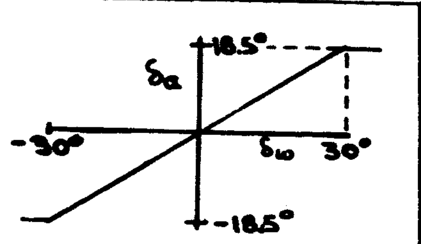
DEPENDENT VARIABLES

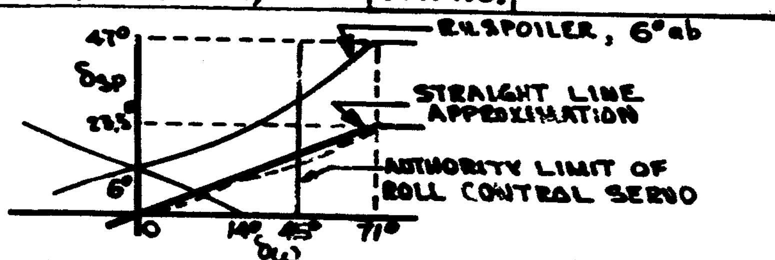
q_{TRIM}	61.8
$q_{TRIM}S$	174,500
$THRUST_{TRIM}$	20,300 lbs.
MASS	4660 SLUGS

$C_{\ell_{\delta\omega}} = +.0653$/RAD
$C_{n_{\delta\omega}} = +.0082$/RAD
$C_{Y_{\delta\omega}} = -.0128$/RAD

MODE SHAPES

SHORT PERIOD	ω_n =	RAD/SEC
	ω_D =	RAD/SEC
	ζ =	
PHUGOID	ω_n =	RAD/SEC
	ω_D =	RAD/SEC
	ζ =	
DUTCH ROLL	ω_n =	RAD/SEC
	ω_D =	RAD/SEC
	ζ =	
ROLL T.C.		SEC
SPIRAL DIV. T.C.		SEC





		REVISED	DATE
CALC	12-4-4		
CHECK		B.B.	1-22-5
APR		D.E.G.	2-15-65
APR		D.E.G.	5-6-65
		D.E.G.	5-11-65

D.E.G. 5-14-65 B.B. 6-1-65
D.E.G. 5-16-65 B.B. 8-17-65
H.P.C. 5 21.65

VARIABLE STABILITY AIRPLANE DESCRIPTION

THE BOEING COMPANY

2

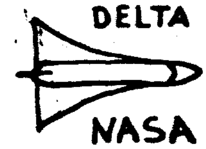
		UNAUGMENTED	UNITS	AUGMENTED	UNITS	DEGRADED	UNITS
DRAG	$C_{D_{TRIM}}$	+.125					
	C_{D_α}	+1.203	/RAD				
LIFT	$C_{L_{TRIM}}$	.54					
	C_{L_α}	+3.266	/RAD				
	$C_{L_{\delta_E}}$	+.8022	/RAD				
PITCH	C_{m_α}	−.0802	/RAD				
	$C_{m_{\dot\alpha}}$	0					
	C_{m_q}	−.1757	/RAD/SEC				
	$C_{m_{\delta_E}}$	−.287	/RAD				
	$C_{m_{\Delta T}}$	$+.045 \times 10^{-6}$	/LB				
ROLL	C_{l_β}	−.0825	/RAD				
	C_{l_p}	−.0438	/RAD/SEC	−.0696	/RAD/SEC		
	C_{l_R}	+.073	/RAD/SEC				
	$C_{l_{\delta_W}}$	+.0573	/RAD				
	$C_{l_{\dot\beta}}$	0					
	$C_{l_{\delta_R}}$	+.0172	/RAD				
YAW	C_{n_β}	+.131	/RAD				
	C_{n_p}	−.0049	/RAD/SEC	−.0152	/RAD/SEC	−.0352	/RAD/SE
	C_{n_R}	−.102	/RAD/SEC				
	$C_{n_{\delta_W}}$	+.0229	/RAD	+.0504	/RAD	+.0504	/RAD
	$C_{n_{\dot\beta}}$	0				−.1680	/RAD/SE
	$C_{n_{\delta_R}}$	−.0745	/RAD				
SIDE FORCE	C_{Y_β}	−.5272	/RAD				
	C_{Y_p}	+.0487	/RAD/SEC				
	C_{Y_R}	+.146	/RAD/SEC				
	$C_{Y_{\delta_W}}$	0					
	$C_{Y_{\dot\beta}}$	0					
	$C_{Y_{\delta_R}}$	+.1146	/RAD				

367-80 CONFIGURATION
FOR SIMULATION of NASA Δ

SOURCES:
-80AERO # 96, UPDATED BY -80AERO # 131
-80 AERO # 132 (GR. EFF.)

SOURCES:
NASA

DELTA



NASA

WEIGHT	280,000
C.G. LOCATION	$.35\bar{c}$
ALTITUDE	SEA LEVEL

MOMENTS OF INERTIA IN BODY AXES

$I_{xx} = 2.222 \times 10^6$ SLUG FT²

$I_{YY} = 18.11 \times 10^6$ SLUG FT²

$I_{zz} = 20.00 \times 10^6$ SLUG FT²

$I_{xz} = 0$

FLIGHT CONDITION

FLAP SETTING	
WING SWEEP ANGLE $\Lambda_{L.E.}$ =	
NOSE POSITION	UP
GEAR	UP

GEOMETRY

$S = 8{,}000$ FT²

$\bar{c} = 89$ FT

$b = 111$ FT

TRIM

SPEED	135 KT	(228 FT/SEC)
α_{TRIM}	12°	(.2094 RAD)

ENGINE CHAR.

$$\frac{\Delta T}{\delta_{TH}} = \frac{170{,}000}{1 + sT_E} \quad \text{LB/RAD}$$

DEPENDENT VARIABLES

q_{TRIM} +61.8

$q_{TRIM}S$ 494,472 lbs.

$THRUST_{TRIM}$ 61,809 lbs.

MASS 8,696 SLUGS

(UNAUGMENTED) MODE SHAPES

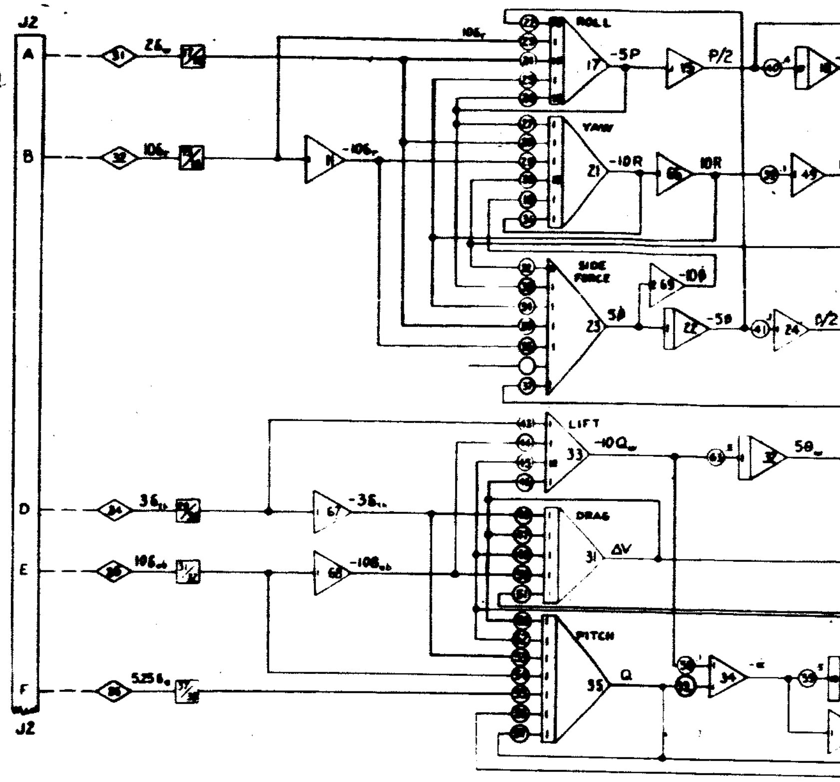
SHORT PERIOD	$\omega_u = .754$ RAD/SEC $\omega_D = .375$ RAD/SEC $\zeta = +.867$
PHUGOID	$\omega_u = .117$ RAD/SEC $\omega_D = .117$ RAD/SEC $\zeta = -.024$
DUTCH ROLL	$\omega_u = .831$ RAD/SEC $\omega_D = .769$ RAD/SEC $\zeta = +.379$
ROLL T.C.	.8 SEC
SPIRAL DIV. T.C.	-50.9 SEC (D.A: -35.2 SEC)

CALC	D.E.G.	2-3-65	REVISED	DATE
CHECK			H.P.C.	4-17-65
APR			S.D.P.	6-7-65
APR			BB	9-8-65

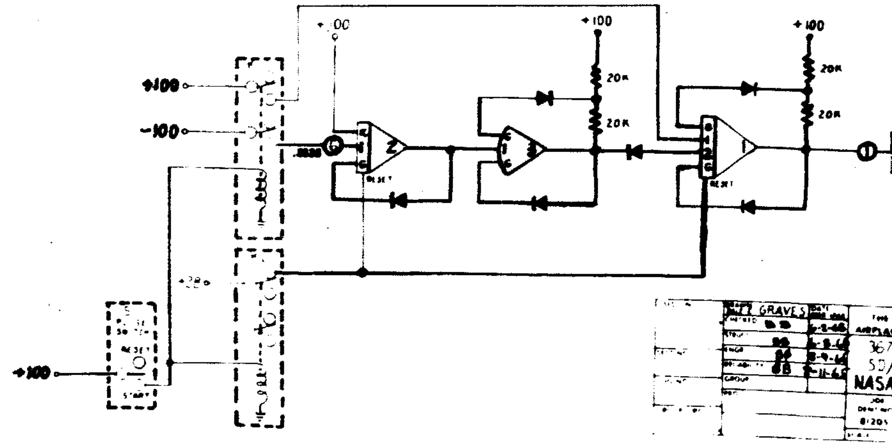
VARIABLE STABILITY AIRPLANE DESCRIPTION

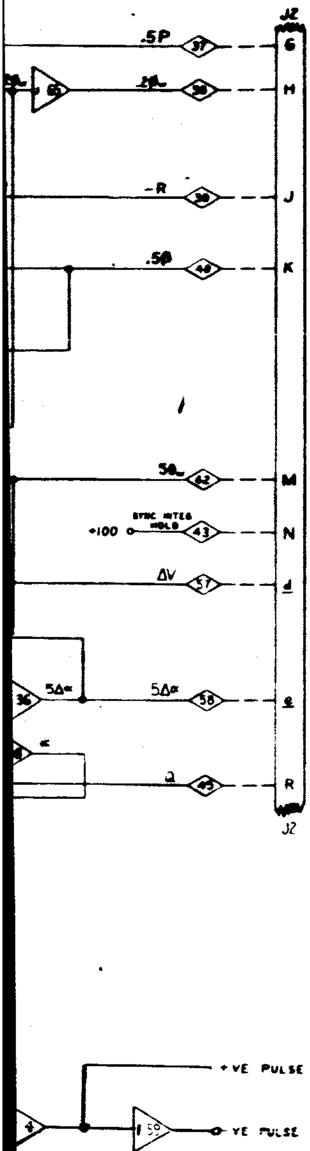
THE BOEING COMPANY

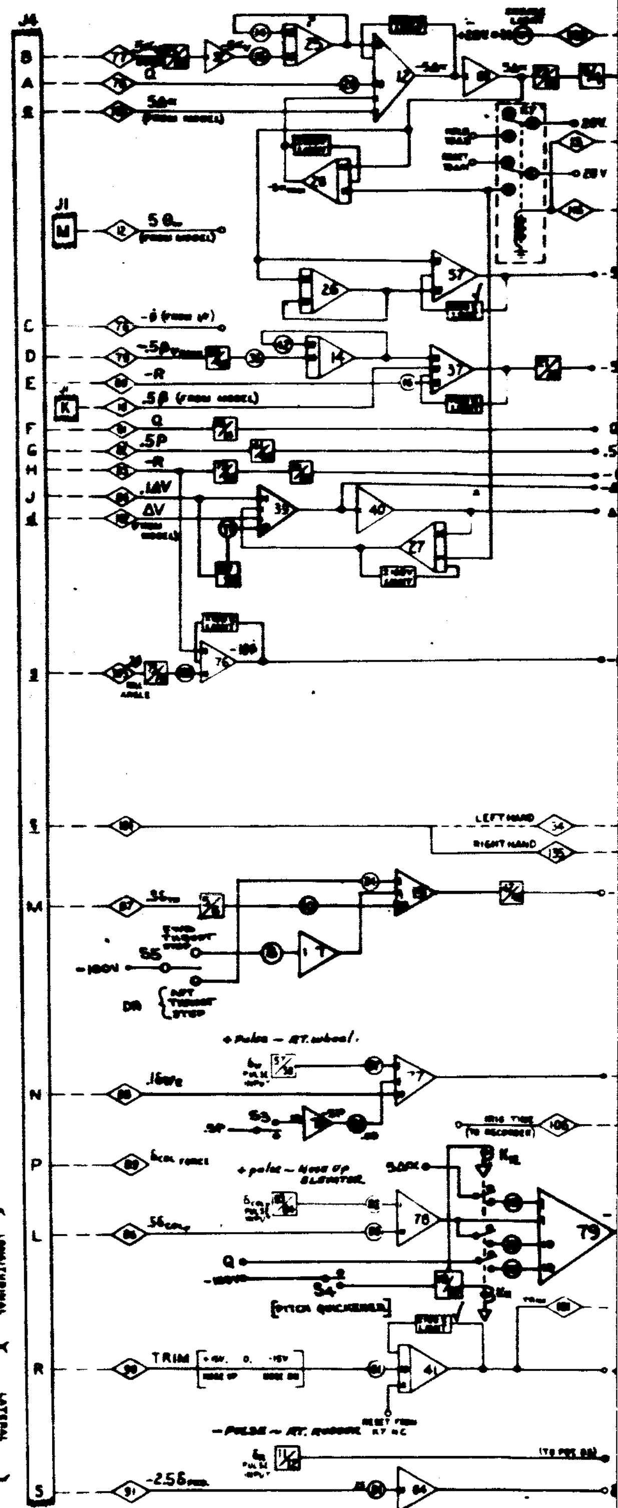
2



PULSE CIRCUIT





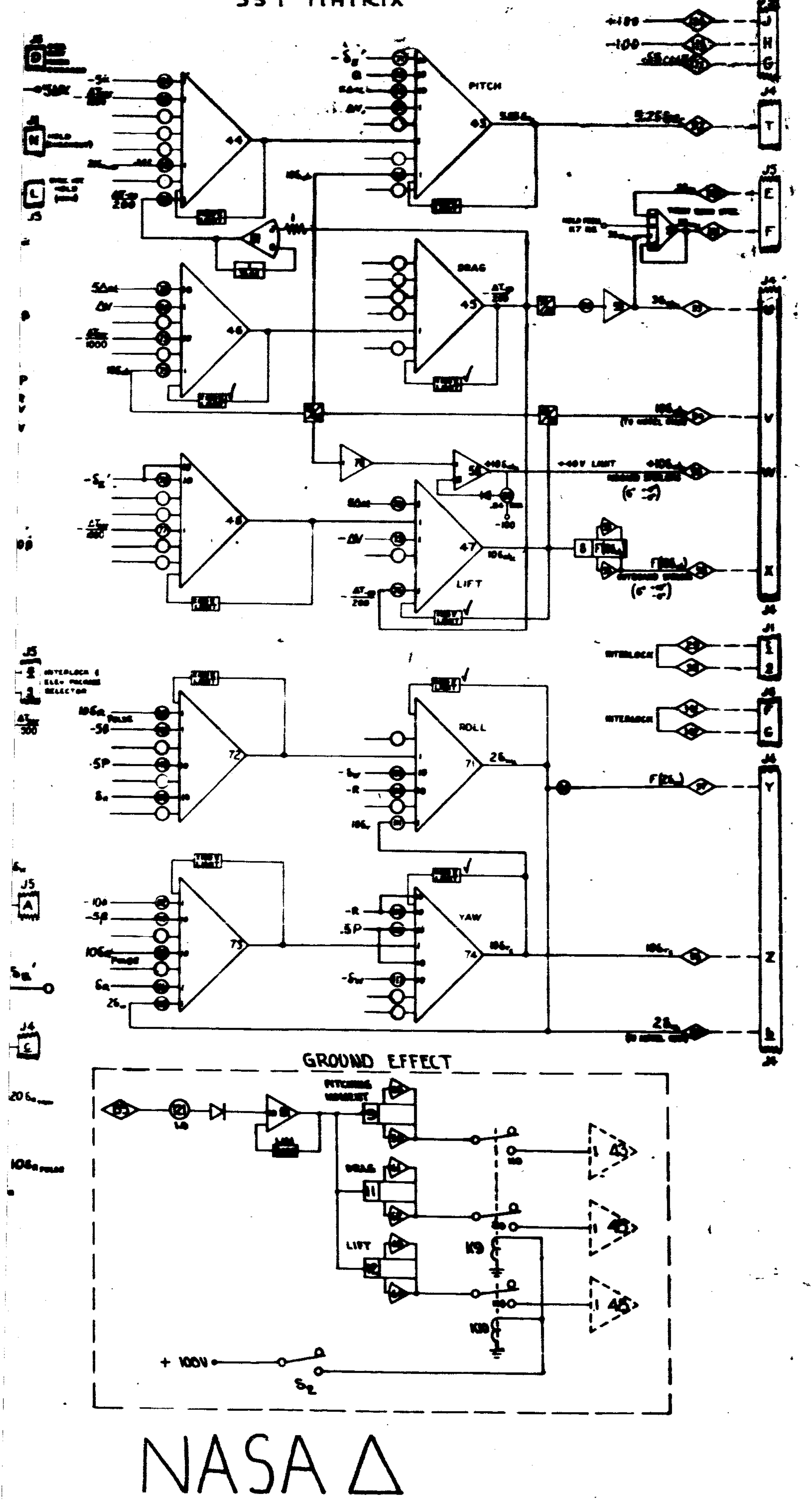


RECORDER								
VARIABLE	RANGE	[illegible]	CHANNEL	[illegible]	[illegible]	[illegible]	[illegible]	PULSE INPUTS
[illegible]	±100V	[illegible]	1	[illegible]	[illegible]	A 47	A 47	
Q	±4V	[illegible]	3	[illegible]	.4000	A [illegible]	[illegible]	
ΔV	±50V	[illegible]	6	[illegible]	[illegible]	A [illegible]	A 40	
Δα	±50V	[illegible]	7	[illegible]	[illegible]	A [illegible]	27/[illegible]	
δ_e	±50V	[illegible]	[illegible]	[illegible]	.3857	37/[illegible]	A 48	SST:
δ_{col}	[illegible]	[illegible]	14	[illegible]	[illegible]	[illegible]	A [illegible]	
[illegible]	±10V	[illegible]	15	[illegible]	[illegible]	—	[illegible]	
P	±10V	[illegible]	2	[illegible]	.1627	A [illegible]	[illegible]	
-R	±10V	[illegible]	4	[illegible]	[illegible]	A 40	[illegible]	
φ	±8V	[illegible]	5	[illegible]	.2263	A [illegible]	[illegible]	
-β	±50V	[illegible]	8	[illegible]	[illegible]	A [illegible]	[illegible]	
-φ	±100V	[illegible]	9	[illegible]	.1007	A [illegible]	A 76	SST
δ_{w}	±100V	[illegible]	11	[illegible]	[illegible]	17/[illegible]	A [illegible]	
δ_{r}	±100V	[illegible]	12	[illegible]	[illegible]	[illegible]	A 74	
PULSE	±100V		13	[illegible]	[illegible]	A 4(+), A [illegible](−)		

BOEING COMPANY
DIVISION RENTON WASHINGTON
80 VARIABLE STABILITY
80 COMPUTER DIAGRAM
SST Δ AERO#96 SST#2
J PATCHBOARD #5
2 OF 4

B-89-2

SST MATRIX



APPENDIX C

DESCRIPTION AND CALCULATION SHEETS FOR

NASA 72

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LINEARIZED EQUATIONS OF MOTION

$$I_{xx}\dot{P} = q_o S b \left(C_{\ell_\beta} \times \beta + C_{\ell_P} \times P + C_{\ell_R} \times R + C_{\ell_{\delta\omega}} \times \delta\omega + C_{\ell_{\delta r}} \times \delta r\right)$$

$$I_{YY}\dot{Q} = q_o S \bar{c} \left(C_{m_\alpha} \times \Delta\alpha + C_{m_{\dot\alpha}} \times \dot\alpha + C_{m_Q} \times Q + C_{m_{\delta e}} \times \delta e + C_{m_{\delta ab}} \times \delta ab + C_{m_{\Delta T}} \times \Delta T + C_{m_{\Delta V}} \Delta V\right)$$

$$I_{ZZ}\dot{R} = q_o S b \left(C_{n_\beta} \times \beta + C_{n_P} \times P + C_{n_R} \times R + C_{n_{\delta\omega}} \times \delta\omega + C_{n_{\delta r}} \times \delta r\right)$$

$$\Delta\dot{V} = -\frac{\rho S}{m} V_o C_{D_{TRIM}} \Delta V + \frac{1}{m}\Delta T - \frac{\rho S}{m}\frac{V_o^2}{2}\left(C_{D_\alpha}\Delta\alpha + C_{D_{\delta ab}} \times \delta ab\right) - g\,\theta_w$$

$$Q_W = \left(\frac{2g}{V_o^2} - \frac{T_o\alpha_o}{mV_o^2}\right)\Delta V + \left(\frac{\rho S}{2m} V_o C_{L_\alpha} + \frac{T_o}{mV_o}\right)\Delta\alpha + \frac{\alpha_o}{mV_o}\Delta T + \frac{\rho S}{2m} V_o C_{L_{\delta ab}} \times \delta ab$$

$$R_W = \frac{\rho S}{m}\frac{V_o}{2}\left(C_{Y_\beta} \times \beta + C_{Y_P} \times P + C_{Y_R} \times R + C_{Y_{\delta\omega}} \times \delta\omega + C_{Y_{\delta r}} \times \delta r\right) + \frac{g}{V_o}\phi_w$$

$$\dot\alpha = Q - Q_w \quad ; \quad \Delta\alpha = \int \dot\alpha\, dt \quad ; \quad \theta_w = \int Q_w\, dt$$

$$\dot\beta = R_W - R \quad ; \quad \beta = \int \dot\beta\, dt \quad ; \quad \phi_W = \int P\, dt.$$

In these equations, the following variables are:

in radians : $\Delta\alpha$, β, $\delta\omega$, δr, δe, δab, θ_w; ϕ_w

in radians/sec : $\dot\alpha$, $\dot\beta$, P, Q, R, Q_w, R_w

in feet/sec : ΔV

in lbs : ΔT

These equations are derived from WADC, Technical Note 55-747 by R.M. Howe, June 1956.

They are valid for small perturbations around the trimmed level flight condition.

ENGR. Jan. 65 HPC	REVISED	DATE	-80 Variable Stability	NASA72
CHECK	3-3-65	HPC.	AIRPLANE MODEL	
APR	4-7-65	HPC.	AIRBORNE COMPUTER	
APR	6-15-65	HPC.	THE BOEING COMPANY RENTON, WASHINGTON	C1

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Eliminating R_W and changing the units of the variables to the following:

in degrees : $\Delta\alpha$, β, $\delta\omega$, δr, δe, δab, θ_w, ϕ_w.

in degrees/sec : $\dot{\alpha}$, $\dot{\beta}$, P, Q, R, Q_W.

in feet/sec : ΔV

in pounds : ΔT

$$\dot{P} = \frac{q_oSb}{I_{xx}} C_{\ell_\beta} * \beta + \frac{q_oSb}{I_{xx}} C_{\ell_p} * P + \frac{q_oSb}{I_{xx}} C_{\ell_R} * R + \frac{q_oSb}{I_{xx}} C_{\ell_{\delta\omega}} * \delta\omega + \frac{q_oSb}{I_{xx}} C_{\ell_{\delta r}} * \delta r$$

$$\dot{Q} = \frac{q_oS\bar{c}}{I_{YY}} C_{m_\alpha} * \Delta\alpha + \frac{q_oS\bar{c}}{I_{YY}} C_{m_{\dot\alpha}} * \dot\alpha + \frac{q_oS\bar{c}}{I_{YY}} C_{m_Q} * Q + \frac{q_oS\bar{c}}{I_{YY}} C_{m_{\delta e}} * \delta e + \frac{q_oS\bar{c}}{I_{YY}} C_{m_{\delta ab}} * \delta ab + 57.3 \frac{q_oS\bar{c}}{I_{YY}} C_{m_{\Delta T}} * \Delta T + \frac{q_oS\bar{c}}{I_{YY}} 57.3\, C_{m_{\Delta V}} * \Delta V$$

$$\dot{R} = \frac{q_oSb}{I_{zz}} C_{n_\beta} * \beta + \frac{q_oSb}{I_{zz}} C_{n_P} * P + \frac{q_oSb}{I_{zz}} C_{n_R} * R + \frac{q_oSb}{I_{zz}} C_{n_{\delta\omega}} * \delta\omega + \frac{q_oSb}{I_{zz}} C_{n_{\delta r}} * \delta r.$$

$$\Delta\dot{V} = -\frac{\rho S}{m} V_o C_{D_{TRIM}} \Delta V + \frac{1}{m}\Delta T - \frac{\rho S}{m}\frac{V_o^2}{2 * 57.3} C_{D_\alpha} * \Delta\alpha - \frac{\rho S}{m}\frac{V_o^2}{2 * 57.3} C_{D_{\delta ab}} * \delta ab - \frac{g}{57.3}\theta_w$$

$$Q_w = \left[57.3\left(\frac{2g}{V_o^2}\right) - \frac{T_o\alpha_o}{mV_o^2}\right]\Delta V + \frac{\alpha_o}{mV_o}\Delta T + \left(\frac{\rho S}{2m}V_o C_{L_\alpha} + \frac{T_o}{mV_o}\right)\Delta\alpha + \frac{\rho S}{2m} V_o C_{L_{\delta ab}} * \delta ab \quad (\alpha_o \text{ in degrees})$$

$$\dot\beta = \frac{\rho S}{m}\frac{V_o}{2} C_{Y_\beta} * \beta + \frac{\rho S}{m}\frac{V_o}{2} C_{Y_P} * P + \frac{\rho S}{m}\frac{V_o}{2} C_{Y_R} * R + \frac{\rho S}{m}\frac{V_o}{2} C_{Y_{\delta\omega}} * \delta\omega + \frac{\rho S V_o}{m2} C_{Y_{\delta r}} * \delta r + \frac{g}{V_o}\phi_w - R$$

$$\dot\alpha = Q - Q_W$$

$$\Delta\alpha = \int\dot\alpha\, dt \; ; \quad \beta = \int\dot\beta\, dt \; ; \quad \theta_W = \int Q_W\, dt \; ; \quad \phi_W = \int P\, dt.$$

In these equations, the aerodynamic and control coefficients have the following units:

/LB : $C_{m_{\Delta T}}$

/radian : C_{ℓ_β} ; $C_{\ell_{\delta\omega}}$; $C_{\ell_{\delta r}}$; C_{m_α} ; $C_{m_{\delta e}}$; $C_{m_{\delta ab}}$; C_{n_β} ; $C_{n_{\delta\omega}}$; $C_{n_{\delta r}}$; C_{D_α} ; $C_{D_{\delta ab}}$; C_{L_α} ; $C_{L_{\delta ab}}$; C_{Y_β} ; $C_{Y_{\delta\omega}}$; $C_{Y_{\delta r}}$

sec/radian : C_{ℓ_P} ; C_{ℓ_R} ; $C_{m_{\dot\alpha}}$; C_{m_Q} ; C_{n_P} ; C_{n_R} ; C_{Y_P} ; C_{Y_R}

ENGR. Jan. 28 HPC	REVISED	DATE	-80 Variable Stability AIRPLANE MODEL AIRBORNE COMPUTER	NASA 72
CHECK		3-3-65 HPC		
APR		3-27-65 HPC		
APR		6-16-65 HPC	THE BOEING COMPANY RENTON, WASHINGTON	C2

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THE FOLLOWING SCALE FACTORS WILL BE USED

Q ; $10\,Q_w$; $\dot{\alpha}$; $5\,\Delta\alpha$; $5\,\theta_w$; ΔV

$.5\,P$; $5\,\dot{\beta}$; $.5\,\beta$; ϕ_w ; R

$5\,\delta e$; $10\,\delta ab$; $10\,\delta r$; $2\,\delta w$; $3\,\delta th$ where $3\delta th = \frac{\Delta T}{278}$

δth in degrees

$$-10\,Q_w = -\left[573\left(\frac{2g}{V_o^2}\right) - \frac{10\,T_o\alpha_o}{mV_o^2}\right](\Delta V) + \left(\frac{\rho S}{m}V_o C_{L_\alpha} + \frac{2T_o}{mV_o}\right)(5\,\Delta\alpha) + \frac{2780\,\alpha_o}{mV_o}(3\delta th) + \frac{\rho S}{2m}V_o\left(-C_{L_{\delta ab}}\right)\left(-10\,\delta_{ab}\right)$$

$$\Delta V = -\int\left[\frac{\rho S}{m}V_o C_{D_{TRIM}}(\Delta V) + \frac{278}{m}(-3\delta th) + \frac{\rho S}{m}\frac{V_o^2}{57.3}\frac{C_{D_\alpha}}{10}(5\,\Delta\alpha) + \frac{\rho S}{m}\frac{V_o^2}{2\times 57.3}\frac{(-C_{D_{\delta ab}})}{10}(-10\,\delta ab) + \frac{2g}{573}(5\,\theta_w)\right]dt$$

$$Q = -\int\left[\frac{q_oS\bar{c}}{I_{YY}}\left(-\frac{C_{m_\alpha}}{5}\right)(5\,\Delta\alpha) + \frac{q_oS\bar{c}}{I_{YY}}\left(-C_{m_{\dot{\alpha}}}\right)(+\dot{\alpha}) + \frac{q_oS\bar{c}}{I_{YY}}\left(-C_{m_Q}\right)(Q) + \frac{q_oS\bar{c}}{I_{YY}}\left(-\frac{C_{m_{\delta e}}}{5}\right)(5\,\delta e) + \frac{q_oS\bar{c}}{I_{YY}}57.3\,C_{m_{\Delta V}}(\Delta V) + \frac{q_oS\bar{c}}{I_{YY}}\left(-\frac{C_{m_{ab}}}{10}\right)(10\,\delta ab) + \frac{q_oS\bar{c}}{I_{YY}}\left(57.3\times 278\,C_{m_{\Delta T}}\right)(-3\delta th)\right]dt$$

$$-\dot{\alpha} = -\left[Q + (.1)(-10\,Q_w)\right] \qquad 5\,\Delta\alpha = -\int\left[.5(10)(-\dot{\alpha})\right]dt$$

$$5\theta_w = -\int .5(-10Q_w)\,dt$$

ENGR Jan. 29 HPC.	REVISED	DATE	-80 Variable Stability AIRPLANE MODEL	NASA 72
CHECK	3-3-65	HPC		
APR	3-27-65	HPC.	LONGITUDINAL SYST. OF EQUATIONS	
APR	4-7-65	HPC.	THE BOEING COMPANY RENTON, WASHINGTON	C 3
	6-16-65	HPC.		

TD 1017-R6

8-7000

$$-5P = -\int\left[\frac{q_0 S b}{I_{xx}}(-C_{\ell_\beta})(-5\beta) + \frac{q_0 S b}{I_{xx}}(-C_{\ell_p})(-5P) + \frac{q_0 S b}{I_{xx}}\frac{C_{\ell_R}}{2}(10R) + \frac{q_0 S b}{I_{xx}}2.5\,C_{\ell_{\delta\omega}}(2\delta\omega) + \frac{q_0 S b}{I_{xx}}\frac{C_{\ell_{\delta r}}}{2}(10\delta r)\right]dt$$

$$-10R = -\int\left[\frac{q_0 S b}{I_{zz}}20C_{n_\beta}(5\beta) + \frac{q_0 S b}{I_{zz}}(-2C_{n_p})(-5P) + \frac{q_0 S b}{I_{zz}}(-C_{n_R})(-10R) + \frac{q_0 S b}{I_{zz}}(-2C_{n_{\dot\beta}})(-5\dot\beta) + \frac{q_0 S b}{I_{zz}}5C_{n_{\delta\omega}}(2\delta\omega) + \frac{q_0 S b}{I_{zz}}\left(-\frac{C_{n_{\delta r}}}{1}\right)(-10\delta r)\right]dt$$

$$5\dot\beta = -\left[\frac{\rho S}{m}\frac{V_0}{2}(-10C_{Y_\beta})(.5\beta) + \frac{\rho S}{m}\frac{V_0}{2}C_{Y_P}(-5P) + \left(\frac{1}{2} - \frac{\rho S}{m}\frac{V_0}{2}\frac{C_{Y_R}}{2}\right)(10R) + \frac{\rho S}{2m}\frac{V_0}{20}(-100\Delta C_Y) + \frac{\rho S}{m}\frac{V_0}{2}(-2.5C_{Y_{\delta\omega}})(2\delta\omega) + \frac{\rho S}{2m}\frac{V_0}{2}C_{Y_{\delta r}}(-10\delta r) + \frac{5g}{V_0}(-\phi_w)\right]$$

$$-2\phi_w = -\int\left[.4(10)(.5P)\right]dt \qquad -5\beta = -\int(5\dot\beta)\,dt$$

ENGR Jan. 29 HPC.	REVISED	DATE	-80 Variable Stability	NASA 72
CHECK	3-3-65	HPC	AIRPLANE MODEL	
APR	3-27-65	HPC	LATERAL-DIR. SYST. OF EQUATIONS	
APR	5-17-65	D.E.G.	THE BOEING COMPANY RENTON, WASHINGTON	C4

ROTATIONS, BODY AXES

$$I_{xx}\dot{P} = (I_{YY}-I_{ZZ})QR + I_{XZ}(\dot{R}+PQ) + T_x + L$$

$$I_{YY}\dot{Q} = (I_{ZZ}-I_{xx})RP + I_{XZ}(R^2-P^2) + T_Y + M$$

$$I_{ZZ}\dot{R} = (I_{xx}-I_{YY})PQ + I_{XZ}(\dot{P}-QR) + T_Z + N$$

ROTATIONS, STABILITY AXES

$$I'_{xx}\dot{P}_S = (I'_{YY}-I'_{ZZ})Q_SR_S + I'_{XZ}(\dot{R}_S+P_SQ_S) + T_X + L_S$$

$$I'_{YY}\dot{Q}_S = (I'_{ZZ}-I'_{xx})R_SP_S + I'_{XZ}(R_S^2-P_S^2) + T_Y + M_S$$

$$I'_{ZZ}\dot{R}_S = (I'_{xx}-I'_{YY})P_SQ_S + I'_{XZ}(\dot{P}_S-Q_SR_S) + T_Z + N_S$$

Where

$$P_S = P\cos\alpha + R\sin\alpha$$
$$Q_S = Q$$
$$R_S = -P\sin\alpha + R\cos\alpha$$

$$I'_{xx} = I_{xx}\cos^2\alpha + I_{ZZ}\sin^2\alpha - 2I_{XZ}\sin\alpha\cos\alpha$$
$$I'_{YY} = I_{YY}$$
$$I'_{ZZ} = I_{ZZ}\cos^2\alpha + I_{xx}\sin^2\alpha + 2I_{XZ}\sin\alpha\cos\alpha$$
$$I'_{XZ} = (I_{xx}-I_{ZZ})\sin\alpha\cos\alpha + I_{XZ}(\cos^2\alpha - \sin^2\alpha)$$

NEGLECTING THE NON-LINEAR TERMS:

$P_s Q_s$; $Q_s R_s$; $R_s P_s$; P_s^2 ; R_s^2 ;

ASSUMING SYMMETRICAL THRUST;

$T_x = 0$; $T_z = 0$

and SINCE THE TERM T_y IS ACCOUNTED FOR BY THE EQUIVALENT AERODYNAMIC COEFFICIENT $Cm_{\Delta T}$,

$$I'_{xx} \dot{P}_s = I'_{xz} \dot{R}_s + L_s$$

$$I_{YY} \dot{Q} = M$$

$$I'_{zz} \dot{R}_s = I'_{xz} \dot{P}_s + N_s$$

ISOLATING $\dot{P}_s$ and $\dot{R}_s$

$$\dot{P}_s = \frac{\frac{1}{I'_{xx}} L_s + \frac{I'_{xz}}{I'_{xx} I'_{zz}} N_s}{1 - \frac{I'^2_{xz}}{I'_{xx} I'_{zz}}} = \frac{1}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}} \left(L_s + \frac{I'_{xz}}{I'_{zz}} N_s \right)$$

$$\dot{R}_s = \frac{\frac{1}{I'_{zz}} N_s + \frac{I'_{xz}}{I'_{xx} I'_{zz}} L_s}{1 - \frac{I'^2_{xz}}{I'_{xx} I'_{zz}}} = \frac{1}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}} \left(N_s + \frac{I'_{xz}}{I'_{xx}} L_s \right)$$

IN ORDER TO INCLUDE IN THE SIMULATION THE EFFECT OF THE CROSS-PRODUCT OF INERTIA, I_{xz}, THE FOLLOWING TECHNIQUE IS PROPOSED:

1. CONVERT THE MOMENTS OF INERTIA I_{xx}, I_{yy}, I_{zz}, I_{xz} FROM BODY AXES TO STABILITY AXES I'_{xx}, I_{yy}, I'_{zz}, I'_{xz} USING (α_{TRIM}) IN THE FORMULAE OF PAGE 1

   — FOR BOTH -80 AND SST AIRPLANES —

2. IN THE ROLL AND YAW EQUATIONS, REPLACE THE ROLLING AND YAWING MOMENTS OF INERTIA I_{xx} and I_{zz} by:

$$I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}} \quad \text{AND} \quad I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}, \text{ respectively.}$$

   — FOR BOTH -80 AND SST AIRPLANES —

3. IN THE ROLL AND YAW EQUATIONS, REPLACE THE AERODYNAMIC AND CONTROL COEFFICIENTS AS FOLLOWS:

REPLACE C_{ℓ_β} BY $C_{\ell_\beta} + \frac{I'_{xz}}{I'_{zz}} C_{n_\beta}$

C_{ℓ_p} BY $C_{\ell_p} + \frac{I'_{xz}}{I_{zz}} C_{n_p}$

etc ...

C_{n_β} BY $C_{n_\beta} + \frac{I'_{xz}}{I'_{xx}} C_{\ell_\beta}$

C_{n_p} BY $C_{n_p} + \frac{I'_{xz}}{I'_{xx}} C_{\ell_p}$

etc....

— FOR BOTH -80 AND SST AIRPLANES —

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$q_0 S = 214,700$

$q_0 S b = 28.08 \times 10^6$

$q_0 S \bar{c} = 4.32 \times 10^6$

$\dfrac{q_0 S b}{I'_{xx} - \frac{I_{xz}'^2}{I'_{zz}}} = 10.95$

$\dfrac{q_0 S \bar{c}}{I_{YY}} = 1.92$

$\dfrac{q_0 S b}{I'_{zz} - \frac{I_{xz}'^2}{I'_{xx}}} = 5.9$

$m V_0 = 4660 \times 253 = 1.18 \times 10^6$

$\dfrac{\alpha_0}{m V_0} = \dfrac{5.3}{1.18 \times 10^6} = 4.5 \times 10^{-6}$ $\alpha_0 = \alpha_{WING,\ TRIM}$ (DEGREES)

$\dfrac{T_0 \alpha_0}{m V_0^2} = \dfrac{19,170 \times 5.3}{1.18 \times 10^6 \times 253} = 3.4 \times 10^{-4}$

$\dfrac{T_0}{m V_0} = \dfrac{19,170}{1.18 \times 10^6} = 16.25 \times 10^{-3}$

$\rho = .002378$

$\rho S = 6.7$

$\dfrac{\rho S}{m} = \dfrac{6.7}{4660} = 1.44 \times 10^{-3}$

$\dfrac{\rho S}{m} \dfrac{V_0}{2} = 1.44 \times 10^{-3} \times 126.5 = .182$

$\dfrac{\rho S}{m} \dfrac{V_0^2}{2} = .182 \times 253 = 46$

$\dfrac{g}{V_0} = \dfrac{32.2}{253} = .127$

$\dfrac{2g}{V_0^2} = \dfrac{2 \times .127}{253} = 10.06 \times 10^{-4}$

For Work in Stability Axes, change roll and yaw terms below to: $-\frac{q_0 S b}{I_{xx}-\frac{I_{xz}^2}{I_{zz}}}\left(C_{l_\beta}+\frac{I_{xz}}{I_{zz}}C_{n_\beta}\right)$ typical

	POTENTIOMETER NO.	SETTING	VARIABLE	
ROLL AMPL. 17	22	$.0589^{10}$	-5β	$-C_{l_\beta}\frac{q_0Sb}{I_{xx}} = [+.0543-.007(.079)]10.95 = .589$
	23	.110	$+10\delta_r$	$.5C_{l_{\delta r}}\frac{q_0Sb}{I_{xx}} = [.0202+.007(-.068)]10.95\times.5 = .11$
	24	$.211^{10}$	$+2\delta_w$	$2.5C_{l_{\delta w}}\frac{q_0Sb}{I_{xx}} = 2.5[.077+.007(.015)]10.95 = 2.11$
	25	.175	$+10R$	$\frac{C_{l_R}}{2}\frac{q_0Sb}{I_{xx}} = .5[.032+.007(-.0183)]10.95 = .175$
	26	$.149^{10}$	$-5P$	$-C_{l_P}\frac{q_0Sb}{I_{xx}} = [.1361-.007(-.017)]10.95 = 1.49$
	21	.423	$-10\dot\beta$	$-.5\frac{q_0Sb}{I_{xx}}C_{l_{\dot\beta}} = .5[.0778+.007(-.0916)]10.95 = .423$
YAW AMPL. 21	27	.228	$-5P$	$-2C_{n_P}\frac{q_0Sb}{I_{zz}} = 2[.0166-.014(-.136)]5.9 = .228$
	28	.529	$+2\delta_w$	$5C_{n_{\delta w}}\frac{q_0Sb}{I_{zz}} = 5[.0168+.014(.077)]5.9 = .529$
	29	.403	$-10\delta_r$	$-C_{n_{\delta r}}\frac{q_0Sb}{I_{zz}} = [.068-.014(.02)]5.9 = .403$
	30	$10+.30^{10}$	$+.5\beta$	$20C_{n_\beta}\frac{q_0Sb}{I_{zz}} = 20[.1167-.014(-.4927)]5.9 = 15.0$
	19	.605	$-10\dot\beta$	$-C_{n_{\dot\beta}}\frac{q_0Sb}{I_{zz}} = [-.1021+.014(.0778)]5.9 = .605$
	31	.104	$-10R$	$-C_{n_R}\frac{q_0Sb}{I_{zz}} = [.0183-.014(.041)]5.9 = .104$
SIDE FORCE AMPL. 23	32	$.1502^{10}$	$+.5\beta$	$-10C_{Y_\beta}\frac{\rho S}{m}\frac{V_0}{2} = .182\times10\times.825 = 1.502$
	33	.0157	$-5P$	$C_{Y_P}\frac{\rho S}{m}\frac{V_0}{2} = .182\times.0864 = .0157$
	34	.493	$+10R$	$-\frac{C_{Y_R}}{2}\frac{\rho S}{m}\frac{V_0}{2}+\frac{1}{2} = .182\times(-.0382)+.5 = .493$
	38	.0058	$+2\delta_w$	$-2.5C_{Y_{\delta w}}\frac{\rho S}{m}\frac{V_0}{2} = 2.5\times.182\times.0128 = .0058$
	35	.0016	$-10\delta_r$	$.5C_{Y_{\delta r}}\frac{\rho S}{m}\frac{V_0}{2} = .5\times.182\times.0177 = .0016$
	37	.318	$-2\phi_w$	$2.5\frac{g}{V_0} = 2.5\times.127 = .318$

H. P-C 6-16-65	D.E.G. 3-10-65	-80 VARIABLE STABILITY AIRPLANE MODEL AIRBORNE COMPUTER	NASA 72
	D.E.G. 3-27-65	THE BOEING COMPANY RENTON, WASHINGTON	C9
	D.E.G. 3-30-65		
	D.E.G. 5-17-65		

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	POTENTIOMETER NO.	SETTING	VARIABLE	
LIFT AMPL. 33	43	.0125	$+3\delta_{th}$	$\frac{2780\,\alpha_0}{m\,V_0} = 2780\times4.5\times10^{-6} = .0125$
	44	.0812	$-10\delta_{ab}$	$\frac{\rho S}{m}\frac{V_0}{2}\left(-C_{L\delta_{ab}}\right) = .182\times.446 = .0812$
	45	.168 10	$+5\Delta\alpha$	$\frac{\rho S}{m}\frac{V_0}{}C_{L\alpha} + \frac{2T_0}{mV_0} = 2\times.182\times4.55 + 2\times16.25\times10^{-3} = 1.68$
	46	.571	$+\Delta V$	$573\left(\frac{2g}{V_0^2}\right) - \frac{10T_0\alpha_0}{mV_0^2} = 573\left[\frac{1.44\times10^{-3}}{2}\times.6935 + 503\times10^{-4}\right]$ $-10\times3.4\times10^{-4} = .5743 - .0034 = .571$
				α_0 IN DEGREES
DRAG AMPL. 31	48	.0597	$-3\delta_{th}$	$\frac{278}{m} = \frac{278}{4660} = .0597$
	47	.0325	$+\Delta V$	$\frac{\rho S}{m}V_0\,C_{D\,TRIM} = 1.44\times10^{-3}\times253\times.0892 = .0325$
	49	.0525	$+5\Delta\alpha$	$\frac{\rho S}{m}\frac{V_0^2}{57.3}\frac{C_{D\alpha}}{10} = \frac{46\times2\times.327}{57.3\times10} = .0525$
	50	.0014	$-10\delta_{ab}$	$\frac{\rho S}{m}\frac{V_0^2}{2\times57.3}\frac{(-C_{D\delta_{ab}})}{10} = \frac{46\times-.0178}{57.3\times10} = -.0014$
	51	.1124	$+5\theta_w$	$\frac{2g}{573} = \frac{64.4}{573} = .1124$
PITCH AMPL. 35	62	.428	$+5\Delta\alpha$	$-C_{m\alpha}\frac{q_0S\bar{c}}{5I_{YY}} = -1.11\times\frac{1.92}{5} = .428$
	53	0	$-3\delta_{th}$	$+C_{m\Delta T}\frac{q_0S\bar{c}}{I_{YY}}57.3\times278 = 0$
	54	.028	$+10\delta_{ab}$	$-C_{m\delta_{ab}}\frac{q_0S\bar{c}}{10I_{YY}} = +.146\times\frac{1.92}{10} = .028$
	55	.329	$+5.25\,\delta_e$	$-\frac{C_{m\delta_e}}{5.25}\frac{q_0S\bar{c}}{I_{YY}} = \frac{+.90}{5.25}\times1.92 = .329$
	56	.693	$+\dot{\alpha}$	$-C_{m\dot{\alpha}}\frac{q_0S\bar{c}}{I_{YY}} = .361\times1.92 = .693$
	57	.816	$+Q$	$-C_{mQ}\frac{q_0S\bar{c}}{I_{YY}} = +.425\times1.92 = .816$
	60	.0329	$+\Delta V$	$-57.3\frac{q_0S\bar{c}}{I_{YY}}C_{m\Delta V} = 57.3\times.0003\times1.92 = .0329$

ENGR H. P-C 6-16-65
CHECK
APR
APR

D.E.G. 3-18-65
D.E.G. 3-27-65
H.P.C. 4-7-65
D.E.G. 5-17-65

-80 VARIABLE STABILITY
AIRPLANE MODEL
AIRBORNE COMPUTER

THE BOEING COMPANY
RENTON WASHINGTON

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POTENTIOMETER NO.	POTENTIOMETER SETTING		VARIABLE	CALCULATED FROM
39	.1	A 49	+ 10 R	$\frac{R}{10R} = .1$
40	.4 10	A 18	+ .5 P	$\frac{P}{.25P} = 4.0$
41	.1	A 4	− 5β	$\frac{-.5\beta}{-5\beta} = .1$
58	.1	A 34	− 10 Q_w	$\frac{-Q_w}{-10Q_w} = .1$
59	.5 10	A 36	− $\dot{\alpha}$	$\frac{-5\dot{\alpha}}{-\dot{\alpha}} = 5$
63	.5	A 32	− 10 Q_w	$\frac{-5Q_w}{-10Q_w} = .5$

DRAG AXIS ; UNITS : LBS

$$\Delta T_{-80} = \Delta T_{-80_{\Delta V}} \times \Delta V + \Delta T_{-80_{\Delta T_{SST}}} \times \Delta T_{SST} + \Delta T_{-80_{\delta ab}} \times \delta ab + \Delta T_{-80_{\Delta\alpha}} \times \Delta\alpha + \Delta T_{-80_{\delta_{TH}'}} \times \delta_{TH}'$$

LIFT AXIS ; UNITS : DEGREES

$$\delta ab = \delta ab_{\Delta\alpha} \times \Delta\alpha + \delta ab_{\Delta T_{SST}} \times \Delta T_{SST} + \delta ab_{\Delta T_{-80}} \times \Delta T_{-80} + \delta ab_{\delta E} \times \delta E + \delta ab_{\delta e} \times \delta e + \delta ab_{\Delta V} \times \Delta V + \delta ab_{\delta_{TH}'} \times \delta_{TH}'$$

PITCH AXIS ; UNITS : DEGREES

$$\delta e = \delta e_{\Delta T_{SST}} \times \Delta T_{SST} + \delta e_{\Delta T_{-80}} \times \Delta T_{-80} + \delta e_{\Delta V} \times \Delta V + \delta e_{\Delta\alpha} \times \Delta\alpha + \delta e_{\dot\alpha} \times \dot\alpha + \delta e_{Q} \times Q + \delta e_{\delta ab} \times \delta ab + \delta e_{\delta E} \times \delta E + \delta e_{\delta_{TH}'} \times \delta_{TH}'$$

ROLL AXIS ; UNITS : DEGREES

$$\delta\omega = \delta\omega_{\beta} \times \beta + \delta\omega_{P} \times P + \delta\omega_{R} \times R + \delta\omega_{\delta w} \times \delta w + \delta\omega_{\delta R} \times \delta R + \delta\omega_{\delta r} \times \delta r$$

YAW AXIS ; UNITS : DEGREES

$$\delta r = \delta r_{\beta} \times \beta + \delta r_{\dot\beta} \times \dot\beta + \delta r_{P} \times P + \delta r_{R} \times R + \delta r_{\delta w} \times \delta w + \delta r_{\delta R} \times \delta R + \delta r_{\delta\omega} \times \delta\omega$$

SIDE FORCE AXIS ; UNITS : DIMENSIONLESS.

$$\Delta C_Y = \Delta C_{Y_{\beta}} \times \beta + \Delta C_{Y_{P}} \times P + \Delta C_{Y_{R}} \times R + \Delta C_{Y_{\delta w}} \times \delta w + \Delta C_{Y_{\delta R}} \times \delta R + \Delta C_{Y_{\delta\omega}} \times \delta\omega + \Delta C_{Y_{\delta r}} \times \delta r$$

THE FOLLOWING VARIABLES ARE IN DEGREES $\begin{cases} \delta e \; ; \; \delta r \; ; \; \delta\omega \; ; \; \delta ab \; ; \; \Delta\alpha \; ; \; \beta . \\ \delta E \; ; \; \delta R \; ; \; \delta w \; ; \end{cases}$

IN DEGREES PER SECOND : P ; Q ; R ; $\dot\beta$; $\dot\alpha$

IN POUNDS : ΔT_{-80} ; ΔT_{SST}

IN FEET PER SECOND : ΔV

			REVISED	DATE		
ENGR	Jan. 65	WPC.			-80 Variable Stability DEFINITION OF AIRBORNE COMPUTER COEFFICIENTS	NASA 72
CHECK	Apr. 5. 65	WPC.				
APR						
APR					THE BOEING COMPANY RENTON, WASHINGTON	C12

$I'_{xx} = I_{xx}\cos^2\alpha + I_{zz}\sin^2\alpha - 2I_{xz}\sin\alpha\cos\alpha$

$I'_{xx} = 1.67\times10^6 \times .9547 + 20\times10^6 \times .04537 - 0 = 2.499\times10^6$

$I'_{zz} = I_{zz}\cos^2\alpha + I_{xx}\sin^2\alpha + 2I_{xz}\sin\alpha\cos\alpha$

$I'_{zz} = 20\times10^6 \times .9547 + 1.67\times10^6 \times .04537 + 0 = 19.17\times10^6$

$I'_{xz} = (I_{xx} - I_{zz})\sin\alpha\cos\alpha + I_{xz}(\cos^2\alpha - \sin^2\alpha)$

$I'_{xz} = -18.37 \times .21303 \times .97705 + 0 = -3.823\times10^6$

SST AIRPLANE.

$$\frac{q_0 S \bar{c}}{I_{yy}} = \frac{560{,}310 \times 70}{18.58 \times 10^6} = 2.11$$

$$\frac{q_0 S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}} = \frac{560{,}310 \times 85}{(2.499 - .763)\times10^6} = 27.45$$

$$\frac{q_0 S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}} = \frac{560{,}310 \times 85}{(19.17 - 5.85)\times10^6} = 3.575$$

$$\frac{q_0 S}{m} = \frac{560{,}310}{8{,}385} = 66.8$$

ENGR.	May 7. 65	HPC.	REVISED	DATE	-80 Variable Stability DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS	NASA 72
CHECK						
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APR					THE BOEING COMPANY RENTON, WASHINGTON	C13

TD 1017-R6

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367-80 AIRPLANE

$$I'_{xx} = I_{xx}\cos^2\alpha + I_{zz}\sin^2\alpha - 2I_{xz}\sin\alpha\cos\alpha$$

$$I'_{xx} = 2.57\times.9966 + 4.73\times10^6\times.00331 - 2\times16\times10^6\times.0575 = 2.557\times10^6$$

$$I'_{zz} = I_{zz}\cos^2\alpha + I_{xx}\sin^2\alpha + 2I_{xz}\sin\alpha\cos\alpha$$

$$I'_{zz} = 4.73\times.9966 + 2.57\times.00331 + 2\times16\times10^6\times.0575 = 4.747\times10^6$$

$$I'_{xz} = (I_{xx}-I_{zz})\sin\alpha\cos\alpha + I_{xz}(\cos^2\alpha - \sin^2\alpha)$$

$$I'_{xz} = (2.57-4.73)\times.0575 + .16(.9966 - .00331) = .0347\times10^6$$

$$\frac{q_0 S\bar{c}}{I_{YY}} = \frac{214{,}697\times20.1}{2.25\times10^6} = 1.917$$

$$\frac{q_0 S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}} = \frac{214{,}697\times130.8}{\left[2.557 - \frac{(.0347)^2}{4.747}\right]\times10^6} = 10.98$$

$$\frac{q_0 S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}} = \frac{214{,}697\times130.8}{\left[4.747 - \frac{(.0347)^2}{2.557}\right]\times10^6} = 5.94$$

$$\frac{q_0 S}{m} = \frac{214{,}697}{4660} = 46.1$$

PITCH	$K_{PITCH} = \dfrac{\left.\frac{q_0 S\bar{c}}{I_{YY}}\right]_{SST}}{\left.\frac{q_0 S\bar{c}}{I_{YY}}\right]_{-80}} = 1.1$	ROLL	$K_{ROLL} = \dfrac{\left.\frac{q_0 S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}}\right]_{SST}}{\left.\frac{q_0 S b}{I'_{xx} - \frac{I'^2_{xz}}{I'_{zz}}}\right]_{-80}} = 2.5$
LIFT, DRAG	$K_{LIFT/DRAG} = \dfrac{\left.\frac{q_0 S}{m}\right]_{SST}}{\left.\frac{q_0 S}{m}\right]_{-80}} = 1.448$	YAW	$K_{YAW} = \dfrac{\left.\frac{q_0 S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}}\right]_{SST}}{\left.\frac{q_0 S b}{I'_{zz} - \frac{I'^2_{xz}}{I'_{xx}}}\right]_{-80}} = .602$

			REVISED	DATE		
ENGR	May. 7. 65	HPC.			-80 Variable Stability DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS	NASA 72
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APR						
APR					THE BOEING COMPANY RENTON, WASHINGTON	C14

TD 1017-R6

	2.5( )=	SST		-80	
$\delta\omega_\beta$	$C_{l_\beta} + \frac{I'_{xz}}{I'_{zz}} C_{n_\beta}$	-.553	$C_{l_{\delta\omega}} + \frac{I'_{xz}}{I'_{zz}} C_{n_{\delta\omega}}$	+.056	-7.86
$\delta\omega_p$	$C_{l_p} + \frac{I'_{xz}}{I'_{zz}} C_{n_p}$	-.0589	$\boxed{+.0772}$	-.1361	+1.00
$\delta\omega_R$	$C_{l_R} + \frac{I'_{xz}}{I'_{zz}} C_{n_R}$	+.0796	$\left(\frac{I'_{xz}}{I'_{zz}}\right) = -.1996$	+.0321	+.615
$\delta\omega_{\delta w}$	$C_{l_{\delta w}} + \frac{I'_{xz}}{I'_{zz}} C_{n_{\delta w}}$	+.0205	ROLL	—	+.286
$\delta\omega_{\delta R}$	$C_{l_{\delta R}} + \frac{I'_{xz}}{I'_{zz}} C_{n_{\delta R}}$	+.0428	$\left(\frac{I'_{xz}}{I'_{zz}}\right) = +.007$	—	+.556
$\delta\omega_{\delta r}$	$C_{l_{\delta r}} + \frac{I'_{xz}}{I'_{zz}} C_{n_{\delta r}}$	—		+.0197	-.255
$\delta\omega_{\dot\beta}$	$C_{l_{\dot\beta}} + \frac{I'_{xz}}{I'_{zz}} C_{n_{\dot\beta}}$	0		-.0772	-1.00
	.602( )=				
δr_β	$C_{n_\beta} + \frac{I'_{xz}}{I'_{xx}} C_{l_\beta}$	+.271	$C_{n_{\delta r}} + \frac{I'_{xz}}{I'_{xx}} C_{l_{\delta r}}$	+.109	-2.39
δr_p	$C_{n_p} + \frac{I'_{xz}}{I'_{xx}} C_{l_p}$	+.0189	$\boxed{-.0677}$	-.01845	-.551
δr_R	$C_{n_R} + \frac{I'_{xz}}{I'_{xx}} C_{l_R}$	-.0525	$\left(\frac{I'_{xz}}{I'_{xx}}\right) = -1.53$	-.01815	+.506
$\delta r_{\delta w}$	$C_{n_{\delta w}} + \frac{I'_{xz}}{I'_{xx}} C_{l_{\delta w}}$	-.0067	YAW	—	+.099
$\delta r_{\delta R}$	$C_{n_{\delta R}} + \frac{I'_{xz}}{I'_{xx}} C_{l_{\delta R}}$	-.0517	$\left(\frac{I'_{xz}}{I'_{xx}}\right) = +.0136$	—	+.764
$\delta r_{\delta\omega}$	$C_{n_{\delta\omega}} + \frac{I'_{xz}}{I'_{xx}} C_{l_{\delta\omega}}$	—		+.0167	+.247
$\delta r_{\dot\beta}$	$C_{n_{\dot\beta}} + \frac{I'_{xz}}{I'_{xx}} C_{l_{\dot\beta}}$	0		-.1015	-1.50
ΔC_{Y_β}	C_{Y_β}				
ΔC_{Y_p}	C_{Y_p}		$\boxed{57.3}$		
ΔC_{Y_R}	C_{Y_R}				
$\Delta C_{Y_{\delta w}}$	$C_{Y_{\delta w}}$		SIDE FORCE		
$\Delta C_{Y_{\delta R}}$	$C_{Y_{\delta R}}$				
$\Delta C_{Y_{\delta\omega}}$	$C_{Y_{\delta\omega}}$				
$\Delta C_{Y_{\delta r}}$	$C_{Y_{\delta r}}$				

NASA 72

-80 Variable Stability

DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS

	SST			-80		
	1.1( )$_s$					
$\delta e_{\Delta\alpha}$	C_{m_α}	-.378	$C_{m\delta e_{-80}}$ $\boxed{-.900}$	-1.11	-.816
$\delta e_{\dot\alpha}$	$C_{m_{\dot\alpha}}$	-.0317		-.361	-.366
δe_Q	C_{m_Q}	-.1755		-.425	-.277
$\delta e_{\Delta V}$	$57.3C_{m_{\Delta V}}$	0	PITCH	-.0171	-.019
δe_{δ_E}	$C_{m_{\delta_E}}$	-.789		—	+.877
$\delta e_{\Delta T_{SST}}$	$57.3C_{m_{\Delta T_{SST}}}$	$+8.0\times10^{6}$		—	-8.93×10^{-6}
$\delta e_{\delta_{TH}}$	$C_{m_{\delta_{TH}}}$	0		—	0
$\delta e_{\Delta T_{-80}}$	$57.3C_{m_{\Delta T_{80}}}$	—		0	0
$\delta e_{\delta_{ab}}$	$C_{m_{\delta_{ab}}}$	—		-.146	-.162

$$\delta e_c = \underset{\delta e_{\Delta\alpha}}{-.816}\,\Delta\alpha \;\underset{\delta e_{\dot\alpha}}{-.366}\,\dot\alpha \;\underset{\delta e_Q}{-.277}\,Q \;\underset{\delta e_{\Delta V}}{-.019}\,\Delta V$$

$$\underset{\delta e_{\delta_E}}{+.877}\,\delta_E \;\underset{\delta e_{\Delta T_{SST}}}{-8.93\times10^{-6}}\,\Delta T_{SST} \;\underset{\delta e_{\delta_{TH}}}{+0} \;\underset{\delta e_{\Delta T_{80}}}{+0}\,\Delta T_{80} \;\underset{\delta e_{\delta_{ab}}}{-.162}\,\delta_{ab}$$

ENGR.	April 5.65	HRC	REVISED	DATE	-80 Variable Stability DERIVATION OF AIRBORNE COMP. COEFFICIENTS.	NASA 72
CHECK						PITCH
APR					THE BOEING COMPANY RENTON, WASHINGTON	C16
APR						

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$$\frac{m_{-80}}{m_{SST}} = \frac{4660}{8385} = .556$$

$$\Delta T_{-80_{\Delta V}} = \left(2\frac{q_0 S}{V_0} C_{D_{TRIM}}\right)_{-80} - \left(2\frac{q_0 S}{V_0} C_{D_{TRIM}} + q_0 S C_{D_{\Delta V}}\right)_{SST} \frac{m_{-80}}{m_{SST}}$$

$$= \left(2\frac{214{,}700}{253} \times .0892\right)_{-80} - \left(2\frac{560{,}310}{307} \times .145 + 0\right)_{SST} .556 = 142.7$$

$$\Delta T_{-80_{\Delta T_{SST}}} = \frac{m_{-80}}{m_{SST}}\left(1 - q_0 S C_{D_{\Delta T}}\right)_{SST} = .556$$

$$\Delta T_{-80_{\delta_{ab}}} = q_0 S \frac{C_{D_{ab}}}{57.3} = 214{,}697 \times \frac{.0178}{57.3} = 66.7$$

$$\Delta T_{-80_{\Delta\alpha}} = \left(q_0 S \frac{C_{D_\alpha}}{57.3}\right)_{-80} - \left[\left(q_0 S \frac{C_{D_\alpha}}{57.3}\right)_{SST} \frac{m_{-80}}{m_{SST}}\right] = \left(214{,}697 \frac{.327}{57.3}\right)_{-80} - \left[\left(560{,}310 \frac{.373}{57.3}\right)_{SST} \times .556\right] = -1889$$

$$\Delta T_{-80_{\delta'_{TH}}} = \frac{m_{-80}}{m_{SST}}\left(q_0 S \frac{C_{D_{\delta_{TH}}}}{57.3}\right)_{SST} = 0$$

$$\Delta T_{-80_{\Delta V}} \times \Delta V + \Delta T_{-80_{\Delta T_{SST}}} \times \Delta T_{SST} + \Delta T_{-80_{\delta_{ab}}} \times \delta_{ab} + \Delta T_{-80_{\Delta\alpha}} \times \Delta\alpha + \Delta T_{-80_{\delta'_{TH}}} \times \delta'_{TH}$$

$$\Delta T_{-80} = -142.7\ \Delta V + .556\ \Delta T_{SST} + 66.7\ \delta_{ab} - 1889\ \Delta\alpha + 0\ \delta'_{TH}$$

ENGR.	Dec. 64	HRC.	REVISED	DATE	-80 Variable Stability DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS	NASA 72
CHECK	March. 30.65	HRC.				DRAG
APR	April 5.65	HRC.				
APR					THE BOEING COMPANY RENTON, WASHINGTON	C17

$$\delta ab_{\Delta\alpha} = \frac{\left(\frac{q_0 S}{m} C_{L_\alpha} + \frac{T_0}{m}\right)_{SST} - \left(\frac{q_0 S}{m} C_{L_\alpha} + \frac{T_0}{m}\right)_{-80}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{\left(66.8 \times 3.209 + \frac{81{,}245}{8385}\right)_{SST} - \left(46 \times 4.55 + \frac{19{,}170}{4660}\right)_{-80}}{\left(46 \times .446\right)_{-80}} = -.475$$

$$\delta ab_{\Delta T_{SST}} = \frac{\left(\frac{\alpha_0}{m}\right)_{SST} + 57.3\left(\frac{q_0 S}{m} C_{L_{\Delta T}}\right)_{SST}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{\frac{12.3}{8385} + 0}{-20.7} = -70.9 \times 10^{-6}$$

α_0 in degrees

$$\delta ab_{\Delta T_{-80}} = \frac{-\left(\frac{\alpha_0}{m}\right)_{-80}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{-\left(\frac{5.3}{4660}\right)_{-80}}{\left(20.7\right)_{-80}} = 55 \times 10^{-6}$$

$\alpha_0 = \alpha_{TRIM,\ WING}$ in degrees

$$\delta ab_{\Delta V} = \frac{57.3\left[\left(\frac{q_0 S}{m} C_{L_{\Delta V}}\right)_{SST} + \left(\frac{2g}{V_0}\right)_{SST} - \left(\frac{2g}{V_0}\right)_{-80}\right]}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{57.3\left[0 + \frac{64.4}{307} - \frac{64.4}{253}\right]}{-20.7} = +.122$$

$$\delta ab_{\delta_E} = \frac{\left(\frac{q_0 S}{m} C_{L_{\delta_E}}\right)_{SST}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = \frac{\left(66.8 \times .487\right)_{SST}}{\left(20.7\right)_{-80}} = -1.57$$

$$\delta ab_{\delta_e} = -\left(\frac{C_{L_{\delta e}}}{C_{L_{ab}}}\right)_{-80} = -\left(\frac{.244}{.446}\right)_{-80} = .547 \qquad \delta ab_{\dot\delta_{TH}} = \frac{\left(\frac{q_0 S}{m} C_{L_{\dot\delta_{TH}}}\right)_{SST}}{\left(\frac{q_0 S}{m} C_{L_{ab}}\right)_{-80}} = 0$$

$$\delta ab_c = \underbrace{-.475}_{\delta ab_{\Delta\alpha}}\ \Delta\alpha \ \underbrace{-70.9\times10^{-6}}_{\delta ab_{\Delta T_{SST}}}\ \Delta T_{SST} \ \underbrace{+55\times10^{-6}}_{\delta ab_{\Delta T_{-80}}}\ \Delta T_{-80} \ \underbrace{+0}_{\delta ab_{\Delta V}}\ \Delta V$$
$$\underbrace{-1.57}_{\delta ab_{\delta E}}\ \delta_E \ \underbrace{+.547}_{\delta ab_{\delta e}}\ \delta_e \ \underbrace{\pm 0}_{\delta ab_{\dot\delta_{TH}}}\ \dot\delta_{TH}$$

CALC	March 30.65	HPC.	REVISED	DATE	−80 Variable Stability DERIVATION OF AIRBORNE COMPUTER COEFFICIENTS	NASA 72
CHECK	April 5.65	HPC.				LIFT
APR					THE BOEING COMPANY RENTON, WASHINGTON	PAGE C18
APR						

ΔT_{-80}	δ_{ao}	δ_e	VARIABLE	VARIABLE	δ_ω	δ_r
−1889.0	−.475	−.816	$\Delta\alpha$	β	−7.88	−2.39
—	—	−.366	$\dot{\alpha}$	$\dot{\beta}$	−1.00	−1.50
—	—	−.277	Q	P	+1.00	−.551
−142.7	+.122	−.019	ΔV	R	+.615	+.506
+.556	-70.9×10^{-6}	-8.93×10^{-6}	ΔT_{SST}	δ_W	+.266	+.099
—	55×10^{-6}	0	ΔT_{-80}	δ_ω	—	+.247
+66.7	—	−.162	δ_{ab}	δ_R	+.556	+.764
—	−1.57	+.877	δ_E	δ_r	−.255	—
—	+.547	—	δ_e			
	0	0	δ_{TH}'			

Example: if $\underbrace{\ ?\ }$, then the following equations apply:

ΔT_{-80}	δ_{ab}	δ_e	
+217	+2.1	−.63	$\Delta\alpha$
−33	+.07	−.007	ΔV
+.25	$-3\cdot10^{-6}$	$+4.6\cdot10^{-5}$	ΔT_{SST}
—	$+1.7\cdot10^{-5}$	$+2\cdot10^{-4}$	ΔT_{-80}
0	−.09	+.38	δ_E

$$\Delta T_{-80} = 217\,\Delta\alpha - 33\,\Delta V + .25\,\Delta T_{SST}$$

$$\delta_{ab} = 2.1\,\Delta\alpha + .07\,\Delta V - 3\times10^{-6}\,\Delta T_{SST} + 1.7\times10^{-5}\,\Delta T_{-80} - .09\,\delta_E$$

$$\delta_e = -.63\,\Delta\alpha - .007\,\Delta V + 4.6\times10^{-5}\,\Delta T_{SST} + 2\times10^{-4}\,\Delta T_{-80} + .38\,\delta_E$$

CALC	March 30 65	HRC.	REVISED	DATE	−80 Variable Stability NUMERICAL VALUES OF AIRBORNE COMPUTER COEFFICIENTS	NASA 72
CHECK						
APR					THE BOEING COMPANY RENTON, WASHINGTON	PAGE C19
APR						

	POTENTIOMETER NO	SETTING		VARIABLE	CALCULATED FROM
PITCH	18	.262	A44	$-20\,\delta e_{TRIM}$	$1.05\,(.25) = .262$ Note: the factor of 1.05 in the pitch axis computations arises from the inability of the elevator to respond to a command in a one to one ratio.
	64	.384	A44	$-5\dot{\alpha}$	$1.05(-\delta e_{\dot{\alpha}}) = .384$
	65	$.1455^{10}$	A43	$+Q$	$1.05\times(-5\,\delta e_{Q}) = 1.455$
	66	.8575	A43	$+5\,\Delta\alpha$	$1.05(-\delta e_{\Delta\alpha}) = .8575$
	67	.100	A43	$+\Delta V$	$1.05\times(-5\,\delta e_{\Delta V}) = .100$
	68	.0469	A44	$-.001\,\Delta T_{SST}$	$1.05\times(-5000\,\delta e_{\Delta T_{SST}}) = .0469$
	69	.085	A43	$+10\,\delta ab_{c}$	$1.05\times(-5\,\delta e_{\delta ab}) = .085$
			A44	$+.005\,\Delta T_{-80}$	$1.05\times(+1000\,\delta e_{\Delta T\text{-}80})\left[\frac{1}{TS+1}\right] = 0$
	71	$.461^{10}$	A44	$-\delta_E'$	$1.05\times(+5\,\delta e_{\delta E'}) = 4.61$
DRAG	72	$.1889^{10}$	A46	$+5\,\Delta\alpha$	$-.001\,\Delta T_{\Delta\alpha} = -1.889$
	73	$.278^{10}$	A46	$-.001\,\Delta T_{SST}$	$+5\,\Delta T_{\Delta T_{SST}} = 5\times.556 = 2.78$
	74	.713	A46	$+\Delta V$	$-.005\,\Delta T_{\Delta V} = .005\times -142.7 = -.713$
	75	.0333	A45	$+10\,\delta ab$	$-.0005\,\Delta T_{\delta ab} = .0005\times 66.7 = -.0333$
					$\left(\frac{\delta_{CLAM}}{\delta_{THC}} = .80\right)$
	80	.697	A50	$-.005\,\Delta T_{-80}$	$\frac{\delta th}{\Delta T\text{-}80}(600) = \frac{600}{861} = .697$ (861 based on $\Delta T/_{DEG\ clam} = 1080$)
LIFT	76	.11	A47	$-.005\,\Delta T_{-80}$	$+2000\,\delta ab_{\Delta T\text{-}80} = 2000\times 55\times10^{-6} = .11$
	77	.709	A48	$-.001\,\Delta T_{SST}$	$-10\,000\,\delta ab_{\Delta T_{SST}} = 70.9\times10^{-2} = .709$
	78	$10+.57^{10}$	A47	$-\delta_E'$	$-10\,\delta ab_{\delta_E} = 1.57\times10 = 15.7$
	79	.95	A47	$+5\,\Delta\alpha$	$-2\,\delta ab_{\Delta\alpha} = 2\times.475 = .95$
	70	$.122^{10}$	A47	$-\Delta V$	$+10\,\delta ab_{\Delta V} = 10\times.122 = 1.22$

LONGITUDINAL

			REVISED	DATE			
CALC	March 30.65	HPC	D.E.G.	4-19-65	80 Variable Stability NUMERICAL VALUES OF POTENTIOMETER SETTINGS	LONG.	NASA 72
CHECK	3-31-65	HPC	BASKA	4-26-65			
APR	4-25-65		D.E.G.	5-15-65	THE BOEING COMPANY RENTON, WASHINGTON		PAGE C20
APR							

	POTENTIOMETER NO	SETTING	VARIABLE		CALCULATED FROM
ROLL	106	$.123^{10}$	A71	$-R$	$+2\delta\omega_R = 2\times.615 = 1.23$
	107	$.400^{10}$	A72	$+.5P$	$+4\delta\omega_P = 4\times1.0 = 4.0$
	108	$.315^{10}$	A72	-5β	$-.4\delta\omega_\beta = .4\times7.88 = 3.15$
	109	$*.127^{10}$	A71	$-\delta w$	$+2\delta\omega_{\delta w} = 2\times.266 = .532$
	110	$.1112^{10}$	A72	$+\delta R$	$+2\delta\omega_{\delta R} = 2\times.556 = 1.112$
	111	$.051$	A71	$+10\delta r$	$-.2\delta\omega_{\delta r} = .2\times.255 = .051$
	90	$.848$	A63	$+2\delta_{\omega_c}$	ROLL CONTROL EFFECTIVENESS
	86	$.200$	A72	$-10\dot\beta$	$-.2\delta_{\omega_{\dot\beta}} = .2\times1.0 = .20$
	13	$.0556$	A72	$+20\delta_{R\,pulse}$	$+.1\delta\omega_{\delta_R} = .1\times.556 = .0556$
YAW	112	$.150^{10}$	A73	$-10\dot\beta$	$-\delta r_{\dot\beta} = 1.50$
	113	$10+.102^{10}$	A74	$+.5P$	$+20\delta r_P = 20\times.551 = 11.02$
	114	$.506^{10}$	A74	$-R$	$+10\delta r_R = 10\times.506 = 5.06$
	115	$.478^{10}$	A73	-5β	$-2\delta r_\beta = 2\times2.39 = 4.78$
	116	$.236^{10}$	A74	$+\delta R$	$+10(\delta r_{\delta R}-1) = 10(.764-1) = 2.36$
	117	$.99$	A74	$-\delta w$	$+10\delta r_{\delta w} = 10\times.099 = .99$
	118	$.1048^{10}$	A73	$+2\delta w$	$+5\delta r_{\delta w}(.848) = 5\times.247\times.848 = 1.048$
	85	$.382$	A73	$+20\delta_{R\,pulse}$	$+.5\delta_{R\delta_R} = .5\times.764 = .382$

LATERAL

* Result of in-flight matching

CALC	March 30 '65	[illegible]	REVISED	DATE	-8? Variable Stability NUMERICAL VALUES OF POTENTIOMETER SETTINGS	LATERAL DIRECT.	NASA72
CHECK			D.E.G	4-19-65			
APR					THE BOEING COMPANY RENTON WASHINGTON		PAGE C21
APR							

1. Control Column

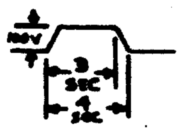
$$\delta E = K_E \, \delta CP + K_{32} \text{ Pulse}$$

Where δE = Simulated SST elevator position

K_E = SST column to elevator gearing

δCP = Eval. Pilot's column position

K_{82} = ELEVATOR PULSE-SCALE FACTOR (USED ONLY FOR CHECKOUT)

PULSE = 

2. Pitch Trim

$$\delta e_{TRIM} = \frac{K_{TR}}{S} \, TRIM$$

Where δe_{TRIM} = Fake trim signal to -80 elevator

K_{TR} = gain factor to simulate SST trim rate

$TRIM$ = Eval Pilot trim signal (-15V, 0V, +15V)

$$K_{TR} = \frac{\left(\frac{q_0 S \bar{c}}{I_{YY}} \times Cm_{\delta H} \times \text{Stabilizer trim rate}\right)_{SST}}{\left(\frac{q_0 S \bar{c}}{I_{YY}} \, Cm_{\delta e}\right)_{-80}}$$

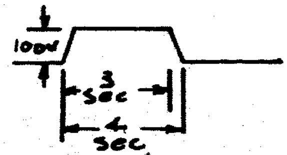
3. Control Wheel

$$\boxed{\delta_W = \delta_{W_E} + K_{87}(\text{Pulse})}$$

where δ_W = Simulated SST Wheel Position

δ_{W_E} = Eval. Pilot Wheel Position

K_{87} = Wheel Pulse Scale Factor

Pulse =


4. Rudder Pedals and Rudder

$$\boxed{\delta_R = K_P \delta_P}$$

where δ_R = Simulated SST Rudder Position

K_P = SST Pedal to Rudder gearing

δ_P = Rudder Pedal Position

Rudder Pulse circuit

$$\boxed{\delta_{R_{Pulse}} = \frac{1}{20}(\text{Pulse})}$$ Used only for Checkout.

where $\delta_{R_{Pulse}}$ = 5° Simulated SST Rudder Position, under control of a computer derived pulse


ENGR	May 65		REVISED	DATE	80 Variable Stability COMPUTER EQUATIONS FOR EVALUATION PILOT'S CONTROLS	NASA 72
CHECK						
APR						
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5. Fake Throttle

$$\boxed{\Delta T_{SST} = K_{TH}\,\delta_{TH} \begin{array}{l} + K_{84}(\text{Pulse}) \quad \text{AFT} \\ \text{or} \\ - K_5\,(\text{Pulse}) \quad \text{FWD} \end{array}}$$

Where

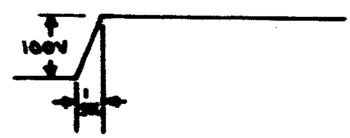
ΔT_{SST} = Simulated SST Thrust Increment.

K_{TH} = SST Thrust to Throttle ratio

δ_{TH} = Eval. Pilot Fake Throttle lever Position

K_{84} = AFT THRUST PULSE SCALE FACTOR

K_5 = FWD " " " "

PULSE = 

SCALED EQUATIONS

$$+\ \delta E = -\left[(-2K_E)(+.5\,\delta_{CP}) + K_{82}(\text{Pulse})\right]$$

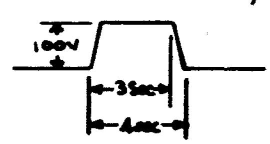
$$+\ 20\ \delta e_{TRIM} = -\int\left[\frac{20}{15}K_{TR}(\text{TRIM})\right]dt$$

$$-\ \delta w = -\left[10\,(.1\,\delta w_E) + K_{87}(\text{Pulse})\right]$$

$$\delta R = -\left[\frac{K_P}{2.5}\left(-2.5\,\delta_{PED}\right)\right]$$

$$20\ \delta R_{Pulse} = \text{Pulse } (15^\circ \text{ SST RUDDER})$$

$$-\frac{\Delta T_{SST}}{1000} = -\left[\left(\frac{K_{TH}}{1000\times .3}\right)(.3\,\delta_{TH}) \begin{matrix} +K_5\ \text{PULSE} \\ -K_{84}\ \text{PULSE} \end{matrix}\right]$$

FOR THE 367-80	FOR NASA 72 SST
$K_E = -2.2$ degree/degree	$K_E = -1.3$ degree/degree
$K_{TR} = 1.385$ degree/sec	$K_{TR} = 1.20$ degree/sec
$K_P = 6.25$ degree/inch	$K_P = 6.25$ degree/inch
$K_{th} = 1080$ lbs/degree (~~deg~~)	Pulse = 
THRUST RATE LIMIT $\simeq$ 14,000 lb/SEC	
	$K_{TH} = \frac{170\,000}{57.3} \cong 3000$ lbs/degree for the throttle

ENGR	May 65	WPC	REVISED	DATE	-80 Variable Stability COMPUTER EQUATIONS FOR EVALUATION PILOT'S CONTROLS	NASA 72
CHECK						
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POTENTIOMETER NO.	SETTING		VARIABLE	CALCULATED FROM
5	.150	A7	FWD THRUST STEP (-100V)	$\frac{3\delta_{TH}}{100} = \frac{3\times5}{100} = .15$
61	.160$^{\underline{10}}$	A41	TRIM	$\frac{20}{15}K_{TR} = \frac{20}{15}(1.2) = 1.6$
81	.250$^{\underline{10}}$	A84	$-2.5\delta_p$	$\frac{K_P}{2.5} = 2.5$
82	.020	A78	ELEV. PULSE (+100V)	$\frac{\delta_E}{100} = .01 \times 2.0 = .020$
84	.300	A9	AFT THRUST STEP (-100V)	$\frac{3\delta_{TH}}{100} = \frac{3\times10}{100} = .30$
85*	.382	A73	$20\,\delta_R$ PULSE (+100V)	$10\,\frac{\delta_{r\delta_R}}{20} = \frac{10}{20}(.764) = .382$
87	.500	A77	WHEEL PULSE (+100V)	$\frac{\delta_W}{100} = \frac{50}{100} = .50$
88	.260$^{\underline{10}}$	A78	$+.5\delta_{Cp}$	$-2K_E = -2(-1.3) = +2.6$
DIRECT INPUT	g_{10}	A77	$+.1\delta_{W_E}$	$10\,\frac{\delta_W}{\delta_{W_E}} = 10$
13	.0556	A72	$20\delta_R$ pulse (+100V)	$2\,\frac{\delta_{W\delta_R}}{20} = \frac{2}{20}\times.556 = .0556$

* SET TO PRODUCE A 5° SST PULSE

ENGR	REVISED BY	DATE	-80 VARIABLE STABILITY COMPUTER EQUATIONS FOR EVALUATION PILOT CONTROLS	NASA 72
CHECK	BB	9-15-63		
APR				
APR			THE BOEING COMPANY RENTON WASHINGTON	C26

1. Change in Angle of Attack $\Delta\alpha$:

$$\Delta\alpha = \alpha_{-80} - \alpha_{TRIM}$$

$$\alpha_{-80} = \alpha_{VANE,\ CALM\ AIR} + Q\frac{\ell}{V} + \Delta\alpha_{VANE,\ TURBULENCE}\ e^{-s\frac{\ell}{V}}$$

$$\alpha_{-80} \cong Q\frac{\ell}{V_o} + \alpha_{V,C} + \Delta\alpha_{V,T}\left(1 - s\frac{\ell}{V_o}\right)$$

by definition $\alpha_V = \alpha_{V,C} + \Delta\alpha_{V,T}$

Replacing $s\frac{\ell}{V_o}\Delta\alpha_{V,T}$ by $s\frac{\ell}{V_o}\alpha_V$

since no $\Delta\alpha_{V,T}$ signal is available

approximating $\left(1 - s\frac{\ell}{V_o}\right)$ with $\frac{1}{1+s\frac{\ell}{V_o}}$, and replacing α_V by $1.4\alpha_V$ since the electrical scale factor of α_V is 1.4,

$$\boxed{\Delta\alpha \cong Q\frac{\ell}{V_o} + \frac{1.4\alpha_V}{1+s\frac{\ell}{V_o}} - \alpha_{TRIM}}$$

2. Rate of change of angle of attack $\dot{\alpha}$

The $\dot{\alpha}$ signal will be derived from the $\Delta\alpha$ signal, using a pseudo-differentiating circuit having the following transfer function

$$\boxed{\frac{\dot{\alpha}}{\Delta\alpha} \cong \frac{s}{1+.1s}}$$

CALC	March 29	HPC	REVISED	DATE	-80 Variable Stability COMPUTER EQUATIONS FOR AIR DATA VARIABLES	NASA72
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3. Angle of Sideslip β

$$\beta = \beta_{VANE,\,CALM} - R\frac{\ell}{V} + \Delta\beta_{VANE,\,TURBULENCE}\; e^{-s\frac{\ell}{V}}$$

Following steps similar to those of page 1 — derivation of the simplified $\Delta\alpha$ formula — results in:

$$\boxed{\beta \cong -R\frac{\ell}{V_o} + \frac{\beta_V}{1+s\frac{\ell}{V_o}}}$$

4. Rate of change of angle of sideslip $\dot{\beta}$

The $\dot{\beta}$ signal will be derived from a roll gyro signal (ϕ) and a yaw rate gyro signal (R), using the following equation:

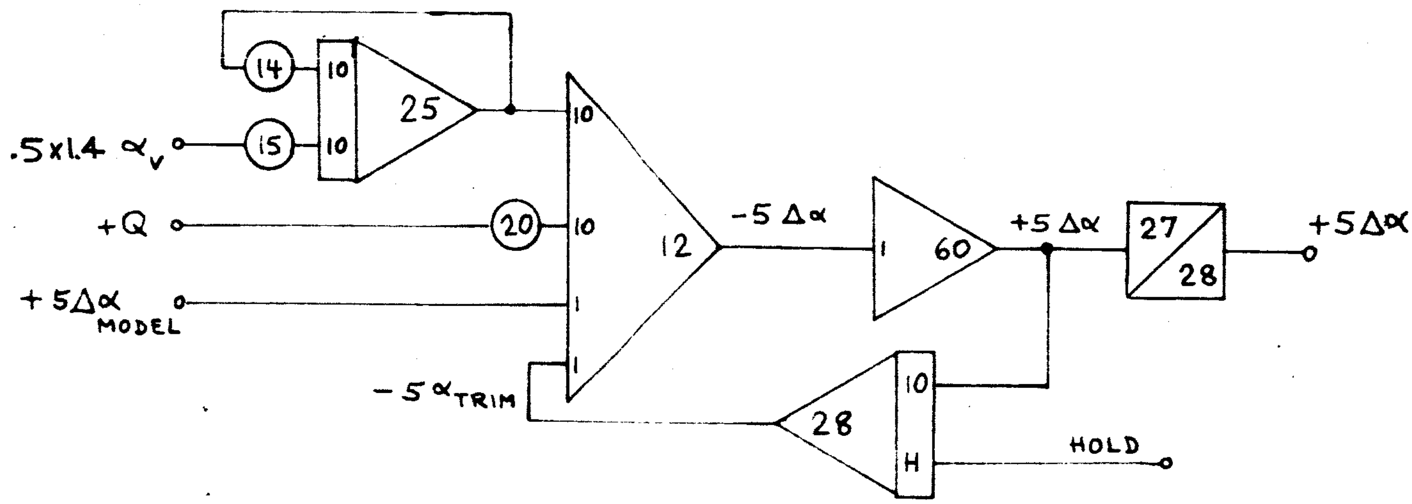
$$\boxed{\dot{\beta} = \phi\frac{g}{V_o} - R}$$

5. Change in True Airspeed ΔV

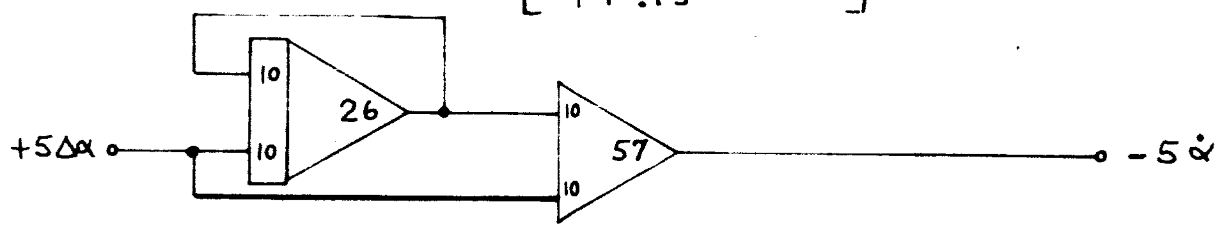
$$\boxed{\Delta V = V - V_{TRIM}}$$

SCALED EQUATIONS

$$-5\,\Delta\alpha = -\left[\frac{5\ell}{V_o}(+Q) - 10\left(-\frac{.5\times 1.4\alpha_v}{1+\frac{\ell}{V_o}S}\right) + \left(5\alpha_{TRIM}\right)\right]$$



$$-5\,\dot{\alpha} = -\left[\frac{S}{1+.1S}\left(5\,\Delta\alpha\right)\right]$$



CALC	March 29 65	HRC.	REVISED	DATE	−80 Variable Stability COMPUTER EQUATIONS FOR AIR DATA VARIABLES	
CHECK	3-31-65	HRC				
APR						
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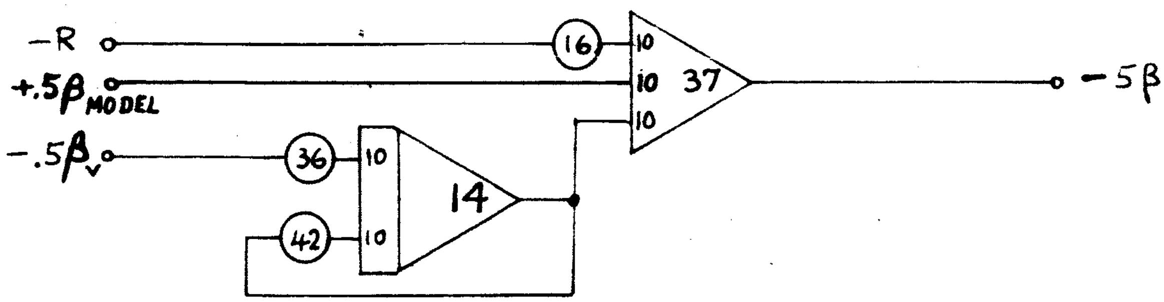
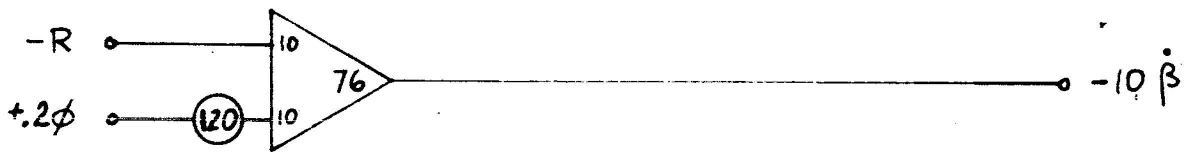
SCALED EQUATIONS

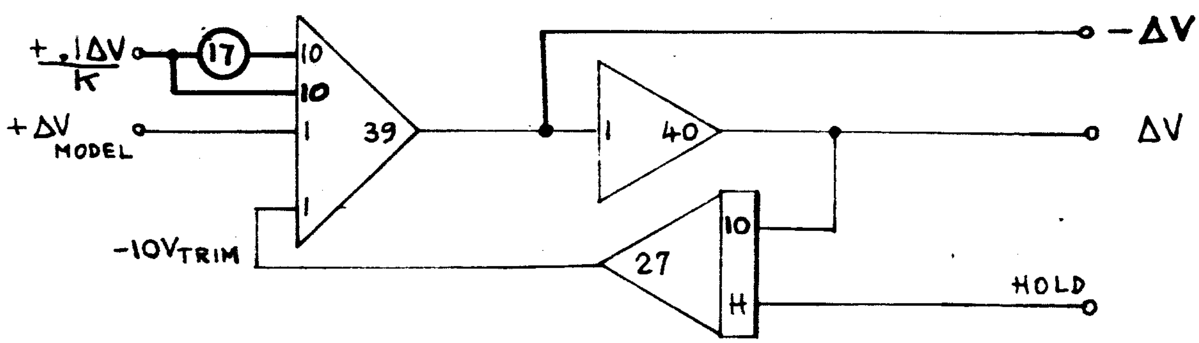
$$-5\beta = -\left[\frac{s\ell}{V_0}(-R) + 10\left(+\frac{.5\beta_v}{1+\frac{\ell}{V_0}s}\right)\right]$$



$$-10\dot{\beta} = -\left[\frac{10g}{V_0}(+\phi) + 10(-R)\right]$$



$$-\Delta V = -\left[10K\left(+\frac{.1\Delta V}{K}\right) + (-V_{TRIM})\right]$$



K = 1.06 determined from in-flight calibration

CALC	March 29, 65	HPC.	REVISED	DATE
CHECK	3.31.65	HPC.	D.E.G.	5-6-65
APR				
APR				

−80 Variable Stability
COMPUTER EQUATIONS FOR
AIR DATA VARIABLES

THE BOEING COMPANY
RENTON, WASHINGTON

POTENTIOMETER NO.	SETTING		VARIABLE	CALCULATED FROM
14	1.00^{10}	A25	$+\frac{.5\alpha_v}{1+\frac{\ell}{V_0}s}$	$\tau = .1$, $K_{14} = \frac{1}{\tau} = 10$
15	$.700^{10}$	A25	$-.5(1.4\alpha_v)$	$\lvert G\rvert = \frac{K_{15}}{K_{14}} = \frac{.5}{.5(1.4)}$; $\therefore K_{15} = \frac{10}{1.4} \approx 7.0$
20	$.144^{10}$	A12	$+Q$	$\frac{5\ell}{V_0} = \frac{5\times 72.9}{253} = 1.44$
42	$.3475^{10}$	A14	$+\frac{.5\beta_v}{1+\frac{\ell}{V_0}s}$	$\frac{V_0}{\ell} = \frac{1}{\tau} = \frac{253}{72.9} = 3.475$
36	$.3475^{10}$	A14	$-.5\beta_v$	$\frac{V_0}{\ell} = \lvert G\rvert = \frac{K_{36}}{K_{42}} = 1$; $\therefore K_{36} = 3.475$
16	$.144^{10}$	A37	$-R$	$\frac{5\ell}{V_0} = \frac{5\times 72.9}{253} = 1.44$
120	$.637^{10}$	A76	$.2\phi$	$\frac{10g}{.2V_0} = \frac{322}{.2\times 253} = 6.37$
17	$10 + .06^{10}$	A39	$+\frac{.1}{K}\Delta V$	Result of in-flight calibration

			REVISED	DATE	
CALC	March 29.65	JHC.			-80 Variable Stability COMPUTER EQUATIONS FOR AIR DATA VARIABLES
CHECK	3.31.65	JHC.	D. E. G.	5-6-65	
APR					
APR					

THE BOEING COMPANY
RENTON, WASHINGTON

NASA 72

TD 1017-R8 6-7000

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Pot No.		Setting 10-3-65	Pot No.		Setting 10-3-65	
6	pulse width	.3333	66		.3575	
7			67		.100	
8			68		.0469	
9			69		.085	
10			70		.122 ^{10}	
11			71		.461 ^{10}	
12			72		.1889 ^{10}	
13		.0556	73		.278 ^{10}	
14		1.0 ^{10}	74		.713	
15		.700 ^{10}	75		.0333	
16		.144 ^{10}	76		.110	
17		10+.06 ^{10}	77		.709	
18		.262	78		10+.57 ^{10}	
19		.605	79		.950	
20		.144 ^{10}	80		.697	
21		.423	81		.25 ^{10}	
22		.0589 ^{10}	82		.020	
23		.110	83			
24		.211 ^{10}	84		.300	
25		.175	85		.382	
26		.149 ^{10}	86		.200	
27		.228	87		.500	
28		.529	88		.260 ^{10}	
29		.403	89		+ 40V	(LIMIT ON INBD SPOILERS)
30		10 +.30 ^{10}	90		.848	
31		.104	91		.0166	
32		.150 ^{10}	92		.1627	
33		.0157	93		.4610	
34		.493	94		.1633	
35		.0016	95		.2263	
36		.3475 ^{10}	96		.3229	
37		.318	97		.9046	
38		.0058	98	Recorder	.3252	
39		.100	99		.1875	
40		.400 ^{10}	100		.3767	
41		.100	101		.2234	
42		.3475 ^{10}	102		.1843	
43		.0125	103		.1841	
44		.0812	104		.0184	
45		.168 ^{10}	105		.1861	
46		.571	106		.123 ^{10}	
47		.0325	107		.400 ^{10}	
48		.0597	108		.315 ^{10}	
49		.0525	109		.127 ^{10}	
50		.0014	110		.111 ^{10}	
51		.1124	111		.051	
52			112		.150 ^{10}	
53		0	113		10+10 ^{10}	
54		.028	114		.506 ^{10}	
55		.329	115		.478 ^{10}	
56		.693	116		.235 ^{10}	
57		.816	117		.989	
58		.100	118		.105 ^{10}	
59		.500 ^{10}	119			
60		.0329	120		.637 ^{10}	
61		.160 ^{10}				
62		.428				
63		.500				
64		.384				
65		.1455 ^{10}	5		.150	

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		UNAUGMENTED		UPDATED	FLIGHT 663 MAY 11.65	Flt 667-2 June 15 '65	FLT 678- 10-5-6
			UNITS	JUNE 10. 15	UNITS		
DRAG	$C_{D_{TRIM}}$	+.0892					
	$C_{D_{\alpha}}$	+.327	/RAD				
	$C_{D_{\delta ab}}$	+.0178	/RAD				
LIFT	$C_{L_{TRIM}}$	+.6935					
	$C_{L_{\alpha}}$	+4.06	/RAD	+4.61	/RAD		+4.55/R
	$C_{L_{\delta ab}}$	-.446	/RAD	$C_{L_{\delta e}}$=+.244	/RAD	$C_{L_{\delta e}}$: 0	
PITCH	$C_{m_{\alpha}}$	-1.275	/RAD	-1.01	/RAD		-1.11/R
	$C_{m_{\dot{\alpha}}}$	-.209	/RAD/SEC	-.361	/RAD/SEC		
	$C_{m_{Q}}$	-.475	/RAD/SEC	-.425	/RAD/SEC		
	$C_{m_{\delta e}}$	-.85	/RAD	-.9	/RAD		
	$C_{m_{\delta ab}}$	-.146	/RAD	$C_{m_{\Delta V}}$=-.00057	/FT/SEC		$C_{m_{\Delta V}}$=-.
ROLL	$C_{\ell_{\beta}}$	-.143	/RAD	-.207	/RAD		+.0543/
	$C_{\ell_{p}}$	-.230	/RAD/SEC	-.136	/RAD/SEC		
	$C_{\ell_{R}}$	+.0626	/RAD/SEC	+.055	/RAD/SEC	+.0422	+.0320
	$C_{\ell_{\delta a}}$	+.	/RAD				
	$C_{\ell_{\delta SP}}$	+.	/RAD				
	$C_{\ell_{\delta r}}$	+.0202	/RAD				
	$C_{\ell_{\dot{\beta}}}$	0		+.027	/RAD/SEC	0	+.0778
YAW	$C_{n_{\beta}}$	+.0788	/RAD			+.107	+.1167
	$C_{n_{p}}$	-.0166	/RAD/SEC				
	$C_{n_{R}}$	-.0393	/RAD/SEC			-.0183	
	$C_{n_{\delta a}}$	+.	/RAD				
	$C_{n_{\delta SP}}$	+.	/RAD				
	$C_{n_{\delta r}}$	-.0759	/RAD	-.068	/RAD		
	$C_{n_{\dot{\beta}}}$	-.0495	/RAD/SEC	-.0236	/RAD/SEC	-.0811	-.1021
SIDE FORCE	$C_{Y_{\beta}}$	-.825	/RAD				
	$C_{Y_{p}}$	+.0864	/RAD/SEC				
	$C_{Y_{R}}$	+.0764	/RAD/SEC				
	$C_{Y_{\delta a}}$	+.	/RAD				
	$C_{Y_{\delta SP}}$	-.	/RAD				
	$C_{Y_{\delta r}}$	+.0177	/RAD				
U3 4038 9000	$C_{Y_{\phi}}$	+.697	/RAD				

SIMULATING NASA 72

Sources:
AERO #96
SST #3
AIR WORK
FLIGHT 663

-80

WEIGHT = 150,000 lbs
C.G. LOCATION = 30% $\bar{c}$
ALTITUDE = SEA LEVEL

DEPENDENT VARIABLES

$q_{TRIM} = 76.1$
$q_{TRIM} S = 214,697$
$THRUST_{TRIM} = 19,170$ lbs.

MASS = 4660 SLUGS

MOMENTS OF INERTIA IN BODY AXES

$I_{xx} = 2.57 \times 10^6$ SLUGS FT^2
$I_{yy} = 2.25 \times 10^6$ SLUGS FT^2
$I_{zz} = 4.73 \times 10^6$ SLUGS FT^2
$I_{xz} = .16 \times 10^6$ SLUGS FT^2

FLIGHT CONDITION

FLAP SETTING	20°
BLOWING PRESSURE RATIO	1
SPEED BRAKE SETTING	6°
GEAR	DOWN

$C_{\ell_{\delta w}} = +.077$ /RAD
$C_{n_{\delta w}} = +.0168$ /RAD
$C_{Y_{\delta w}} = -.0128$ /RAD

GEOMETRY

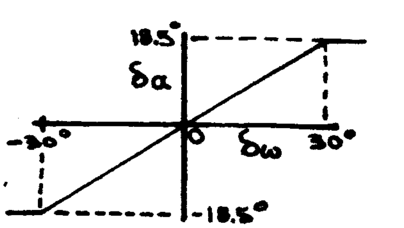
$S = 2821$ FT^2
$\bar{c} = 20.1$ FT
$b = 130.8$ FT

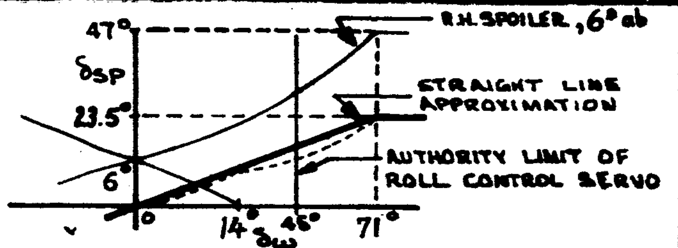
MODE SHAPES

SHORT PERIOD	$\omega_u =$ $\omega_D =$ $\zeta =$	RAD/SEC RAD/SEC
PHUGOID	$\omega_u =$ $\omega_D =$ $\zeta =$	RAD/SEC RAD/SEC
DUTCH ROLL	$\omega_u =$ $\omega_D =$ $\zeta =$	RAD/SEC RAD/SEC
ROLL T.C.		SEC
SPIRAL DIV. T.C.		

TRIM

SPEED = 150 KTS (253 FT/SEC)
$\alpha_{TRIM_{BODY}} = 3.3°$ (.0576 RAD)
$\alpha_{TRIM, WING} = 5.3°$





CALC	12-16-64	REVISED	DATE	VARIABLE STABILITY AIRPLANE DESCRIPTION	
CHECK		D.E.G.	2-18-65		
APR		H.P.C.	5-24-65		
APR		HPC.	6-10-65	THE BOEING COMPANY	PAGE C33
		W.E.B.	6-17-65		

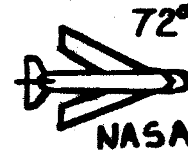
LDP 6-18-65
W.E.B 11-4-65

-2

		UNAUGMENTED		AUGMENTED	
			UNITS		UNITS
DRAG	$C_{D_{TRIM}}$	+.145			
	C_{D_α}	+.573	/RAD		
LIFT	$C_{L_{TRIM}}$	+.4507			
	C_{L_α}	+3.209	/RAD		
	$C_{L_{\delta E}}$	+.487	/RAD		
PITCH	C_{m_α}	−.3438	/RAD		
	$C_{m_{\dot\alpha}}$	−.0288	/RAD/SEC		
	C_{m_q}	−.1596	/RAD/SEC	−.695	/RAD/SEC
	$C_{m_{\delta E}}$	−.7163	/RAD		
	$C_{m_{\Delta T}}$	$+.1275 \times 10^{-4}$	/LB		
ROLL	C_{l_β}	−.1891	/RAD		
	C_{l_p}	−.0249	/RAD/SEC	−.0378	/RAD/SEC
	C_{l_R}	+.0208	/RAD/SEC		
	$C_{l_{\delta W}}$	+.0129	/RAD		
	$C_{l_{\ldots}}$	0			
	$C_{l_{\delta R}}$	0			
YAW	C_{n_β}	+.1604	/RAD		
	C_{n_p}	−.0067	/RAD/SEC		
	C_{n_R}	−.0554	/RAD/SEC	−.184	/RAD/SEC
	$C_{n_{\delta W}}$	+.002	/RAD		
	$C_{n_{\dot\beta}}$	0			
	$C_{n_{\delta R}}$	−.086	/RAD		
SIDE FORCE	C_{Y_β}	−.4928	/RAD		
	C_{Y_p}	+.0346	/RAD/SEC		
	C_{Y_R}	+.0692	/RAD/SEC		
	$C_{Y_{\delta W}}$	0			
	$C_{Y_{\ldots}}$	0			
	$C_{Y_{\delta R}}$	+.1146	/RAD		

U3 4038 9000

SOURCES: -80 AERO # 96, UPDATED BY -80 AERO # 131; -80 AERO # 132 (GR. EFF.)	367-80 CONFIGURATION FOR SIMULATION of NASA 72	SOURCES: NASA AND C/S 733 AERO-217	72° NASA



	WEIGHT 270,000 C.G. LOCATION .46 $\bar{c}$ (WINGS SWEPT) ALTITUDE SEA LEVEL	**DEPENDENT VARIABLES** q_{TRIM} + 112.1 $q_{TRIM}S$ 560,320 $THRUST_{TRIM}$ 81,245 LBS MASS 8,385 SLUGS
MOMENTS OF INERTIA IN BODY AXES	I_{XX} 1.667×10^6 SLUG FT^2 I_{YY} 18.58×10^6 SLUG FT^2 I_{ZZ} 20.00×10^6 SLUG FT^2 I_{XZ} 0	
FLIGHT CONDITION	FLAP SETTING WING SWEEP ANGLE $\Lambda_{L.E.} = 72°$ NOSE POSITION UP GEAR DOWN	

(UNAUGMENTED) MODE SHAPES

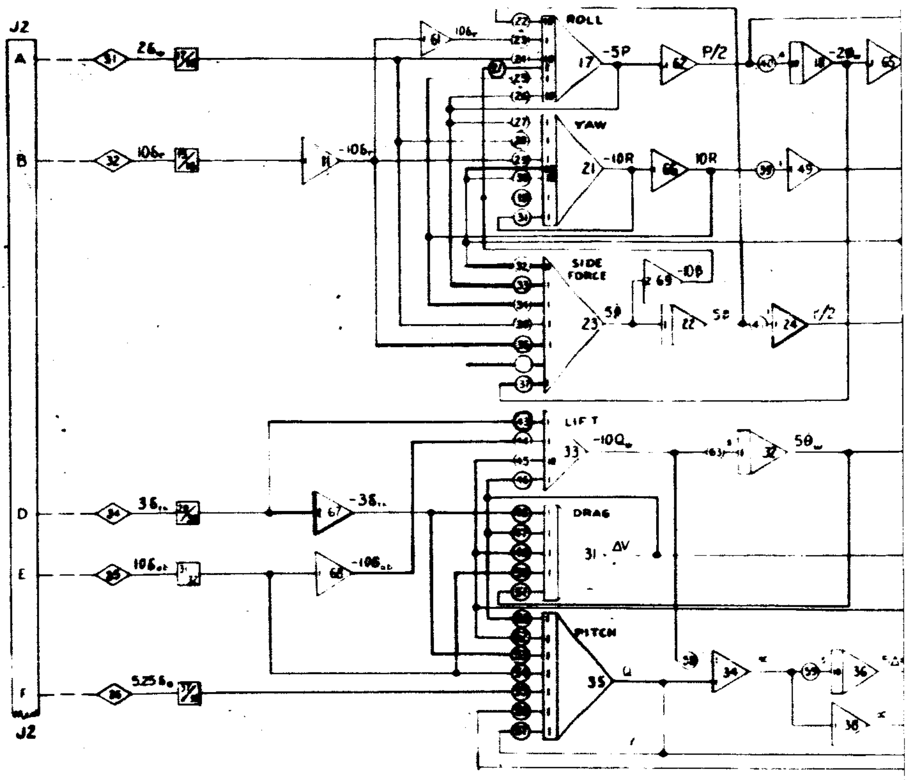
SHORT PERIOD	ω_u = .981 RAD/SEC ω_D = .807 RAD/SEC ζ = .569
PHUGOID	ω_u = .129 RAD/SEC ω_D = .127 RAD/SEC ζ = .170
DUTCH ROLL	ω_u = 1.24 RAD/SEC ω_D = 1.22 RAD/SEC ζ = +.169
$\frac{\lvert\phi\rvert}{\lvert\beta\rvert}$	4.07
ROLL T.C.	1.7 SEC
SPIRAL DIV. T.C.	−17.7 SEC (D.A. = −12.2 SEC)

GEOMETRY	S 5,000 FT^2 (SWEPT REFERENCES) $\bar{c}$ 70 FT b 85 FT
TRIM	SPEED 182 KT (307 FT/SEC) α_{TRIM} 12.3 DEG (.2147 RAD)
ENGINE CHAR.	$\frac{\Delta T}{\delta_{TH}} = \frac{170,000}{1 + sT_E}$ LB/RAD

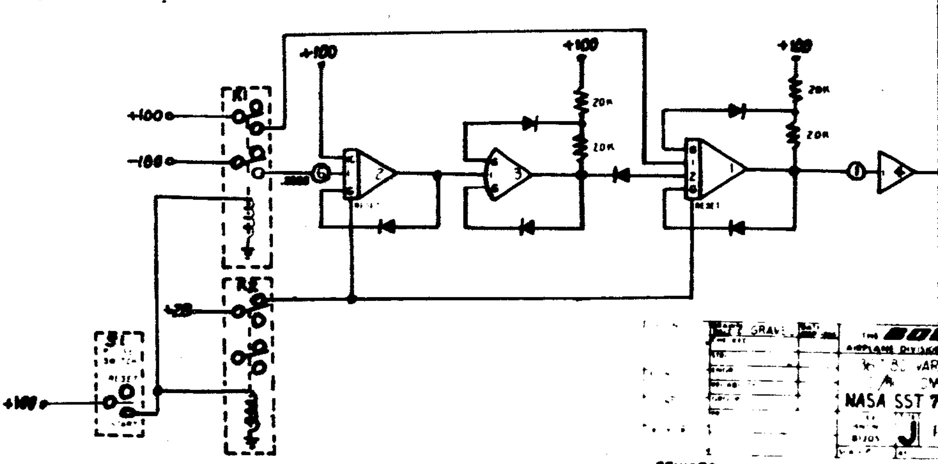
			REVISED	DATE	
CALC	D.E.G.	2-3-65			VARIABLE STABILITY AIRPLANE DESCRIPTION
CHECK			D.E.G.	3-22-65	
APR			H.P.C.	4-14-65	
APR			B.B.	10-11-5	THE BOEING COMPANY

2

-80 MODEL

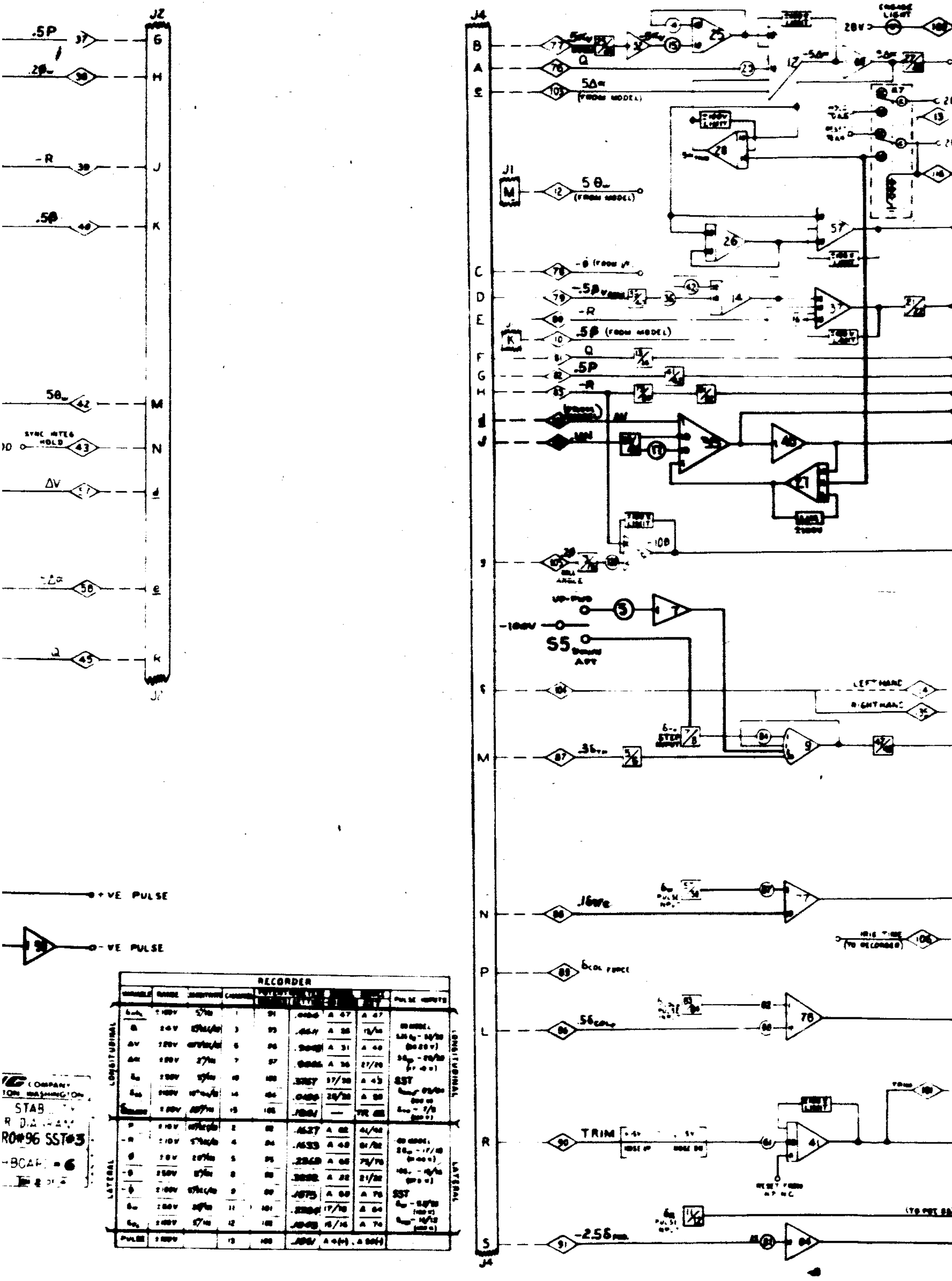


PULSE CIRCUIT



REVISED
6-12-65 BB
6-13-65
6-16-65
6-17-65 W.E.B.
10-14-65 W.E.B.

C-35-1

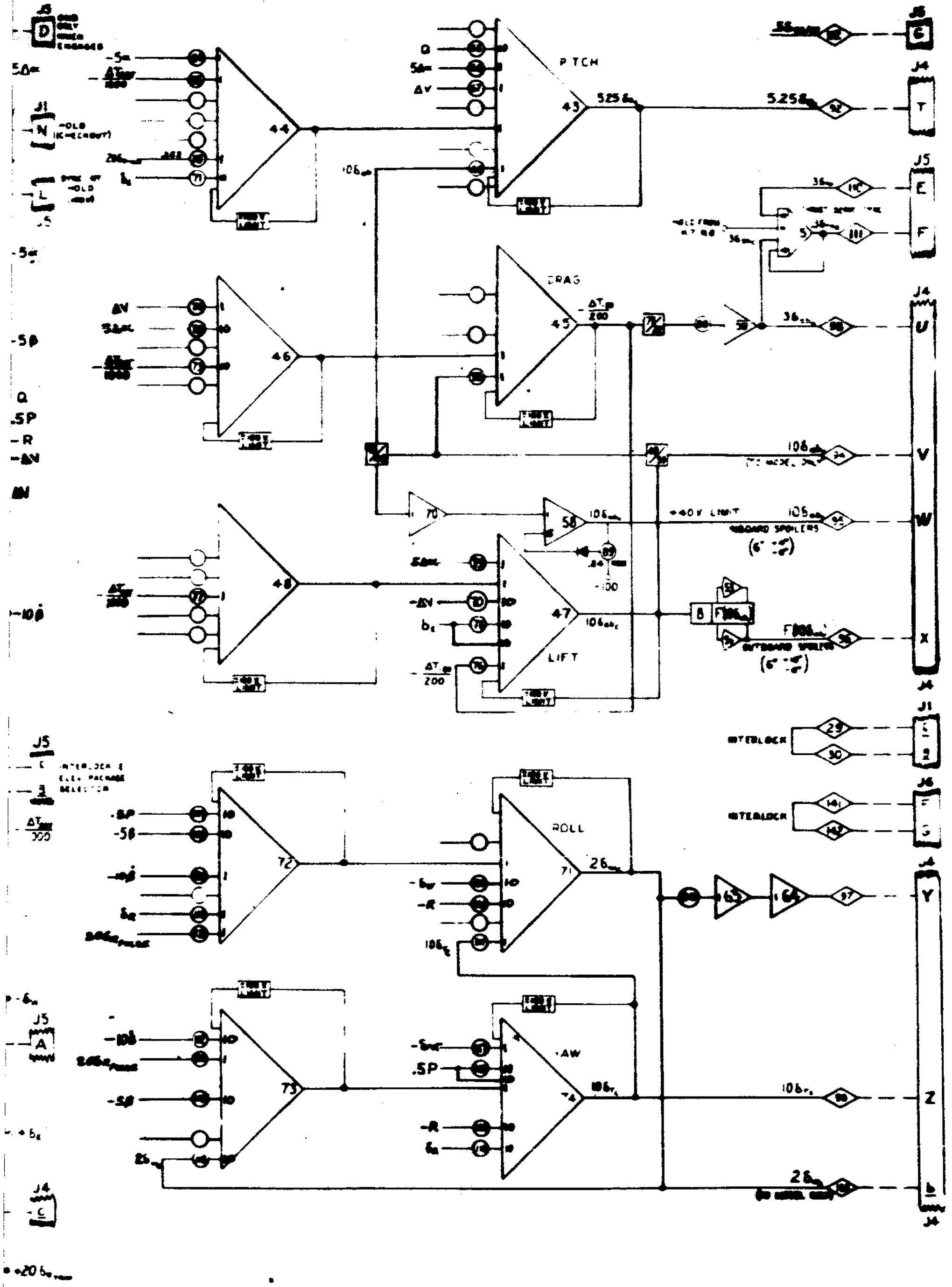


RECORDER

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	PULSE INPUTS	
LONGITUDINAL	[illegible]	±100V	5/10	1	91	[illegible]	A 47	A 47	SST	LONGITUDINAL
	θ	±4V	[illegible]	3	93	[illegible]	A [illegible]	[illegible]		
	ΔV	±20V	[illegible]	6	96	[illegible]	A 31	A 40		
	Δα	±10V	27/10	7	97	[illegible]	A 36	27/20		
	[illegible]	±50V	5/10	10	[illegible]	.3367	17/20	A 43		
	[illegible]	±100V	[illegible]	14	[illegible]	[illegible]	20/20	A [illegible]		
	[illegible]	±50V	[illegible]	15	105	[illegible]	—	TR [illegible]		
LATERAL	P	±10V	[illegible]	2	[illegible]	.4627	A [illegible]	[illegible]	SST	LATERAL
	-R	±10V	[illegible]	4	94	.4633	A 40	[illegible]		
	φ	±8V	[illegible]	5	95	[illegible]	A [illegible]	[illegible]		
	-β	±50V	[illegible]	8	[illegible]	[illegible]	A [illegible]	21/[illegible]		
	-φ̇	±100V	[illegible]	9	[illegible]	.4675	A [illegible]	A 76		
	[illegible]	±50V	[illegible]	11	101	[illegible]	17/16	A 64		
	[illegible]	±100V	5/10	12	[illegible]	[illegible]	15/16	A 76		
	PULSE	±100V		13	[illegible]	[illegible]	A 4(+), A 80(-)			

Q-35-2

SST MATRIX



NASA 72°

APPENDIX D

AIRPLANE ELECTRO-HYDRAULIC POWER CONTROL UNITS

LIST OF ILLUSTRATIONS

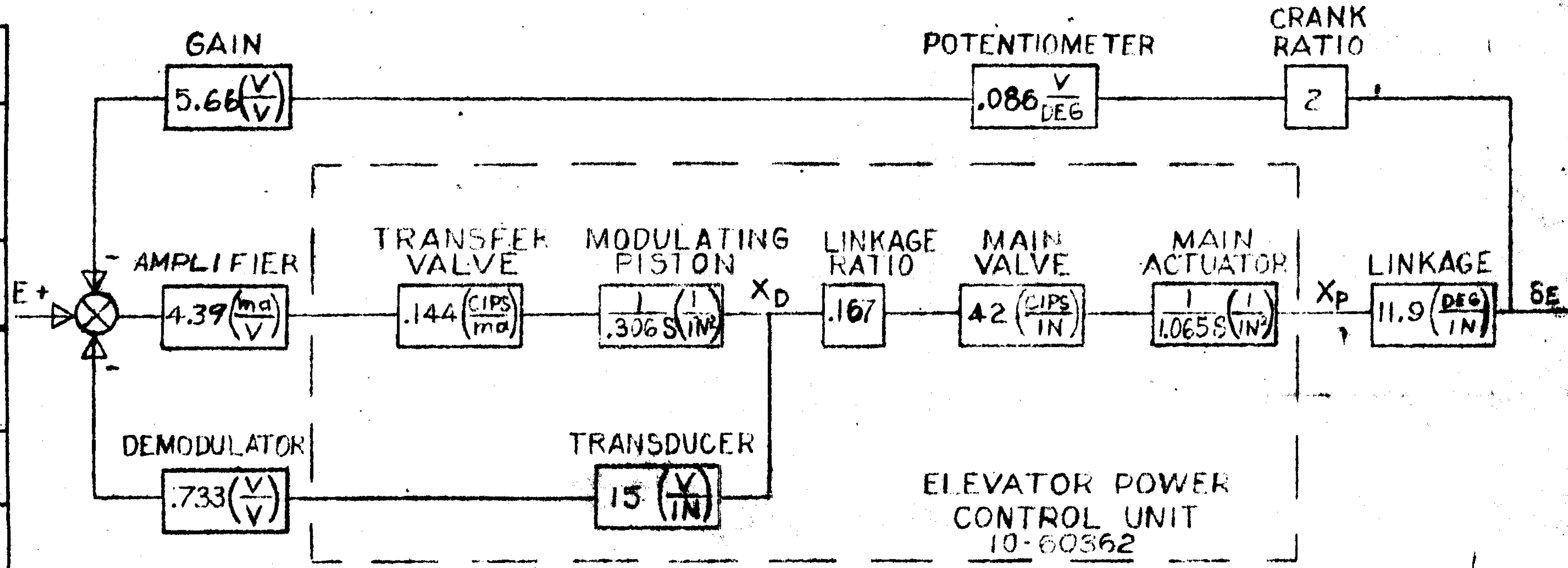
APPENDIX D - AIRPLANE ELECTRO-HYDRAULIC POWER CONTROL UNITS

The 367-80 airplane is equipped with electro-hydraulic power control units on the following controls: Left hand elevator, right hand elevator, spoilers, rudder, aileron, lateral control system (spoiler drive PCU).

In addition, the thrust reversers are controlled by an electric servo system which drives the reverser levers which in turn control the clam shell hydraulic actuators.

During the -80 variable stability programs, the electro-hydraulic actuators are utilized to accept signals from the airborne computer and drive the -80 control surfaces to perform the dynamics of the simulated airplane. For this we have 5 degree of freedom control, the pitching equation by elevator, the roll equation by wheel (lateral control), the drag equation by thrust reverser modulation, the yawing moment equation by rudder, and the lift equation by spoilers. For each of the aforementioned systems this appendix contains a block diagram, transient response, frequency response, the linearized transfer functions, surface rate limits, and displacement limits. Also, the hysteresis of the lateral control system is included.

In summarizing, the 367-80 is equipped with the electro-hydraulic actuators on each controlled axes except thrust reversers, the dynamics of which are very good and the frequency response entirely sufficient for use in a variable stability control system.



NOMENCLATURE

E - INPUT VOLTAGE, VOLTS

X_D - MODULATING ACTUATOR DISPLACEMENT, INCHES

X_P - MAIN ACTUATOR DISPLACEMENT, INCHES

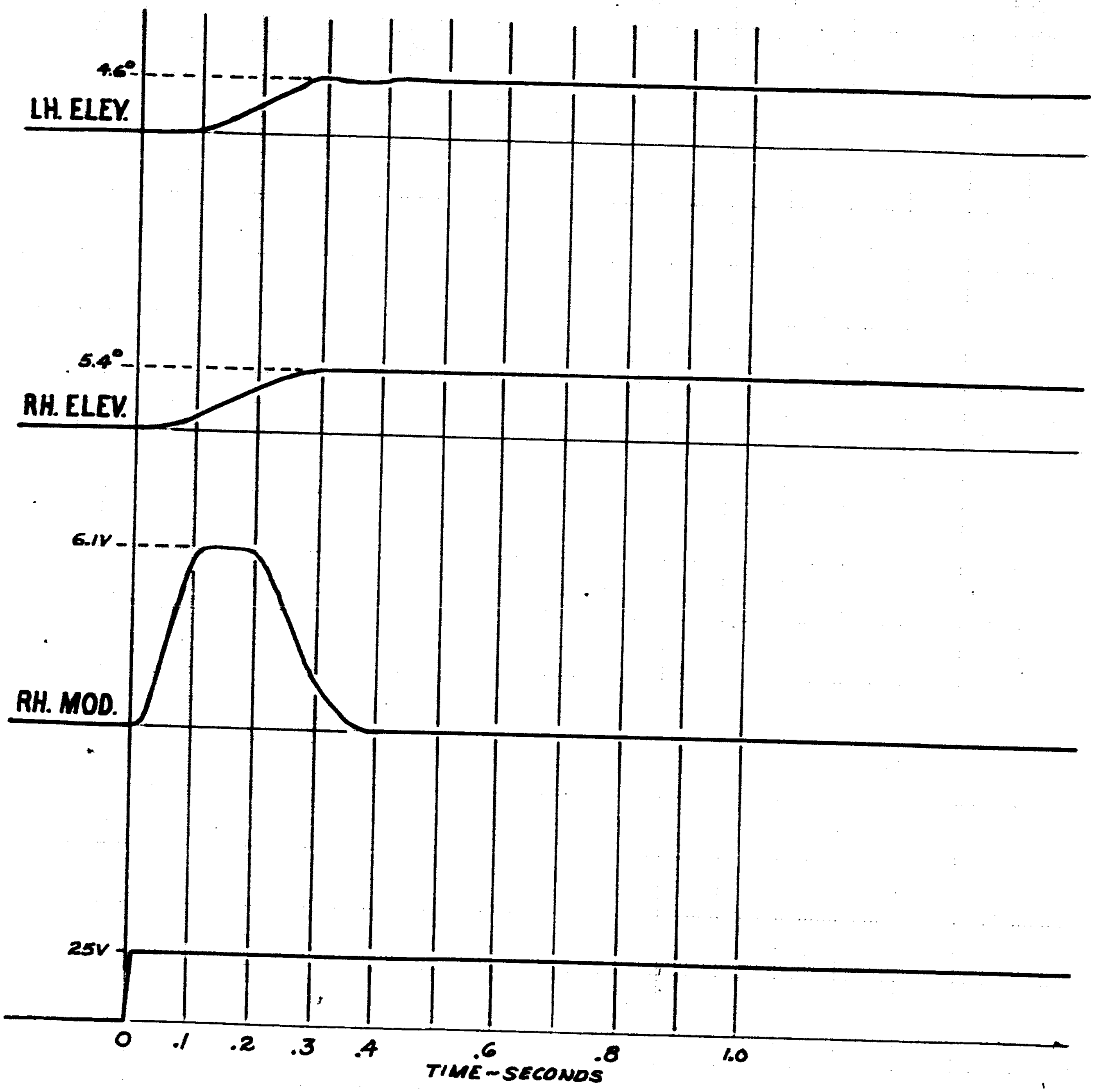
δ_E - ELEVATOR DISPLACEMENT, DEGREES

S - LAPLACE OPERATOR

MAX NO LOAD SURFACE RATE = 25°/sec (ELECT. MODE)

$$\delta_E / E = \frac{K}{.06S+1}$$

CALC			REVISED	DATE	BLOCK DIAGRAM ELEVATOR (AUTOPILOT MODE)	367-80
CHECK						FIG. 1
APR					THE BOEING COMPANY RENTON, WASHINGTON	PAGE D3
APR						



TEST NO 655-1 COND. 1. 38. 03. 05

CALC	D.E.G.	4-13-65	REVISED	DATE	RIGHT HAND MASTER
CHECK					ELEVATOR TRANSIENT RESPONSE (ELECTRICAL MODE)
APR					
APR					THE BOEING COMPANY

FIG. 2

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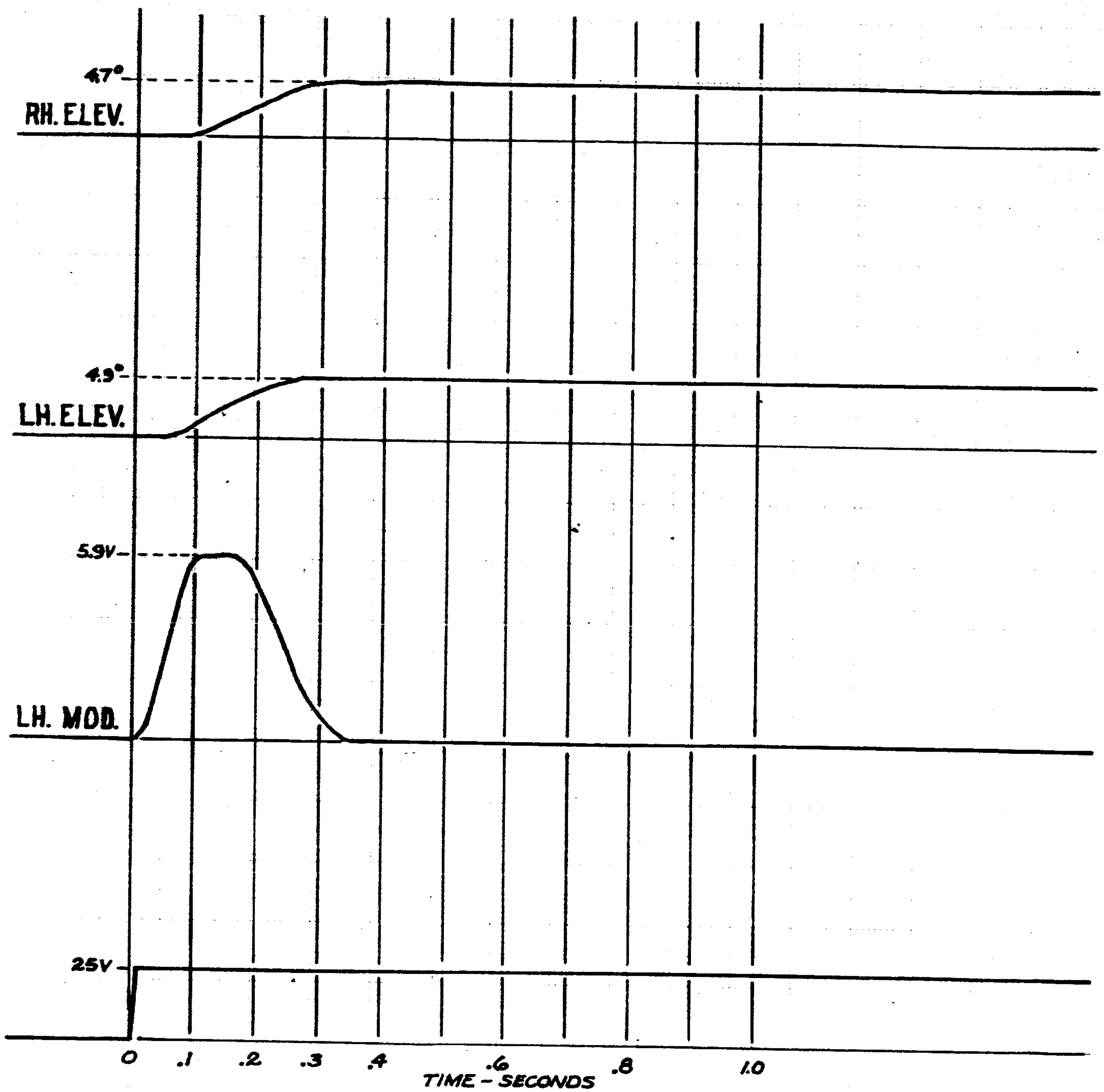

TEST NO 655-1 COND 1.38.03.05

CALC	D. E. G.	4-13-65	REVISED	DATE	LEFTHAND MASTER	FIG. 3
CHECK					ELEVATOR TRANSIENT RESPONSE	
APR					(ELECTRICAL MODE)	
APR					THE BOEING COMPANY	PAGE D5

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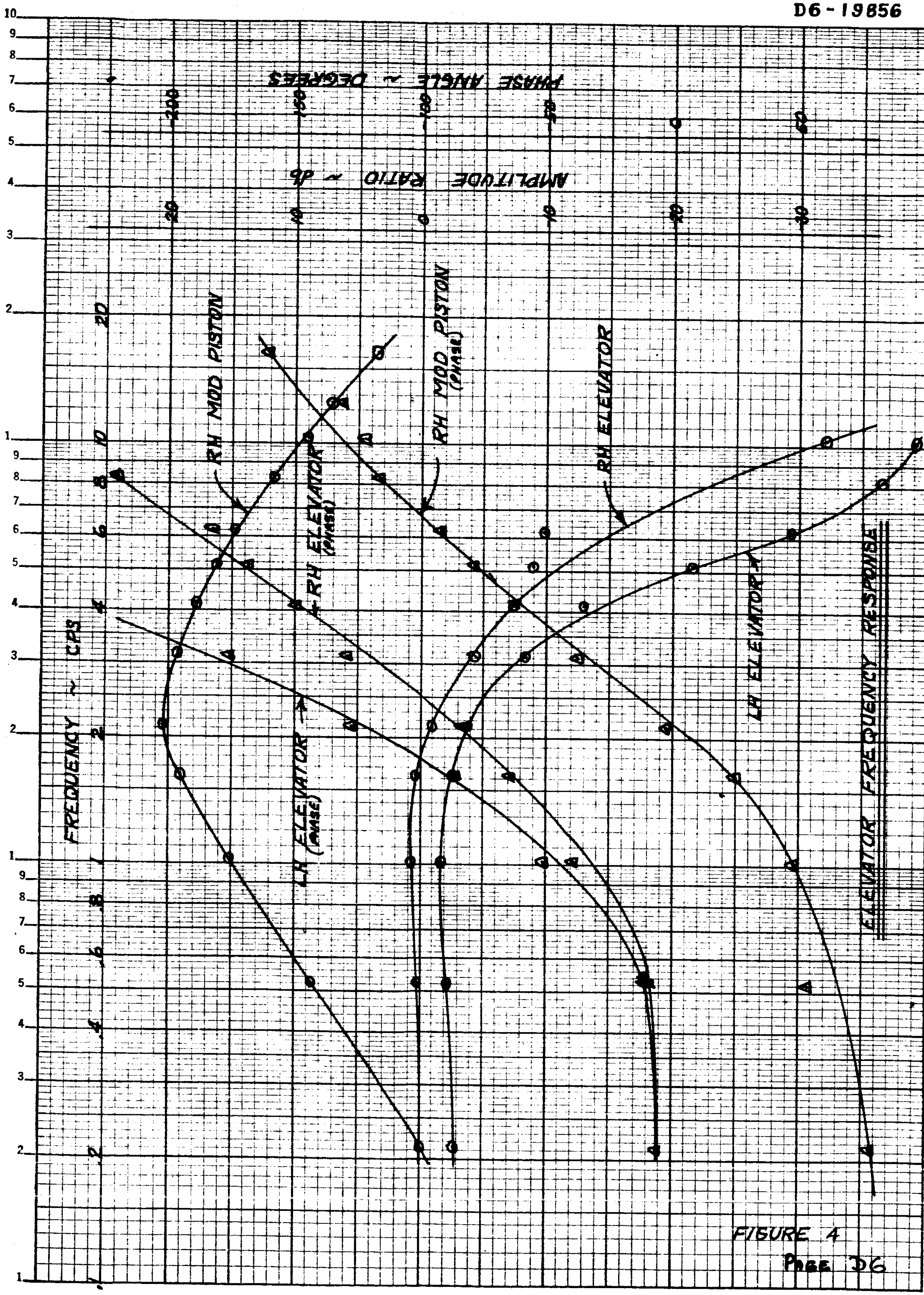
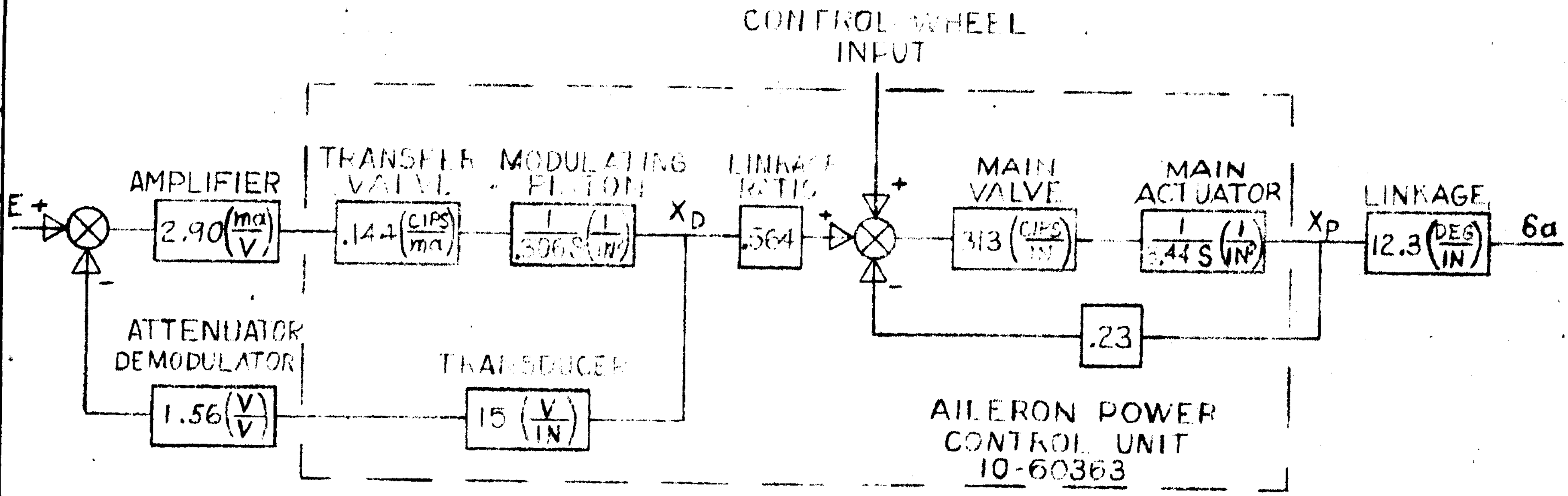

PHASE ANGLE ~ DEGREES
AMPLITUDE RATIO ~ db
FREQUENCY ~ CPS
RH MOD PISTON
RH MOD PISTON (PHASE)
RH ELEVATOR
RH ELEVATOR (PHASE)
LH ELEVATOR
LH ELEVATOR (PHASE)
ELEVATOR FREQUENCY RESPONSE
SEMI-LOGARITHMIC 359-71
KEUFFEL & ESSER CO. MADE IN U.S.A.
3 CYCLES X 70 DIVISIONS

FIGURE 4

183



NOMENCLATURE

E - INPUT VOLTAGE, VOLTS

X_D - MODULATING ACTUATOR DISPLACEMENT, INCHES

X_P - MAIN ACTUATOR DISPLACEMENT, INCHES

δ_a - AILERON DISPLACEMENT, DEGREES

S - LAPLACE OPERATOR

δ_a MAX NO LOAD SURFACE RATE = 68 °/sec (ELECT. MODE)

$$\delta_a / E = \frac{K}{(.014S+1)(.05S+1)}$$

CALC			REVISED	DATE	BLOCK DIAGRAM AILERON (AUTOPILOT MODE)	367-80
CHECK						FIG. 5
APR					THE BOEING COMPANY RENTON, WASHINGTON	PAGE D7
APR						

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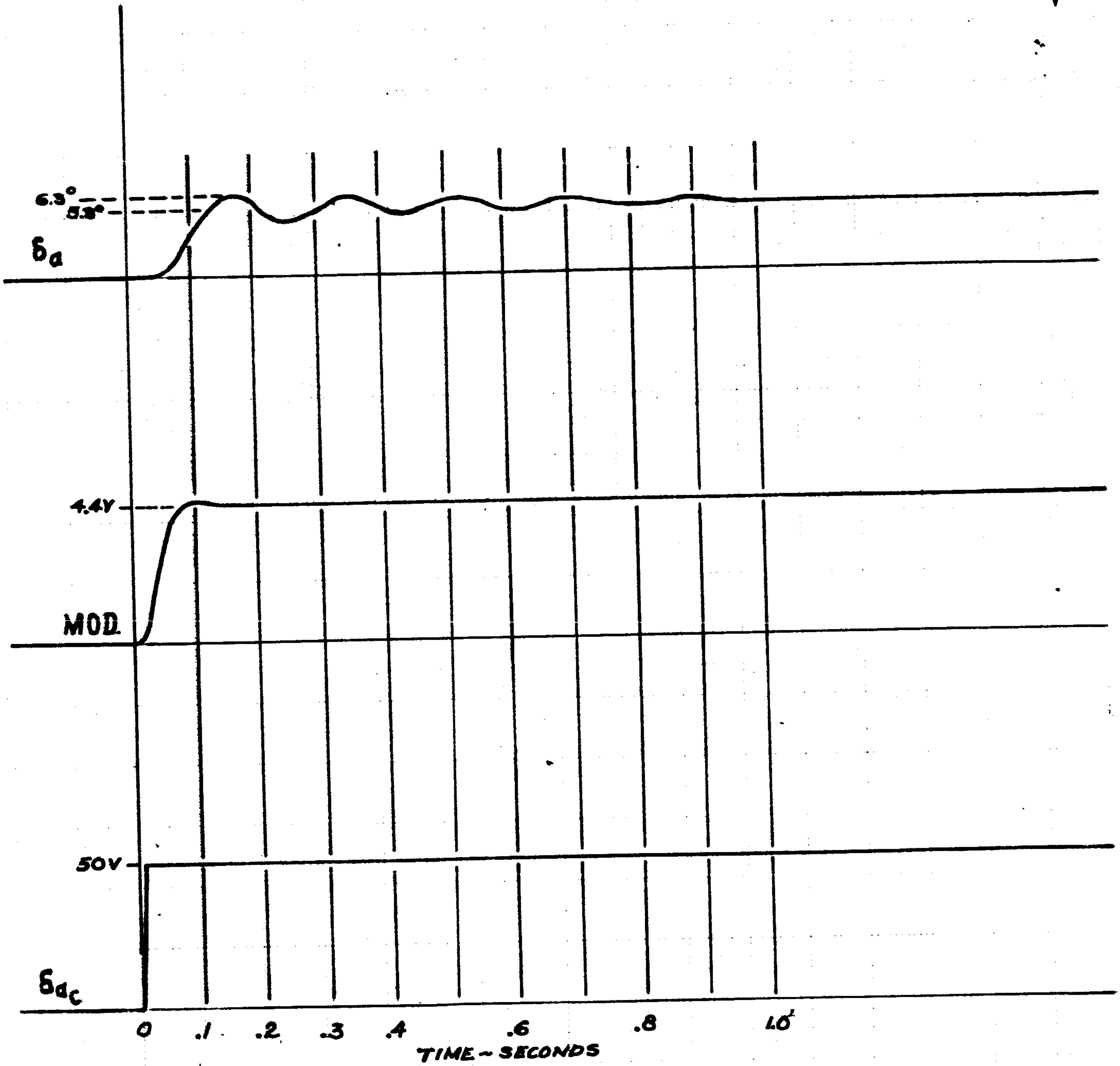
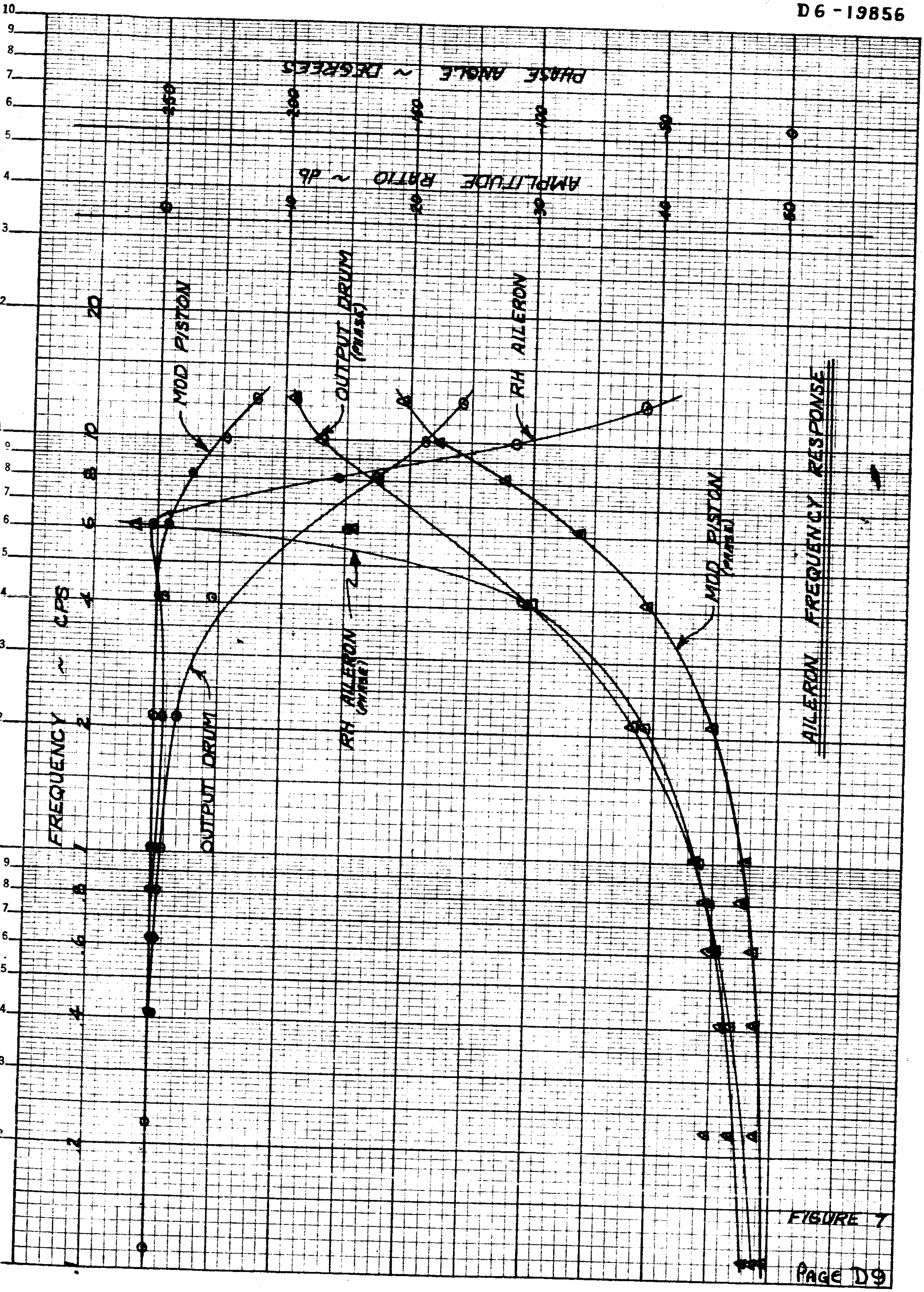


TEST NO 655-1 COND. 1.38.03.04

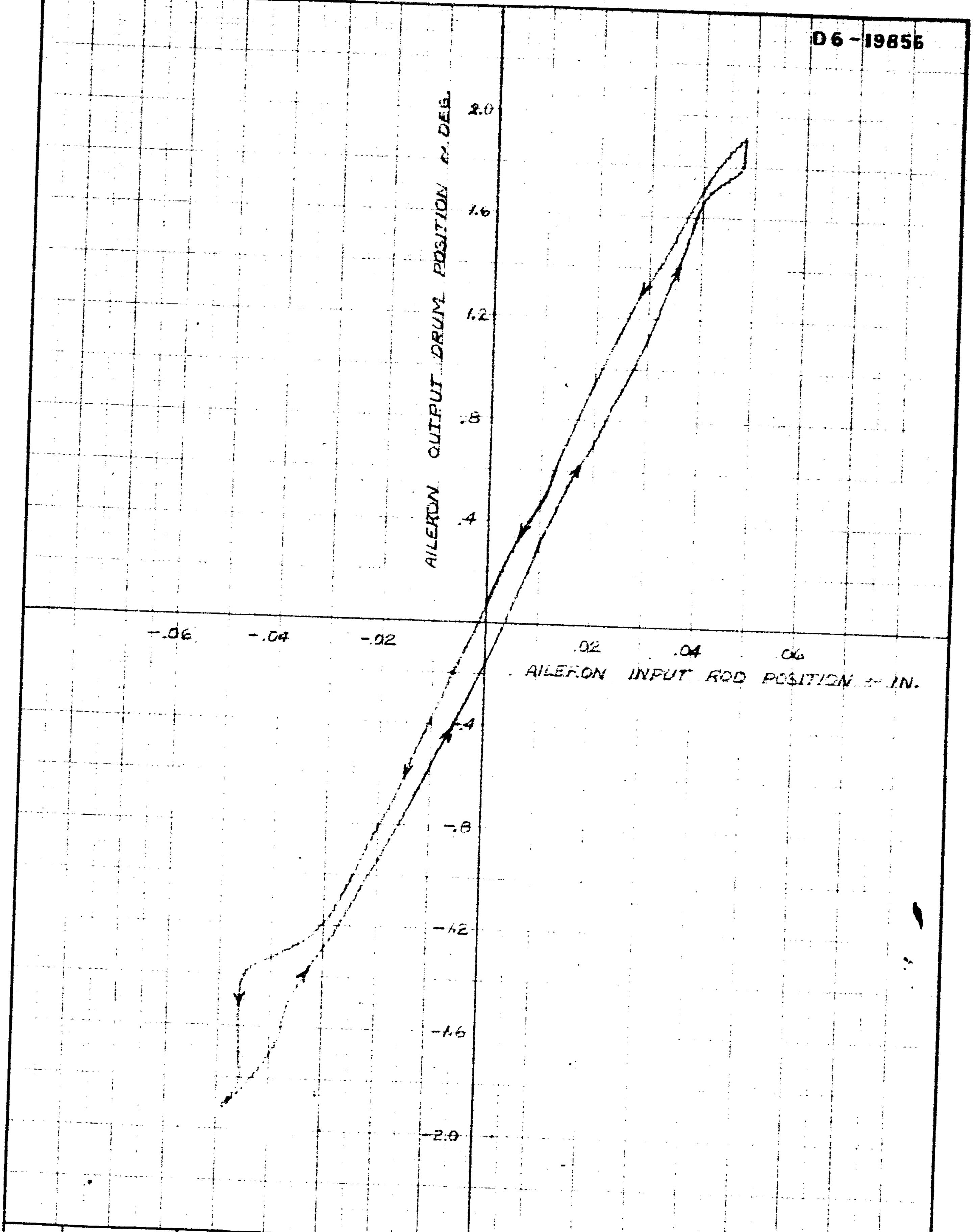
CALC	D.E.G.	4-13-65	REVISED	DATE	AILERON TRANSIENT RESPONSE (ELECTRICAL MODE)	FIG. 6
CHECK						
APR					THE BOEING COMPANY	PAGE D8
APR						



AILERON FREQUENCY RESPONSE
PHASE ANGLE ~ DEGREES
AMPLITUDE RATIO ~ db
FREQUENCY ~ CPS
MOD PISTON
OUTPUT DRUM (PHASE)
RH AILERON
MOD PISTON (PHASE)
RH AILERON (PHASE)
OUTPUT DRUM

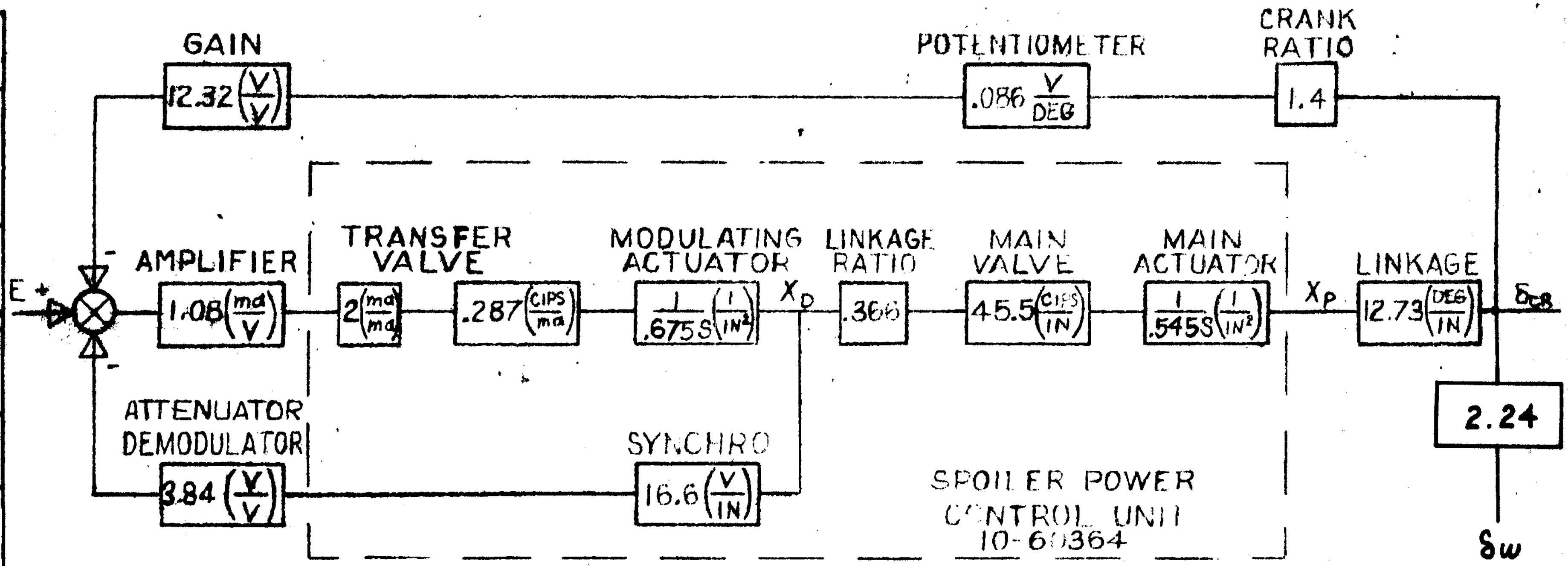
FIGURE 7

181



CALC			REVISED	DATE	AILERON PCU HYSTERESIS	367-80
CHECK						
APR						FIG. 8
APR						
					THE BOEING COMPANY	PAGE D10

TD 461 C-R4



NOMENCLATURE

E - INPUT VOLTAGE, VOLTS

X_D - MODULATING ACTUATOR DISPLACEMENT, INCHES

X_P - MAIN ACTUATOR DISPLACEMENT, INCHES

δ_{CR} - SPOILER ACTUATOR CRANK DISPLACEMENT, DEGREES

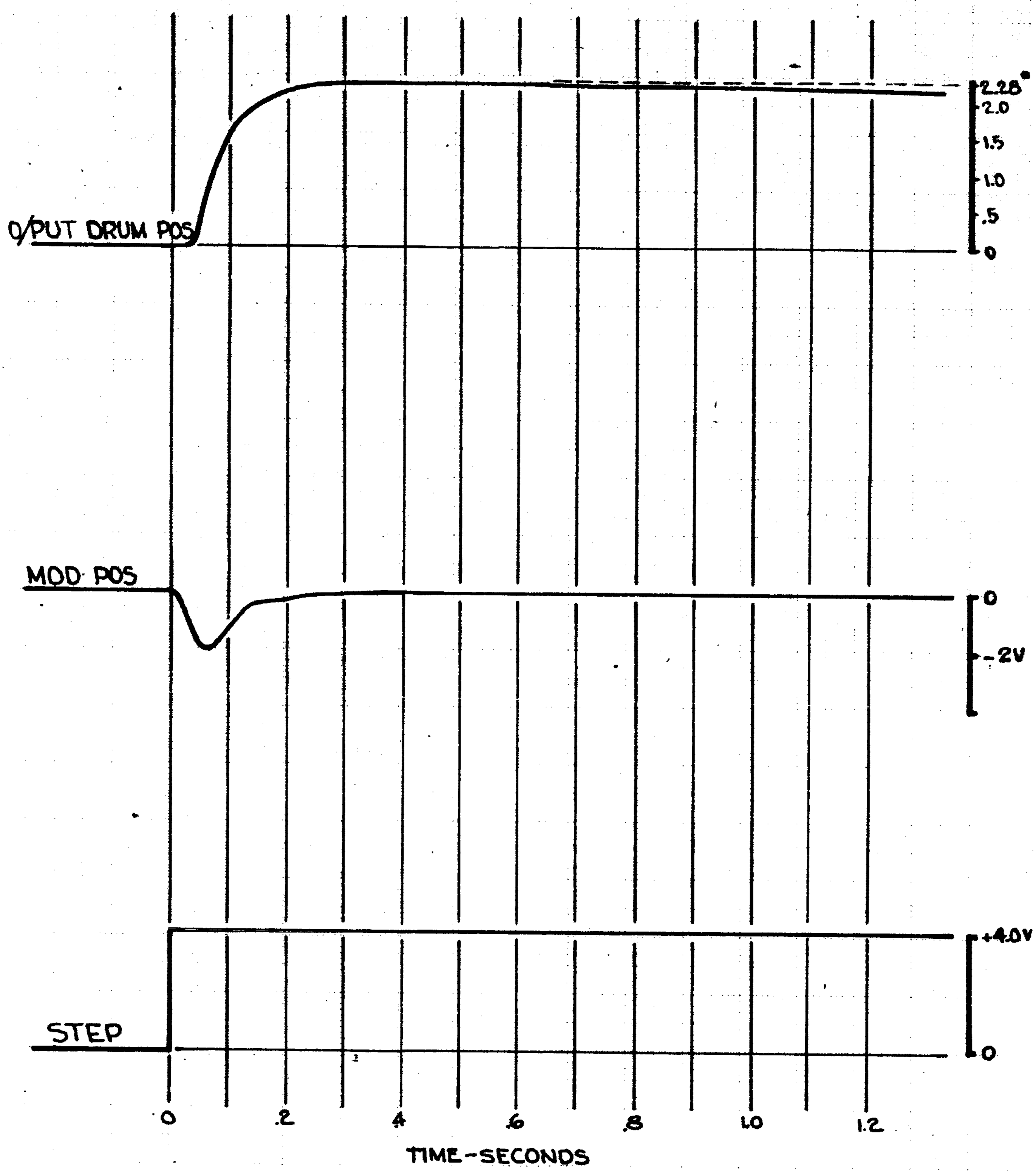
S - LAPLACE OPERATOR

δ_W - SAFETY PILOTS WHEEL POSITION, DEGREES

MAX δ_W RATE = 180 °/sec (ELECT. MODE)

δ_W MAX = ± 63° (ELECT. MODE)

CALC			REVISED	DATE	BLOCK DIAGRAM	367-80
CHECK					SPOILER DRIVE P.C.U.	FIG. 9
APR						
APR					THE BOEING COMPANY RENTON, WASHINGTON	PAGE D11



ELECTRICAL MODE

CALC			REVISED	DATE	SPOILER DRIVE ACTUATOR TRANSIENT RESPONSE	FIG. 10
CHECK						
APR					TEST NO 655-1 COND. 1.38.03.03	
APR						
					THE BOEING COMPANY	PAGE D12

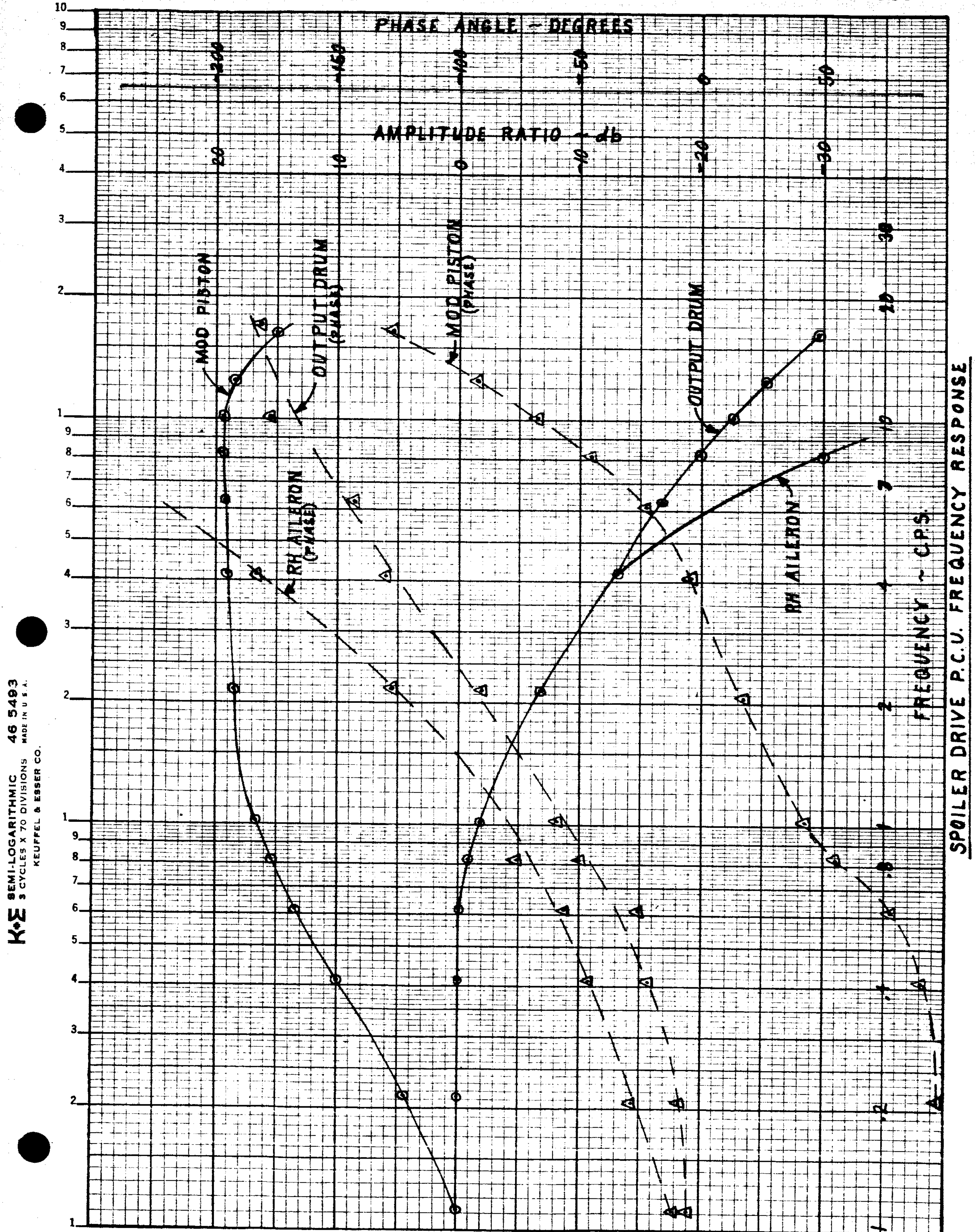

PHASE ANGLE ~ DEGREES
-200
-150
-100
-50
0
50
AMPLITUDE RATIO ~ db
20
10
0
-10
-20
-30
MOD PISTON
OUTPUT DRUM (PHASE)
MOD PISTON (PHASE)
OUTPUT DRUM
RH AILERON (PHASE)
RH AILERON
FREQUENCY ~ C.P.S.
SPOILER DRIVE P.C.U. FREQUENCY RESPONSE
K+E SEMI-LOGARITHMIC 46 5493
3 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

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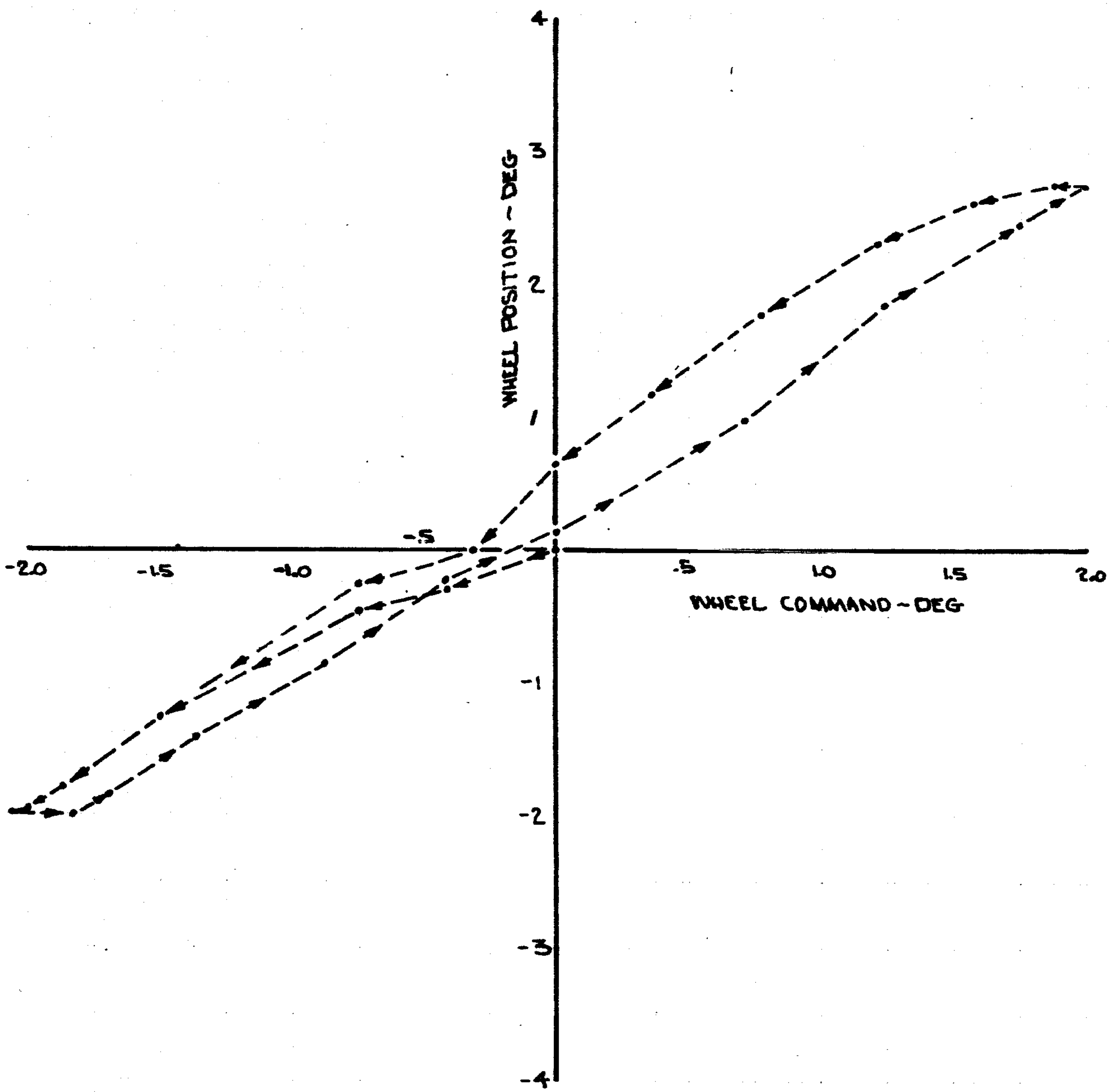
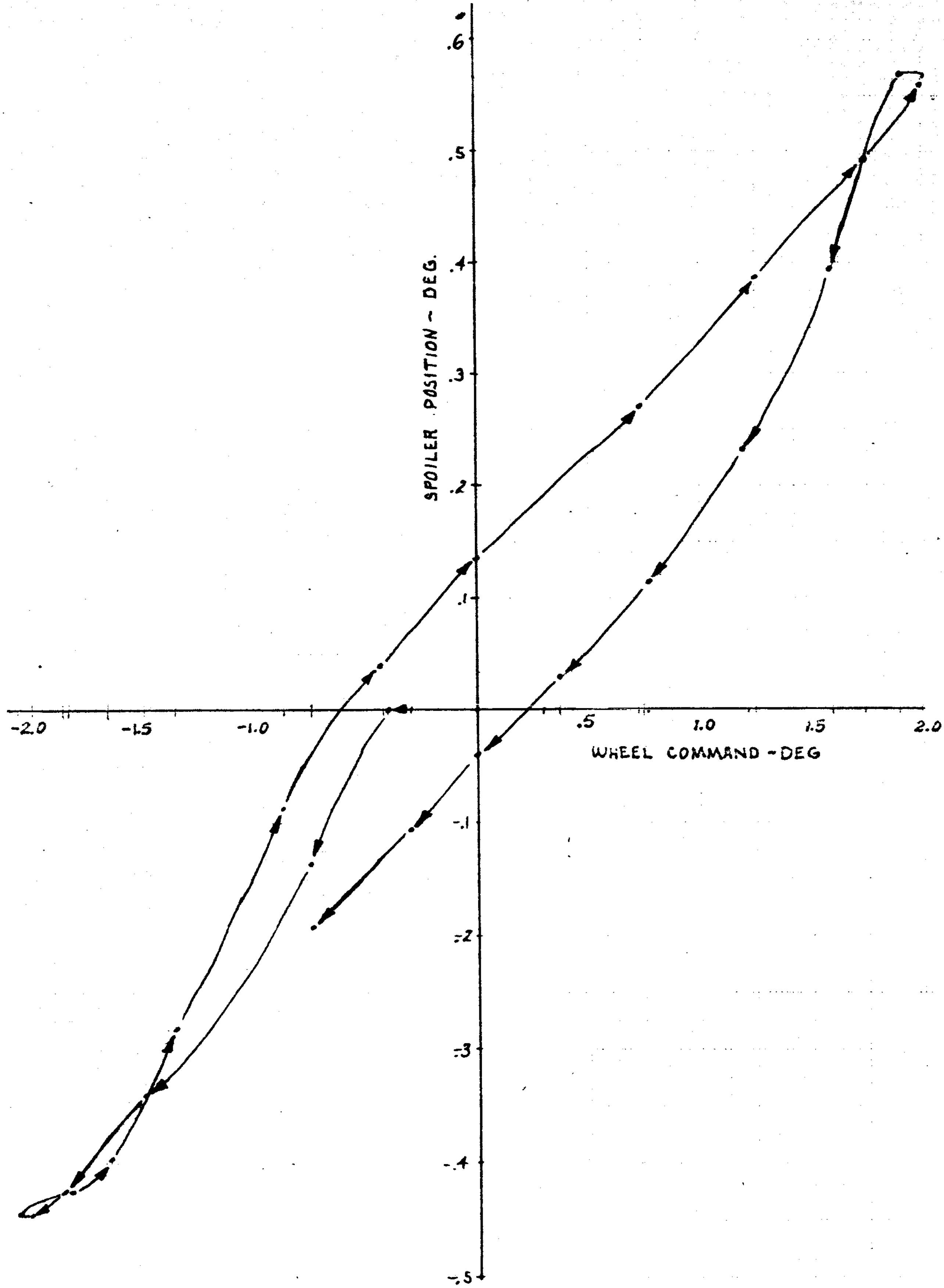
FIG. 11



ELECTRICAL MODE

CALC			REVISED	DATE	SPOILER CONTROL SYSTEM HYSTERESIS	FIG. 12
CHECK					δ_ω VS δ_{ω_c}	
APR					TEST NO 655-1 1.38.03.02	
APR					THE BOEING COMPANY	PAGE D14



TEST NO. 655-1 1.32.03.02

DE. GRAVES 7-7-65

SPOILER CONTROL SYSTEM HYSTERESIS

NO. 7 SPOILER POSITION vs δ_{w_c}

FIG. 13

THE BOEING COMPANY

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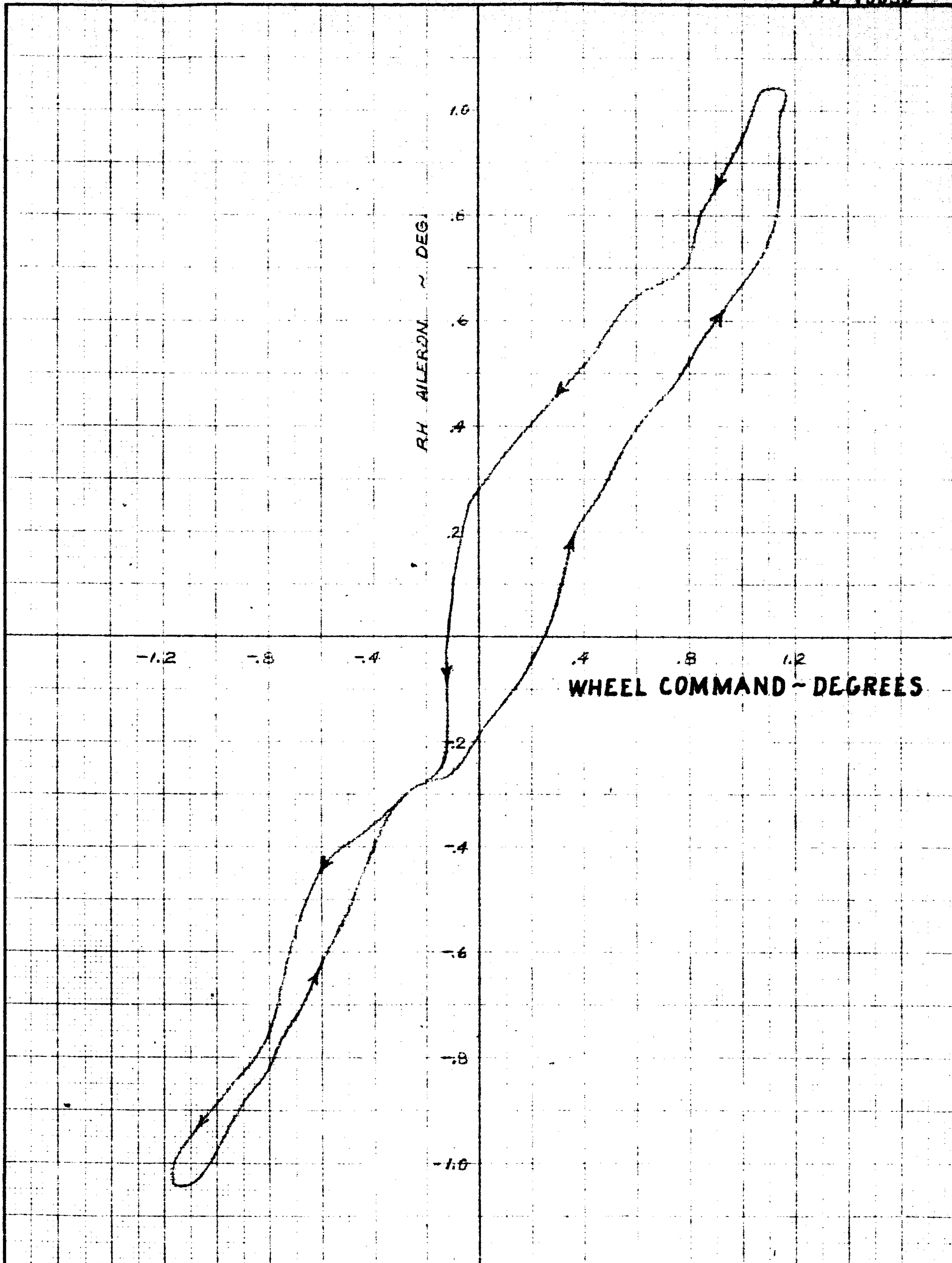

CALC			REVISED	DATE	SPOILER PCU INPUT TO RH AILERON HYSTERESIS	367-80
CHECK						FIG. 14
APR					THE BOEING COMPANY	PAGE D16
APR						

TD 461 C-R4

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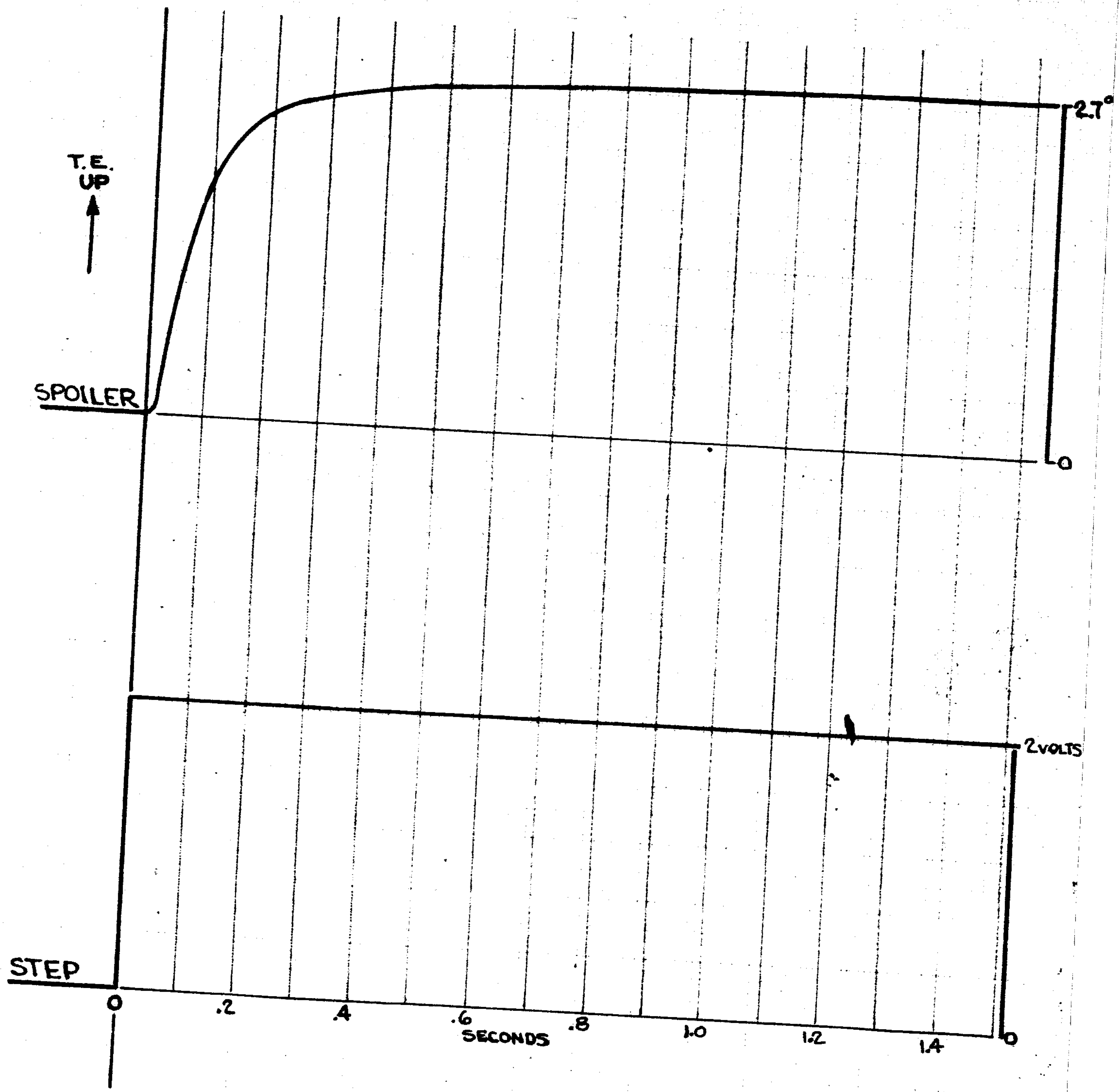


MAX. NO LOAD RATE = 50°/SEC (ELECTRICAL MODE)

$$\delta_{SP}/E_{IN} \approx \frac{K}{(.06S+1)}$$

LIMIT ±10°

CALC			REVISED	DATE	TEST NO. 655-1 COND L38.03.09	
CHECK					SPOILER ACTUATOR #6 TRANSIENT RESPONSE (ELECTRICAL MODE)	FIG. 15
APR						
APR						
					THE BOEING COMPANY	PAGE D17

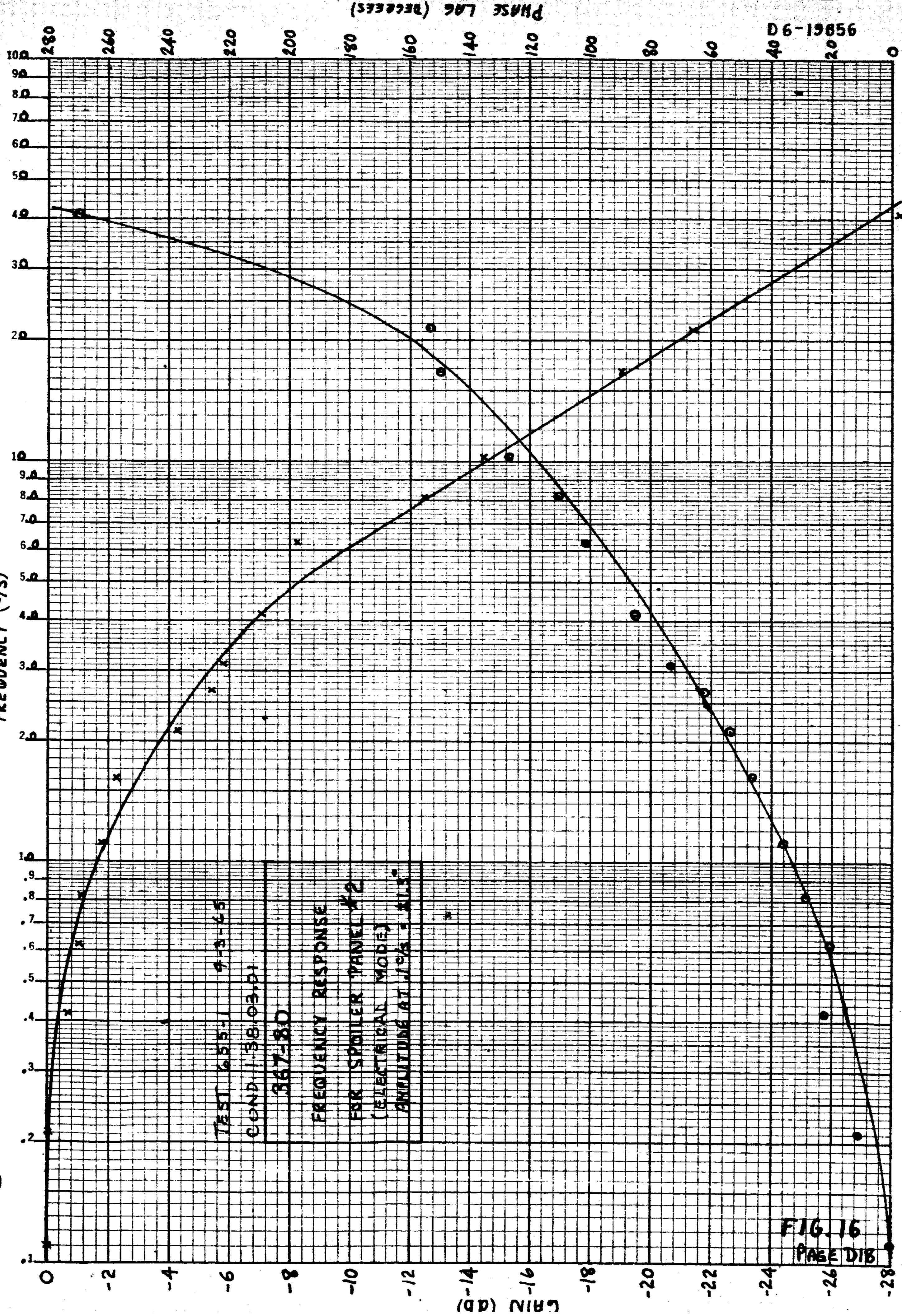
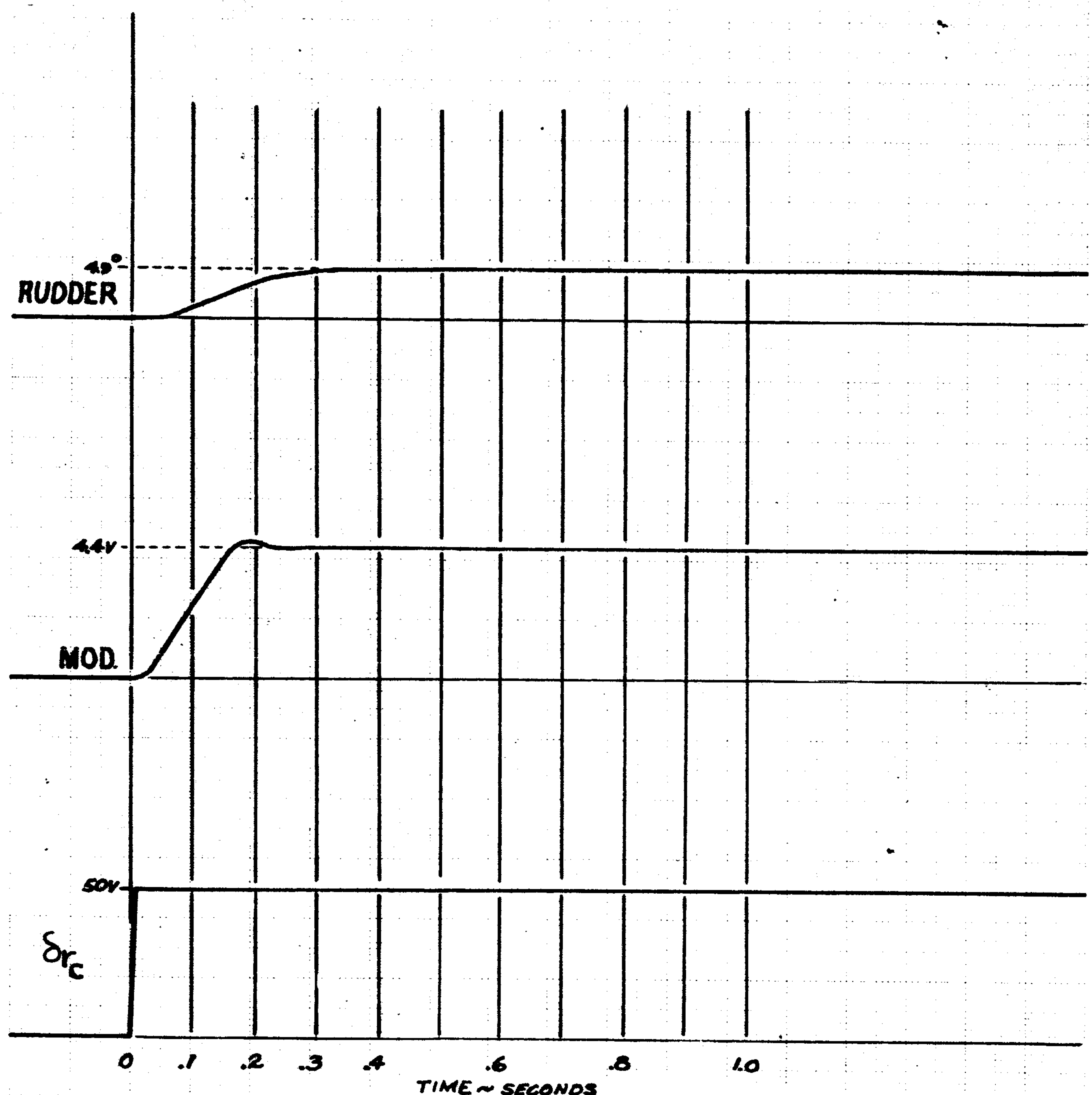

PHASE LAG (DEGREES)
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
FREQUENCY (C/S)
10
9
8
7
6
5
4
3
2
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
GAIN (dB)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
TEST 655-1 4-5-65
COND 1.38.03.01
367-80
FREQUENCY RESPONSE
FOR SPOILER PANEL #2
(ELECTRICAL MODE)
AMPLITUDE AT .1 C/S = ±1.3°
K+E SEMI-LOGARITHMIC 46 5493
3 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

FIG. 16



MAX NO LOAD RATE = 33 °/sec

$$\delta r / E_{IN} = \frac{K}{(.06S+1)(.028S+1)}$$ LIMIT ±10° ELECT.

TEST NO. 655-1 COND 1.38.03.07

CALC	D.E.G.	4-13-65	REVISED	DATE	RUDDER TRANSIENT RESPONSE (ELECTRICAL MODE)	FIG. 17
CHECK						
APR						
APR					THE BOEING COMPANY	PAGE D19

TD 461 D

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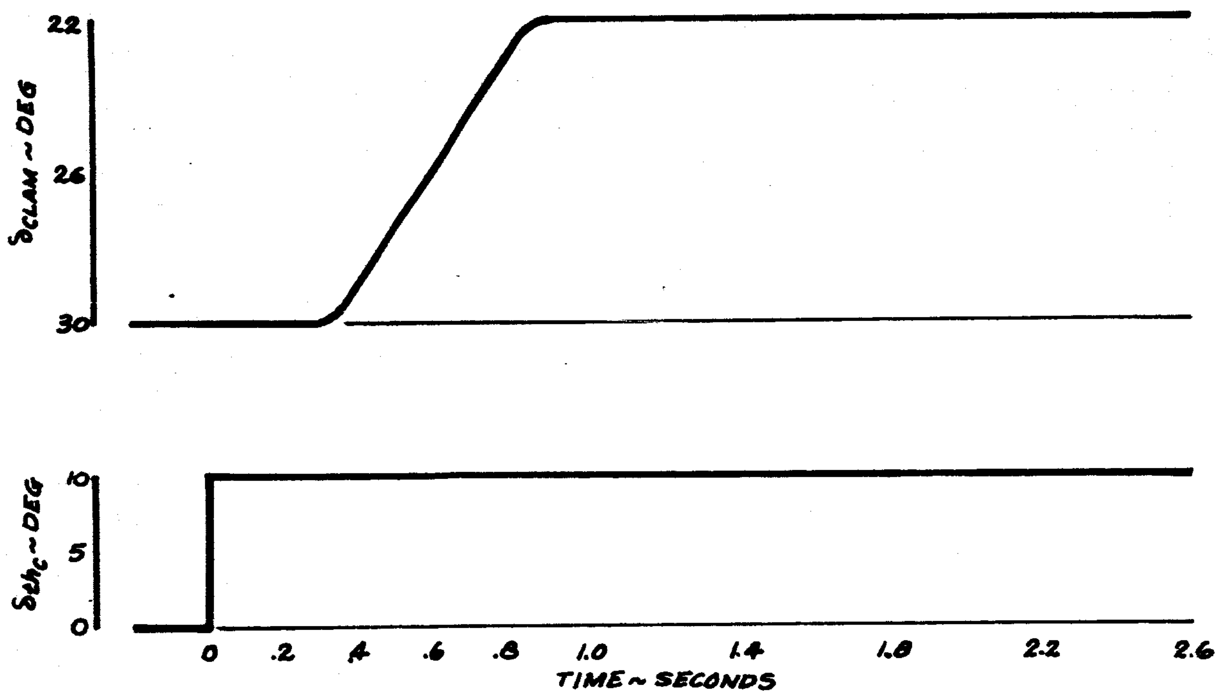

MAX CLAM SHELL RATE = 14 °/sec

$$\frac{\delta_{CLAM}}{E_{IN}} \approx \frac{K}{(.04S+1)(.19S+1)}$$

CALC		REVISED	DATE	THRUST MODULATION SYSTEM ELECTRICAL MODE TRANSIENT RESPONSE
CHECK				
APR				
APR				THE BOEING COMPANY

FIG. 18

THE BOEING COMPANY

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PROPRIETARY NOTES

23. masa

70-90

ACTIVE SHEET RECORD

SHEET NUMBER	REV LTR	ADDED SHEETS				SHEET NUMBER	REV LTR	ADDED SHEETS			
		SHEET NUMBER	REV LTR	SHEET NUMBER	REV LTR			SHEET NUMBER	REV LTR	SHEET NUMBER	REV LTR
1						46					
2						47					
3						48					
4						49					
5						50					
6						51					
7						52					
8						53					
9						54					
10						55					
11						56					
12						57	A				
13						58					
14						59					
15						60					
16						APPENDIX A					
17						A-1					
18						A-2					
19						A-3					
20						A-4					
21						A-5					
22						A-6					
23						A-7					
24						A-8					
25						A-9					
25a						A-10					
26						A-11					
27						A-12					
28						A-13					
29	A					A-14					
30	A					A-15					
31						A-16					
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41						A-26					
42											
43											
44											
45											

THE BOEING COMPANY

NUMBER D6-19856
REV LTR

ACTIVE SHEET RECORD

SHEET NUMBER	REV LTR	ADDED SHEETS SHEET NUMBER	REV LTR	SHEET NUMBER	REV LTR	SHEET NUMBER	REV LTR	ADDED SHEETS SHEET NUMBER	REV LTR	SHEET NUMBER	REV LTR
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A-28						B-34					
A-29						B-35					
A-30						B-36					
A-31						B-37					
A-32						B-38					
A-33						B-39					
A-34						APPENDIX C					
A-35						C-1					
A-36						C-2					
A-37						C-3					
A-38						C-4					
A-39						C-5					
APPENDIX B						C-6					
B-1						C-7					
B-2						C-8					
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B-4						C-10					
B-5						C-11					
B-6						C-12					
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B-18						C-24					
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B-20						C-26					
B-21						C-27					
B-22						C-28					
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B-24						C-30					
B-25						C-31					
B-26						C-32					
B-27						C-33					
B-28						C-34					
B-29						C-35					
B-30						APPENDIX D					
B-31						D-1					
B-32						D-2					

200

AD 4572B-R1

ACTIVE SHEET RECORD

SHEET NUMBER	REV LTR	ADDED SHEETS: SHEET NUMBER	REV LTR	ADDED SHEETS: SHEET NUMBER	REV LTR	SHEET NUMBER	REV LTR	ADDED SHEETS: SHEET NUMBER	REV LTR	ADDED SHEETS: SHEET NUMBER	REV LTR
D-3											
D-4											
D-5											
D-6											
D-7											
D-8											
D-9											
D-10											
D-11	A										
D-12											
D-13											
D-14											
D-15											
D-16											
D-17											
D-18											
D-19											
D-20											
a											
b	A										
c											
d	A										
e	A										

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVAL
A	Update information.	2/14/66	R.A. Smith