STUDY AND SIMULATION PROGRAM TO INVESTIGATE THE MECHANIZATION OF AN AIRCRAFT FLIGHT CONTROL SYSTEM THAT EMPLOYS DIRECT LIFT

Volume II: Pilot-in-the-Loop Simulation Study of Direct Lift Control

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FOREWORD

This study was conducted under Air Force Systems Command Contract No. F-33615-67-C-1502, "Study and Simulation Program to Investigate the Mechanization of an Aircraft Flight Control System that Employs Direct Lift," Project No. 8225, "Flight Control Equipment Techniques," and Task No. 822505, "Self-Adaptive and Invariant Control Techniques." The work was administered under the direction of the Air Force Flight Dynamics Laboratory. Mr. Paul Blatt, FDCL, was the project monitor. The work was conducted during the period March 1967 through February 1968. This report is Volume II of three volumes of the final report.

This report was prepared by the Aerospace Flight Systems Group of the Aerospace Division, Honeywell Inc., 2600 Ridgway Road, Minneapolis, Minnesota 55413. The project engineer was J. C. Larson. Principal contributors to the effort were T. W. Chase, V. L. Falkner, and R. F. Helfinstine.

The study reported in this volume was conducted in September 1967. It was made possible only through the enthusiasm and effort of all those who took part. Paul Blatt, in addition to his normal assistance as monitor, devoted considerable time to simulation design, checkout and operation. Particular thanks are due the pilots, the essential elements in a program of this type: Lt. Cmdr. Glenn Hostetler, USN; Major Frank Koval, USAF; Major Conrad "Marty" Martinez, USANG; Captain Gary Nelsen, USAF; Sqdn. Ldr. Bill Smith, RCAF; and Mr. Ray Haas, director of the simulation laboratory. The long and sometimes awkward hours that each devoted to "flying" the simulator and evaluating the tasks involved in the test are sincerely appreciated.

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This technical report has been reviewed and is approved.

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ABSTRACT

A moving base pilot-in-the loop simulator study was conducted to evaluate the effectiveness of direct lift control systems in improving the mission effectiveness of two types of aircraft. The missions considered were in-flight refueling, terrain following, and landing. The aircraft considered were the C-5A heavy cargo plane and the F-104 fighter-bomber. Improved performance was obtained for all missions with direct lift control augmentation systems when compared with conventional stability augmentation systems utilizing elevator control alone. This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Flight Dynamics Laboratory (FDCL), Wright-Patterson AFB, Ohio 45433.

TABLE OF CONTENTS

TABLE OF CONTENTS -- CONCLUDED

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS -- CONTINUED

LIST OF ILLUSTRATIONS -- CONCLUDED

LIST OF TABLES

LIST OF TABLES -- CONTINUED

NOMENCLATURE

C^*	A combination of pilot's acceleration and pitch rate. In this report, C^* (g's) = $n_{zp} + 12.4\,\dot{\theta}$
DLC	Direct lift control
F_S	Stick force, pounds
L_α	Steady-state term in pitch rate to control input transfer function; also termed $1/T_\theta$, or $1/T_a$.
K	Control system gain
K_{C^*F}	C^* command, g's/lb stick force
K_{δ_e}	Elevator command, rad/g C^*
$K_{n_{z_F}}$	Normal acceleration command, g's/lb stick force
K_{δ_F}	Flap command, rad/g normal acceleration
$K_{\delta_{FF}}$	Flap command, rad/lb stick force
K_1	$U_{c/g}$, gain in C^* equation
K_2	$1_{p/g}$ gain in C^* equation (1p = 90 ft, C-5A, and 22.4 ft, F-104)
K_3	gain in C^* equation
L	Scale length used in turbulence model
M	Nose-up pitching acceleration, rad/sec^2
$M_{\dot\alpha}$, q	Pitch acceleration per rad/sec $\dot\alpha$ or q
M_{α}, δ, δ_e, or δ_F	Pitch acceleration per radian α, δ, δ_e, or δ_F
M_w	Pitch acceleration per ft/sec vertical velocity
T	Flap high-pass filter time constant, 2 seconds
T_e	Elevator response time constant, seconds

NOMENCLATURE -- CONTINUED

T_F - Flap response time constant, seconds

T_θ - Pitch transfer function numerator time constant, seconds

U (or U_1) - Airspeed, ft/sec

U_c - Gain term in C* equation, termed cross-over velocity

W.N. - White noise

X, Y, Z - Right-handed earth-fixed coordinates used in landing simulation, X along runway, Z down

Z - Normal acceleration, ft/sec^2, positive down

$Z_{\alpha}, _{\delta}, _{\delta_e}, _{\delta_F}$ - Normal acceleration per rad α, δ, δ_e, or δ_F

Z_w - Normal acceleration per ft/sec vertical velocity

g - Acceleration due to gravity

h - Altitude, feet

h_o - Altitude bias in flare equation, feet

n_z - Normal acceleration, g's, positive up

$n_{z_{c.g.}}$ - Normal acceleration at center of gravity

n_{z_α} - Normal acceleration per radian angle of attack

p - Roll rate, rad/sec

q - Dynamic pressure, lb/ft^2

q - Pitch rate, rad/sec

r - Yaw rate, rad/sec

w - Vertical velocity, ft/sec = $U\alpha$

α_G - Angle of attack due to vertical gust

NOMENCLATURE -- CONCLUDED

α	-	Angle of attack, rad = $\frac{w}{U}$
$\dot{\alpha}$	-	Rate of change of angle of attack, rad/sec
δ	-	Control deflections, rad
δ_e	-	Elevator deflection, positive for an up acceleration
δ_F	-	Flap deflection, positive for an up acceleration
δ_{ps}	-	Pitch stick deflection
ζ	-	Damping ratio
θ	-	Elevation angle in ψ θ ϕ Euler angle system
σ_w	-	RMS value for vertical turbulence, ft/sec
ϕ	-	Roll angle in ψ θ ϕ Euler angle system
ψ	-	Heading angle in ψ θ ϕ Euler angle system
ω	-	Frequency, rad/sec

SECTION I

INTRODUCTION AND SUMMARY

BACKGROUND

Significant improvements in aircraft stability and handling have been achieved with high-gain, wide-bandwidth flight control systems using the elevator as the control means. However, with conventional elevator control both lift and normal acceleration are controlled by pitching the aircraft. With the large pitching motions and lag in lift build-up, precise control of flight path remains a difficult control task in certain flight regimes. Also associated with conventional elevator control is the initial acceleration reversal due to elevator lift. Use of direct lift control (DLC) blended with elevator control provides a means of speeding up the acceleration response and reducing the pitch rate overshoot. A "direct lift" control is any device that produces lift without significant pitching moment.

Flight control systems that employ direct lift are those that modulate a second control surface, in addition to the elevator, to achieve longitudinal control. The second control surface may be wing flaps, symmetrically-operated ailerons or spoilers, or a canard surface. By using two control surfaces, a multitude of possibilities present themselves that allow improved flight path control that were unattainable with elevator alone.

References 1 and 2 report Navy-sponsored studies which included DLC as an aid to carrier landings. These studies used separate manual control of the DLC device; a spring-return-to-center thumbwheel on the grip commanded DLC position. In Reference 3, a high-passed stick position-to-spoilers signal was used. In each of these studies, DLC was found to be a distinct aid in the landing task.

The studies reported herein were conducted to determine the increased mission effectiveness that can be achieved with control systems using DLC. While approach and landing phases are considered, DLC is also evaluated for other mission phases such as weapon delivery, in-flight refueling, and terrain following. Major emphasis was on "blended" DLC systems, in which DLC is used to modify aircraft response to normal longitudinal control, rather than as a separate control.

Handling qualities criteria have been developed to a high degree for aircraft using elevator-type longitudinal control systems. These criteria do not, in general, give the required guidance to the design of flight control systems using direct lift. For this reason, a pilot-in-the-loop simulator study was required as a first step toward verifying the benefits attributable to direct lift control systems.

SIMULATION

This pilot-in-the-loop simulator study was conducted at the Air Force Flight Dynamics Laboratory during September 1967. Figure 1 shows the AFFDL moving base simulator used in these experiments. The simulator has limited motion capabilities in pitch, roll, and heave. Figure 2 shows the instruments used to display appropriate parameters from the analog computer simulation of the aircraft dynamics (attitude, rate of climb, altitude, airspeed, engine rpm, g' s, angle of attack, sideslip, and separate DLC position).

Aircraft dynamics were simulated using a six-degree-of-freedom equation set. Certain terms, unimportant to the study of direct lift control systems, were omitted from the equations of motion. The lateral-directional equations were modified so that a well-damped and coordinated yaw axis was evident, thus avoiding the necessity of a simulated yaw axis stability augmentation system. Figure 3 shows simplified block diagrams of the three direct lift control systems and the conventional control system simulated.

EXPERIMENTS

Seven pilots participated in the test program. Varied aircraft experience was sought to get as objective an evaluation as possible. Four tasks (general handling, in-flight refueling, terrain following, and approach and landing) were performed.

The control tasks, control systems, and turbulence conditions used in the study are shown in Table I. Two-hundred-twenty-nine runs were made to test various combinations of parameters. At least two pilots "flew" each control system/aircraft type/control task combination. Vertical turbulence was simulated in approximately half of the runs.

Table I. Experiment Variables

Pilot Subject	Control Task	Control System	Vertical Turbulence	Aircraft Type
Seven pilots	1) General handling tasks 2) Landing 3) Flight path tracking (terrain following task) 4) Altitude tracking (in-flight refueling task)	1) Conventional elevator 2) Blended, closed-loop direct lift control 3) Blended, open-loop direct lift control 4) Separate direct lift control	1) Mild 2) None	1) C-5A 2) F-104

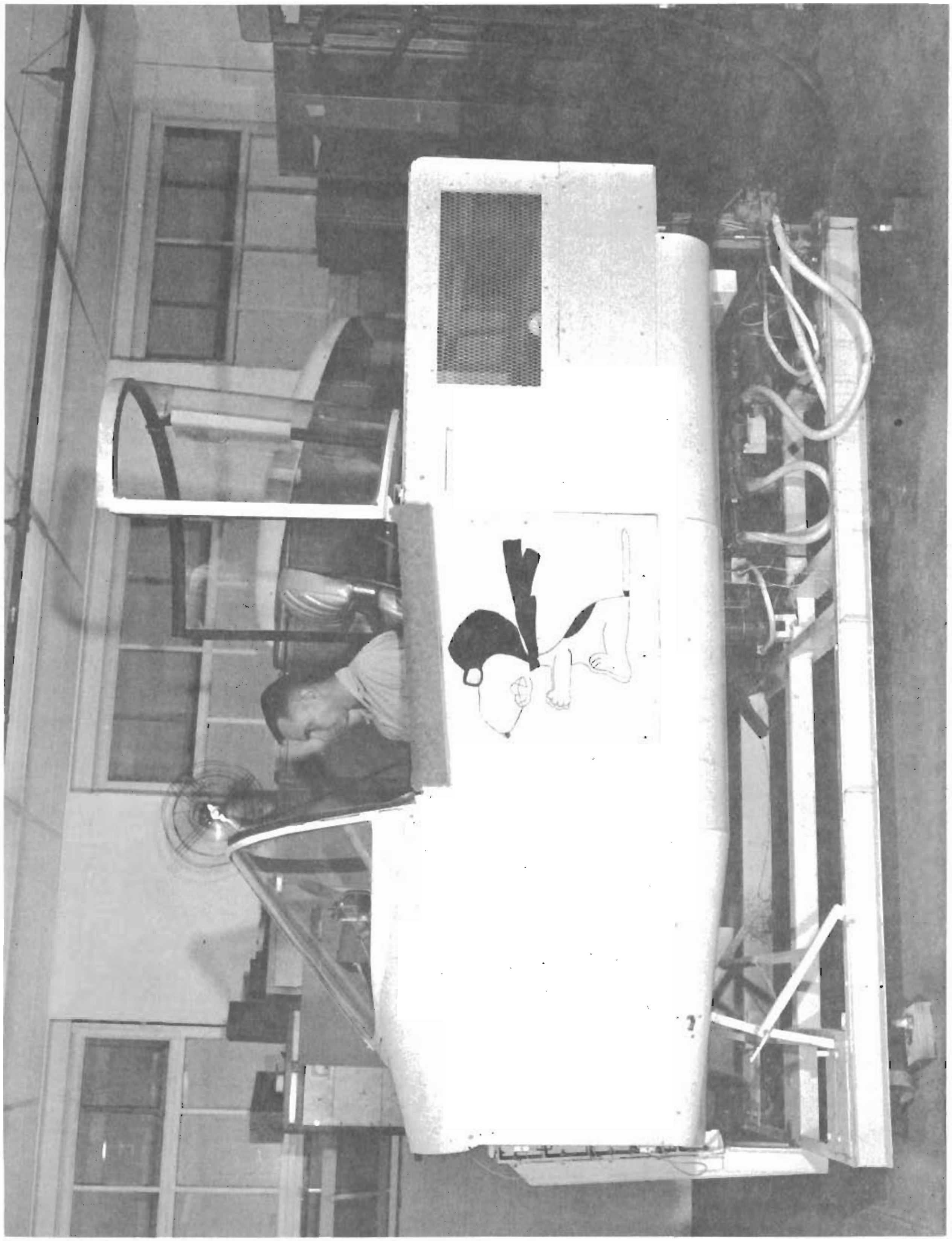
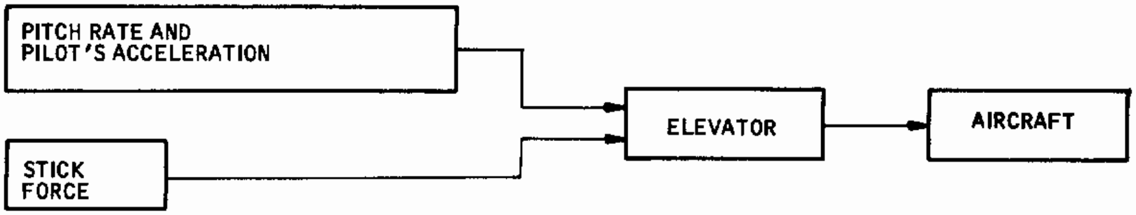
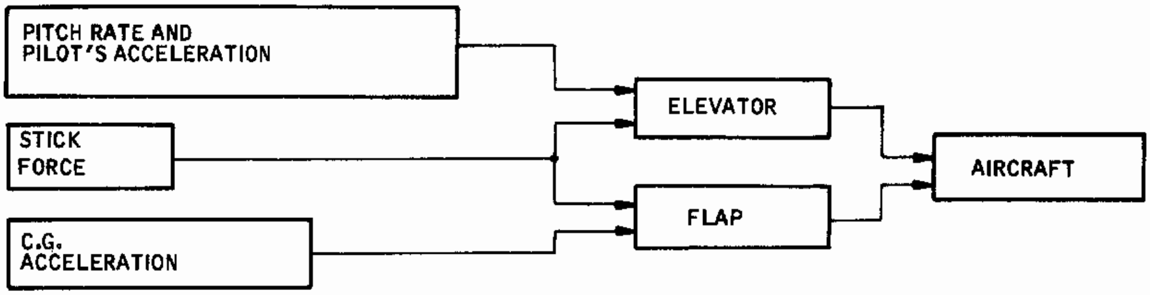


Figure 1. AFFDL Moving Base Simulator

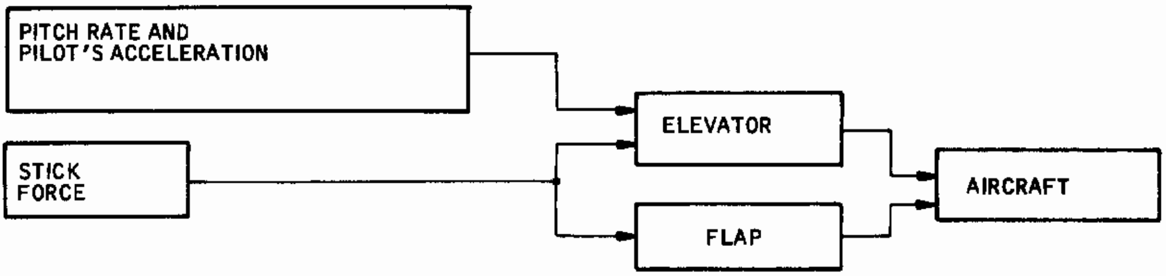
Figure 2. Moving Base Simulator Cockpit



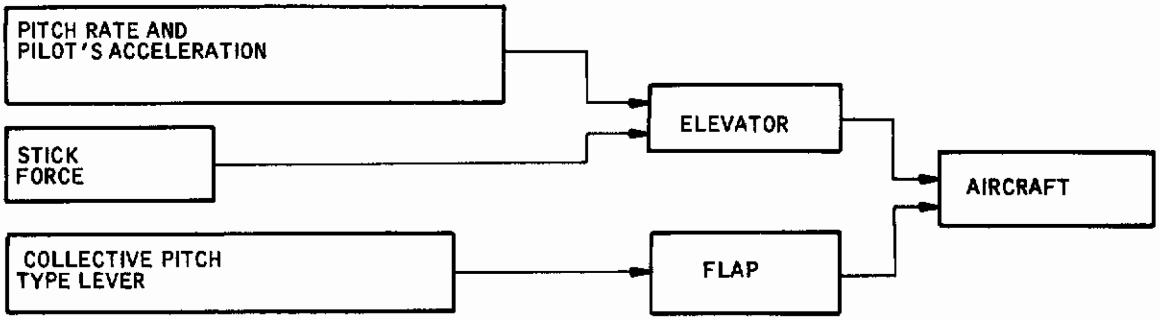
A. CONVENTIONAL ELEVATOR CONTROL



B. BLENDED CLOSED-LOOP DLC



C. BLENDED OPEN-LOOP DLC



D. SEPARATE DLC

Figure 3. Simplified Block Diagrams of Pitch Controllers Used

All tasks were performed solely by reference to the cockpit instruments and motion cues. In the general handling task, the horizontal and vertical bars on the attitude director indicator (ADI) were not used. The pilots were asked to make constant-altitude turns, 1000-foot altitude changes, and sharp pull-ups and descents. In all other tasks, the ADI horizontal bar was the primary pitch reference; it was to be nulled. While this permitted a realistic simulation of glide slope instrument control and flight path angle tracking (terrain following task), this single needle could not provide the visual cues available to a pilot in normal in-flight refueling and landing flare maneuvers. Thus, while controllers could be compared in these two latter tasks, performances were not as good as could be expected in actual flight.

RESULTS

Results were of three types: (1) pilot comments and opinions; (2) Cooper ratings; and (3) mean absolute values of significant parameters, approximating rms values (mean absolute values were not recorded in the general handling task).

Table II summarizes the pilot' s Cooper ratings. The pilots favored blended direct lift controls over conventional elevator controls for all tasks and both aircraft. Blended closed-loop DLC was favored over blended open-loop DLC because of the gust alleviation provided. The separate DLC system was felt to be considerably inferior to the blended DLC systems, but the mechanization provided was considered poor; the thumbwheel controller used in Navy-sponsored studies probably would have been easier to use and received a better rating.

Table II. Averaged Pitch Cooper Ratings

Task	Control System and Aircraft Type							
	Conventional Elevator		Closed-Loop Direct Lift		Open Loop Direct Lift		Separate Direct Lift	
	C-5A	F-104	C-5A	F-104	C-5A	F-104	C-5A	F-104
General evaluation	3.0	3.9	2.1	2.4	2.6	2.8	4.5	Not Tested
Landing - glideslope	3.2	3.5	2.1	2.6	2.6	3.2	2.5	3.2
Landing - flare	4.0	4.9	2.6	3.3	3.4	3.5	4.0	4.3
Terrain following	3.4	4.1	2.4	3.1	3.0	3.4	4.5	Not Tested
Tracking	3.0	---	2.1	---	2.8	---	5.0	---

NOTE: Separate direct lift control not run with turbulence.
All other data averages turbulence and not turbulence runs.

Measured performance data is presented in Tables III, IV, and V. Table III compares elevator and closed-loop DLC in approach and landing. With DLC, glide slope tracking error was reduced 20 percent in the C-5A and 40 percent in the F-104. Pitch workload was reduced about 30 percent in both aircraft. Touchdown sink rates were excessive with all controllers; thus, flare simulation was clearly inadequate. It is of interest to note that touchdown sink rates were significantly reduced with DLC.

Table III. Comparison of Mean of Mean Absolute Values of Conventional Elevator Control and Closed-Loop Direct Lift Control in Approach and Landing

Parameter	Aircraft and Control			
	C-5A		F-104	
	Conventional Elevator	Direct Lift	Conventional Elevator	Direct Lift
Glideslope tracking error, % of horizontal bar full scale	16.7	13.5	23.2	14.0
Pitch workload (pitch stick position, deg)	2.38	1.65	1.73	1.28
Flap position, deg	---	1.89	---	3.0
Flap rate, deg/sec	---	2.5	---	6.7
Touchdown sink rate, ft/sec	15.0	6.0	7.4	3.7

Table IV compares elevator and DLC in the C-5A in-flight refueling (altitude tracking) task. This task was not performed in the F-104. The horizontal bar which the pilots tracked was driven by altitude error plus five parts error rate; this proportion was set to provide stability in the conventional elevator-controlled mode. With DLC, tracking error was reduced 30 percent and workload 49 percent, but altitude error increased 15 percent. (Altitude error was not displayed to the pilot.) It seems likely that, had the error rate proportion for DLC tracking been reduced, or the bar gain increased, a workload comparable to that for elevator control would have been demanded and obtained, with a consequent reduction in altitude error when using DLC. However, optimized flight director signals are needed to completely evaluate DLC in the in-flight refueling task.

Table V compares elevator and DLC in flight path (altitude rate) tracking, referred to as the terrain following task. The horizonal bar was driven by altitude rate error. With DLC, altitude rate error was reduced 40 percent in the C-5A, but only 6 percent in the F-104. Workload results were similar; these showed a 22 percent reduction in the C-5A and a 9 percent reduction in the F-104. While the pilots preferred DLC for the F-104, they noted that with elevator control "it was a good airplane."

Table IV. Comparison of Mean of Mean Absolute Values of C-5A Conventional Elevator Control and Closed-Loop Direct Lift Control in Altitude Tracking (In-flight Refueling Task)

Parameter	Control System	
	Conventional Elevator	Direct Lift
Pitch tracking error, % of horizontal bar full scale	13.0	9.0
Pitch workload (pitch stick position, deg)	0.94	0.50
Altitude error, ft	20.0	23.0

Table V. Comparison of Mean of Mean Absolute Values of Conventional Elevator Control and Closed-Loop Direct Lift Control in Flight Path Tracking (Terrain Following Task)

Parameter	Aircraft and Control			
	C-5A		F-104	
	Conventional Elevator	Direct Lift	Conventional Elevator	Direct Lift
Altitude rate error, % of horizontal bar full scale	13.0	7.7	13.4	12.6
Pitch workload (pitch stick position, deg)	2.34	1.82	1.73	1.58

Tables III, IV, and V show that blended DLC performance was consistently better than that with conventional elevator except in the F-104 terrain following task, where performance was comparable.

Flap rms data, together with estimated hinge moment coefficients (based on Reference 4), was used to estimate power consumed by the C-5A and F-104 direct lift controllers. The approach condition was the most demanding for both aircraft, where, in rms turbulence of six feet per second, the closed-loop direct lift control systems required 61 horsepower in the C-5A and 3.0 horsepower in the F-104. These results are discussed in Appendix XII.

SECTION II

GENERAL CONSIDERATIONS OF DIRECT LIFT CONTROL

SIMPLIFIED EQUATIONS

The transfer functions of $\dot{\theta}$, $\dot{\alpha}$, and $a_{z_{c.g.}}$ for a control surface input can be written as:

$$\frac{\dot{\theta}}{\delta} = \frac{M_\delta \left[S \left(1 + \frac{Z_\delta}{U} \; \frac{M_{\dot{\alpha}}}{M_\delta} \right) + \left(-Z_w + \frac{Z_\delta}{U} \; \frac{M_\alpha}{M_\alpha} \right) \right]}{\Delta} \approx \frac{\left(S + \frac{1}{T_\theta} \right)}{\Delta} \qquad (1)$$

$$\frac{\dot{\alpha}}{\delta} = \frac{S \frac{Z_\delta}{U} \left[S + \left(-M_q + U \frac{M_\delta}{Z_\delta} \right) \right]}{\Delta} \qquad (2)$$

$$\frac{a_{z_{c.g.}}}{S} = \frac{Z_\delta \left[-S^2 + S \left(M_q + M_{\dot{\alpha}} \right) - Z_w \;\; U \frac{M_\delta}{Z_\delta} + M_\alpha \right]}{\Delta} \qquad (3)$$

These equations assume two degrees of freedom and apply to an elevator or DLC input. With elevator control the aircraft time constant, T_θ, is essentially determined by $-\frac{1}{Z_w}$. With DLC (flap), the terms resulting from control derivative Z_δ and M_δ combined with $M_{\dot{\alpha}}$ and M_α are not negligible. The numerator time constant in the $\frac{\dot{\alpha}}{\delta}$ transfer function is not determined primarily by $U \frac{M_\delta}{Z_\delta}$ since M_q and $U \frac{M_\delta}{Z_\delta}$ are of the same order of magnitude. The $-Z_w \;\; U \frac{M_\delta}{Z_\delta}$ term is no longer the dominant term in the $\frac{a_{z_{c.g.}}}{\delta}$ transfer function. Rather than factoring in to a positive and negative real root, an underdamped quadratic numerator normally results for a DLC (flap) input.

The use of one control surface results in a unique relationship between normal acceleration and pitch rate. For elevator control this relationship can be approximated by

$$\frac{\dot{\theta}}{a_{z_{c.g.}}} = \frac{(1 + T_a S)}{U} \qquad (4)$$

By using multiple control surfaces with different feedbacks to each surface this unique relationship no longer exists. It is possible to obtain a wide variation in transfer of $\dot{\theta}$ to $a_{z_{c.g.}}$. Figure 4 shows frequency responses of pitch rate and normal acceleration for various values of elevator-to-flap interconnect. It can be seen that, as the proportion of flap to elevator, k, increases, pitch rate overshoot decreases and normal acceleration quickens. With k = -2, the normal acceleration response is flat.

Reference 5 has noted a significant decrease in carrier landing accidents as the pitch transfer function numerator term, $1/T_\theta$ (termed L_α in Reference 7) increases. In this example, the transfer function for pitch rate and normal acceleration response to command are:

- No flap interconnect

$$\frac{\dot{\theta}}{\delta} = \frac{-0.41\ (S + 0.51)}{S^2 + 2(0.81)\ (0.85)\ S + 0.85^2} \qquad (5)$$

$$\frac{n_z}{\delta} = \frac{-6.0\ (S - 2.2)\ (S + 3.0)}{\Delta} \qquad (6)$$

- k = -2

$$\frac{\dot{\theta}}{\delta} = \frac{-0.41\ (S + 0.82)}{\Delta} \qquad (7)$$

$$\frac{n_z}{\delta} = \frac{78\ [S^2 + 2(0.48)(0.89)\ S + 0.89^2]}{\Delta} \qquad (8)$$

T_θ increased from 0.51 to 0.82. This alone would improve handling qualities, but normal acceleration response also improved.

The addition of flap feed from the stick has, in effect, provided an aircraft pitch control system which should be much preferred over pure elevator control. The blend uses the elevator for the moment control deriative, M_δ, and the flap to give a favorable (rather than opposing) lift

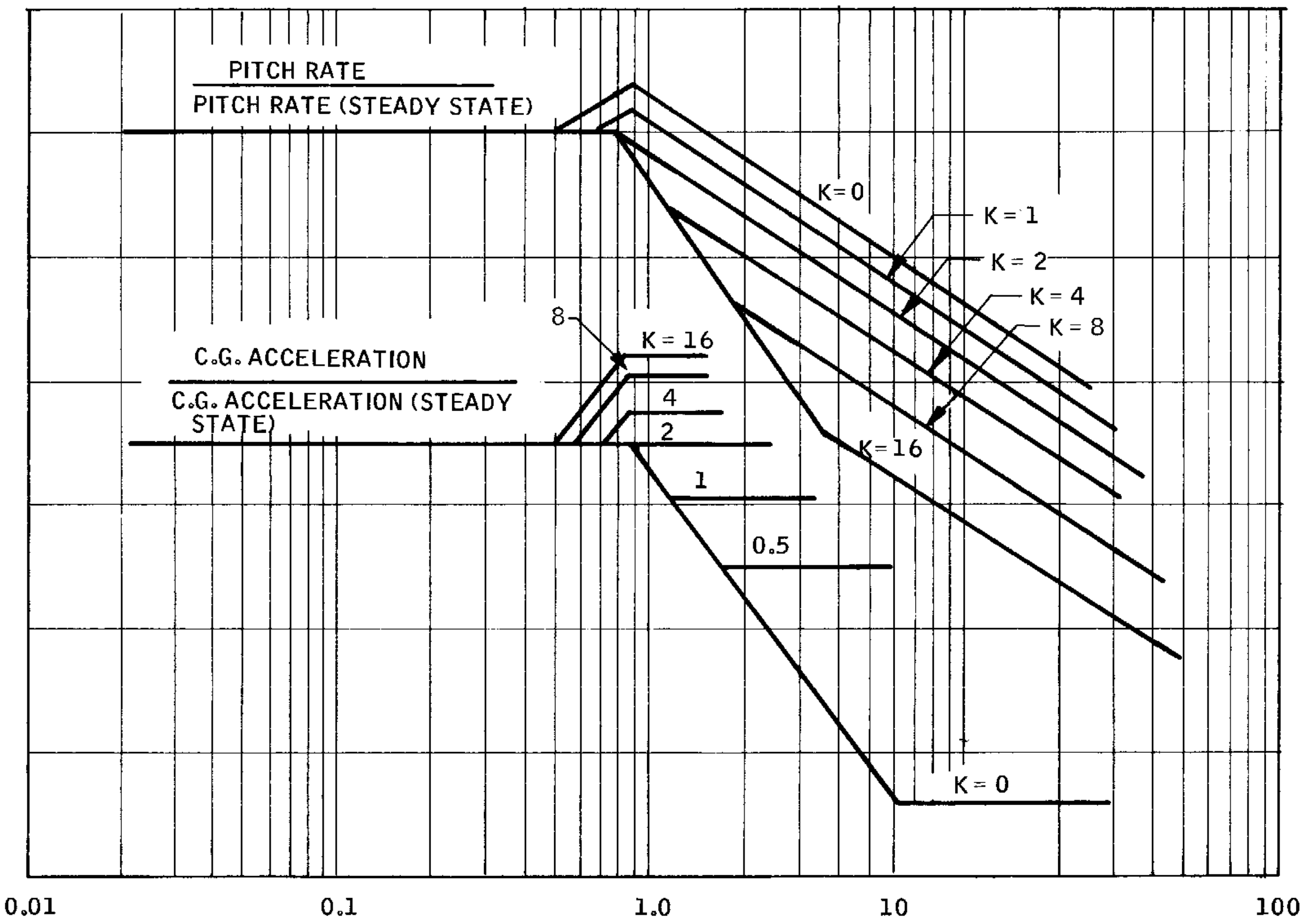


Figure 4. C-5A Approach/landing Response to Combined Elevator and Flaps: $\delta_F = K\delta_e$

derivative, Z_δ.

The use of DLC as an effective gust alleviation device is shown by the simple control below. Assume that δ_{F_c} (flap command) = $K_{\delta_F} n_z$. The normal acceleration response to an alpha gust, α_G, can then be written as:

$$\frac{n_z}{\alpha_G} = \left(\frac{Z_\delta}{1 + Z_{\delta_F} K_{\delta_F}} \right) \left\{ \frac{S(S - M_{\dot{\alpha}} - M_q)}{S^2 + S\left(\frac{-Z_w}{1+Z_{\delta_F} K_{\delta_F}} - M_{\dot{\alpha}} - M_q \right) + \left[-M_\alpha + \left(\frac{Z_w}{1+Z_{\delta_F} K_{\delta_F}} \right) \left(M_q + M_{\delta_F} K_{\delta_G} U \right) \right]} \right\} \quad (9)$$

The normal load for an alpha gust is effectively reduced by the factor:

$$\frac{1}{1 + Z_{\delta_F} K_{\delta_F}}$$

The use of a normal acceleration feedback also reduces the short-period damping and frequency.

HANDLING QUALITY CONSIDERATIONS

In Reference 6, various criteria for satisfactory handling quality characteristics resulting from previous handling quality research involving simulations and variable stability aircraft are reviewed and compared to determine significant areas of agreement and disagreement. Based on areas of agreement among the different studies, new handling quality criteria are proposed. The parameter L_α / ω_n versus ζ for the low n_{z_α} region and the parameter n_{z_α} versus ζ for the high n_{z_α} regime are used for the new handling quality criteria.

Reference 7 proposes a handling quality criteria in the time domain. This time response envelope is based on the C* response to elevator or stick force, where C* is computed from the following parameters:

$$C* = K_1 n_z + K_2 \dot{\theta} + K_3 \ddot{\theta} \quad (10)$$

Reference 8 conducted an investigation of pilot objection to pitch rate overshoot while making "g" commands. To maintain a constant "g" response for a stick command it is necessary for the pitch rate to change, since

$$\dot{\theta} = \frac{(1 + T_\alpha S)}{U} \quad a_{z_{c.g.}} \tag{11}$$

The major effort on longitudinal handling quality research is based on the availability of one control surface (elevator). With one control surface, fixed relationships exist between the various aircraft response parameters. With two control surfaces, it is possible to vary the relationship between the various aircraft parameters. For instance, normal acceleration response to a step stick command could be made to look like a short time constant first-order lag with little or no overshoot in pitch rate. In addition, angle of attack response is slow.

With the variable responses between aircraft parameters that resulted from blended DLC, it was not obvious how present and proposed longitudinal handling qualities requirements would apply to the control configurations that were evolved. Consequently, the need for a pilot-in-the-loop study was established.

Based on previous studies of longitudinal handling qualities and direct lift control, the following considerations were used in evolving the nominal blended DLC configuration:

- A fast $n_{z_{c.g.}}$ response to a stick force command was desired.
- The initial pitch rate overshoot for a stick force command should be reduced.
- The elevator should provide the steady-state g-per-stick force gradient.
- Gust alleviation should be provided by the DLC device.
- A different stick force-per-g gradient was desired at different aircraft velocities.

TRANSIENT AND STABILITY ANALYSIS OF MANUAL DIRECT LIFT CONTROLLER

Stability and transient data on DLC configurations used in the study are shown as an example of the performance that was obtained with the direct lift controllers. The data used is for the C-5A landing condition used in the study. The control configuration is described in detail in Section III and will not be repeated here. The following transfer functions were obtained for the blended closed-loop direct lift controller for a step force input:

$$\frac{n_{z_{c.g}}}{F_S} = \frac{-10.7 \begin{pmatrix} \omega_n = 0.32 \\ \zeta = 0.46 \end{pmatrix} (S + 3.58)\ (S - 15.5)}{\Delta = 33.9 \begin{pmatrix} \omega_n = 0.36 \\ \zeta = 0.71 \end{pmatrix} (S + 2.94)\ (S + 5.0)\ (S + 13)} \qquad (12)$$

$$\frac{C*}{F_S} = \frac{107 \begin{pmatrix} \omega_n = 0.36 \\ \zeta = 0.71 \end{pmatrix} (S + 2.67)\ (S + 5.47)}{\Delta} \qquad (13)$$

$$\frac{\dot{\theta}}{F_S} = \frac{41 \begin{pmatrix} \omega_n = 0.39 \\ \zeta = 0.91 \end{pmatrix} (S + 1.62)}{\Delta} \qquad (14)$$

Inspection of the $n_{z_{c.g.}}$ and C* transfer functions shows that in each case all denominator roots are nearly cancelled by numerator roots except one. The location of this root determines the transient $n_{z_{c.g.}}$ and C* response.

Figure 5 shows the transient response for this case for both an alpha gust and a stick force. The low-frequency second-order characteristic previously mentioned is evident in the response. With the nominal blended DLC configuration, the transient response for a step force input shows a faster acceleration response, reduced pitch rate overshoot, and slowing down of the angle of attack response. Transient data obtained for the case with C*-to-elevator control system and the nominal blended direct lift control system (C* to elevator and n_z to flap) is shown in Table VI.

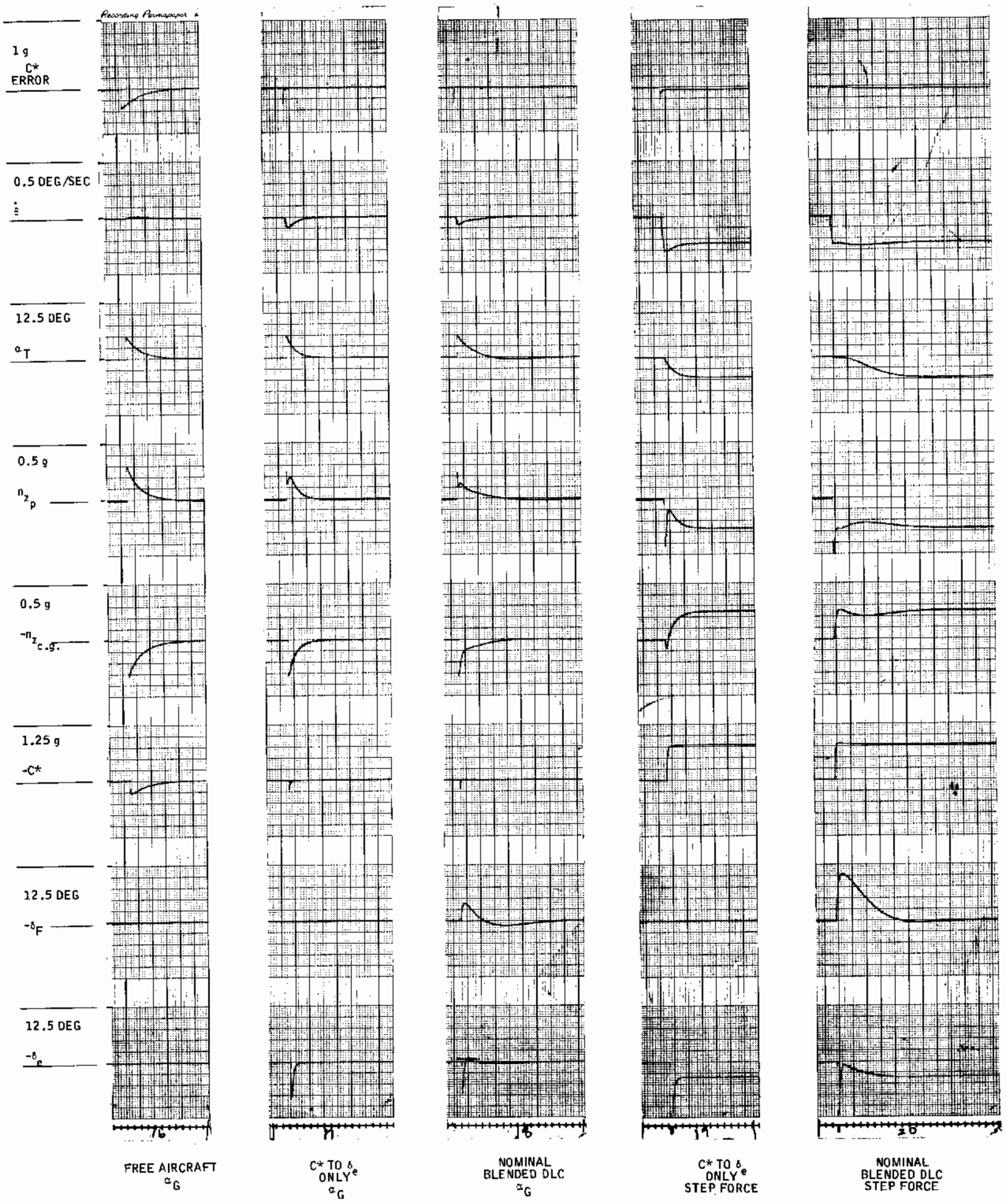


Figure 5. Alpha Gust and Stick Force Transient Response for C-5A Landing

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Inspection of the $n_{z_{c.g.}}$ and C* transfer functions shows that in each case all denominator roots are nearly cancelled by numerator roots except one. The location of this root determines the transient $n_{z_{c.g.}}$ and C* response.

Figure 5 shows the transient response for this case for both an alpha gust and a stick force. The low-frequency second-order characteristic previously mentioned is evident in the response. With the nominal blended DLC configuration, the transient response for a step force input shows a faster acceleration response, reduced pitch rate overshoot, and slowing down of the angle of attack response. Transient data obtained for the case with C*-to-elevator control system and the nominal blended direct lift control system (C* to elevator and n_z to flap) is shown in Table VI.

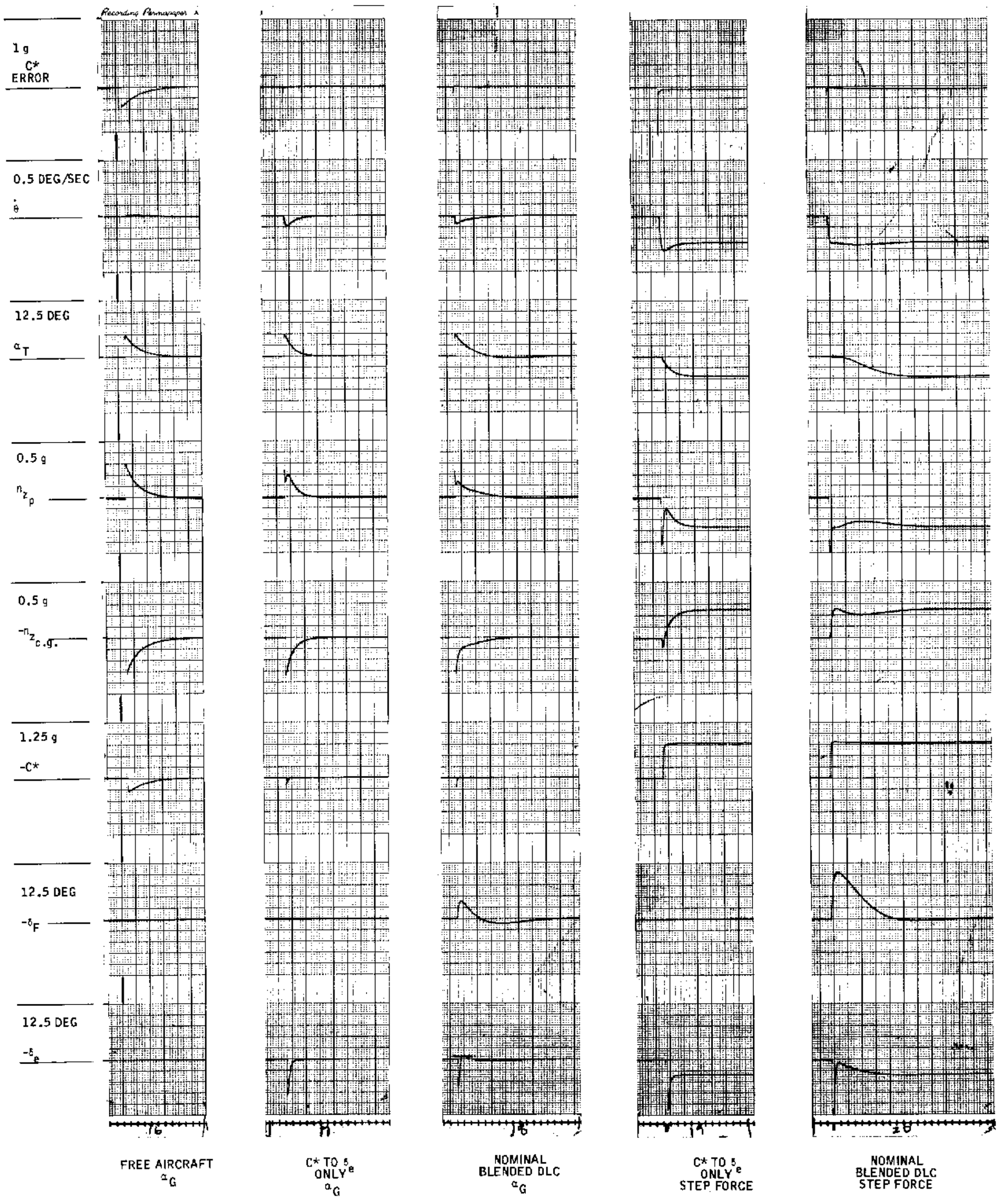


Figure 5. Alpha Gust and Stick Force Transient Response for C-5A Landing

Table VI. Transient Data

Parameter	Control System	
	C* to Elevator	Nominal Blended Direct Lift Control
n_z - overshoot, %	0	0
n_z - time to 90%, sec	3.6	0.6
C* - overshoot, %	0	4.0
C* - time to 90%, sec	0.3	0.2
$\dot{\theta}$ - overshoot, %	35.0	14.0

SECTION III

MANUAL CONTROL CONFIGURATION

GENERAL

To test the concepts discussed in Section II, it was necessary to develop longitudinal manual controllers that could be used for comparison purposes. Since lateral manual control was not a variable, it was desired to provide a lateral aircraft that flew reasonably well and that would not distract the pilot from the primary task of evaluating longitudinal control systems. Figure 6 is a block diagram showing the longitudinal control configurations evaluated. Figure 7 shows the lateral control system and thrust simulation. High-passed yaw rate was used to provide damping. Control configuration gains are shown in Table VII.

CONVENTIONAL ELEVATOR CONTROL

The conventional elevator control system used in the evaluation was a fly-by-wire C* system. It was conventional in the sense that C* (normal acceleration, pitch rate, and pitch acceleration) was summed with stick force and fed to the elevator. Gains were adjusted to give good gust damping and good speed of response with elevator control at each flight condition. Mechanization of the trim system was not considered. The control law can be written as:

$$\delta_{e_c} = K_{\delta_e} \left(\underbrace{n_{z_{c.g.}} + K_1 \dot{\theta} + K_2 \ddot{\theta}}_{C*} - \underbrace{F_S K_{C*_F}}_{C*\text{ command}} \right) \tag{15}$$

With this configuration it was desired to provide a relatively constant C* response to stick force input. The stick force gradient on the C-5A primary flight control system (PFCS) is about 20 pounds per g at the high-q condition (450 psf), based on aerodynamic data and PFCS characteristics. The electrical stick force gradient, K_{C*_F}, was determined in the following way:

$$C^*_{cmd} = F_S K_{C*_F} \tag{16}$$

$$= n_{z_{c.g.}} + \frac{400}{g} \dot{\theta} = n_{z_{c.g.}} \left(1 + \frac{400}{U} \right) \text{s.s.} \tag{17}$$

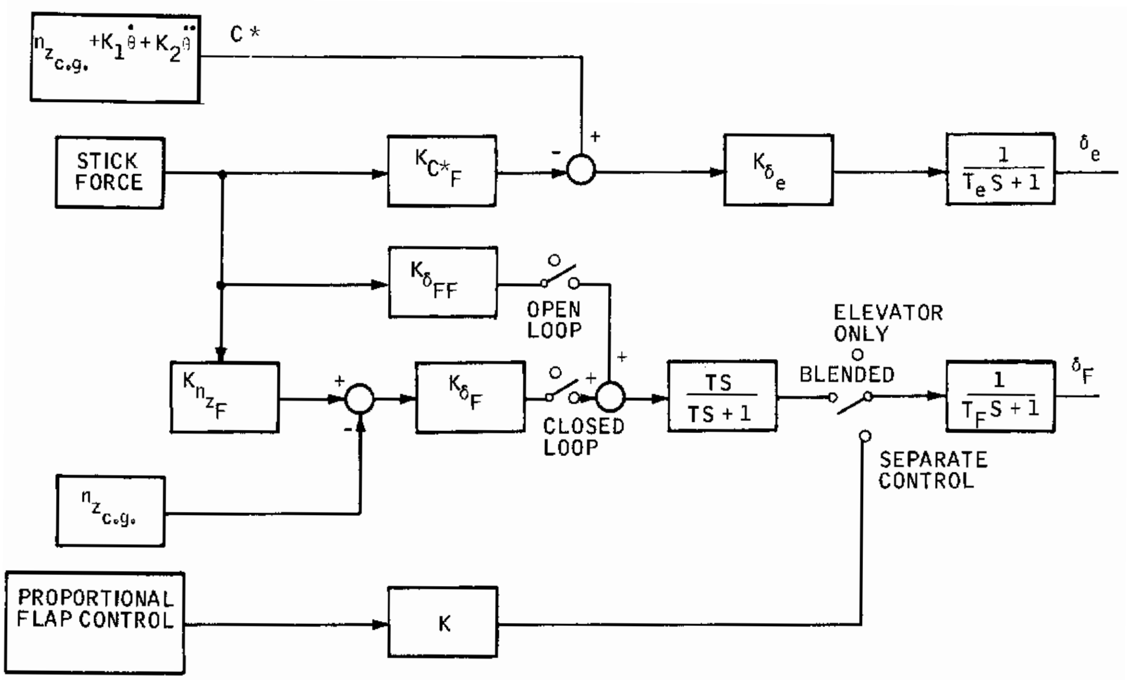


Figure 6. Longitudinal Control Configurations

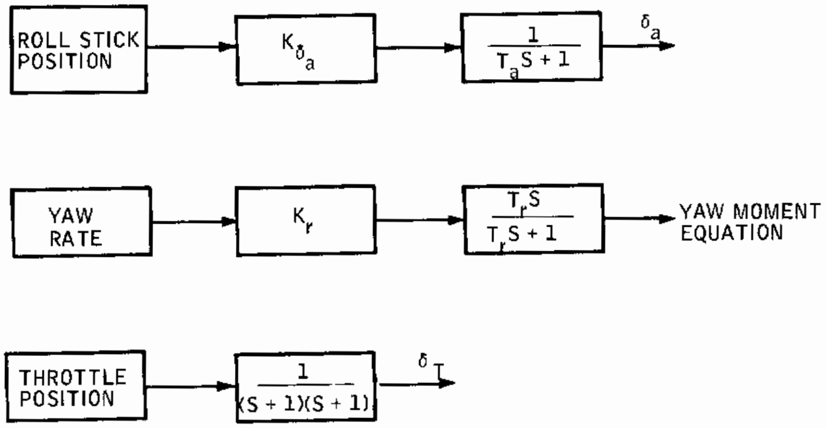


Figure 7. Lateral Control Configuration and Throttle

Table VII. Control Configuration Gains

Aircraft	Flight Condition		$K_{C^*_F}$	K_{δ_e}	$K_{n_{z_F}}$	K_{δ_F}	K_2	T_e	T_F	$\dot{\delta}_e$ Limit	K_{δ_a}	K_r	T_r	T_a	$\dot{\delta}_a$ Limit	$K_{\delta_{FF}}$
	Mach No.	Altitude (ft)	(g/lb)	(rad/g)	(g/lb)	(rad/g)	(g/rad/sec^2)	(sec)	(sec)	(deg/sec)	(deg/deg)	(deg/sec^2/deg/sec)	(sec)	(sec)	(deg/sec)	(deg/deg)
C-5A	0.17	sea level	0.08	2.0	0.06	1.0	2.9	0.167	1.0	±25	2.0	0.1	3.0	0.167	±25	1.8
	0.6	sea level	0.08	0.2	0.06	1.0	2.9	0.167	1.0	+25	2.0	0.1	3.0	0.167	±25	1.5
	0.6	20,000	0.08	0.4	0.06	1.0	2.9	0.167	1.0	±25	2.0	0.1	3.0	0.167	±25	2.5
F-104	0.9	5,000	0.28	0.04	0.2	0.5	0.62	0.02	0.2	±50	0.8	0.1	1.0	0.02	±50	4.2
	0.9	35,000	0.28	0.15	0.2	0.9	0.62	0.02	0.2	±50	2.0	0.2	1.0	0.02	±50	14.0
	0.3	sea level	0.28	0.2	0.2	1.0	0.62	0.02	0.2	±50	1.0	1.0	1.0	0.02	+50	5.6

* K adjusted for ±15 degrees δ_F full authority.

K_1 = 12.8 g's per radian per second.

T = 2.0 seconds.

δ_e limit = +25 degrees.

δ_F limit = ±15 degrees.

$\dot{\delta}_F$ limit = ±20 degrees per second.

$$K_{C*_F} = \frac{\left(1 + \frac{400}{U}\right)}{\left(F_S/n_{z_{c.g.}}\right)} \tag{18}$$

For this flight condition, U = 670 feet/second; therefore, K_{C*_F} = 0.08 g per pound.

Using this gradient for Mach 0.17 at sea level, $\frac{F_S}{n_{z_{c.g.}}}$ = 40 pounds per g. The same method was used to determine the desired electrical gradient for the F-104. Assuming a gradient of 0.2 g per pound is desired for a fighter aircraft high-speed flight condition, the electrical stick gradient (K_{C*_F}) is determined to be 0.28 g per pound:

$$K_{C*_F} = 0.2 \left(1 + \frac{400}{U}\right) \tag{19}$$

for U = 1000 feet per second. Solving for K_{C*_F} = 0.28 g per pound.

This elevator control was used in all DLC systems as well.

BLENDED CLOSED-LOOP DIRECT LIFT CONTROL

Blended closed-loop DLC was the area primarily investigated during the DLC study. This applies to outer-loop automatic control as well as for manual control. The blended closed-loop configuration has the same conventional elevator control. In addition, high-passed normal acceleration and stick force are summed and added to the flap. The steady-state g's for a force input are determined by the elevator loop, since the steady-state flap for a force command is zero because of the high-pass. The closed-loop flap gain is chosen to give an initial acceleration response approximately equal to the steady-state g's from the elevator. The flap control law for this configuration is:

$$\delta_{F_c} = K_{\delta_F} \left(- n_{z_{c.g.}} + F_S K_{n_{z_F}}\right) \left(\frac{TS}{1 + TS}\right) \tag{20}$$

BLENDED OPEN-LOOP DIRECT LIFT CONTROL

Some investigations were made to determine the benefits of blended open-loop DLC. This configuration uses high-passed stick position to spoiler or symmetric aileron. A configuration similar to this is included in this study to determine the benefits of closed-loop DLC over open-loop

DLC in the manual control problem. The open-loop configuration in this study used conventional elevator control and high-passed stick force. The gain on the stick force signal to flap was adjusted to give essentially the same normal acceleration transient response to a step force command as the blended closed-loop DLC. The flap control law for this configuration is:

$$\delta_{F_c} = F_S K_{\delta_{FF}} \left(\frac{TS}{1 + TS}\right) \tag{21}$$

SEPARATE DIRECT LIFT CONTROL

References 1 through 3 describe the results of investigations using a separate direct lift controller. In most cases, this separate direct lift controller was a spring-return thumbwheel located on the grip which commanded flap, spoiler, or symmetric aileron position. In this study an attempt was made to evaluate a system of this type by using a collective lever as the separate DLC device. This lever was not spring-returned to center. Conventional elevator control was used along with this.

SECTION IV
EXPERIMENTAL PROCEDURE

EXPERIMENT DESIGN

The purpose of the simulator program was to obtain information on the benefits that can be obtained by the use of direct lift control in manual piloted tasks. A moving base simulator was used in the experiment. Four pilot tasks were used to evaluate four basic control configurations: conventional elevator control; blended closed-loop direct lift control; blended open-loop direct lift control; and separate direct lift control (landing only). Two types of aircraft, a large transport (C-5A), and a fighter (F-104), were used in the evaluation. Flight conditions and associated tasks are listed in Table VIII.

Table VIII. Tasks and Flight Conditions Used in Moving Base Simulator Program

Control Task	Flight Condition			
	F-104 Aircraft		C-5A Aircraft	
	Mach No.	Altitude (ft)	Mach No.	Altitude (ft)
Landing	0.3	sea level	0.17	sea level
Tracking - in-flight refueling	---	---	0.6	20,000
Tracking - terrain following	0.9	5000	0.6	sea level
General handling qualities[a]	0.9	20,000	0.6	20,000

[a] Includes attitude, altitude stabilization, and maneuverability.

Each combination of task and control configuration was run with and without vertical turbulence, and each distinct run was repeated twice. Once an aircraft was set up for a particular task, the pilots evaluated all combinations of control configuration and turbulence in random order.

Seven pilots were used in the evaluations. Only one pilot completed all tasks except one for one aircraft. Each combination of task and aircraft was flown by two pilots. In two combinations, three pilots were used. Tasks and pilots are listed in Table IX.

Table IX. Pilot-Task Combinations Used in Moving Base Simulator Program

Control Task	Pilot Combination	
	F-104 Aircraft	C-5A Aircraft
Landing	1, 2, 7	3, 1
Tracking - in-flight refueling	---	2, 4
Tracking - terrain following	1, 2	5, 6
General handling qualities	2, 3	1, 2, 3

At the end of each distinct set of runs, numerical (Cooper) ratings, answers to pilot questionnaire, and pilot comments (written and oral) were obtained (Appendixes II, V, and VII). When a tracking task was being performed, quantitative data indicative of performance and workload was obtained (Appendix IX). Three-minute runs were made for the tracking task. The quantitative data was obtained as mean absolute values defined as:

$$MAV = \frac{\int_{t_1}^{t_2} | f(t) | \, dt}{(t_2 - t_1)} \qquad (22)$$

and as final values (at touchdown) for the landing task.

Mean absolute values were obtained for the following parameters:

- Horizontal bar
- Vertical bar
- Pitch pointer
- δ_{PS}, pitch stick position
- θ, pitch attitude
- ψ, heading
- ϕ, roll attitude
- δ_{RS}, roll stick position

- $n_{z_{c.g.}}$, normal acceleration at c. g.
- α_G, vertical turbulence
- δ_e, elevator position
- δ_F, flap position
- $\dot{\delta}_e$, elevator rate
- $\dot{\delta}_F$, flap rate
- q, pitch rate

Values of the following parameters at touchdown were obtained for the landing task:

- $\dot{h}$, altitude rate
- X_{GI}, distance to glide slope intercept
- Y_{CL}, distance to runway centerline
- θ, pitch attitude
- ϕ, roll attitude
- α, angle of attack

Twenty-four channels of continuous data were recorded during the experiment. This data was displayed continuously, primarily as a means of monitoring the simulation. The following parameters were recorded:

- Recorder 1

  Channel 1. θ, pitch attitude
  2. q, pitch rate
  3. h, altitude
  4. $\dot{h}$, altitude rate
  5. $-n_{z_{c.g.}}$, c. g. acceleration
  6. $-n_{z_p}$, pilot acceleration
  7. $-\delta_F$, flap position
  8. $-\delta_e$, elevator position

- Recorder 2

  Channel 1. α_T, angle of attack
  2. ψ, heading

3. p, roll rate
4. ϕ_a, roll attitude
5. δ_a, aileron position
6. δ_{PS}, pitch stick position
7. δ_{TH}, throttle position
8. U, airspeed

- Recorder 3

Channel 1. θ_{sim}, base pitch
2. ϕ_{sim}, base roll
3. Z_{sim}, base heave
4. α_G or h_w
5. Pitch pointer
6. Pitch bar
7. Lateral pointer
8. Lateral bar

PILOT INSTRUCTIONS

The pilots were briefed about the study program (Appendix V) and about what they would be flying and what they were to look for when flying the simulator. Each pilot was given ample time to make a number of practice runs before making production runs. The pilots were provided with task cards and a pilot comment checklist for each task.

SIMULATOR DESCRIPTION

A complete description of the simulation model, analog diagrams, potentiometer settings, and moving base simulator is contained in Appendixes I, III, IV, and XI. The moving base simulator and analog computers were located in adjoining buildings. Limited six-degree-of-freedom constant-coefficient equations of motion were used. Some simplifications were made in the lateral axis to eliminate the need for a complicated lateral augmentation system; i.e., $C_{n\delta_a}$ was assumed equal to zero. Ground effects were simulated for the C-5A landing.

The cockpit was a modified Link-T-37 trainer. The following visual information was presented to the pilot:

- Altitude
- Rate of climb

- Airspeed
- Sideslip
- Flare light
- ADI (roll, pitch, heading, horizontal and vertical command bars, raw glide slope, and localizer)
- Angle of attack
- Incremental g's
- Engine rpm
- Separate DLC position

Controls available to the pilot were pitch stick, roll stick, throttle, and collective lever. Rudder pedals were inoperative, and pitch and roll trim were disabled during the study in an attempt to overcome undesirable stick characteristics around center. Control stick force versus displacement characteristics were provided by a pneumatic system. These characteristics were adjusted to fit the aircraft and flight condition.

The motion system provided a limited three degrees of freedom, pitch, roll, and heave. The following parameters were used to drive the three degrees of freedom:

- Pitch: $\theta_p = f(\theta, q) = K_1 (\theta + K_2 q)$ (23)
- Roll: $\phi_p = f(\phi, p) = K_3 (\phi + K_4 p)$ (24)
- Heave: $Z_p = f(n_{z_p}) = K_5 (n_{z_p})$ (25)

The values of K_2 and K_4 were adjusted to give some degree of realistic feel to the pilot. The values of K_1, K_3, and K_5 were adjusted to keep the motion base within the mechanical limits. The maximum displacements, based on ±3 inches of actuator motion, and the geometry were:

- θ_p max. = ±7.5 degrees
- ϕ_p max. = 19 degrees
- Z_p max. = ±5 inches

Actual displacements were less than this because of electrical stops.

PILOT EXPERIENCE

Pilot experience is discussed in Appendix VI.

Based on pilot experience, opinions of the value of the moving base simulator varied. Pilot experience and opinions are discussed in detail in Appendixes VI and VII, respectively.

SECTION V
RESULTS

SUMMARY OF PILOT'S COMMENTS

Comments are presented for the following tasks:

- C-5A General Handling Qualities
- C-5A In-Flight Refueling
- C-5A Terrain Following
- F-104 General Handling Qualities
- F-104 Terrain Following
- F-104 Landing
- C-5A Landing

In all tasks, pilots experienced some difficulty due to stick characteristics which, because of play in the linkage, permitted some deflection without force. (In the C-5A general task, 0.3 g could be pulled without force, and in the F-104 general task, 0.4 g could be pulled without force.) This did not detract noticeably from the first three C-5A tasks. It became a more severe problem in Task 4, however, causing severe pilot-induced oscillations. Starting with Task 4 (run 119), the pitch trim was disabled and a dead zone was introduced to reduce the amount of electrical output in the regions of excessive stick play. This helped, but did not eliminate, the PIO.

C-5A General Handling Qualities Task

This task was performed by Pilots 2 and 3 on 13 September 1967. Pilot-induced oscillations were present in all trials (due to stick play) with blended DLC tending to make the oscillations easier to control. Comparing the various DLCs with elevator:

(1) Separate DLC was no help at all, although it should be noted that neither pilot spent much time practicing (perhaps 20 minutes) prior to evaluation. Both felt that a better mechanization might make it more useful. Pilot 3 suggested the flap handle be spring-loaded to neutral with a reasonable bleedoff time when released. Pilot 2 thought a separate DLC like the normal trim control would be better than the "collective pitch-like" handle.

(2) Both open- and closed-loop DLC made the task easier. The 1000-foot altitude change maneuver was easier; with elevator control Pilot 2 found there was a tendency to overshoot the given altitude. Pilot 3 thought that altitude changes were

quicker with closed-loop DLC, that the 4000-fpm rate of climb was easier to establish, and that he was able to level off "quite well." (With open-loop DLC, Pilot 3 had some trouble maintaining rate of climb; he attributed this to PIO.) In turbulence, the load alleviation of closed-loop DLC over open-loop DLC was noted. In turns, both DLCs were preferred over elevator control. Altitude was easier to maintain, and turn entries and roll outs were smoother.

C-5A In-flight Refueling Task

This task was performed by Pilots 2 (on 13 September) and 4 (14 September). Pilot 2's experience was predominantly in the F-84, while Pilot 4's experience was in the KC-97 and KC-135. Pilot 2 was more demanding of the aircraft, while Pilot 4 exercised the same caution in maneuvering the C-5A as he would in the KC-135. The KC-135 apparently must be "herded along" rather than "flown" to avoid exciting fuselage bending. Since piloting techniques differed so, the comments will be discussed separately:

(1) With closed-loop DLC, Pilot 2 felt the task was relatively easy, the turbulence condition requiring a little more concentration. The task was more difficult to perform with open-loop DLC; the turbulence condition required more concentration and more work to maintain the stabilized condition. With elevator control and no turbulence, the task was performed easily, but turbulence made it difficult. Separate DLC was of no value. Commenting on the four controllers as a group, Pilot 2 rated them: (1) closed-loop DLC; (2) open-loop DLC; (3) elevator; (4) separate DLC.

(2) Pilot 4 found no significant differences between closed-loop DLC, open-loop DLC, and elevator control. Separate DLC was, at times, a handicap.

C-5A Terrain Following Task

This task was performed by Pilots 5 and 6 on 16 September 1967.

With no turbulence present, Pilot 5 said the task was easy with all controllers (elevator, closed-loop DLC, and open-loop DLC) except separate DLC. He rated closed-loop DLC best, open-loop DLC second, and elevator third, but found it more difficult (than when turbulence was present) to distinguish between the three. Pilot 6 said the task with closed-loop DLC was easier than with the other configurations. Separate DLC was of no value at all for this task. He rated closed-loop DLC first, open-loop DLC second, and elevator control third.

With turbulence present, Pilot 5 said closed-loop DLC was by far the easiest to fly, and the response of the pitch steering bar relative to the dot on the attitude indicator was easier to control. The next easiest was open-loop DLC; it seemed much like closed-loop DLC. With elevator control there was considerable tendency to have the dot overshoot the pitch steering bar, in other words, to overcontrol. Pilot 6 definitely preferred closed-loop DLC, the accelerometer feedback making a significant difference. It was significantly easier to fly with DLC than with elevator. In maintaining heading, Pilot 6 noticed little difference between any of the three different (pitch control) modes.

F-104 General Handling Qualities Task

This task was performed by Pilots 2 and 3 on 18 September 1967.

With no turbulence present, Pilot 2 felt the task was more difficult with elevator control. He could detect little difference between open- and closed-loop DLC modes. With elevator control, he had PIO tendency on attitude control; this was significantly improved with the DLC controllers. Pilot 3 thought airspeed, heading, rate of climb, and rate of descent were easier to control with closed-loop DLC. The task also was easier because of his ability to maintain the limits he was trying to set. The throttle/airspeed response seemed slow for an F-104. In open-loop DLC mode, heading tended to be more critical than in closed-loop DLC or elevator control.

With turbulence present, Pilot 2 reported attitude control required more work with elevator control (than open-loop DLC in prior run). Vertical acceleration response was not as satisfactory during recovery from pull-ups (as with open-loop DLC in prior run). In closed-loop DLC mode, vertical acceleration response was very satisfactory as compared with elevator control. In turns, altitude was easier to control with DLC. There was little difference between open- and closed-loop DLC. Pilot 3 said the aircraft handled better with closed-loop than open-loop DLC, and was very prone to PIO with elevator control.

Pilot 3 found 70-degree bank angles and altitudes (particularly right banks) hard to hold with all controllers. This is believed to be due to an error in the attitude-direction indicator; 70 degrees indicated was actually a higher bank angle. Earlier tests had shown it to read less than actual bank to the right, and more than actual bank to the left. Left 70-degree banks should therefore have been considerably easier to hold than right 70-degree banks.

F-104 Terrain Following Task

This task was performed by Pilots 1 and 2 on 19 September 1967.

With no turbulence present, Pilot 1 found little difference between open- and closed-loop DLC. He rated open-loop DLC a 3 and closed-loop DLC a 2.5. With elevator control he found a bit more bobble trying to zero on the horizontal bar (than with either DLC), but there was no significant change. Pilot 1 felt that the task, while acceptable for comparing controllers, was quite difficult and also unrealistic, since it definitely would be uncomfortable going up to an increment of two negative g's. Pilot 2 said the task ranged from easy to difficult with closed-loop DLC, and moderately difficult to difficult with elevator and open-loop DLC. With elevator control, more attention was needed to maintain airspeed (than with closed-loop DLC in a prior run). Airspeed was still difficult to hold with open-loop DLC, but held within ±10 knots.

When comparing the three controllers with turbulence present, Pilot 2 noted a definite decrease in workload and PIO for the DLCs as compared with elevator control. He had difficulty distinguishing between open- and closed-loop DLCs. Stick forces appeared heavier with elevator control. Pilot 1 found turbulence to cause no significant deterioration in performance for any of the controllers. He considered closed-loop DLC best, closely followed by open-loop DLC. Elevator control seemed slightly more sluggish, but still offered good control of the aircraft. He had somewhat more difficulty settling on zero pitch bar error with elevator control. He thought the task to be more like formation flying, where the pilot attempts to follow erratic movements of the other airplane, than what he imagined terrain following would be. He considered the task adequate, however, to demonstrate controller differences.

F-104 Landing Task

This task was performed by Pilots 1, 2, and 7 on 21 September 1967. Pilot 1 made four runs on 20 September, but they were repeated on 21 September so are not summarized here.

With no turbulence present, Pilot 1 liked closed-loop DLC the best, with open-loop DLC a close second. He thought that separate DLC might be as good if pilots were better trained in its use. The elevator was the least effective control of all because of the lack of response. These opinions applied to glide slope and flare. Pilot 2 found the flare maneuver difficult with elevator control, and moderate to normal with either DLC. The presentation of the flare maneuver was adequate for comparative evaluation, but otherwise inadequate. There was less PIO tendency with the blended DLCs. He preferred elevator to separate DLC. Pilot 7 found glide slope and flare easier to execute with blended DLC than with elevator, and that sink rate was harder to control with elevator. The task, however, was not difficult even with elevator control. Pilot 7 did not fly separate DLC.

With turbulence present, Pilot 1 thought the task definitely more difficult, for both glide slope and flare maneuvers, with all controllers. There was little difference between open- and closed-loop DLC, but with elevator, the turbulence appeared more severe; the task became more difficult, particularly in the flare maneuver. Pilot 2 noticed little difference between open- and closed-loop DLC, but the control response was significantly better; instrument readings were easier to maintain using DLC than with elevator control. With DLC there was less PIO, and transition from glide to flare was more comfortable. Pilot 7 reported closed-loop DLC the easiest to control, with little indication of turbulence.

With open-loop DLC and elevator, it was relatively difficult to maintain glide slope and rate of descent. Airspeed was easily maintained with closed-loop DLC, more difficult with elevator, but still held easily within limits.

C-5A Landing Task

This task was performed by Pilots 3 and 1 on 22 September 1967.

With no turbulence, Pilot 3 found separate DLC to be completely ineffective; it caused PIO. However, it might be of use to bleed out a fast sink rate. With elevator there was a slight PIO tendency with airspeed easy to maintain, and sink rate held rather constant. With open-loop DLC, there was some PIO tendency. Closed-loop DLC proved far superior, and the task a lot easier.

Pilot 1 thought the airplane was extremely sluggish, slow on response, but stable with elevator control. He found it difficult in flare to know if sink rate was being arrested. Airspeed was difficult to maintain. Open-loop DLC was quite an improvement; the quick response enabled him to keep the errors small. He thought closed-loop DLC was the best he'd run with no problems arising. Comparing the four controllers, closed-loop DLC was by far superior, open-loop DLC nearly as good, and elevator not too bad except for flare. Separate DLC was the poorest, primarily because airspeed had to be controlled with throttle at the same time.

With turbulence included, Pilot 3 found closed-loop DLC a distinct advantage and probably easier to fly than elevator without turbulence. PIO was very prevalent with elevator control; there was a bit of it with open-loop DLC, and with closed-loop control a little the last 100 feet or so. Airspeed was not difficult to control in any mode except elevator. In open-loop DLC and elevator modes, Pilot 1 found that turbulence mainly made airspeed control difficult. Airspeed was easier to control in closed-loop DLC. Comparing the three, Pilot 3 thought closed-loop DLC gave far better results than elevator control. Open-loop DLC was an improvement over elevator control, but there was some difficulty with airspeed. In closed-loop DLC, turbulence had less effect.

MEAN PILOT NUMERICAL DATA

With each set of runs the pilots were asked to give a numerical Cooper rating and a numerical rating on the workload and on how well they did. These three numerical ratings are defined in Appendix V. The actual data from the pilot questionnaire is given in Appendix VIII.

Since equal intervals of workload, performance, or pilot rating are not represented by equal number interval, the usual techniques (mean, variance, standard deviation) cannot be applied to these subjective numerical ratings rigorously. However, if numerical ratings are close (this is the case here), some significance can be obtained by taking the mean of the subjective numerical ratings.

Figures 8 through 14 summarize the mean Cooper rating, the mean workload rating, and the mean performance rating for each pilot task and each control configuration over all subjects and combinations of turbulence. The range of Cooper ratings is also given. The Cooper ratings are for longitudinal control only; workload and performance ratings are overall ratings.

In all tasks, blended closed-loop DLC was rated better than any of the other control configurations tried. Blended closed-loop DLC was rated approximately one Cooper rating better than conventional elevator control and approximately one-half Cooper rating better than blended open-loop DLC for all tasks. Separate DLC control was rated about the same as conventional elevator control for the landing task. The numerical workload and performance ratings remained essentially the same for each task for all control configurations tried. The use of separate DLC for the C-5A terrain following task tended to increase the workload and decrease performance. This was probably due to the location of the control used for the separate DLC.

It was of interest to know if the pilots agreed in the ranking of the four control configurations evaluated. The ranking method applied was Spearman's Rank Correlation Coefficient. This coefficient is defined by

$$R = 1 - \frac{6 \Sigma d^2}{n^3 - n}$$

where

d = Rank difference

n = Number of control configurations evaluated

When rankings are identical, the rank correlation coefficient has the value of one; when one ranking is exactly the reverse of the other, the rank correlation coefficient is equal to minus one. A correlation coefficient of zero indicates a random ranking. Table X lists the correlation coefficients that were computed. The table shows that the pilots agreed

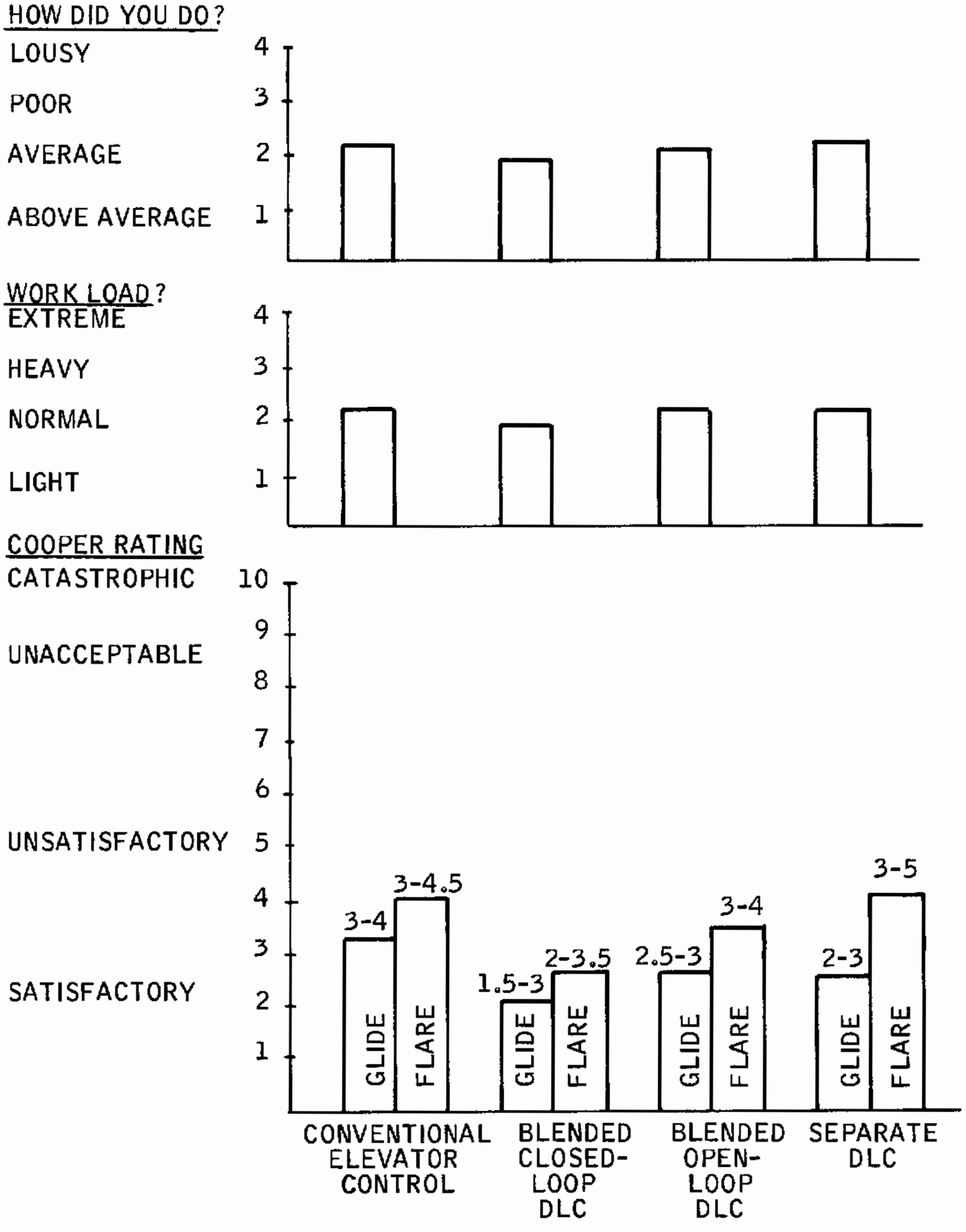


Figure 8. Mean Pilot Longitudinal Numerical Evaluation -- Glide Slope, Flare -- C-5A

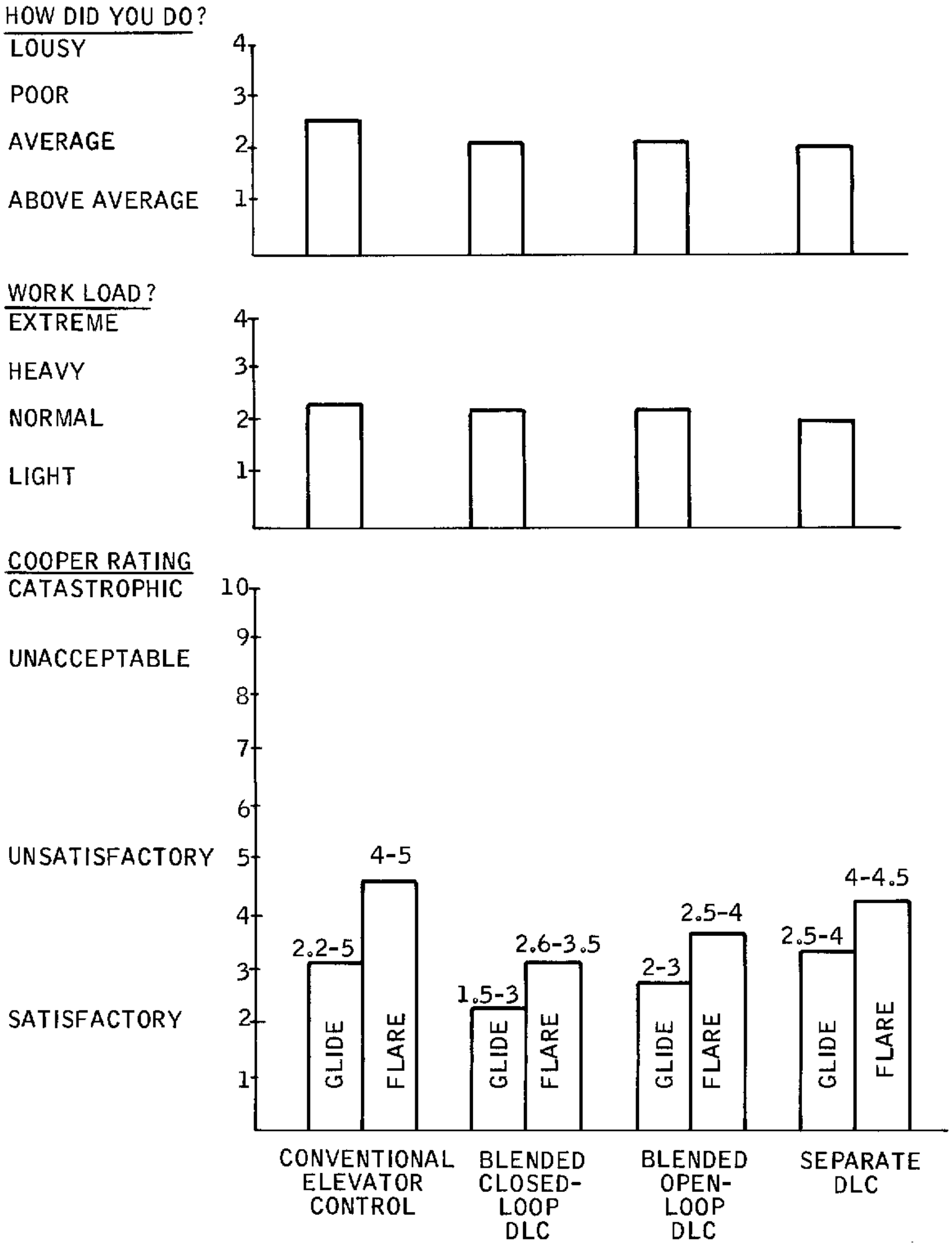


Figure 9. Mean Pilot Longitudinal Numerical Evaluation -- Glide Slope, Flare -- F104

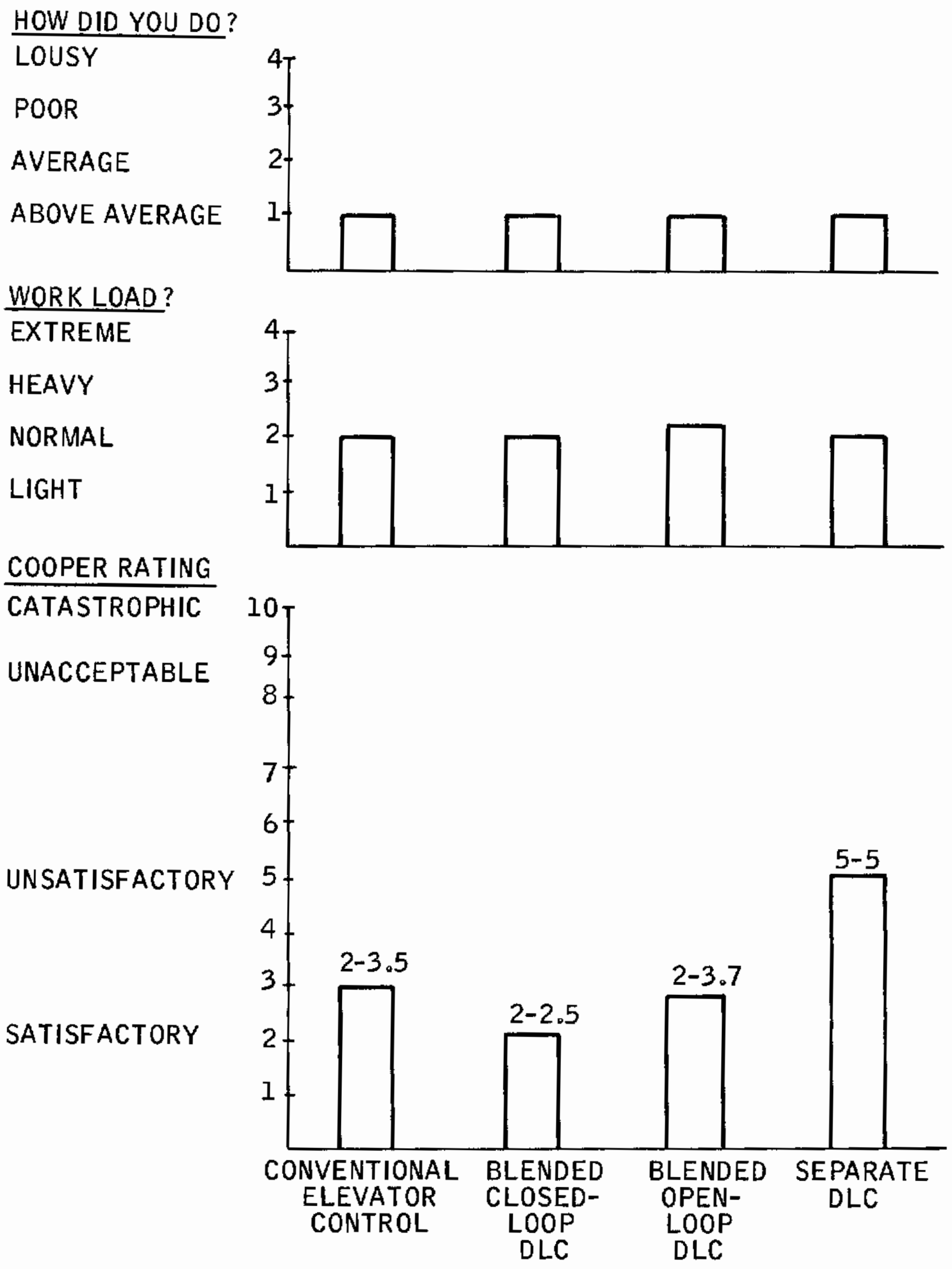


Figure 10. Mean Pilot Longitudinal Numerical Evaluation -- In-flight Refueling -- C-5A

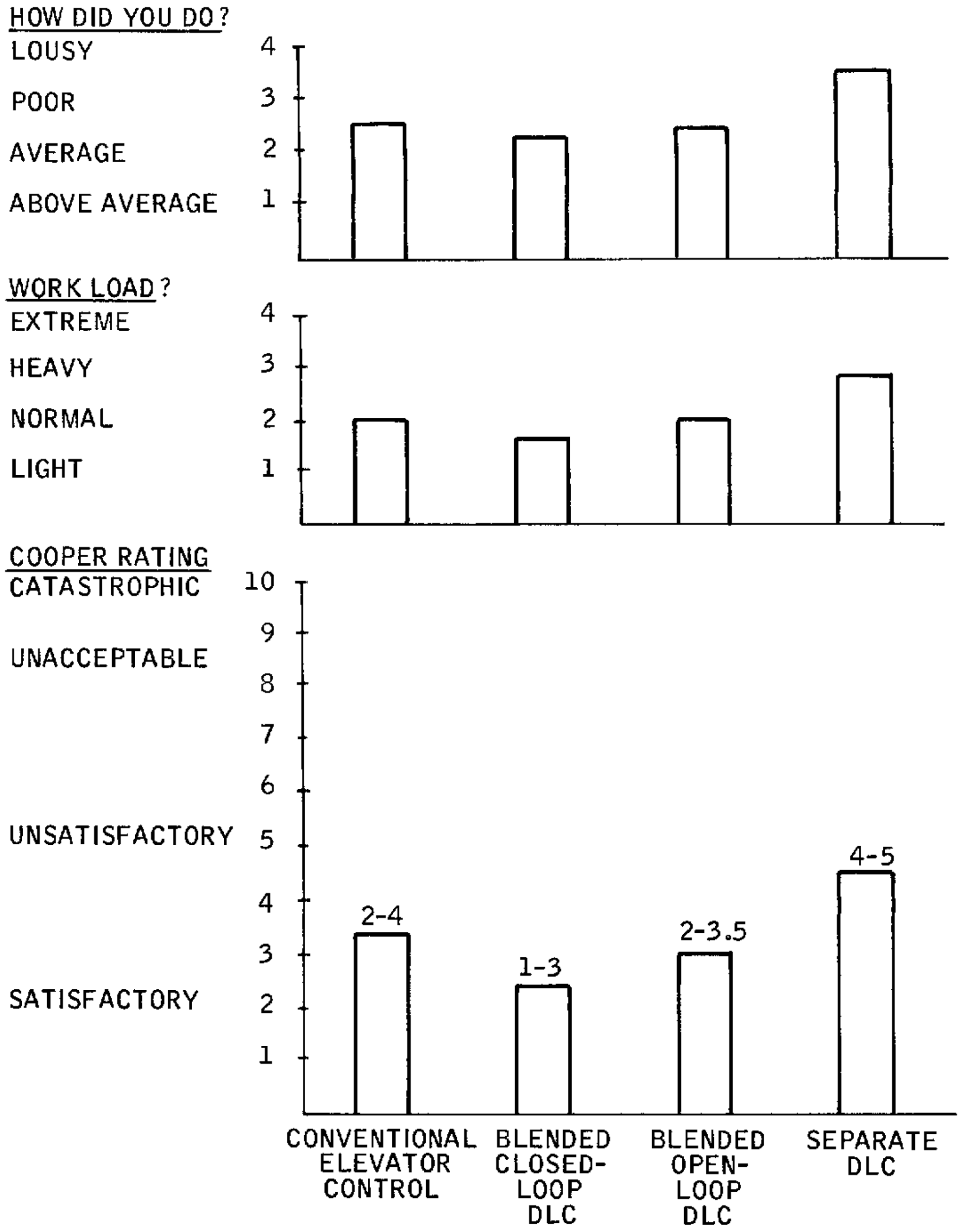


Figure 11. Mean Pilot Numerical Evaluation -- Terrain Following -- C-5A

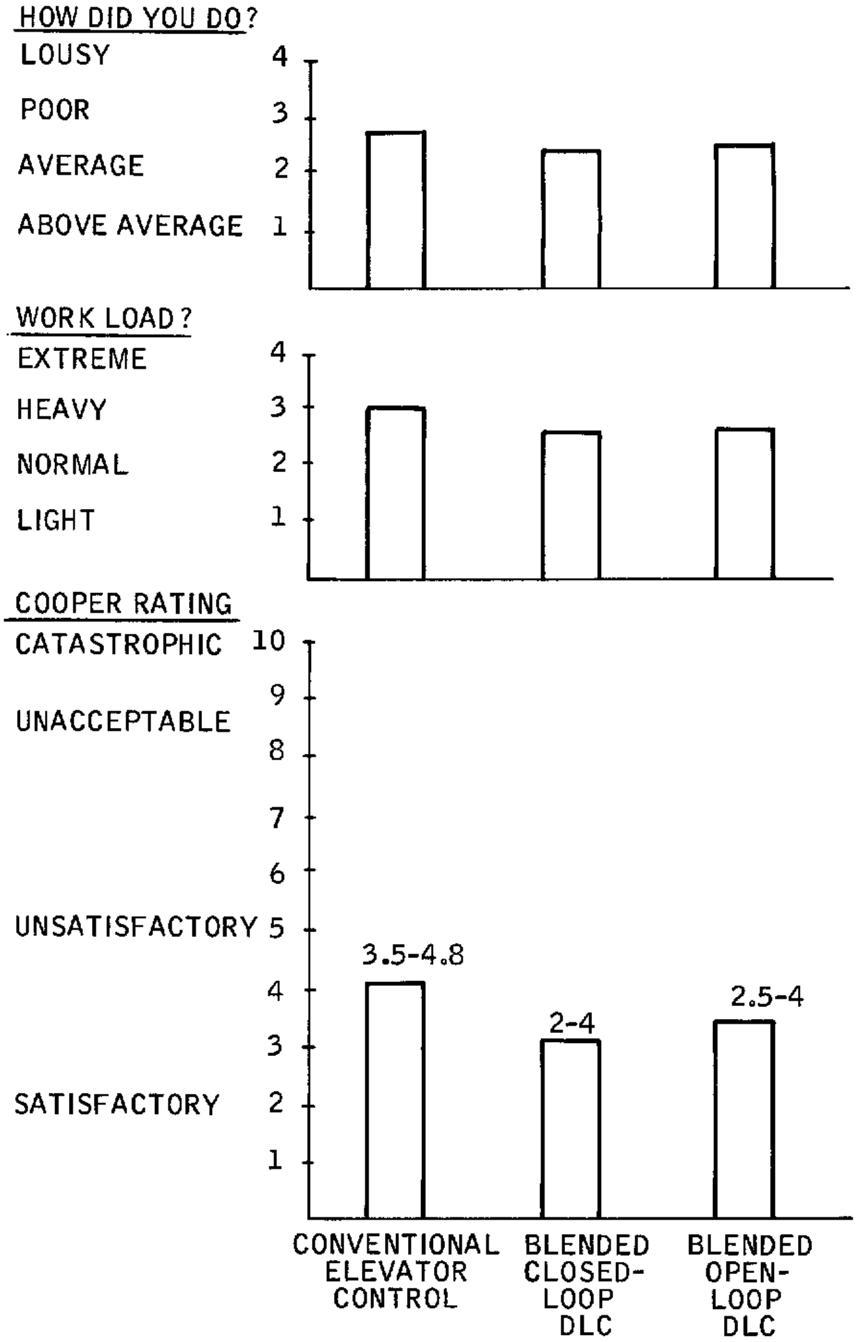


Figure 12. Mean Pilot Numerical Evaluation -- Terrain Following -- F-104

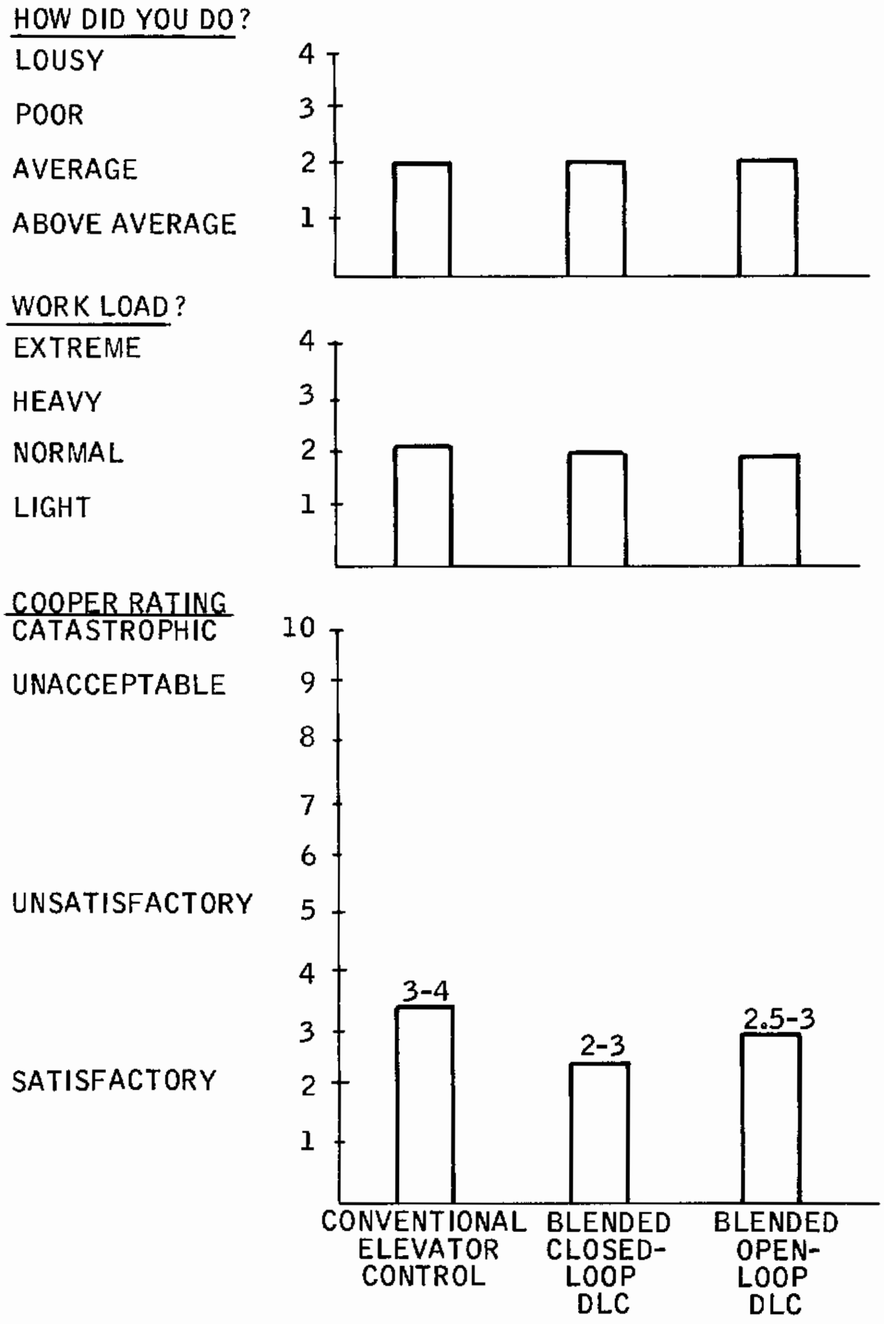


Figure 13. Mean Pilot Numerical Evaluation -- General -- F-104

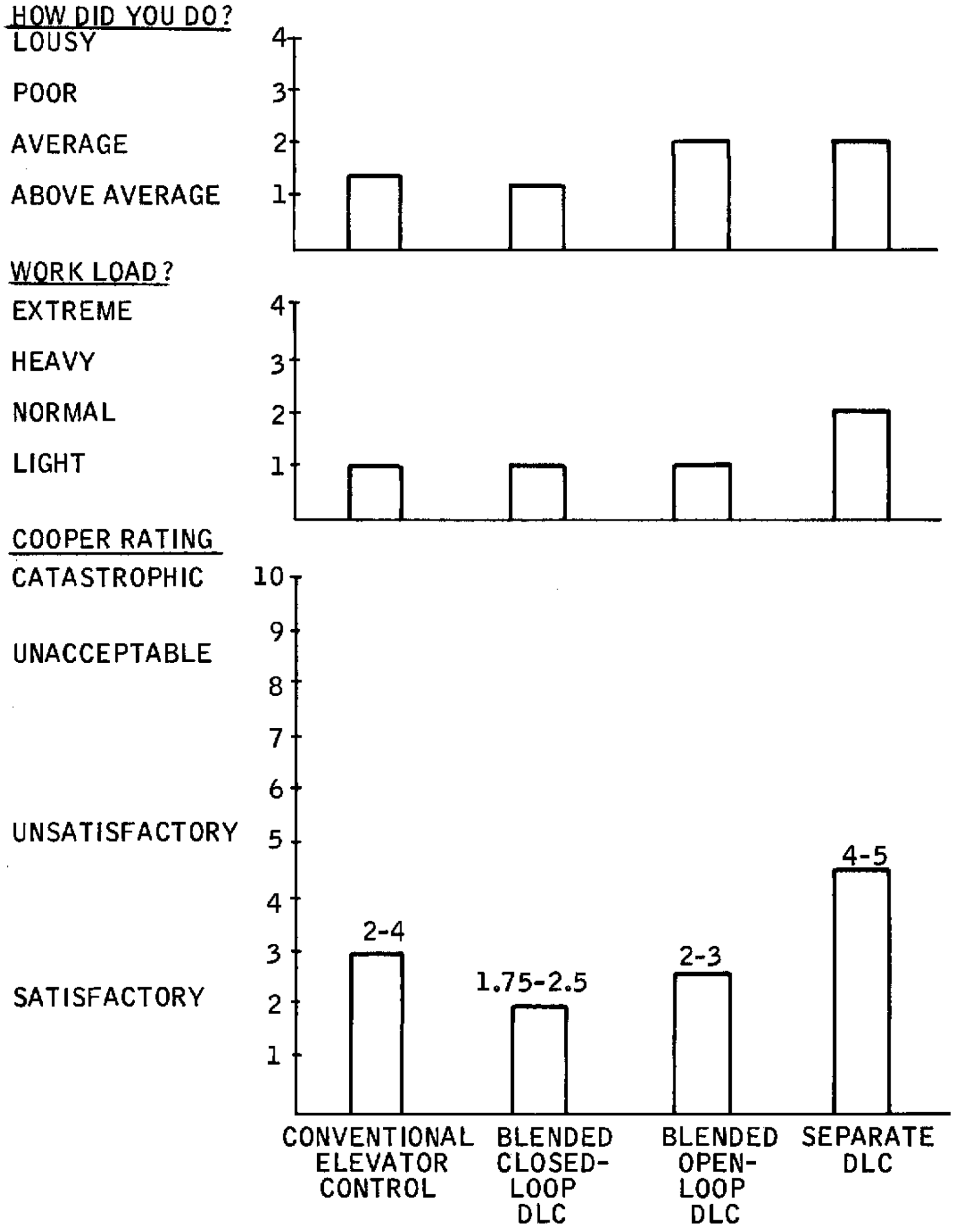


Figure 14. Mean Pilot Numerical Evaluation -- General -- C-5A

Table X. Correlation Coefficients

Control Task	F-104 Aircraft		C-5A Aircraft	
	Turbulence In	Turbulence Out	Turbulence In	Turbulence Out
Glide slope	1. 0	0. 62	1. 0	0. 55
Flare	0. 4	0. 62	0. 9	1. 0
Terrain following	0. 87	0. 85	0. 85	0. 13
In-flight refueling	---	---	0. 65	0. 62
General handling qualities	0. 87	0. 85	1. 0	0. 87

quite well in the ranking of the various control configurations except in one task -- C-5A terrain following without turbulence.

SUMMARY OF QUANTITATIVE DATA

Appendix IX contains a listing of the continuous mean absolute value data and of the final values at touchdown for the landing case.

C-5A In-flight Refueling Task

Figure 15 summarizes some of the more pertinent parameters for the refueling task (horizontal command bar, pitch stick, pitch attitude, and heading). The mean of the mean absolute values is given for the above parameters for each control configuration, with and without turbulence, over both trials for both pilots. Without turbulence there was little difference in the pilots' ability to zero the command bar with any configuration except separate DLC. However, closed-loop DLC showed a significant improvement in turbulence over both conventional elevator control and open-loop DLC. Pitch stick work was significantly less with closed-loop DLC. This was especially true when comparing conventional elevator with closed-loop DLC in turbulence. Use of separate DLC resulted in the most work in smooth air. Mean absolute values of pitch attitude and heading are essentially the same for all control configurations except separate DLC with and without turbulence.

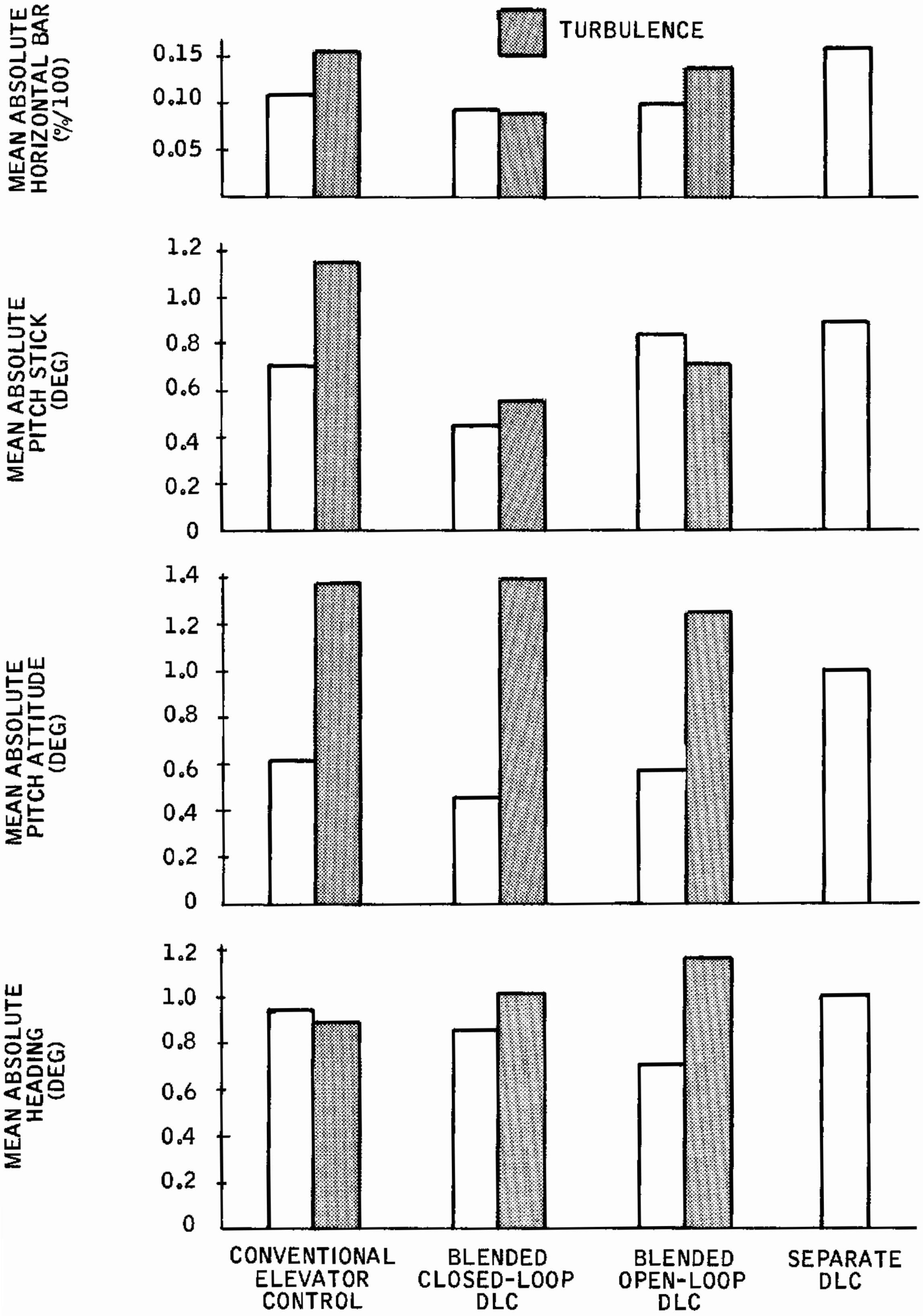


Figure 15. Mean Absolute Values -- C-5A In-flight Refueling

C-5A Terrain Following Task

Figure 16 summarizes some of the parameters for the terrain following task (horizontal command bar, pitch stick, pitch attitude, and heading). The mean of the mean absolute values is given for the above parameters for each control configuration, with and without turbulence, over both trials for both pilots. Closed-loop DLC shows a marked improvement in the horizontal bar error both with and without turbulence. Pitch stick work is also reduced in both smooth and turbulent air with closed-loop DLC. The mean absolute values of pitch attitude and heading do not show any significant differences.

F-104 Terrain Following Task

Figure 17 summarizes the mean absolute value for the F-104 terrain following task. All three control configurations (separate DLC not evaluated) yielded essentially the same results with and without turbulence. The probable reason for this is that the response to both stick commands and gusts is very rapid at this condition for conventional elevator control.

C-5A Landing Task

Figures 18, 19, and 20 summarize the C-5A landing data. With blended closed-loop and open-loop DLC there is a slight improvement in the pilot's ability to zero the horizontal command bar. Pitch stick work is less with the DLC, especially with turbulence present. Pitch rate is also reduced. Roll stick work and roll attitude are essentially the same for all configurations. The information presented on the command bar for the flare maneuver was $h_c = K(h - h_0)$. This information was apparently inadequate, inasmuch as the pilots experienced some difficulty in performing smooth flare maneuvers. Figure 19 shows the mean values of sink rate, pitch attitude, and roll attitude at touchdown. With DLC the pilots appear to have better control of sink rate. The task of controlling the horizontal command bar apparently diverted the pilots from controlling pitch attitude at touchdown. Without turbulence, the pitch altitude at touchdown was greater than 20 degrees for all three controllers. The mean roll attitude at touchdown was about the same for all controllers. Figure 20 shows touchdown dispersions and sink rate with DLC. To properly evaluate the benefits of DLC over conventional control during the flare maneuver, it is probably necessary to provide a visual presentation of the runway, etc. This was not possible during this simulation.

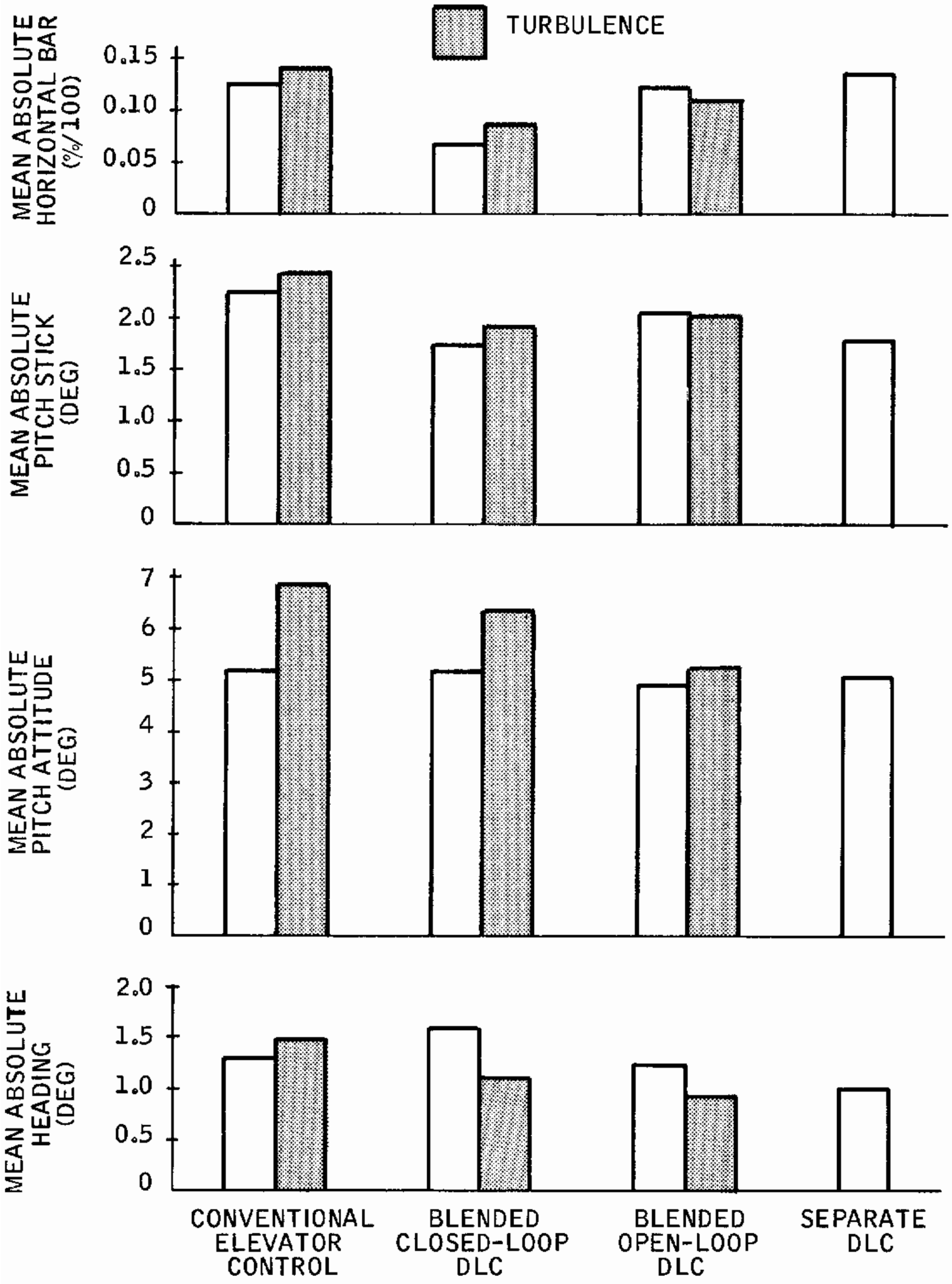


Figure 16. Mean Absolute Values -- C-5A Terrain Following

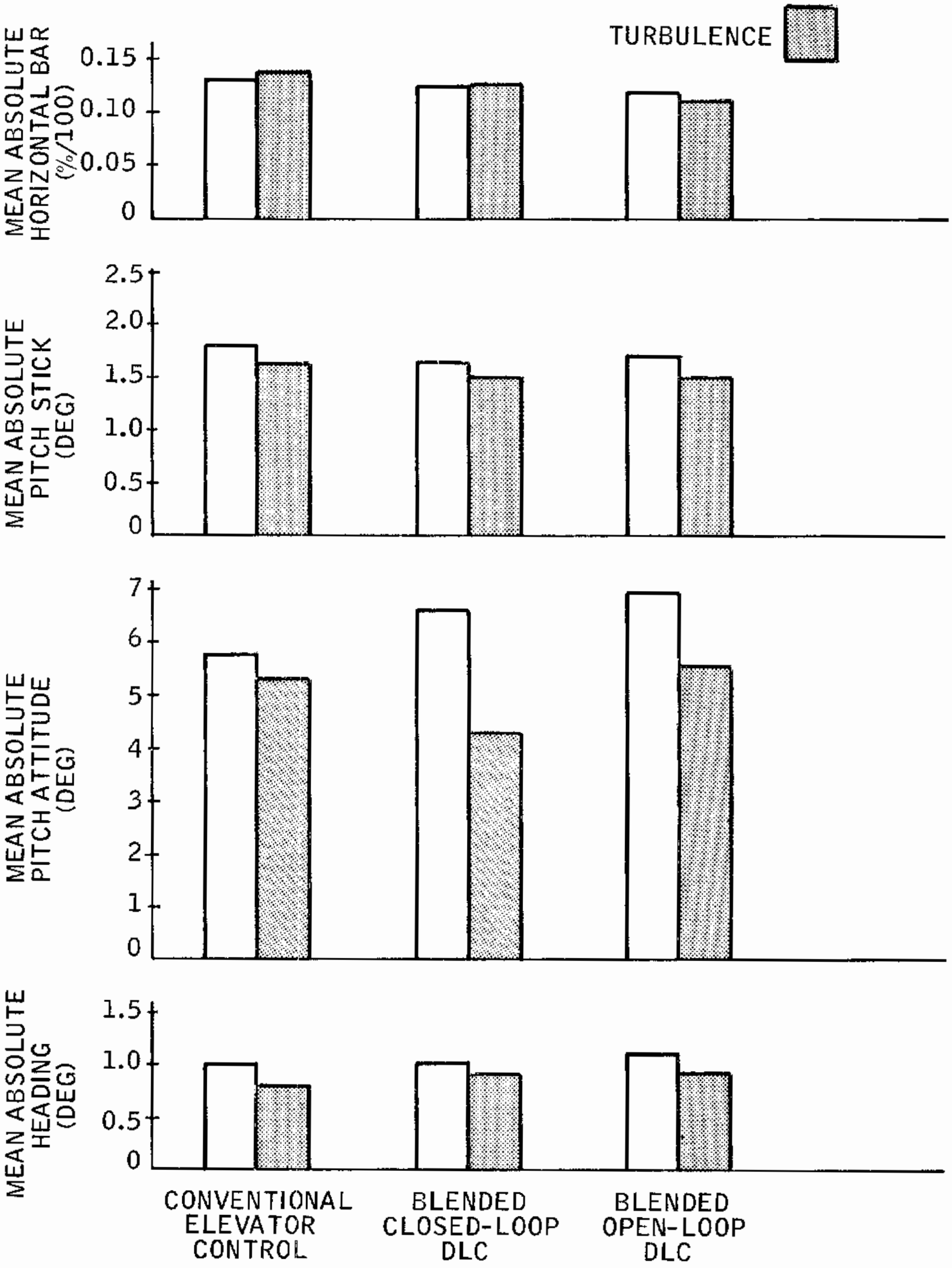


Figure 17. Mean Absolute Values -- F-104 Terrain Following

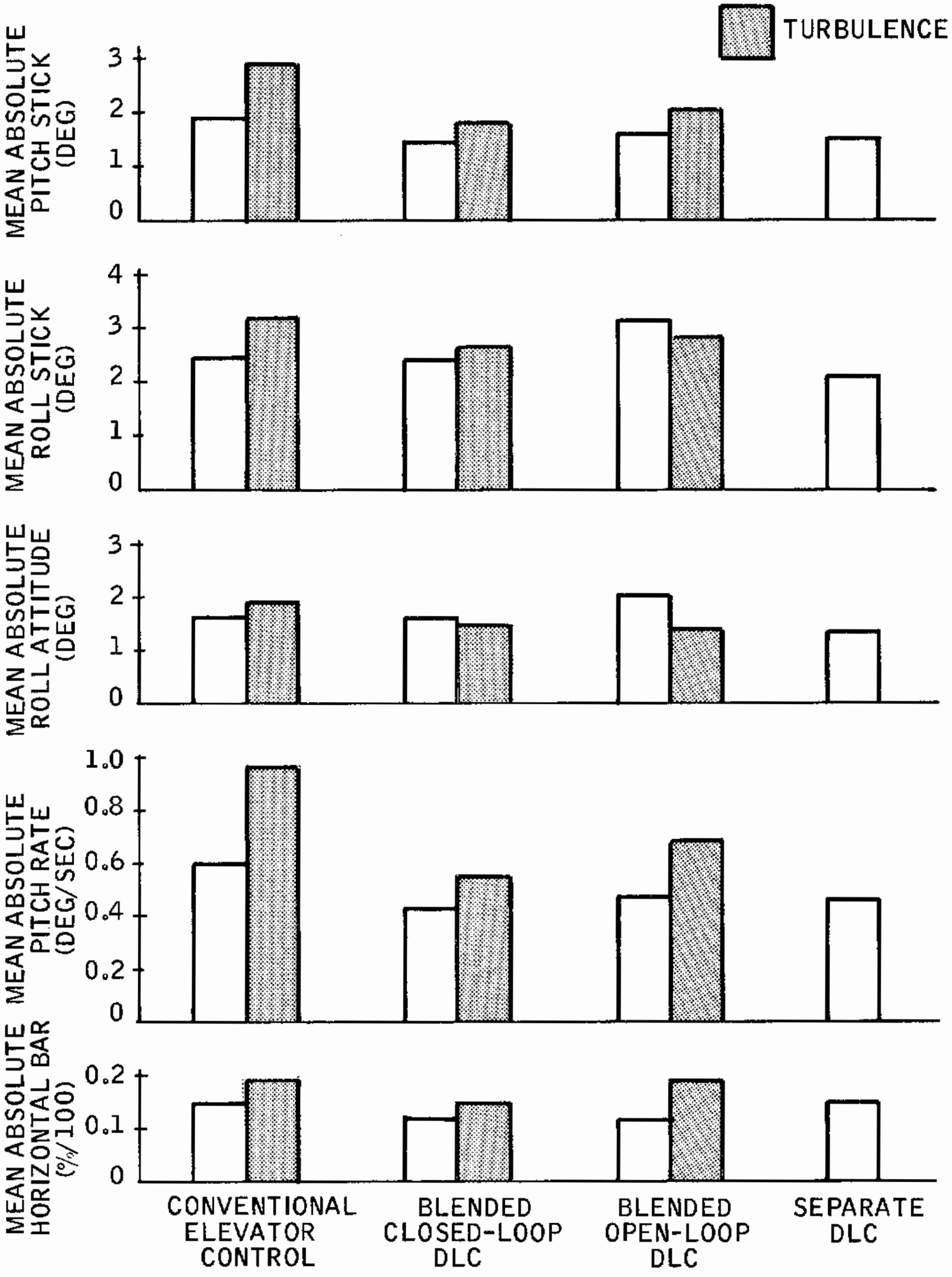


Figure 18. Mean Absolute Values -- C-5A Landing

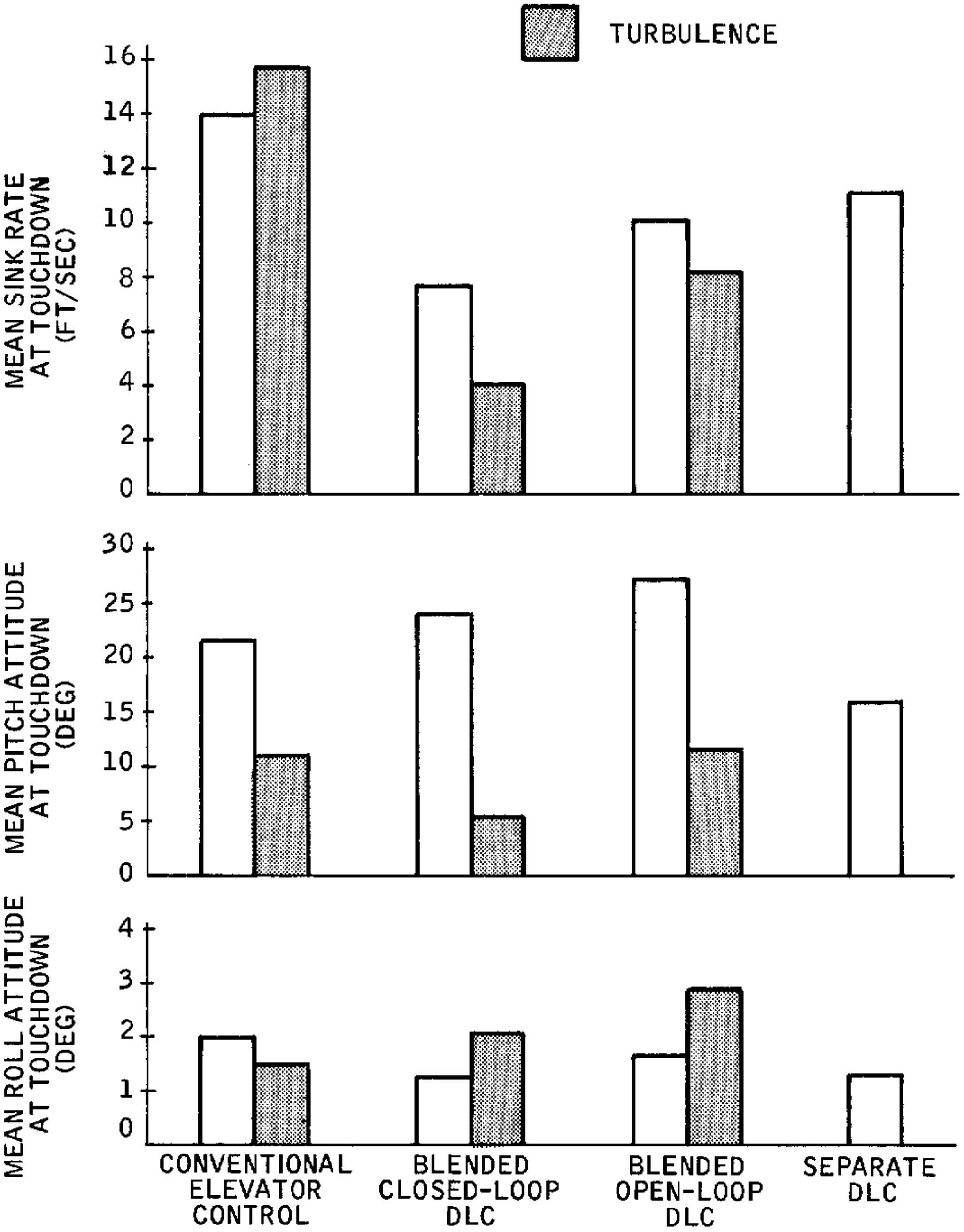


Figure 19. Mean Final Values at Touchdown -- C-5A Landing

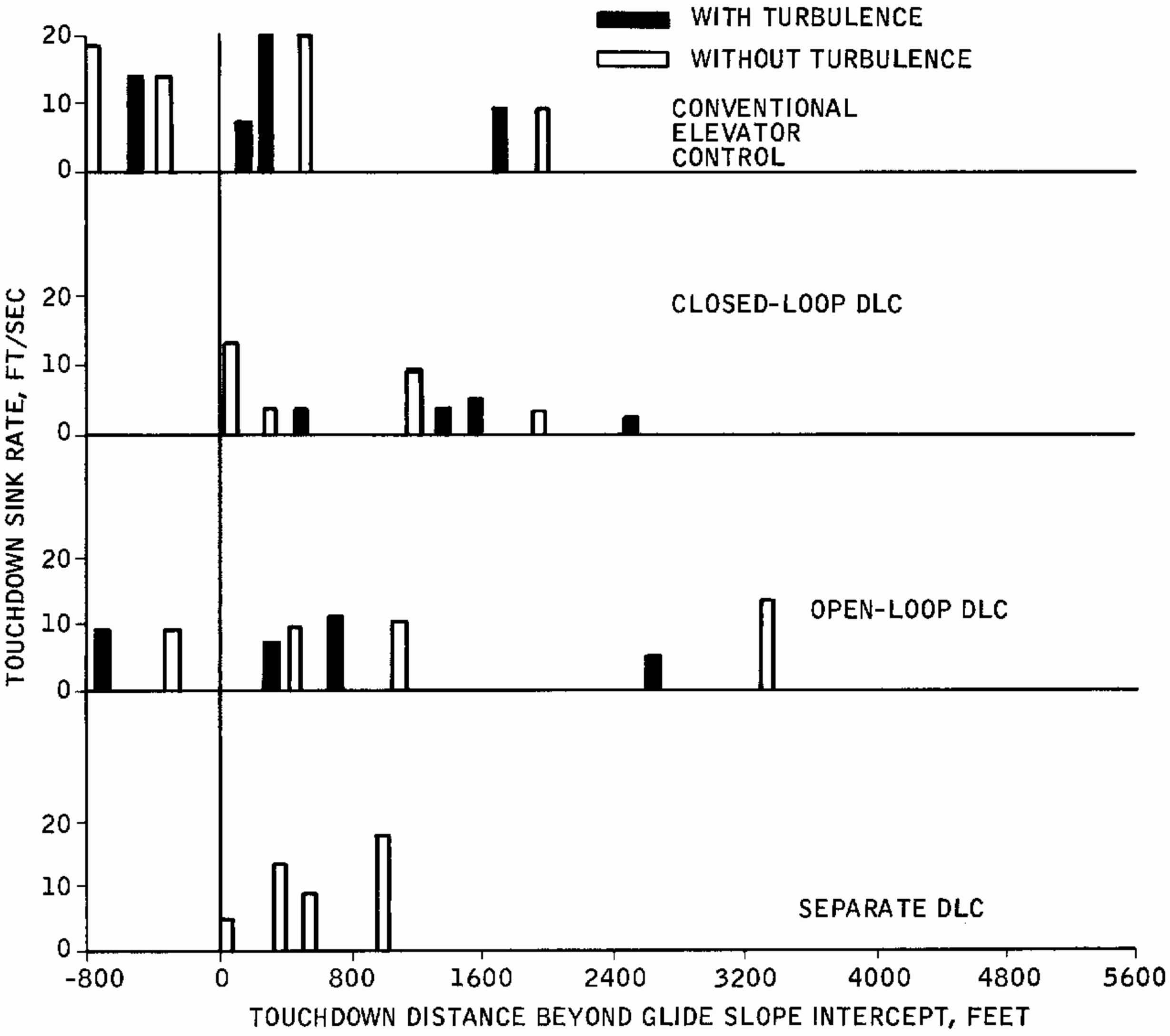


Figure 20. Touchdown Dispersions and Sink Rates at Touchdown -- C-5A

F-104 Landing Task

Figures 21, 22, and 23 summarize the F-104 landing data. There is little difference in pitch stick work, roll stick work, and mean roll attitude between the various controllers. With DLC there is a reduction in mean pitch rate both with and without turbulence. There is an improvement in the pilot's ability to zero the horizontal command bar with DLC, especially in turbulence. Figure 22 shows the mean final values of sink rate, pitch attitude, and roll attitude and again shows better control of sink rate at touchdown with DLC. Mean pitch attitude at touchdown is about the same for all configurations. Figure 23 shows touchdown dispersions and sink rate at touchdown. This data again points out the inadequacy of the display for the flare maneuver.

CORRELATION OF RESULTS

In this section, pilot's comments, pilot's Cooper ratings, and mean absolute value data will be discussed by task.

C-5A General Handling Qualities Task

There was no mean absolute value data for this task. Both pilots preferred open and closed-loop DLC over conventional elevator control, and thought that separate DLC was no help. Closed-loop DLC was better than open-loop DLC in turbulence. These opinions are confirmed in their numerical ratings (see Figure 14).

F-104 General Handling Qualities Task

There was no mean absolute value data for this task. The pilots found little difference between open- and closed-loop DLC, but showed a preference for closed-loop DLC. Both DLC modes made the task easier than with conventional elevator control; PIO tendencies were considerably reduced. Their ratings (see Figure 13) agree with their comments.

C-5A In-flight Refueling Task

Pilot 4 found no significant differences between closed-loop DLC, open-loop DLC, and elevator, and rated them all 2.0. Both pilots rated separate DLC at 5 (see Figure 10). Figure 15 confirms this; separate DLC mean absolute horizontal bar is larger than any of the other controllers.

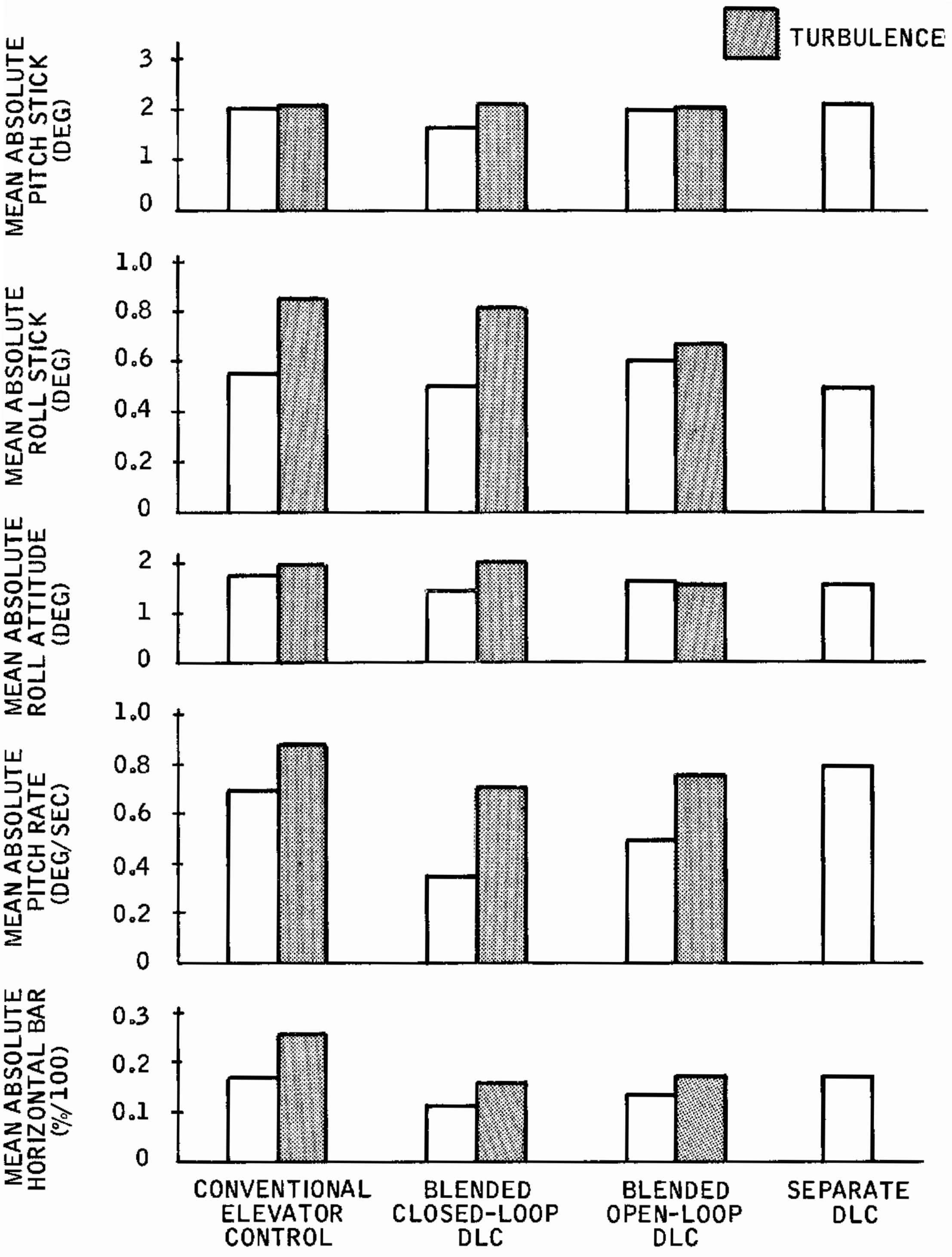


Figure 21. Mean Absolute Values -- F-104 Landing

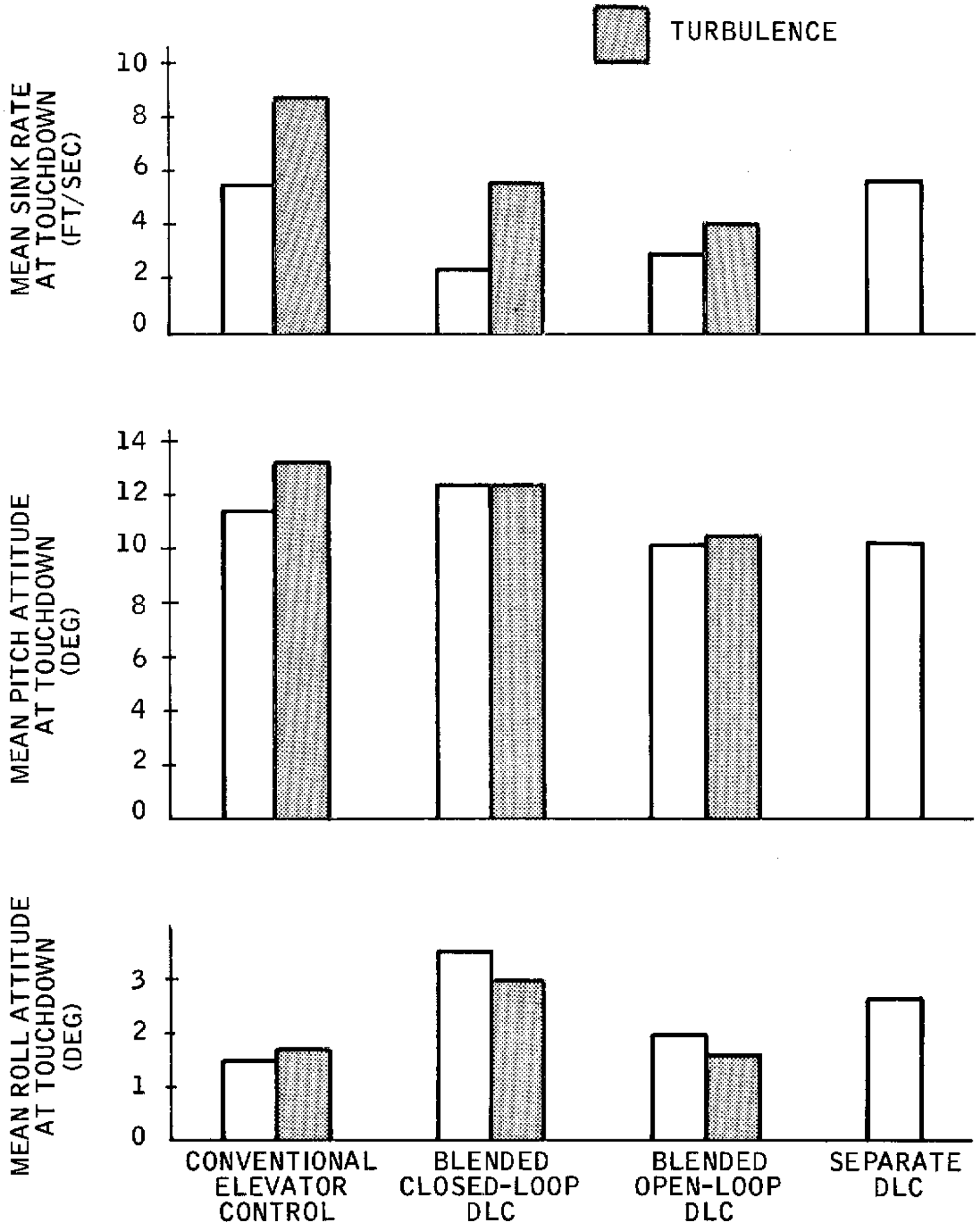


Figure 22. Mean Final Values at Touchdown -- F-104 Landing

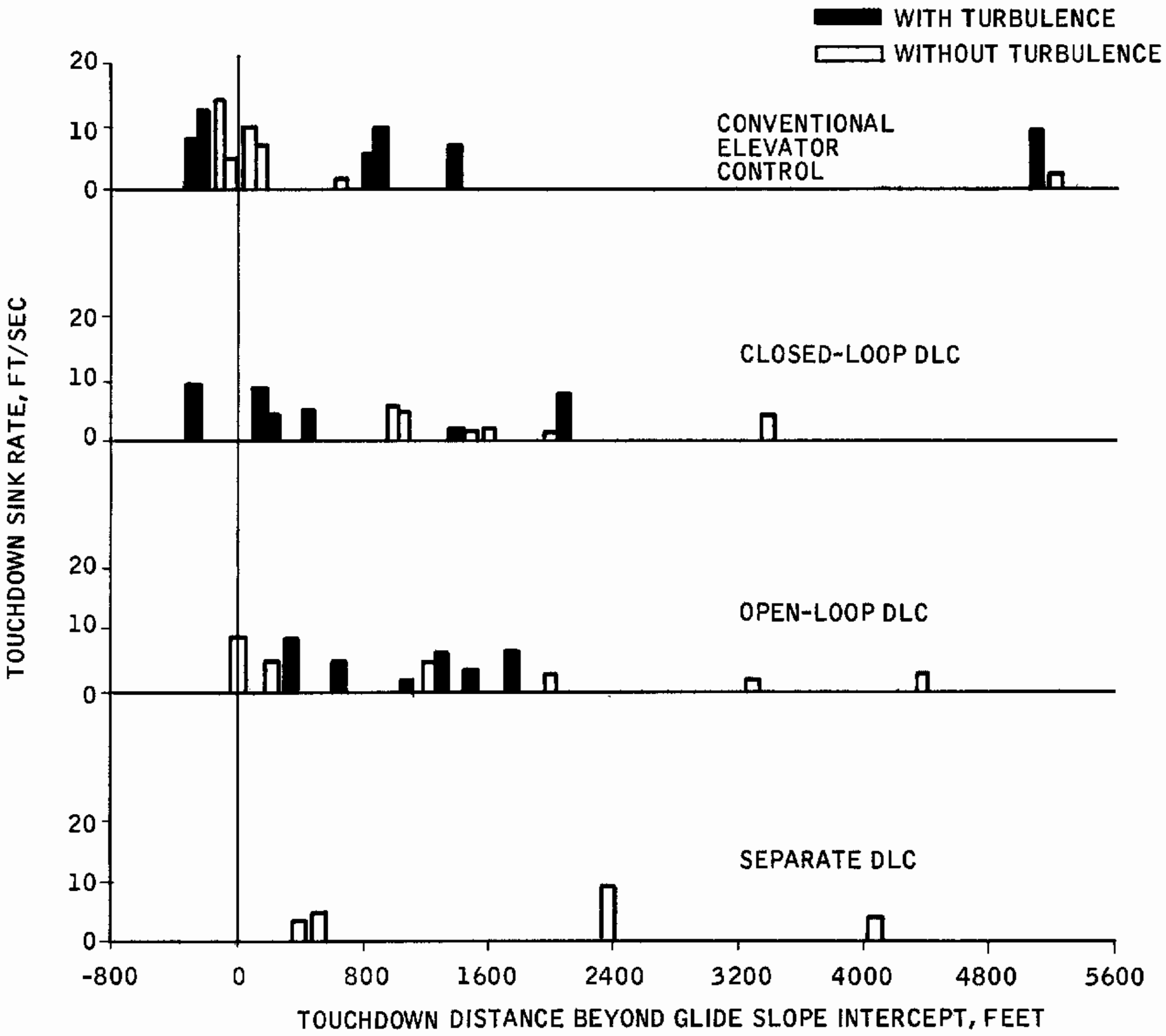


Figure 23. Touchdown Dispersions and Sink Rates at Touchdown -- F-104

Pilot 2 preferred open- and closed-loop DLC over elevator control and indicated that closed-loop DLC was the easiest. Figure 15 shows that, without turbulence, pilots did about as well (mean absolute horizontal bar) with all except separate DLC. In turbulence, closed-loop DLC performance is clearly better and the workload less (mean absolute pitch stick), although pilots rated the workload only slightly less.

The variable pitch work loads do not appear to affect the lateral control accuracy shown by the mean absolute heading. Closed-loop DLC is preferred and gives measurably better performance in turbulence.

C-5A Terrain Following Task

Both pilots rated closed-loop DLC best (see Figure 11) due to its performance in turbulence. Figure 16 confirms this. Pilot 5 thought the task easy with all controllers (except separate DLC) when no turbulence was present. However, Figure 16 shows the mean absolute horizontal bar deviation significantly reduced with closed-loop DLC and a slight reduction in workload (mean absolute pitch stick). Note that terrain following is at low altitudes and high speed where the normal acceleration response to elevator is better than the in-flight refueling task (at 20,000 feet). We should expect less difference between DLC and elevator in this task but find more; i.e., closed-loop DLC shows as much or more performance improvement in terrain following as in flight refueling, where the workload was only half as large.

F-104 Terrain Following Task

Figure 17 shows little difference in performance (mean absolute horizontal bar) among any of the controllers, although the pilots (see comments and Cooper ratings - Figure 12) preferred closed-loop DLC. The normal acceleration response with conventional elevator control was clearly adequate for this difficult task, with DLC providing no significant improvement.

F-104 Landing Task

All pilots again preferred closed-loop DLC, primarily for the flare maneuver. This is shown in their ratings (Figure 9) where differences in glide ratings are not as great as in the flare ratings. Mean and final value data are shown in Figures 21, 22, and 23. Figure 21 shows workload to be about the same for all controllers (mean absolute pitch and roll stick), with some improvement in tracking (mean absolute horizontal bar) when using DLC controllers. Separate DLC was more useful in this than in the other tasks. It was used primarily for flare, where it rated equally with elevator control. Figure 22 shows a distinct improvement in touchdown sink rate with DLC controllers, with open-loop DLC showing up better than closed-loop DLC in turbulence. This sink rate data is also shown (Figure 23) versus touchdown distance beyond the glideslope intercept. Points to the left of the intercept point suggest that no flare was accomplished. The high sink rates support this. Figure 23 indicates that with any of the DLCs the flare maneuver is performed better than with elevator control, sink rates are lower, and there is less dispersion. Pilots felt that the flare presentation was adequate for comparison, but poor for simulating the actual flare maneuver. The additional cues in an actual landing would result in better performance of the landing.

C-5A Landing Task

Pilots preferred blended DLC for both the glideslope and flare maneuvers (Figure 8), again with preference in glide not as sharp as in flare. Mean and final value data are shown in Figures 17, 18, and 19. Figure 17 shows somewhat less pitch workload (mean absolute pitch stick) with the DLCs than with elevator.

The mean absolute horizontal bar (Figure 18) is probably more indicative of glide slope performance than flare, being the mean over the total run time. The differences are not large, suggesting glide slope was about equally controlled with all controllers. Some improvement is shown with closed-loop DLC. Figure 19 shows great improvement in touchdown sink rate with DLC, especially with closed-loop DLC. This is also shown in Figure 20. With closed-loop DLC, sink rates are lower and landing dispersion is lower than with elevator or open-loop DLC. Separate DLC shows the least dispersion but very high sink rates and not much flaring.

SECTION VI
CONCLUSIONS

The following conclusions resulted from the study:

1) Pilots' preference for the control configurations was in this order, first to last: blended closed-loop; blended open-loop DLC; conventional elevator control. Separate DLC was unusable in any tasks except landing flare because of the control location. Blended closed-loop DLC was rated one Cooper rating better than conventional elevator and one-half Cooper rating better than blended open-loop DLC.

2) Closed-loop DLC gust alleviation was noticed by the pilots and was weighted significantly in their ratings.

3) There was general agreement between pilots' qualitative data (opinions and Cooper ratings) and quantitative data indicating their performance. However, differences in quantitative data were not as large as might be expected judging from their comments and Cooper ratings.

4) In F-104 terrain following (Mach 0. 9 at sea level) fast normal acceleration response was provided with conventional elevator. Although pilots preferred closed-loop DLC over elevator control, they did not notice any gross difference. This is confirmed by the quantitative data.

5) Lateral-axis performance was little affected by the various pitch control configurations.

6) The pilots did not notice any objectionable handling qualities characteristics as a result of the use of DLC. The use of two control surfaces with or without feedback allows the relationship between aircraft parameters to be altered. With closed-loop DLC, a low-frequency second-order characteristic was introduced. This was of concern prior to the study but received no pilot objection.

7) The pilots differed on the value of the motion system. Some felt it added some realism, at least in pitch; others thought they could do as well without it.

8) The displacement stick with poor centering characteristics introduced a tendency toward pilot-induced oscillation. This PIO tendency was reduced but not eliminated with the introduction of a stick displacement dead spot.

9) While landing flare sink rates and in-flight refueling tracking errors were significantly reduced with DLC, the simulations were not adequate for evaluation of these tasks. A simulator with a visual display is needed to properly evaluate the flare maneuver. Optimized flight director signals would have improved in-flight refueling tasks.

10) The separate DLC simulation used a collective pitch lever from a VTOL study. Pilots thought a thumbwheel similar to that used in Navy-sponsored studies would have been better. This was not available.

Based on the results of these simulator tests, it is anticipated that flight tests will demonstrate:

1) Significant improvements in the pilot's ability to control an aircraft to the glideslope and to the flare path and thereby a significantly reduced number of go-arounds and hard landings.

2) Controllability that will contribute to the lowering of instrument approach weather minimums.

3) An improvement in both the precision of mission task accomplishment and reduction in pilot fatigue factor.

4) Increased effectiveness for evasive maneuvers requiring rapid pull-ups.

5) A more stable platform (with reduced normal acceleration and pitch rate response to disturbances) for weapon delivery.

APPENDIX I

EQUATIONS OF MOTION

The equations used to simulate aircraft, position, localizer, glide slope, and flare are presented in this appendix. The aircraft equations are six-degree-of-freedom, constant-coefficient equations. A body-axis system was used. Lateral-axis equations were simplified somewhat to eliminate the need to simulate a complicated lateral stability augmentation system. Ground effects were included for the C-5A landing model. Certain small-angle assumptions were made in the position computation equations. First-order lag turbulence models were used.

The glide slope and localizer geometry simulated is shown. The glide-slope beam was 2.87 degrees with ±0.5-degrees width. The localizer beam source was assumed to be 5000 feet beyond the glide slope intercept with ±2 degrees width. An exponential flare equation was used. This is also shown.

SIX-DEGREE-OF-FREEDOM AIRCRAFT EQUATIONS OF MOTION

$$\dot{\alpha} = [C_{z_0} + C_{z_\alpha}(\alpha + \alpha_G) + \frac{\bar{c}}{2U_1}C_{z_q} q + C_{z_{\delta_e}}\delta_e + C_{z_{\delta_F}}\delta_F + C_{z_{\bar{u}}}(\bar{u} + \bar{u}_G)]\frac{\bar{q}S}{mU_1} + \frac{g}{U_1}\cos\theta\cos\phi + q\cos\alpha - \frac{\bar{q}S}{mU_1}\Delta C_{L_{GE}}(HF) \qquad (26)$$

$$\dot{q} = [C_{m_0} + \frac{\bar{c}}{2U_1}C_{m_{\dot{\alpha}}}\dot{\alpha} + C_{m_\alpha}(\alpha + \alpha_G) + \frac{\bar{c}}{2U_1}C_{m_q} + C_{m_{\delta_e}}\delta_e + C_{m_{\delta_F}}\delta_F + C_{m_{\bar{u}}}(\bar{u} + \bar{u}_G)]\frac{\bar{q}SC}{I_y} - pr\frac{(I_x - I_z)}{I_y} + \left(\frac{\Delta T}{\delta_T}\right)\frac{z_T\delta_T}{I_y} + \frac{\bar{q}Sc}{I_y}\Delta C_{m_{GE}}(HF) \qquad (27)$$

$$\dot{\bar{u}} = [C_{x_0} + C_{x_\alpha} (\alpha + \alpha_G) + C_{x_{\bar{u}}} (\bar{u} + \bar{u}_G) + \frac{\bar{c}}{zU_1} C_{x_q} q + C_{x_{\delta_e}} \delta_e + C_{x_{\delta_F}} \delta_F] \frac{\bar{q}S}{mU_1} - \frac{g}{U_1} \sin\theta - q \sin\alpha + \left(\frac{\Delta T}{\delta_T}\right) \frac{\delta_T}{mU_1} - \frac{\bar{q}S}{mU_1} Z \cdot \Delta C_{D_{GE}} \ (HF) \tag{28}$$

$$\dot{\beta} = \frac{g}{U_1} \cos\theta \sin\phi + p \sin\alpha - r + [C_{y_\beta} (\beta + \beta_G) + \frac{b}{2U_1} C_{y_r} r] \frac{\bar{q}S}{mU_1} \tag{29}$$

$$\dot{p} = [C_{\ell_\beta} (\beta + \beta_G) + \frac{b}{2U_1} C_{\ell_p} p + C_{\ell_{\delta_a}} \delta_a] \frac{\bar{q}Sb}{I_x} \tag{30}$$

$$\dot{r} = [C_{n_\beta} (\beta + \beta_G) + \frac{b}{2U_1} C_{n_r} r] \frac{\bar{q}Sb}{I_z} \tag{31}$$

$$\dot{w} = \dot{\alpha} U_1 \tag{32}$$

$$\dot{u} = \dot{\bar{u}} U_1 \tag{33}$$

$$\dot{v} = \dot{\beta} U_1 \tag{34}$$

EULER EQUATIONS

$$\dot{\theta} = q \cos \phi - r \sin \phi \tag{35}$$

$$\dot{\phi} = p - \dot{\psi} \sin \theta \tag{36}$$

$$\dot{\psi} = \frac{1}{\cos \theta} (r \cos \phi + q \sin \phi) \tag{37}$$

POSITION COMPUTATION (EARTH-FIXED COORDINATES)

$$\dot{X} = U + W \sin \theta \cos \phi - V \cos \phi \sin \psi \tag{38}$$

$$\dot{Y} = U \sin \psi - W \cos \phi + V \cos \phi \tag{39}$$

$$\dot{Z} = - U \sin \theta + W \cos \phi + V \sin \phi \tag{40}$$

$$U = U_0 + u \tag{41}$$

$$W = W_0 + w \tag{42}$$

$$X = \int \dot{X} \, dt \tag{43}$$

$$Y = \int \dot{Y} \, dt \tag{44}$$

$$Z = \int \dot{Z} \, dt \tag{45}$$

ACCELERATION COMPUTATIONS (INCREMENTAL)

$$n_{z_{cg}} = - [C_{z_0} + \frac{\bar{c}}{2U_1} C_{z_q} q + C_{z_\alpha} \alpha_T + C_{z_{\delta_e}} \delta_e + C_{z_{\delta_F}} \delta_F] \frac{\bar{q}S}{mg} - 1 \tag{46}$$

$$n_{z_p} = n_{z_{c.g.}} + \frac{\ell p}{g}\dot{q} \tag{47}$$

$$C^* = n_{z_p} + \frac{U_c}{g} q \tag{48}$$

$$n_{z_A} = M_{z_{c.g.}} + \frac{\ell_A}{g} \dot{q} \tag{49}$$

$$n_{y_{c.g.}} = [C_{y_\beta} \beta_T + \frac{b}{2U_1} C_{y_r} r] \frac{\bar{q}S}{mg} \tag{50}$$

TURBULENCE MODEL

$$\alpha_G = \frac{K}{U_1} \frac{W.N.}{\frac{L}{U_1} S + 1} \tag{51}$$

where

$$K = \sigma_w \left(\frac{2L}{U}\right)^{1/2} \tag{52}$$

$$\bar{u}_G = \frac{K}{U_1} \frac{W.N.}{\frac{L}{U_1} S + 1} \tag{53}$$

where

$$K = \sigma_u \left(\frac{2L}{U}\right)^{1/2} \tag{54}$$

$$\beta_G = \frac{K}{U_1} \frac{W.\ N.}{\frac{L}{U_1} S + 1} \tag{55}$$

where

$$K = \sigma_v \left(\frac{2L}{U}\right)^{1/2} \tag{56}$$

and

W. N. = White noise

L = 600 feet sea level

= 5000 feet altitude

GROUND EFFECTS (C-5A)

$$(X_h)_{GE} = - \frac{1}{U_1} \frac{\bar{q}S}{m} \, 2 \, \Delta \, C_{D_{GE}} \quad (HF) \tag{57}$$

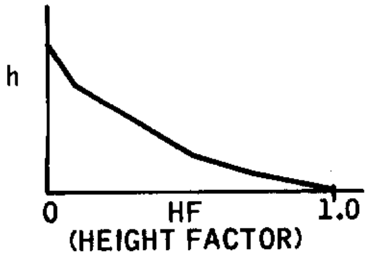
$$(M_h)_{GE} = \frac{\bar{q}Sc}{I_y} \, \Delta \, C_{m_{GE}} \quad (HF) \tag{58}$$

$$(Z_h)_{GE} = - \frac{\bar{q}S}{mU_1} \, \Delta \, C_{L_{GE}} \quad (HF) \tag{59}$$

where

(HF) = Height Factor

= $e^{-0.35h}$ (see Figure 24)

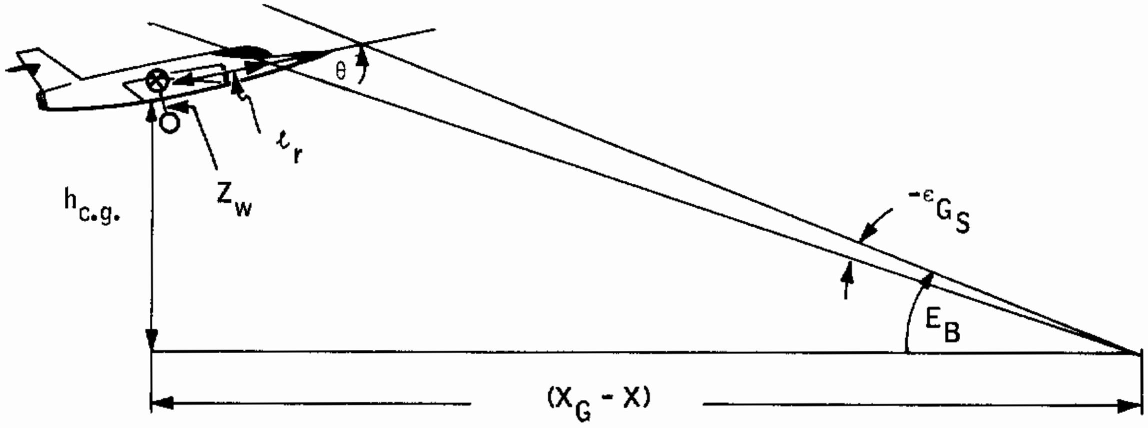


h	$e^{-0.035h}$
0	1.00
10	0.704
20	0.496
50	0.174
100	0.03
30	0.316

Figure 24. Height Factor

GLIDE SCOPE LOCALIZER AND FLARE GEOMETRY

See Figures 25, 26, and 27 respectively.



$$-\epsilon_{G_S} = \frac{(X_G - \int \dot{X}\,dt - \ell_R)\ \text{TAN}\ E_B - (Z_0 + \int \dot{Z}\,dt + \ell_R\ \text{SIN}\ \theta)}{X_G - \int \dot{X}\,dt - \ell_R}$$

$$= \text{TAN}\ E_B - \frac{(Z_0 + \int \dot{Z}dt + \ell_R\ \text{SIN}\ \theta)}{X_G - \int \dot{X}\,dt - \ell_R}$$

X_G = INITIAL X DISTANCE TO GLIDESLOPE RECEIVER

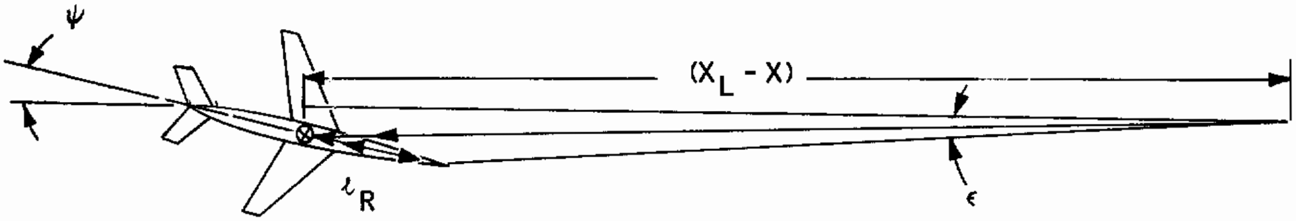
Z_0 = INITIAL Z DISTANCE ABOVE GROUND

E_B = GLIDESLOPE ANGLE

ϵ_{G_S} = GLIDESLOPE ERROR SENSED

ℓ_R = RECEIVER DISTANCE AHEAD OF C.G.

Figure 25. Glide Slope Geometry



$$\epsilon_{\ell oc} = \frac{Y_0 + \int \dot{Y}\,dt + \ell_R \,\mathrm{SIN}\,\psi}{X_L - \int \dot{X}\,dt - \ell_R}$$

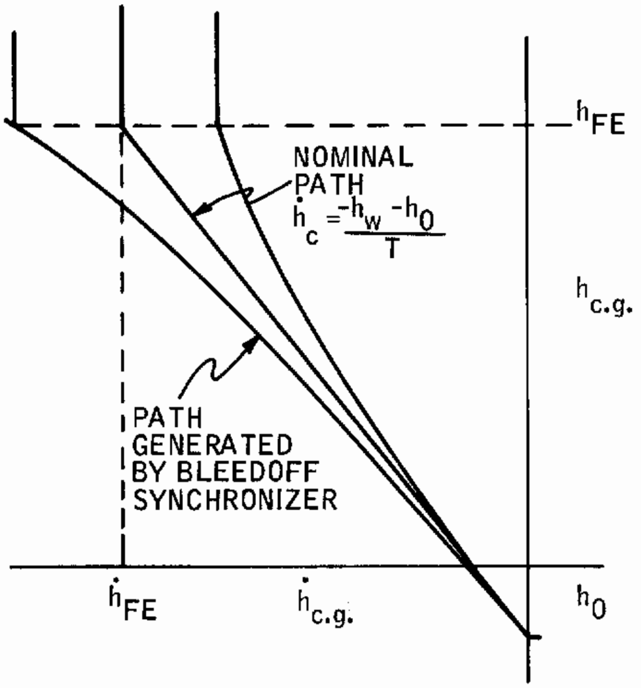
X_L = INITIAL X DISTANCE TO LOCALIZER RECEIVER

Y_0 = INITIAL Y DISTANCE FROM BEAM

RECEIVER DYNAMICS:

$$\frac{e_o}{e_i} = \frac{1}{0.5S + 1}$$

Figure 26. Localizer Geometry



h_w = LANDING GEAR ALTITUDE

h_{FE} = FLARE ENGAGE ALTITUDE

$\dot{h}_{FE}$ = ALTITUDE RATE AT FLARE ENGAGE ALTITUDE

h_0 = PROVIDES NEGATIVE RATE AT TOUCHDOWN

$\dot{h}_c$ = ALTITUDE RATE COMMAND OUT OF FLARE COMPUTER

T = EXPONENTIAL TIME CONSTANT

$\dot{h}_c = \frac{-h_w - h_0}{T}$

T = 8 SEC

h_0 = 10 FT (C-5A)

h_0 = 20 FT (F-104)

Figure 27. Flare Geometry

APPENDIX II

PILOT TASK MODELS

The information presented to the pilots was side slip, angle of attack, altitude, altitude rate, airspeed, normal acceleration, engine rpm, and aircraft attitude. A photograph of the instrument panel is shown in Figure 2. Pitch, roll, and heading information were presented for all tasks. In landing, raw glide slope and raw localizer information was displayed on the side pointer and bottom pointer of the attitude director indicator (ADI), respectively. The information presented on the ADI horizontal and vertical command bars was different for each of the different tasks. In each task the pilot was to fly the bars to zero. The information presented on the command bars is given in Figures 28 through 31 and in Table XI.

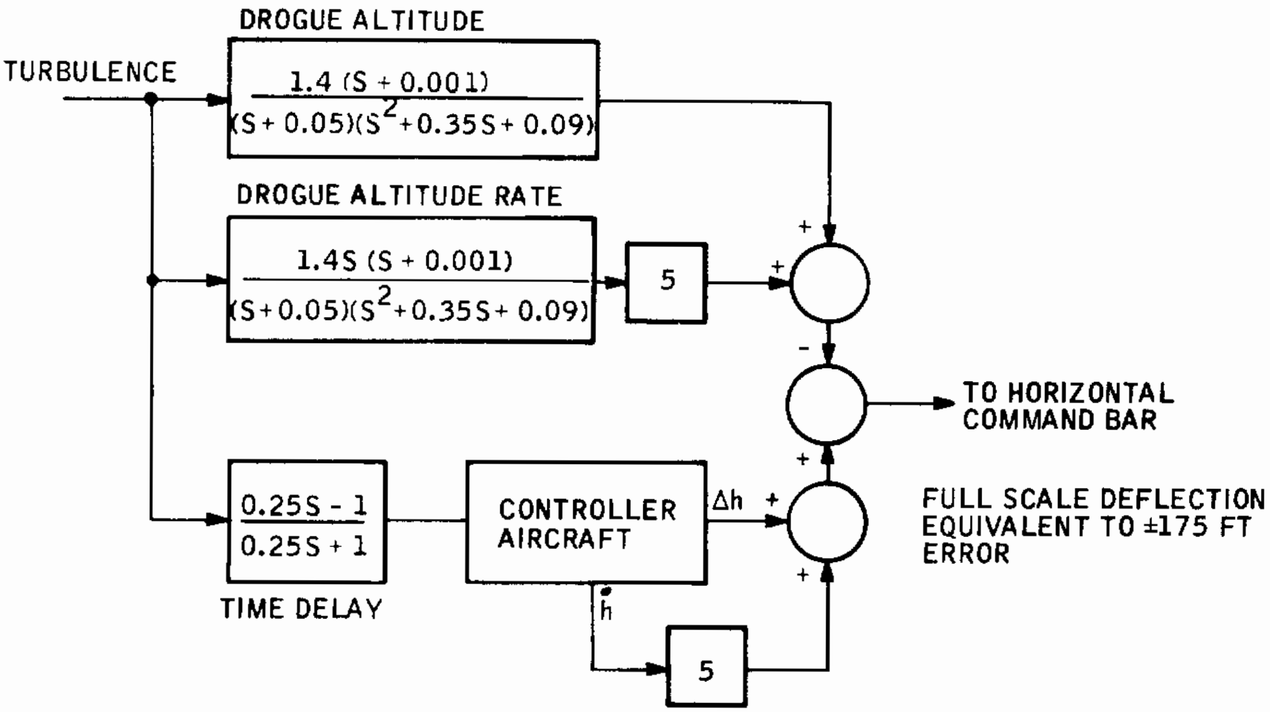


Figure 28. In-flight Refueling Model

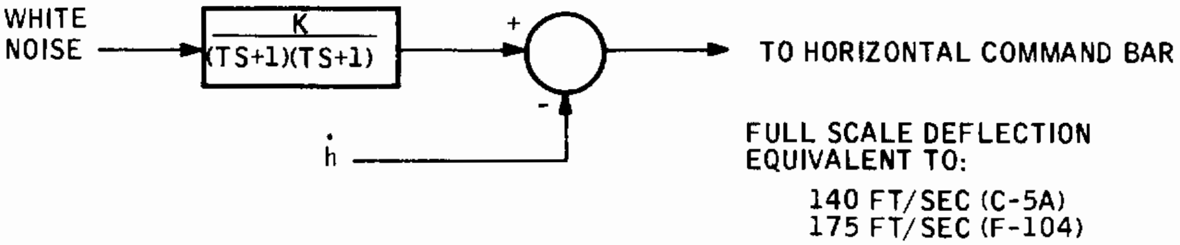


Figure 29. Terrain Following Model

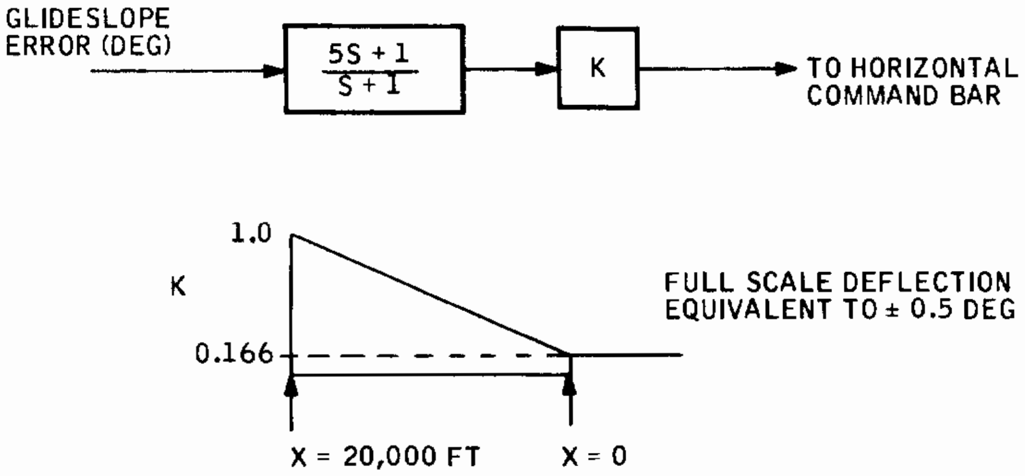


Figure 30. Glide Slope Steering on Horizontal Command Bar

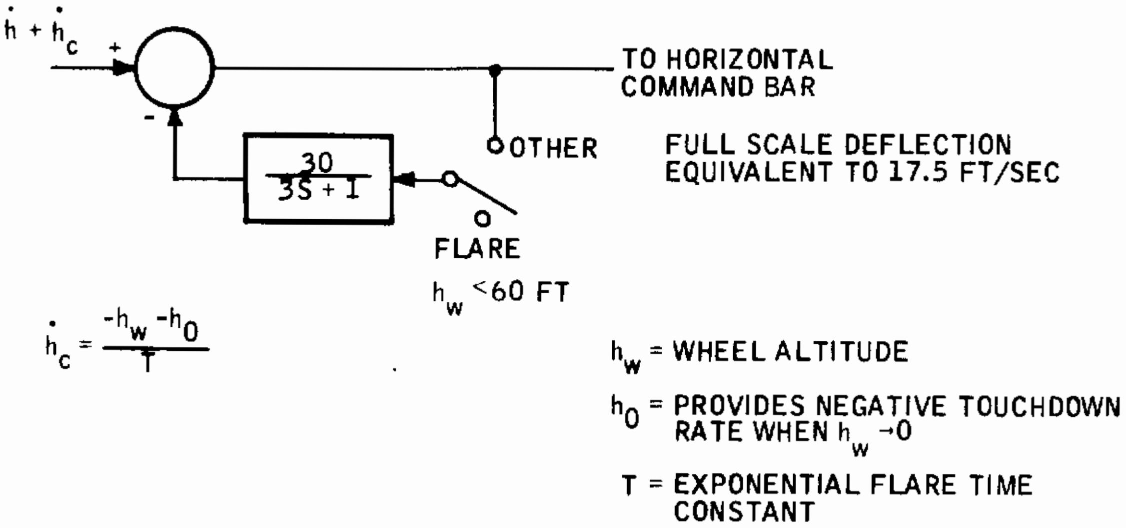


Figure 31. Flare Steering on Horizontal Command Bar

Table XI. Lateral Steering on Vertical Command Bar (Note: Lateral Steering = $\phi + K_1\dot{Y} + K_2Y$)

Parameter	Aircraft	
	F-104	C-5A
K_1, deg ϕ/ft/sec	0.2865	0.573
K_2, deg ϕ/ft	0.02865	0.0573
Bank angle called for at full scale deflection, deg ϕ	90	30

APPENDIX III

ANALOG COMPUTER DIAGRAMS

Figures 32 through 41 are the analog computer diagrams for the simulation. Included are the diagrams for the aircraft, pilot tasks simulation, instrumentation interface, quantitative data measuring, motion drive, and interconnects.

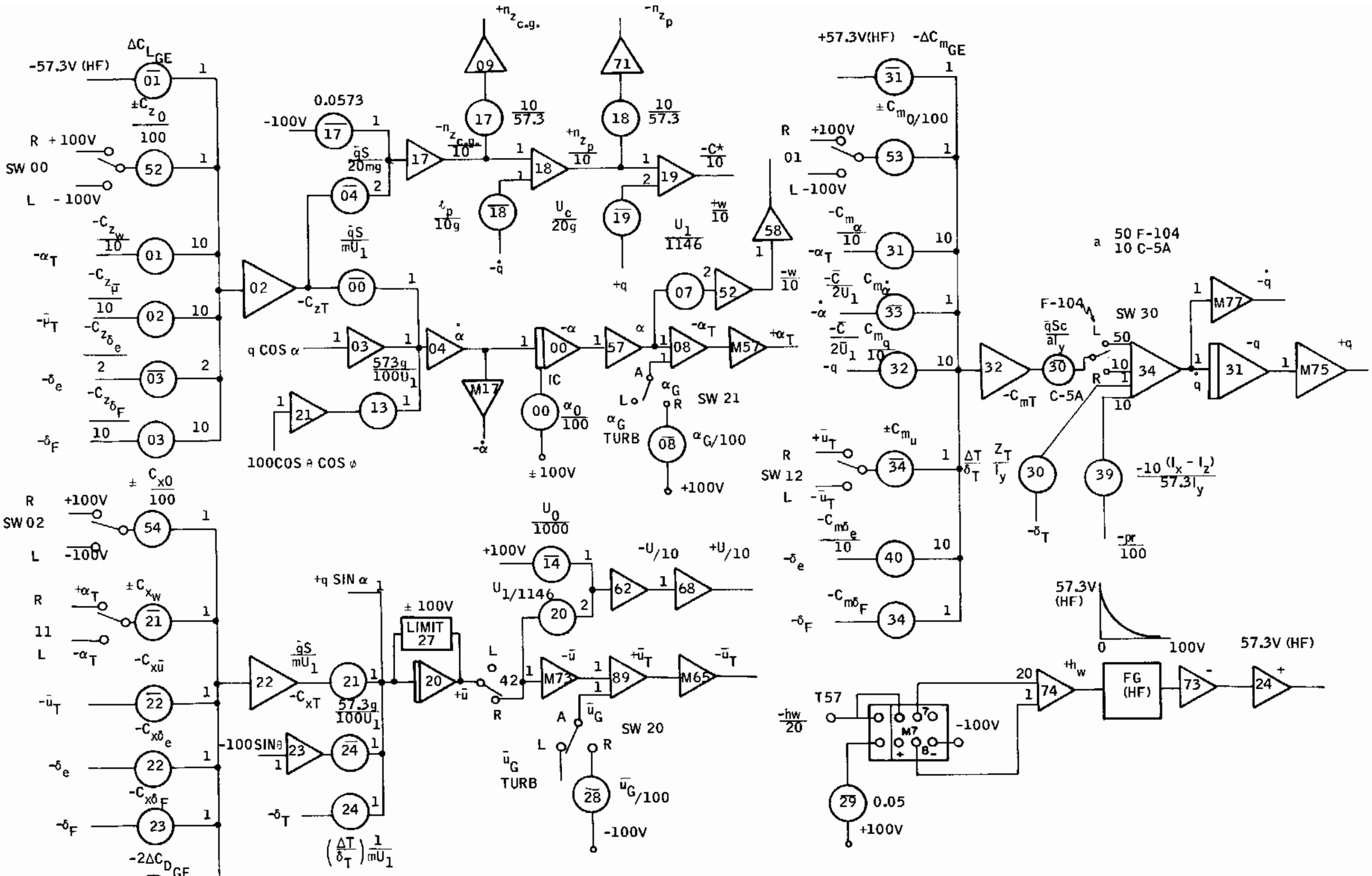


Figure 32. Longitudinal Aircraft Equations of Motion -- Acceleration Computations, Console I

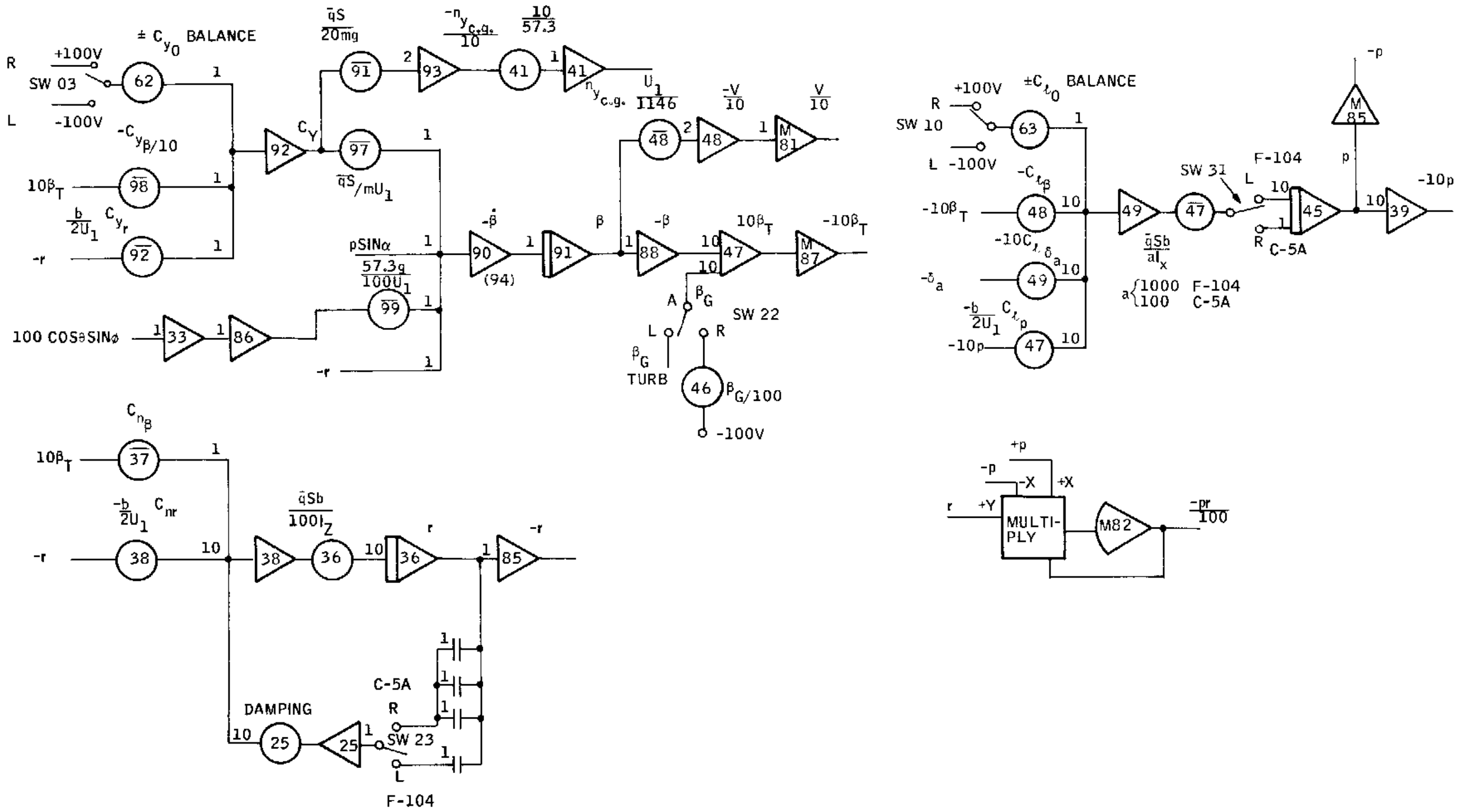


Figure 33. Lateral Aircraft Equations of Motion -- Acceleration Computations, Console I

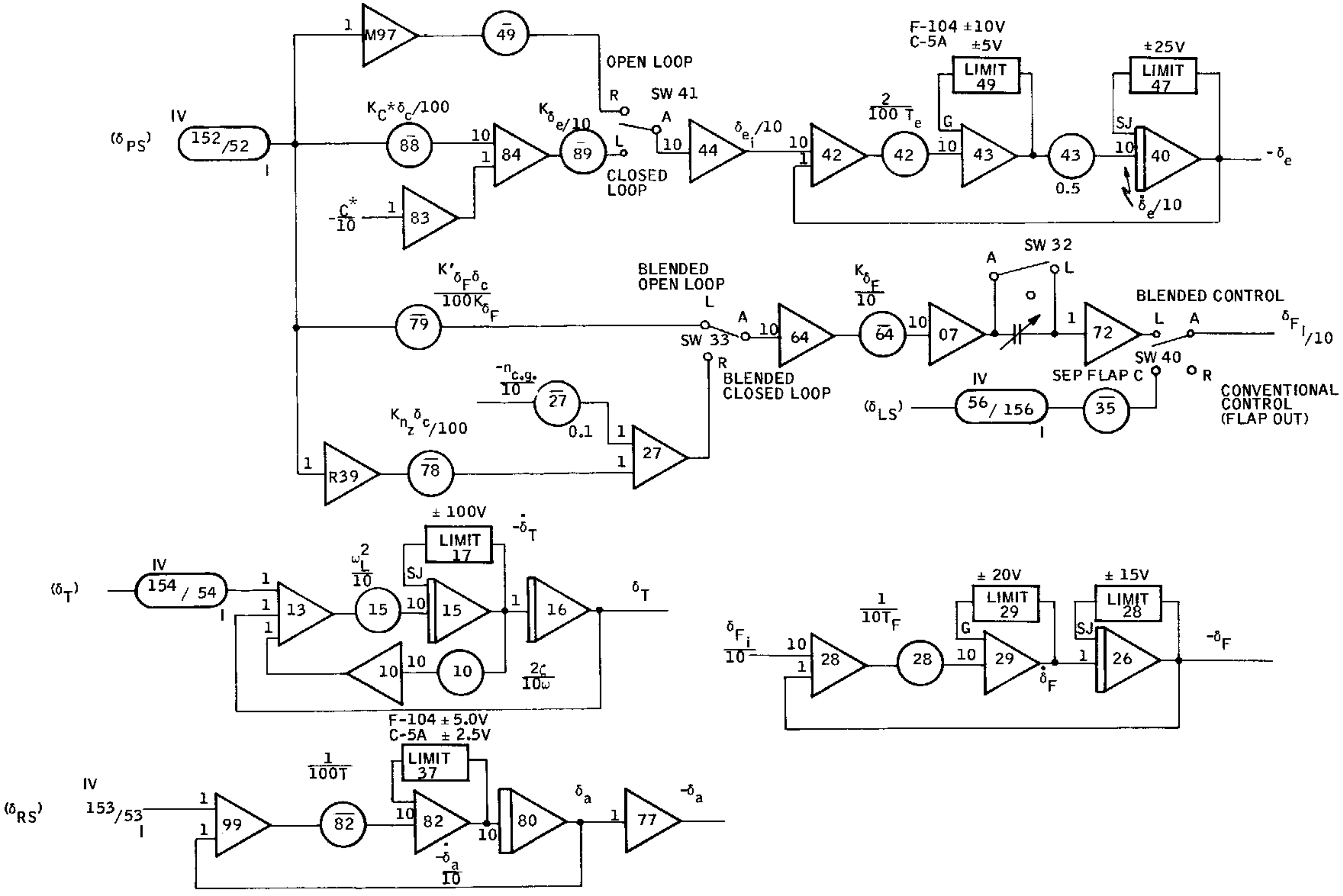


Figure 34. Control System and Actuator Simulations, Console I

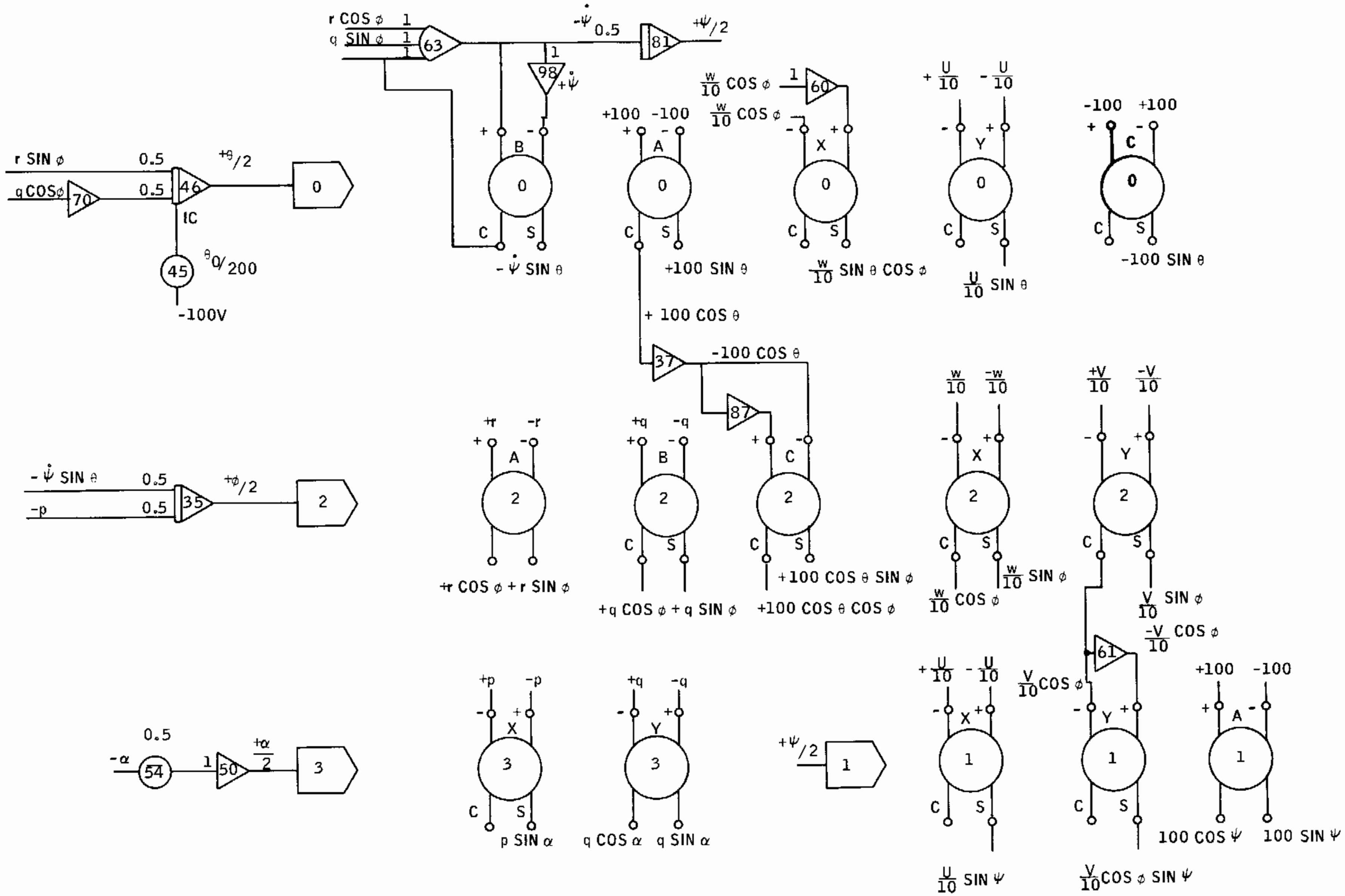


Figure 35. Position Computation (Euler Angles), Console I

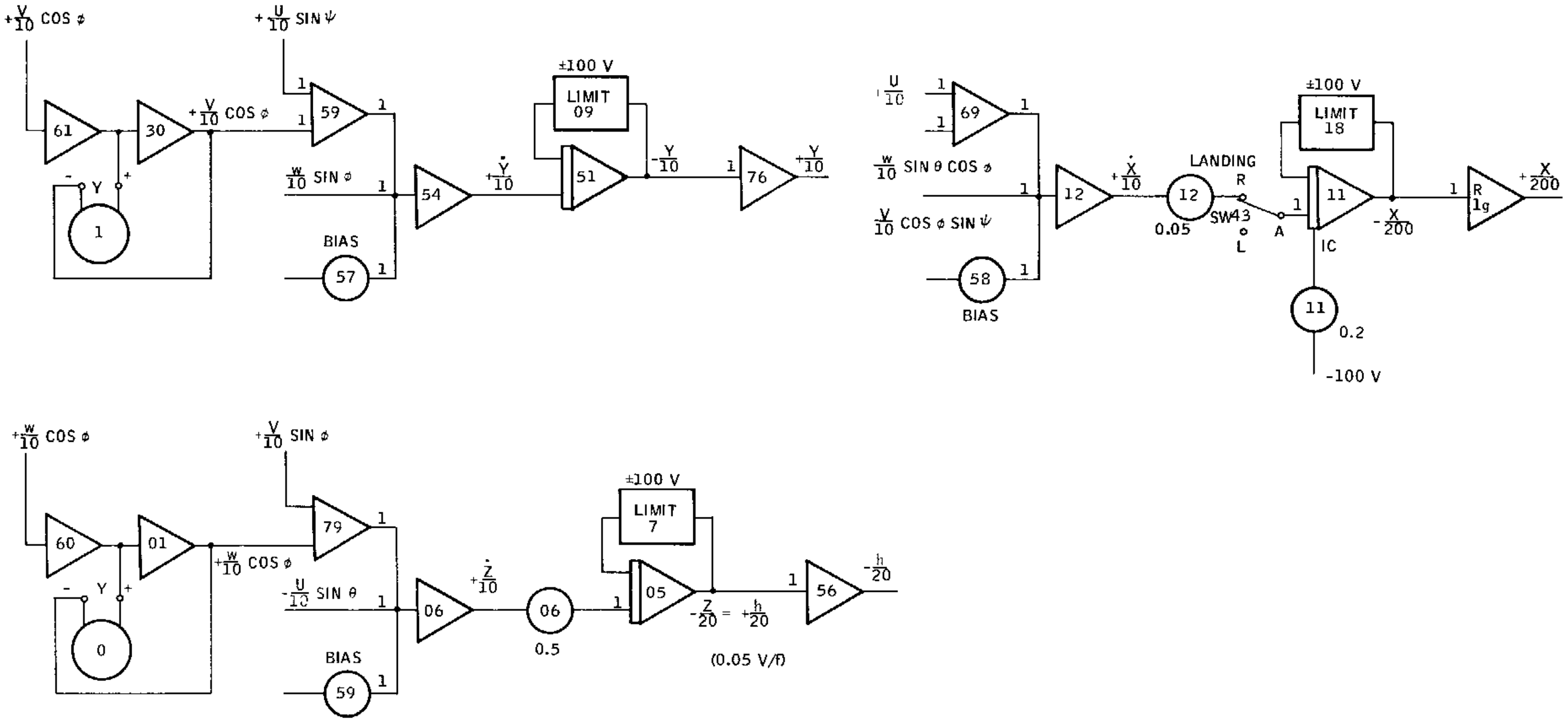


Figure 36. Position Computation (Earth-Fixed Coordinates), Console I

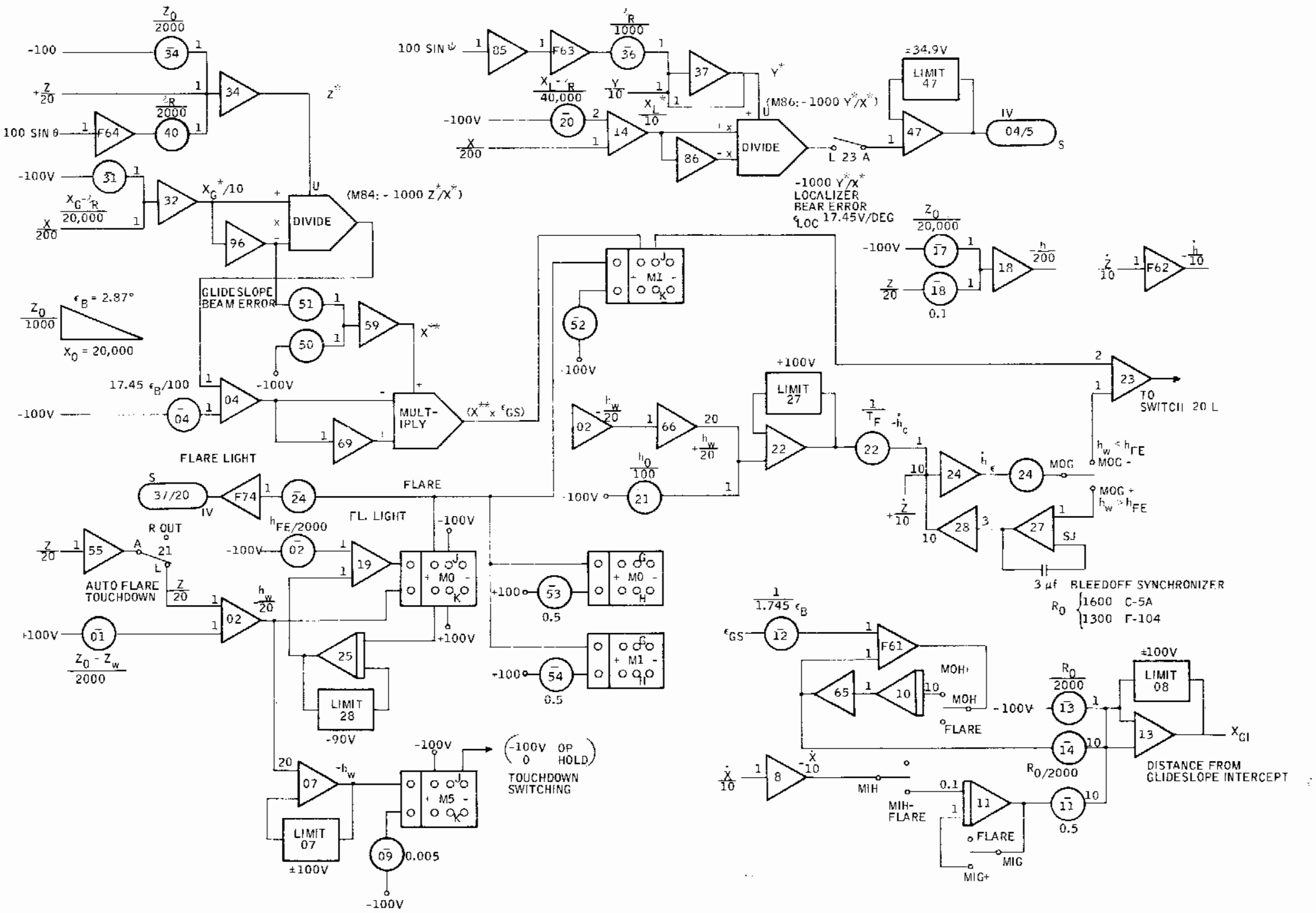


Figure 37. Glide Slope, Localizer, Flare Simulation, Console IV

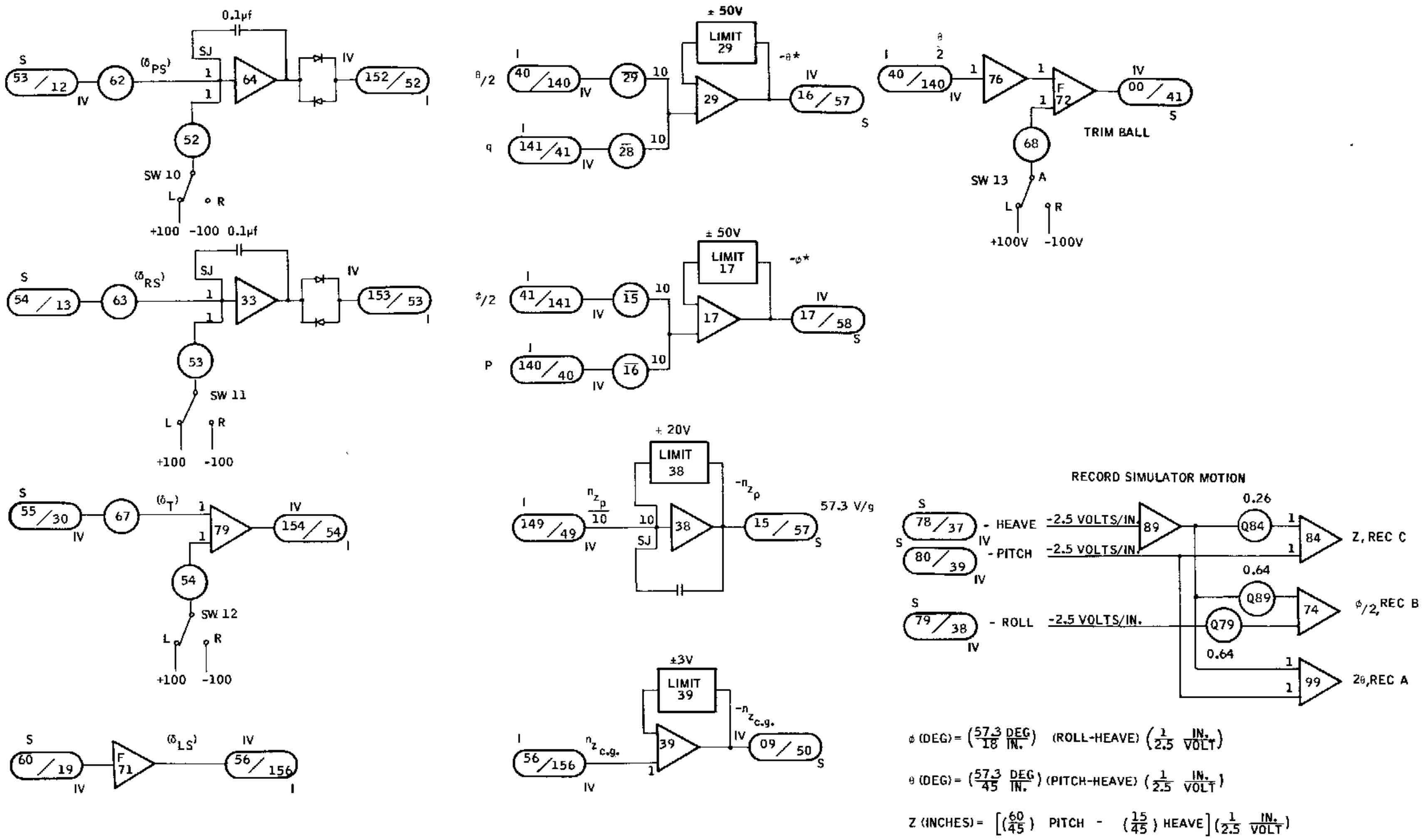


Figure 37. Glide Slope, Localizer, Flare Simulation, Console IV -- Continued

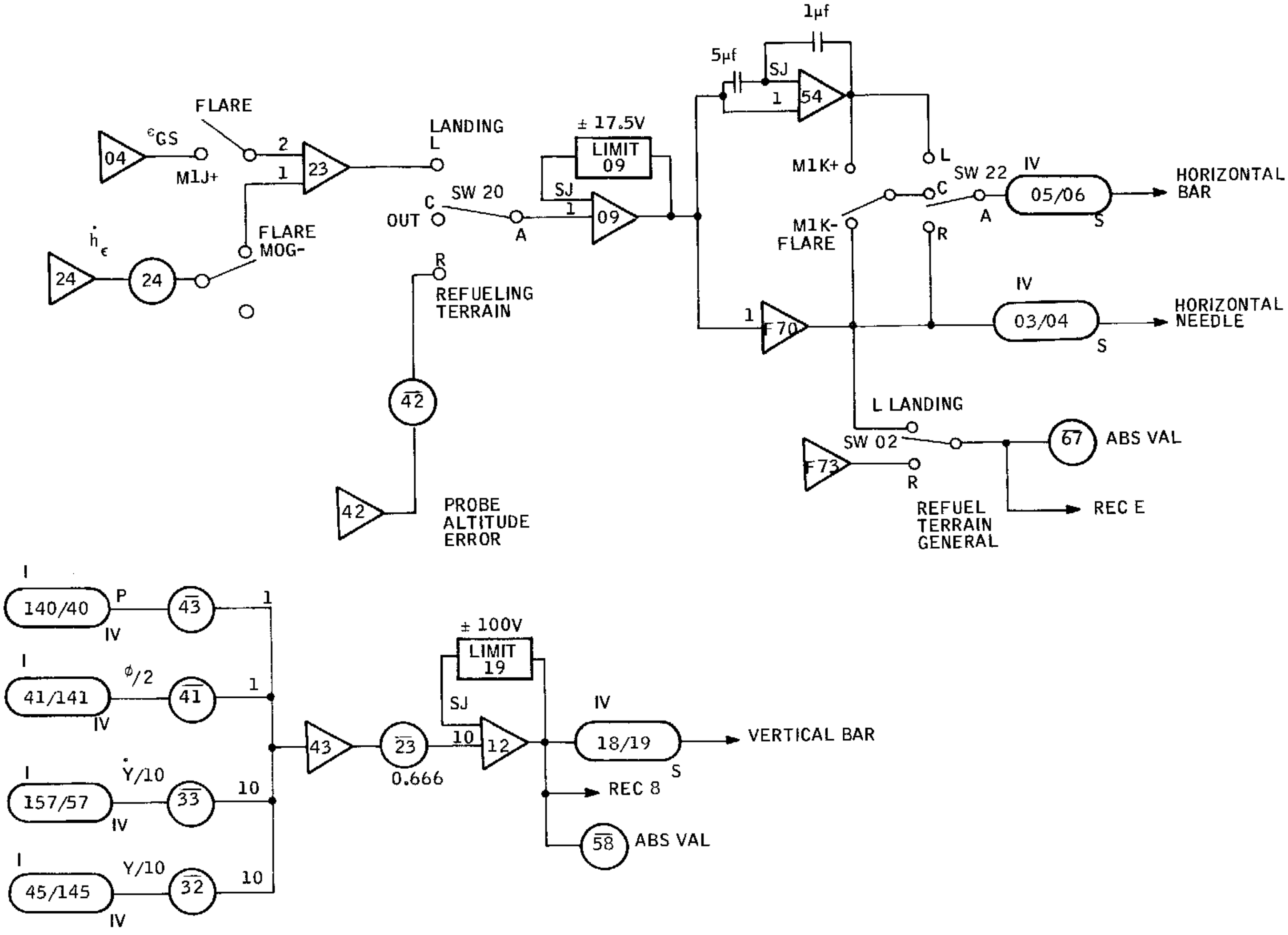


Figure 37. Glide Slope, Localizer, Flare Simulation, Console IV -- Continued

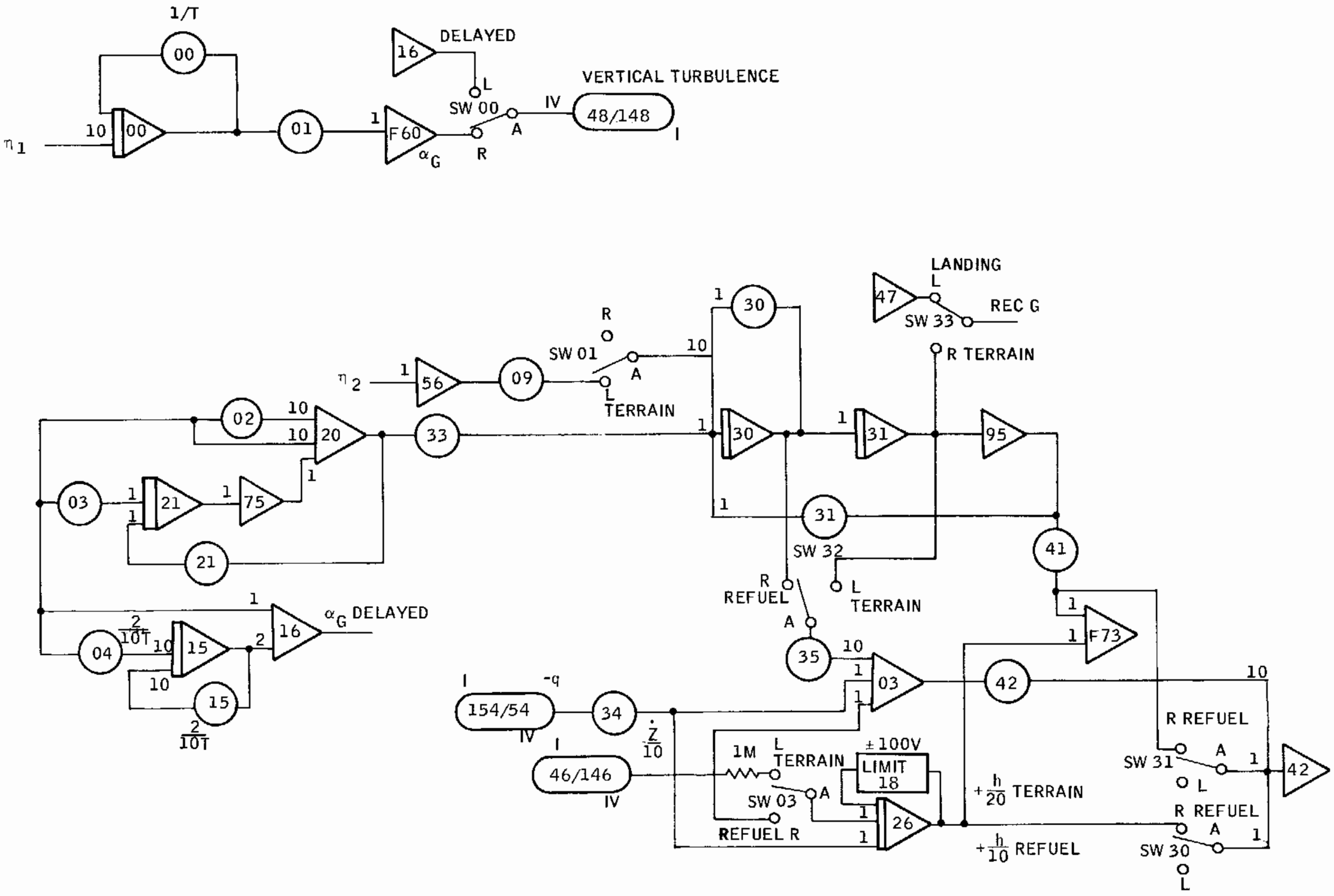


Figure 37. Glide Slope, Localizer, Flare Simulation, Console IV -- Concluded

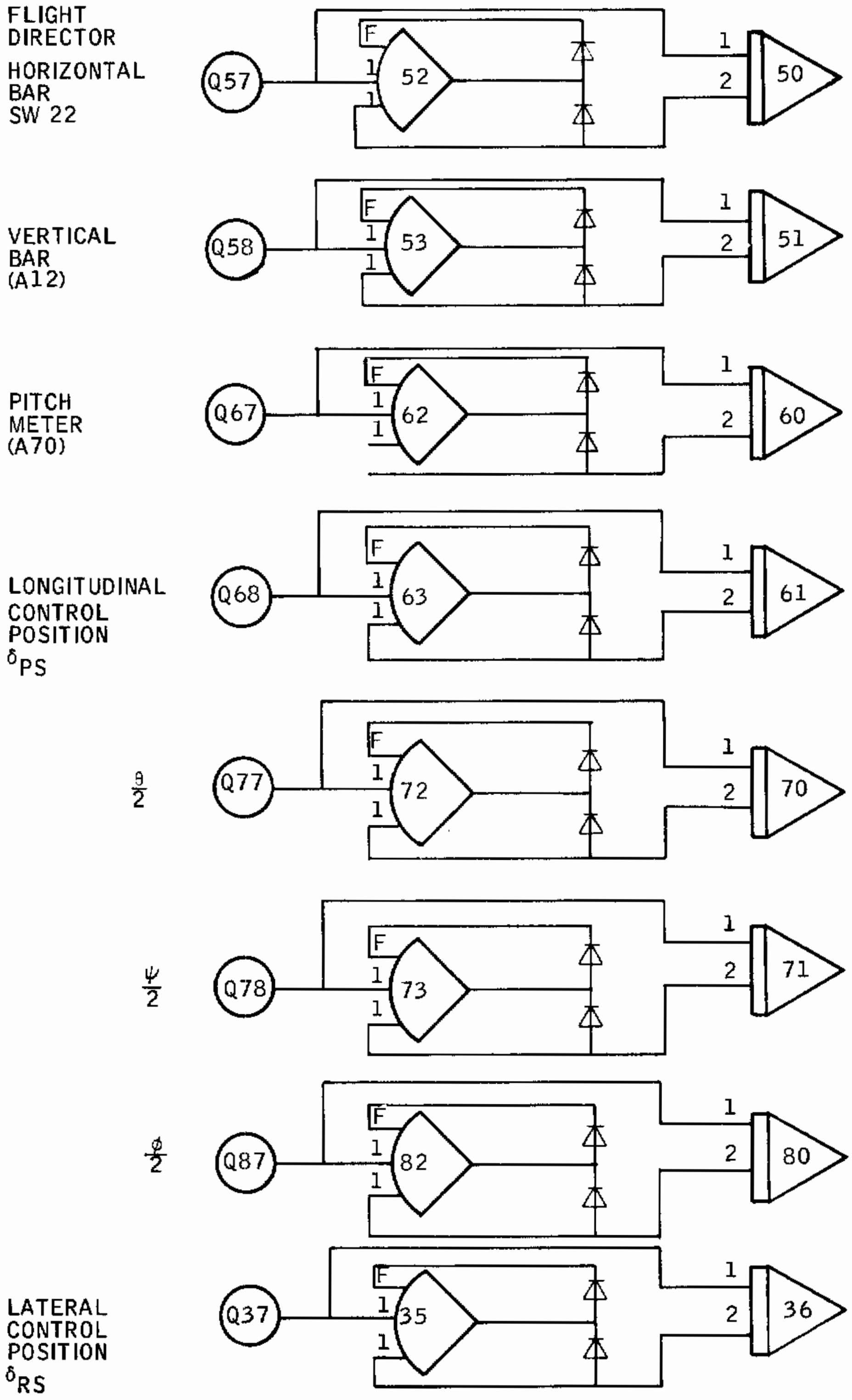


Figure 38. Mean Absolute Value Circuits, Console IV

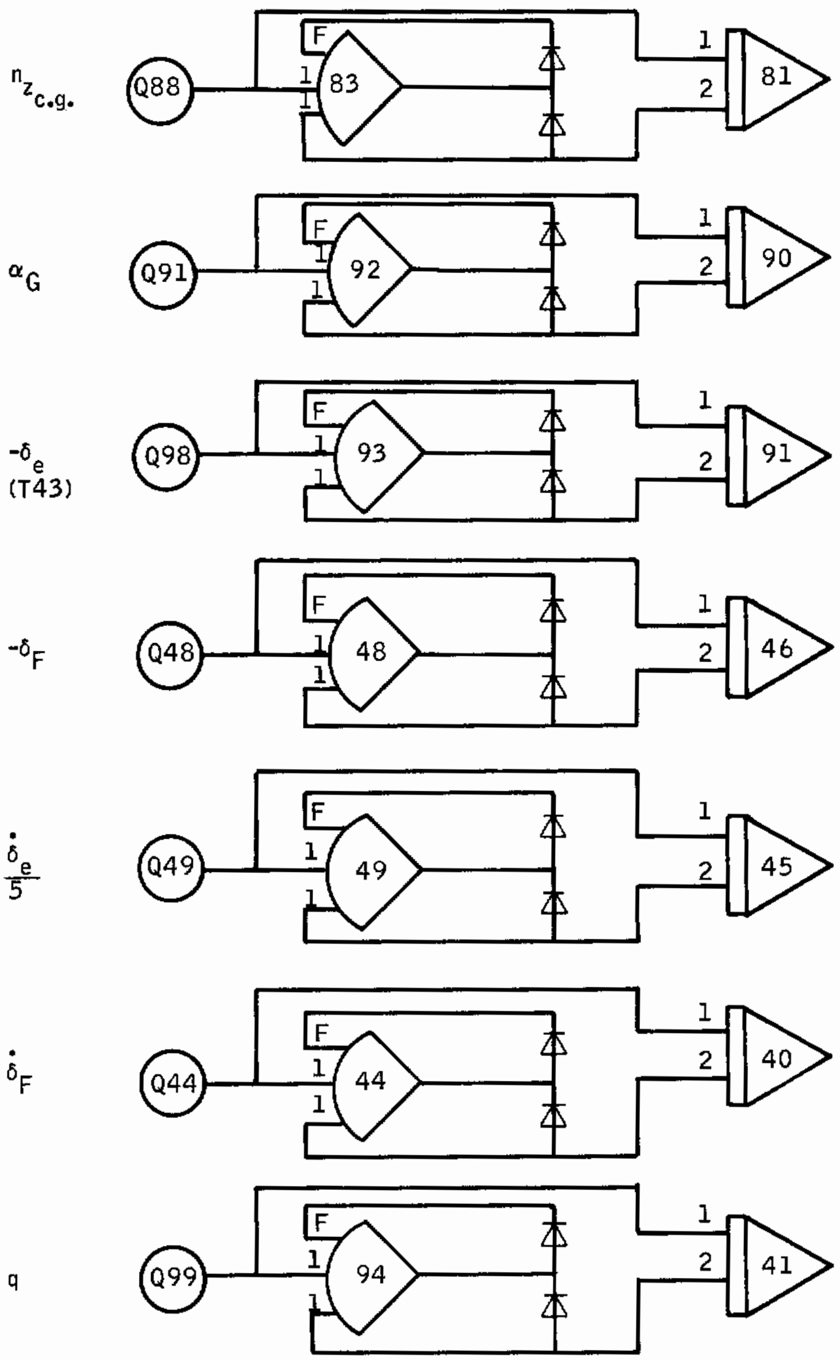


Figure 38. Mean Abolute Value Circuits, Console IV -- Concluded

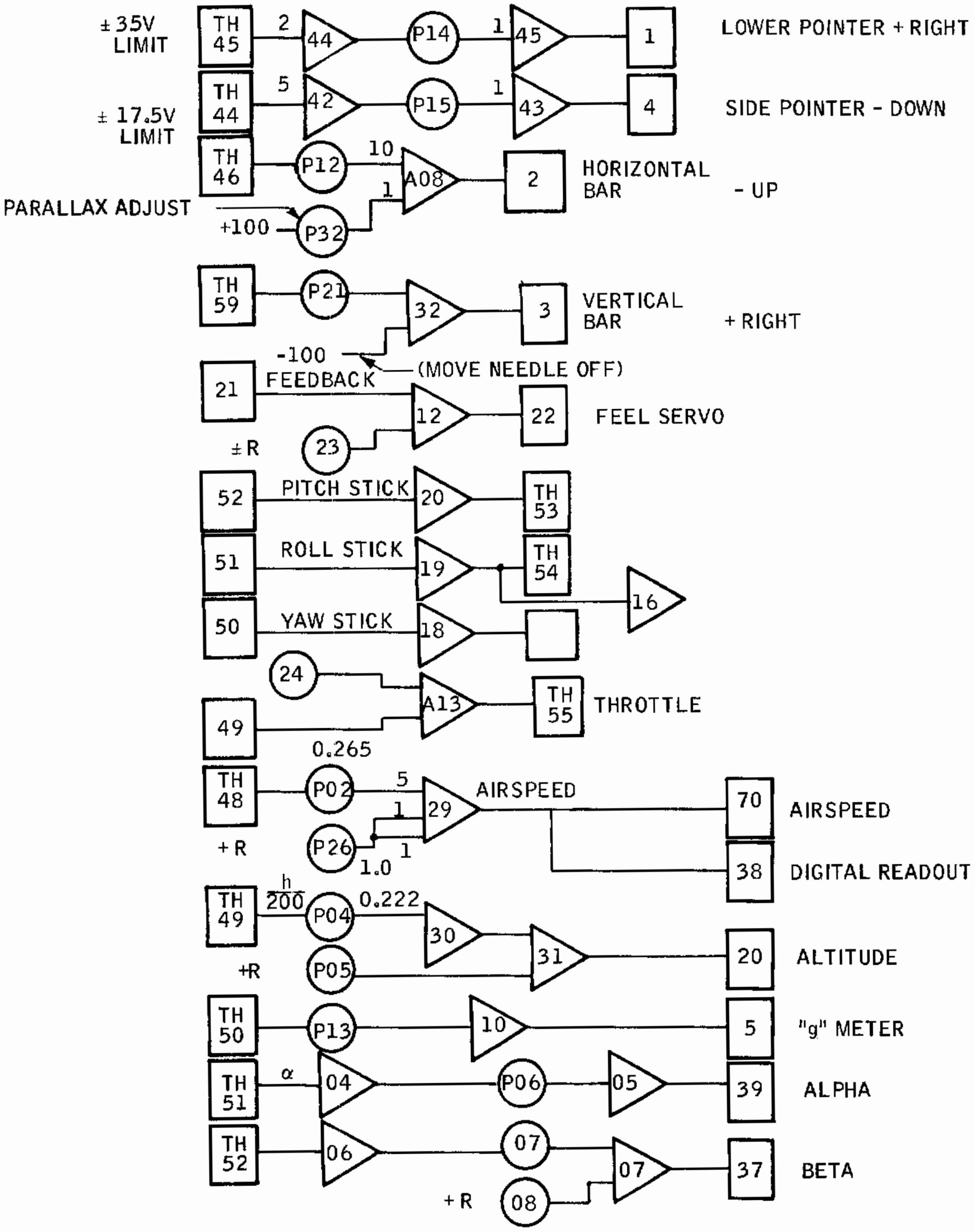


Figure 39. Simulator Instrumentation

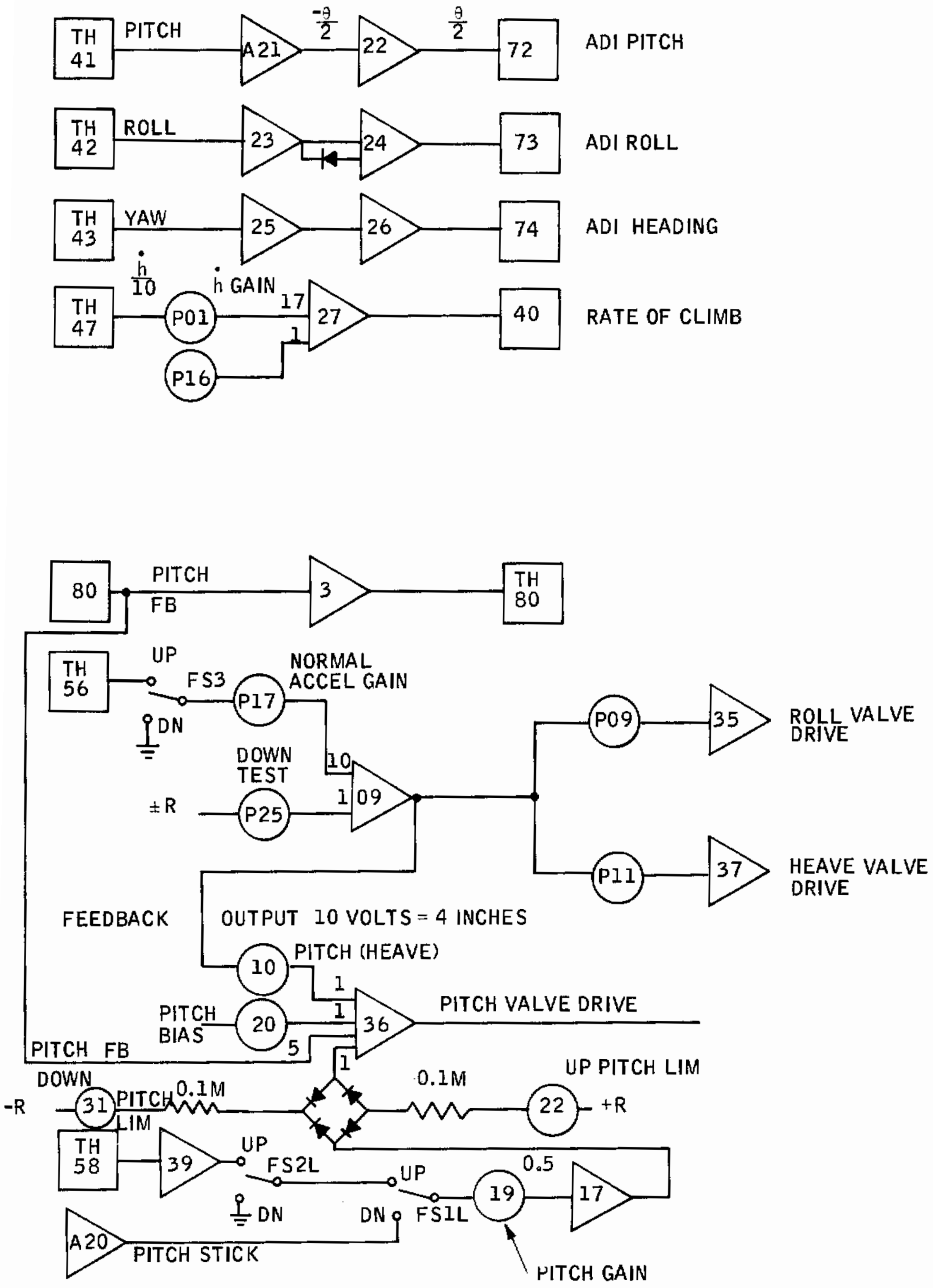


Figure 39. Simulator Instrumentation -- Continued

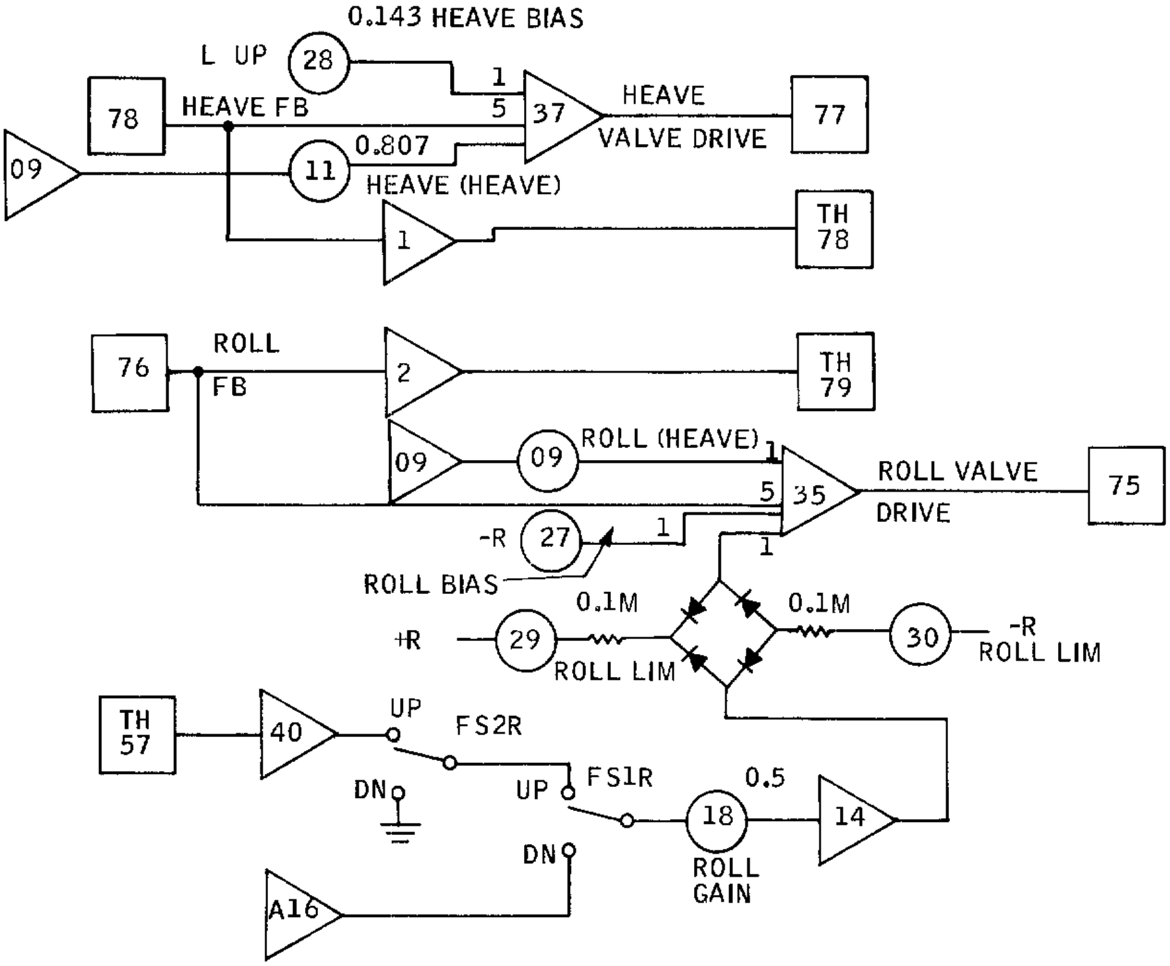


Figure 39. Simulator Instrumentation -- Concluded

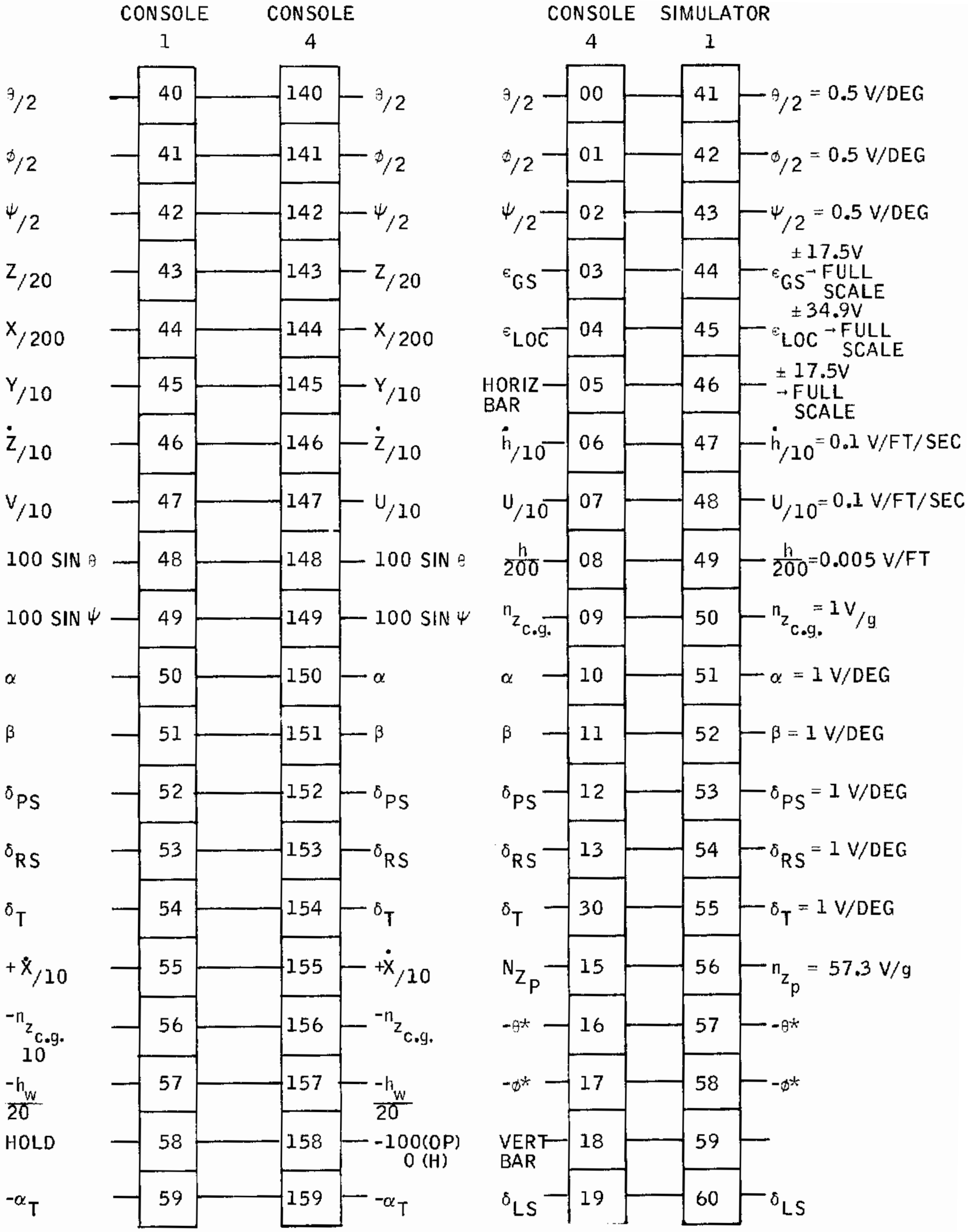


Figure 40. Interconnects

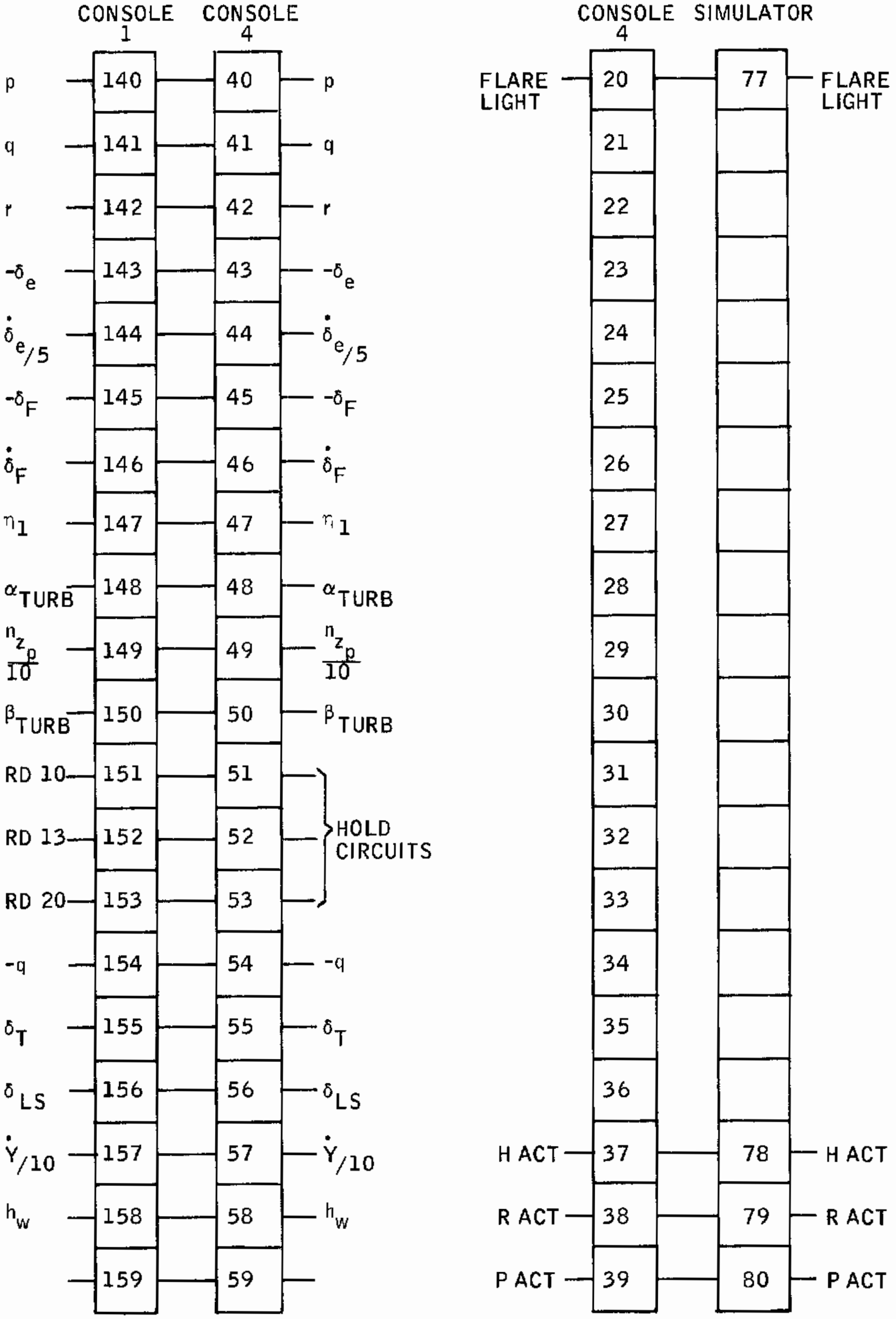


Figure 40. Interconnects -- Concluded

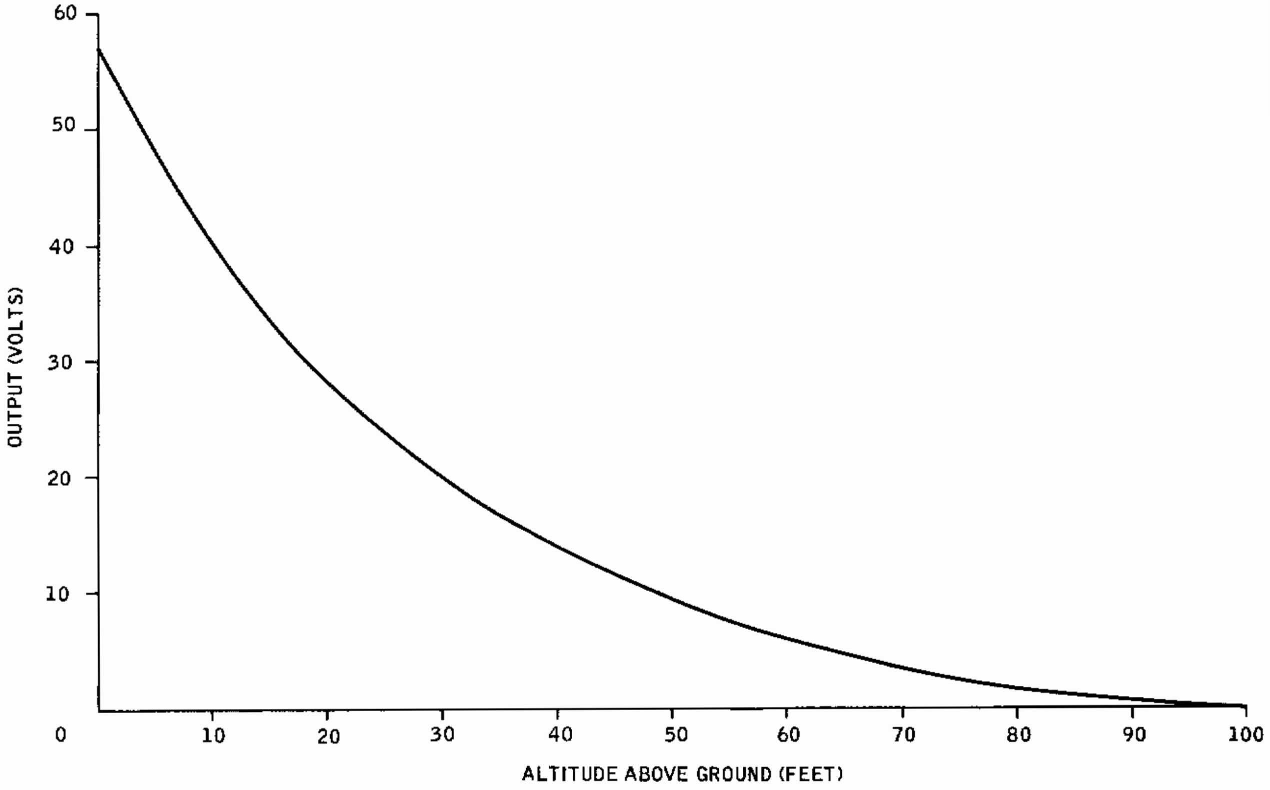


Figure 41. C-17 Ground Effect Simulation

APPENDIX IV

POTENTIOMETER AND LIMITER SETTINGS

Table XII presents aircraft data. Tables XIII through XVI present potentiometer and limiter settings. Lateral potentiometer settings of C-5A condition 29 were used for C-5A conditions 1 and 27.

Table XII. Aircraft Data

NAME ______ DATE ______ PROBLEM ______ SHEET ______ OF ______ BOARD NO. ______

POT. NO.	PARAMETER DESCRIPTION	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 LAND		COND. 104 5		COND. 104 24	
		GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
	MACH NO.		.17		.6		.6		.3		.9		.9
	AIRSPEED, FT/SEC		190		670		622		335		988		875
	DYNAMIC PRESSURE, lbs/ft^2		43		533		245		133		998		282
	c.g., % MAC		19		19		19		7		7		7
	WEIGHT, LBS			450,000						16,300			

Table XIII. Potentiometer Assignment Sheet, Console 1

NAME ____ DATE ____ PROBLEM ____ SHEET ____ OF ____ BOARD NO. ____

POT. NO. Q	PARAMETER DESCRIPTION Console 1	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 LAND		COND. 104 5		COND. 104 24	
		GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
00	qS/mU		.10		.352		.175		.154		.387		.123
01	$\Delta C_{L_{GE}}$		.05		0		0		0		0		0
02													
03	$-C_{Z_{\delta e}}/2$		.16		.11		.15		.405		.50		.539
04	$qS/20\ mg$		.0295		.366		.169		.078		.605		.167
05													
06													
07													
08	$\alpha_G/100$		.025		.025		.025		.025		.025		.025
09													
10													
11													
12													
13	57.3 g/100		.097		.0274		.0296		.055		.0185		.021
14	$U_0/1000$		.188		.670		.622		.335		.988		.875
15													
16													
17	0.0573		.0573		.0573		.0573		.0573		.0573		.0573
18	1p/109		.279		.279		.279		.062		.062		.062
19	Uc/209		.621		.621		.621		.621		.621		.621
20													
21	$\pm C_{x_W}$		+.8		+.106		+.195		+.63		-.033		-.292
22	$-C_{x_{\bar{u}}}$		.40		.034		.036		.78		.104		.17
23	$-2\Delta C_{D_{GE}}$		.170		0		0		0		0		0
24	$57.3\ g/100U_1$		.097		.0274		.0296		.055		.0185		.021
25													
26													
27	0.10		.10		.10		.10		.10		.10		.10
28	$\bar{u}_G/100$												
29	.05		.05		.05		.05		.05		.05		.05
30	$\frac{qSc}{aI_y}$ a=50 104 a=10 C5A		.031		.387		.134		.085		.637		.18
31	$-\Delta C_{M_{GE}}$		.062		0		0		0		0		0
32													
33	$-\left(\frac{c}{2U}\right)C_{m_{\dot{\alpha}}}$		.71		.120		.231		.049		.0212		.0342
34	$\pm C_{m_u}$		0		0		0		0		+.097		-.0907
35	Scaling Sep. Flap		.015		.015		.015		.015		.015		.015
36													
37	C_{m_β}		(.256)		(.105)		.10		.53		.43		.50

Table XIII. Potentiometer Assignment Sheet, Console 1 -- Continued

NAME ________ DATE ________ PROBLEM ________ SHEET ____ OF ____ BOARD NO. ____

POT. NO. Q	PARAMETER DESCRIPTION	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 LAND		COND. 104 5		COND. 104 24	
	Console 1	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
38													
39													
40													
41													
42													
43													
44													
45													
46													
47	qSb/aI_x a=1000 - 104 a=100 C-5A		(.0335)		(.414)		.190		.160		1.0		.340
48	$U_1/1146$		.166		.585		.544		.293		.865		.765
49													
50													
51													
52													
53													
54	0.5		.5		.5		.5		.5		.5		.5
55													
56													
57													
58													
59													
60													
61													
62													
63													
64	$K_{\delta F}/10$		.1		.1		.1		.1		.05		.09
65													
66													
67													
68													
69													
70													
71													
72													
73													
74													
75													

Table XIII. Potentiometer Assignment Sheet, Console 1 -- Continued

NAME ______ DATE ______ PROBLEM ______ SHEET ______ OF ______ BOARD NO. ______

POT. NO. Q	PARAMETER DESCRIPTION Console 1	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 LAND		COND. 104 5		COND. 104 24	
		GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
76													
77													
78	$K_{N_z \delta_c}/100$		.053		.177		.148		.147		.594		.594
79	$\left(\frac{1}{100}\right)\left(K'_{\delta_F \delta_c}/K_{\delta_F}\right)$		.018		.015		.025		.056		.084		.155
80													
81													
82	1/100T		.06		.06		.06		.5		.5		.5
83													
84													
85													
86													
87													
88	$K_{C^* \delta_c}/100$		.071		.238		.197		.206		.832		.832
89	$K_{\delta_e}/10$		.2		.02		.04		.02		.004		.015
90													
91	$qS/20\ mg$		.0295		.366		.169		.078		.605		.167
92	$\left(\frac{b}{2U}\right) C_{Y_r}$		(.27)		(.069)		.072		0		0		0
93													
94													
95													
96													
97	qS/mU		(.1)		(.352)		.175		.154		.387		.126
98	$-C_{Y_p}/10$		(.08)		.086		.086		.1		.11		.12
99	$57.3g/100\ U_1$		(.097)		(.0274)		.0296		.055		.0185		.021

Table XIII. Potentiometer Assignment Sheet, Console 1 -- Continued

NAME ____ DATE ____ PROBLEM ____ SHEET ____ OF ____ BOARD NO. ____

POT. NO. P	PARAMETER DESCRIPTION Console 1	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 LAND		COND. 104 5		COND. 104 24	
		GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
00	$\alpha_o/100$		.074		-.01		.005		.111		.02		.048
01	$-C_{Z_W}/10$		.53		.453		.509		.30		.473		.473
02	$-C_{Z_{\bar{u}}}/10$		.34		.027		.059		.125		.049		.0924
03	$-C_{Z\delta_F}/10$		.230		.149		.150		.085		.085		.086
04													
05													
06	0.5		.5		.5		.5		.5		.5		.5
07	$U_1/1146$		.166		.585		.544		.293		.865		.764
08													
09													
10	$2\delta/10w$ (THROTTLE SIM.)		.2		.2		.2		.2		.2		.2
11	$-X_{1C}$		.2		.2		.2		.2		.2		.2
12	.05		.05		.05		.05		.05		.05		.05
13													
14													
15	$W_e^2/10$		.1		.1		.1		.1		.1		.1
16													
17	10/57.3		.175		.175		.175		.175		.175		.175
18	10/57.3		.175		.175		.175		.175		.175		.175
19													
20	$U_1/1146$		.166		.585		.544		.293		.865		.764
21	qS/mU_1		.10		.352		.175		.154		.387		.123
22	$-C_{x\delta e}$												
23	$-C_{x\delta F}$		.25		.071		.07		.17		.17		.17
24	$\left(\frac{\Delta T}{\delta_T}\right)\frac{1}{mU}$		.067		.0195		.021		.082		.0278		.0312
25	DAMPING r		(1.0)		.1		.1		1.0		.1		.2
26													
27													
28	$1/10T_f$		.1		.1		.1		.5		.5		.5
29													
30	$\left(\frac{\Delta T}{\delta_T}\right)Z/I_y$		.0264		.0264		.0264		0		0		0
31	$-C_{m_\alpha}/10$		.129		.116		.198		.101		.092		.133
32	$-\left(\bar{c}/2U\right)\frac{C_m}{10}q$		.203		.044		.074		.0098		.0046		.0056
33													
34	$-C_{m\delta F}$		.171		.072		.190		.096		.096		.112
35													
36	$qSb/100I_z$		(.0146)		(.180)		.0826		.096		.72		.203
37													

Table XIII. Potentiometer Assignment Sheet, Console 1 -- Concluded

NAME ____ DATE ____ PROBLEM ____ SHEET ____ OF ____ BOARD NO. ____

POT. NO. P	PARAMETER DESCRIPTION Console 1	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 LAND		COND. 104 5		COND. 104 24	
		GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
38	$-(b/2U)C_{n_r}$		(.165)		(.037)		.039		.026		.0096		.012
39	$-10(I_x-I_z)/57.3 I_y$		.173		.137		.137		.164		.164		.164
40	$-Cm_{\delta e}/10$		.132		.093		.169		.158		.217		.23
41	10/57.3		.175		.175		.175		.175		.175		.175
42	2/100Te		.12		.12		.12		1.0		1.0		1.0
43	.5		.5		.5		.5		.5		.5		.5
44													
45	$\theta_0/200$		.037		-.005		.0025		.055		.01		.024
46	$\beta_G/100$		.025		.025		.025		.025		.025		.025
47	$-(b/2U)C_{\ell_p}$		(.27)		(.067)		.081		.0096		.0032		.0045
48	$-C_{\ell_\beta}$		(.032)		(.19)		.16		.12		.133		.12
49	$-10\ C_{\ell_{\delta a}}$		(.45)		(.14)		.27		.43		.38		.45
50													
51													
52	$\pm\ C_{z_0}/100$		SW 00										
53	$\pm\ C_{m_0}/100$		SW 01										
54	$\pm\ C_{x_0}/100$		SW 02										
55													
56													
57	BIAS												
58	BIAS												
59	BIAS												
60													
61													
62	BALANCE	SW 03											
63	BALANCE	SW 10											
64													
65													
66													
67													
68													
69													

Table XIV. Potentiometer Assignment Sheet, Console 4

NAME ____________ DATE ________ PROBLEM ____________ SHEET ______ OF ______ BOARD NO. ________

POT. NO. Q	PARAMETER DESCRIPTION Console 4	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 LAND		COND. 104 5		COND. 104 24	
		GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
00													
01	$\frac{Z_a - Z_w}{2000}$		.390		-		-		.3975		-		-
02	$h_{Ft}/2000$		.03		-		-		.03		-		-
03													
04	$17.45\ \epsilon_B/100$		.5		-		-		.5		-		-
05													
06													
07													
08													
09	.005		.005		.005		.005		.005		.005		.005
10	Scaling ball		.79		.79		.79		.79		.79		.79
11	X_{GI} Scaling		.5						.5				
12	$1/1.745\ \epsilon_B$		.20		-		-		.20		-		-
13	Ro/2000		.80		-		-		.65		-		-
14	Ro/2000		.80		-		-		.65		-		-
15	SIM MOTION $\phi/2$		.1		.1		.1		.1		.1		.1
16	SIM MOTION P		.25		.25		.25		.125		.125		.125
17	Zo/20,000		.04		.25		(1.0)		.04		.25		(1.0)
18	.1		.10		.10		.10		.10		.10		.10
19													
20	$(X_L - \ell_R)/40{,}000$		.625		-		-		.625		-		-
21	ho/100		.10		-		-		.20		-		-
22	$1/T_F$		.125		-		-		.125		-		-
23	BAR GAIN		.666		.666		.666		.666		.666		.666
24	FLARE LIGHT		.28						.28				
25													
26													
27													
28	SIM MOTION q		.5		.5		.5		.25		.25		.25
29	SIM MOTION $\theta/2$		.1		.1		.1		.1		.1		.1
30													
31	$(X_G - \ell_R)/20{,}000$		.8		-		-		.8		-		-
32	VERT BAR Y		.0286		.0143		.0143		.0143		.0143		.0143
33	VERT BAR $\dot{Y}$		.286		.1432		.1432		.1432		.1432		.1432
34	Zo/2000		.4		-		-		.4		-		-
35													
36	$\ell_R/1000$		.10		-		-		.02		-		-
37	RMS LATERAL CONTROL POS.		.1		.1		.1		.1		.1		.1

Table XIV. Potentiometer Assignment Sheet, Console 4 -- Continued

NAME ______ DATE ______ PROBLEM ______ SHEET ______ OF ______ BOARD NO. ______

POT. NO. Q	PARAMETER DESCRIPTION Console 4	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 5		COND. 104		COND. 104 24	
		GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
38													
39													
40	ℓ_R /2000		.05		-		-		.01		-		-
41	VERT BAR GAIN Ø		1.0		1.0		1.0		1.0		1.0		1.0
42	BAR GAIN		1.0		.5		1.0		1.0		.4		.25
43	VERT BAR GAIN P		0.0						0.0				
44	RMS $\dot{\delta}_F$		.05		.025		.05		.025		.025		.025
45													
46													
47													
48	RMS δ_F		.1		.1		.1		.1		.1		.1
49	RMS $\dot{\delta}_e/5$		.1		.1		.1		.1		.1		.1
50			.143						.143				
51	GLIDE S L BEAM GAIN		.857						.857				
52	.5 FLARE SWITCH		.50		.50		.50		.50		.50		.50
53	.5 FLARE SWITCH		.50		.50		.50		.50		.50		.50
54	.5 FLARE SWITCH		.50		.50		.50		.50		.50		.50
55													
56													
57	RMS FLIGHT DIRECTOR LATERAL POINTER		.1		.1		.1		.1		.1		.1
58	RMS FLIGHT DIRECTOR LONGITUDINAL POINT		.1		.1		.1		.1		.1		.1
59													
60													
61													
62													
63													
64													
65													
66													
67	RMS FLIGHT DIRECTOR LONG. METER		.1		.005		.1		.05		.005		.005
68	RMS PITCH CONTROL COLUMN		.1		.1		.1		.1		.1		.1
69													
70													
71													
72													

Table XIV. Potentiometer Assignment Sheet, Console 4 -- Continued

NAME ______ DATE ______ PROBLEM ______ SHEET ______ OF ______ BOARD NO. ______

POT. NO.	PARAMETER DESCRIPTION	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 LAND		COND. 104 5		COND. 104 24	
Q	Console 4	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
73													
74													
75													
76													
77	RMS $\theta/2$		.2		.1		.2		.1		.1		.1
78	RMS $\psi/2$		.5		.1		.1		.5		.1		.1
79	SIM MOTION		.64		.64		.64		.64		.64		.64
80													
81													
82													
83													
84	SIM MOTION		.26		.26		.26		.26		.26		.26
85													
86													
87	RMS $\phi/2$		.1		.1		.1		.1		.1		.1
88	RMS N_Z C.G.		1.0		.2		.2		1.0		.2		.2
89	SIM MOTION		.64		.64		.64		.64		.64		.64
90													
91	RMS, α_G		.2		.2		.5		.2		.2		.2
92													
93													
94													
95													
96													
97													
98	RMS $-\delta_e$		.1		.1		.1		.1		.1		.1
99	RMS, q		.2		.1		.1		.2		.2		.1

Table XIV. Potentiometer Assignment Sheet, Console 4 -- Continued

NAME ____ DATE ____ PROBLEM ____ SHEET ____ OF ____ BOARD NO. ____

POT. NO p	PARAMETER DESCRIPTION	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 LAND		COND. 104 5		COND. 104 24	
	Console 4	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
00	L/U		.32		.67		.125		.55		1.0		.175
01	GUST GAIN		.2		.15		.14		.1		.05		.05
02	IFR		.4		.4		.4		.4		.4		.4
03	IFR		.014		.014		.014		.014		.014		.014
04	TIME DELAY		.8		.8		.8		.8		.8		.8
05			.32		.32		.32		.5		.5		.5
06													
07													
08	$10/T^2$		.28		.28		.28		.63		.63		.63
09	TERRAIN GAIN		.25		.25		.25		.25		.25		.25
10													
11													
12													
13													
14													
15	TIME DELAY		.8		.8		.8		.8		.8		.8
16													
17													
18													
19													
20													
21	IFR		.05		.05		.05		.05		.05		.05
22													
23													
24	FLARE HOR. BAR GAIN		1.0						1.0				
25													
26													
27													
28													
29													
30	IFR, TERRAIN		.35		.32		.35		.35		.50		.35
31	(IFR, .1)(TERRAIN $1/T^2$)		.1		.028		.1		.1		.063		.1
32													
33	IFR		.000		.000		0.1		.000		.000		0.1
34	1 /573		.000		.000		.157		.000		.000		.035
35			0.05		.05		.012		.2		.14		.012
36													
37													

Table XIV. Potentiometer Assignment Sheet, Console 4 -- Concluded

NAME ____________ DATE ________ PROBLEM ____________ SHEET ______ OF ______ BOARD NO. ________

POT. NO P	PARAMETER DESCRIPTION	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. 104 LAND		COND. 104 5		COND. 104 24	
	Console 4	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
38													
39													
40													
41	h gain		1.0		1.0		.117		1.0		1.0		.117
42	$\dot{h}$ gain		.5		.25		.5		.5		.25		.5
43													
44													
45													
46													
47													
48													
49													
50													
51													
52	δ_{PS} Trim												
53	δ_{RS} Trim												
54	δ_T Trim												
55													
56													
57													
58													
59													
60													
61													
62	δ_{PS} Scale		.3		.3		.3		.3		.3		.3
63	δ_{RS} Scale		1.0		1.0		1.0		.5		.4		1.0
64													
65													
66													
67	δ_{TS} Scale		.33		.33		.33		.33		.33		.33
68													
69													

Table XV. Potentiometer Assignment Sheet, Simulation Console

NAME ______ DATE ______ PROBLEM ______ SHEET ______ OF ______ BOARD NO. ______

POT. NO.	PARAMETER DESCRIPTION	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. F104 LAND		COND. F104 5		COND. F104 24	
	SIMULATOR CONSOLE	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
1	$\dot{h}$ Scale		1.0		1.0		1.0		1.0		1.0		1.0
2	U Scale		.22		.22		.22		.22		.22		.22
3	U Bias		0		0		0		0		0		0
4	h Scale		.222		.222		.222		.222		.222		.222
5	h Bias		.552		.552		.552		.552		.552		.552
6	α Scale		.393		.393		.393		.393		.393		.393
7	β Scale		.305		.305		.305		.305		.305		.305
8	β Bias		.016		.016		.016		.016		.016		.016
9	Heave to R Act		.75		.75		.75		.75		.75		.75
10	Heave to P Act		.80		.80		.80		.80		.80		.80
11	Heave to H Act		.806		.806		.806		.806		.806		.806
12	Horiz. Bar Scale		.580		.580		.580		.580		.580		.580
13	"G" Scale		.315		.315		.315		.315		.315		.315
14	Bottom Pointer		.770		.770		.770		.770		.770		.770
15	Side Pointer		.790		.790		.790		.790		.790		.790
16	$\dot{h}$ Bias		.005		.005		.005		.005		.005		.005
17	Heave Scale		.1		.1		.1		.1		.1		.1
18	Roll Scale		.3		.3		.3		.3		.3		.3
19	Pitch Scale		1.0		1.0		1.0		1.0		1.0		1.0
20	Pitch Bias		.07		.07		.07		.07		.07		.07
21	Vert. Bar Scale		1.0		1.0		1.0		1.0		1.0		1.0
22	Pitch Limit		.40		.40		.40		.40		.40		.40
23	Feel Servo		-		-		-		-		-		-
24	Throttle Bias		.41		.41		.41		.41		.41		.41
25	Heave Test		0		0		0		0		0		0
26	Airspeed Bias		.550		.550		.550		.550		.550		.550
27	Roll Bias		.003		.003		.003		.003		.003		.003
28	Heave Bias		.128		.128		.128		.128		.128		.128
29	Roll Limit +		.275		.275		.275		.275		.275		.275
30	Roll Limit -		.275		.275		.275		.275		.275		.275
31	Pitch Limit -		.53		.53		.53		.53		.53		.53
32	Parallax		-		-		-		-		-		-

Table XVI. Potentiometer Assignment Sheet, Limiters

NAME LIMITERS DATE ______ PROBLEM ______ SHEET ____ OF ____ BOARD NO. ______

POT. NO.	PARAMETER DESCRIPTION	COND. C-5A 1		COND. C-5A 27		COND. C-5A 29		COND. F-104 LAND		COND. F-104 5		COND. F-104 24	
	Console 1	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET	GN	SET
17	Throttle Rate		±100		±100		±100		±100		±100		±100
28	Flap Position		±15V		±15V		±15V		±15V		±15V		±15V
29	Flap Rate		±20V		±20V		±20V		±20V		±20V		±20V
37	Aileron Rate/10		±2.5V		±2.5V		±2.5V		±5V		±5V		±5V
47	Elevator Position		±25V		±25V		±25V		±25V		±25V		±25V
49	Elevator Rate/5		±5V		±5V		±5V		±10V		±10V		±10V
18	-$\dot{X}$/200		±100V		±100V		±100V		±100V		±100V		±100V
7	-Z/20		±100V		±100V		±100V		±100V		±100V		±100V
27	Airspeed		±100V		±100V		±100V		±100V		±100V		±100V
09	-Y/10		±100V		±100V		±100V		±100V		±100V		±100V
	Console 4												
09	Horiz. Bar and Glideslope Beam		±17.5		±17.5		±17.5		±17.5		±17.5		±17.5
27	Flare error		±100V		±100V		±100V		±100V		±100V		±100V
47	Localizer Beam Error		±24.9		±34.9		±34.9		±34.9		±34.9		±34.9
08	Glideslope Inter		±100V		±100		±100		±100V		±100		±100
07	Touchdown		±100		±100V		±100V		±100V		±100V		±100V
19	Vertical Bar		±100V		±100V		±100V		±100V		±100V		±100V
38	Heave Drive		±20		±20V		±20V		±20V		±20V		±20V
39	n_{zcg} Display		±3V		±3V		±3V		±3V		±3V		±3V
29	θ* Drive		±50V		±50V		±50V		±50V		±50V		±50V
17	ø* Drive		±50V		±50V		±50V		±50V		±50V		±50V
18	AMP 42		±100		±100V		±100V		±100V		±100V		±100V

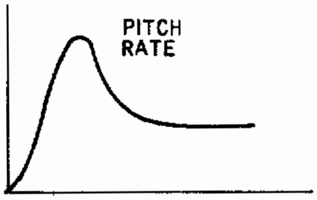
APPENDIX V

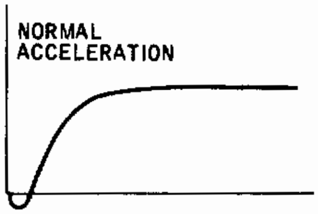
INSTRUCTIONS TO PILOTS -- DIRECT LIFT CONTROL SIMULATOR PROGRAM

INTRODUCTION

This simulator program is designed to obtain information on the benefits that can be obtained by the use of closed-loop direct lift control (DLC) blended with conventional elevator control. Some aerodynamic control surface (flaps, spoilers) combined with elevator is used to control the lift of the aircraft.

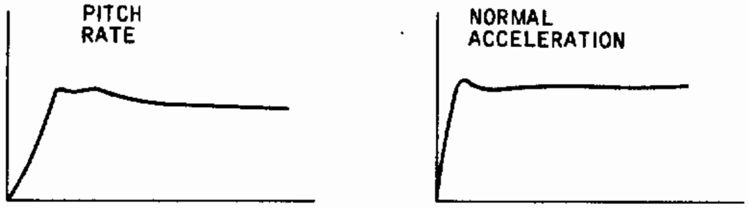
Previous flight tests of high-gain, self-adaptive flight control systems have demonstrated significant improvements in aircraft stability and maneuverability. However, with conventional elevator control precise flight path control is difficult in certain flight regimes because of the pitch rate overshoot that occurs when controlling normal acceleration. Both lift and normal acceleration are controlled by pitching the aircraft with the elevator. This is shown below in a typical transient response for a step elevator input:





There is also the initial acceleration reversal because of the down force of the elevator. The aircraft has to pitch and change angle of attack before normal acceleration builds up in the proper direction.

The DLC configurations that will be investigated will tend to speed up normal acceleration response and reduce pitch rate overshoot as compared with conventional elevator control. This is shown on the following page in a typical transient response for a step control input.



In some of the evaluation tasks you will be required to drive a flight director needle to zero. The signals to this director have not been optimized and in some cases have not even been quickened. This is because the signals and quickening to the director would be different for different control configurations and the purpose is not to evaluate flight director control laws, but rather to evaluate the benefits of DLC.

PROCEDURE

Four basic control configurations will be evaluated. These are conventional elevator control, blended closed-loop DLC, blended open-loop DLC, and separate DLC. Two aircraft types, a large transport (C-5A), and a fighter-bomber (F-104), will be used in the evaluation. The missions to be evaluated are landing, in-flight refueling, and terrain following. A general pilot evaluation of overall handling qualities will also be made at certain flight conditions. Evaluations will be made in turbulence and smooth air and without airspeed control. The primary evaluation will be concerned with the pitch axis.

Numerical (Cooper) ratings, answers to a pilot questionnaire, and pilot comments (written and oral) will be obtained at the end of each set of runs. In addition, when a tracking task is being performed, quantitative data will be taken to evaluate the pilot's performance of the tracking task. The pilots will be told which configuration they are evaluating. Each run will be approximately three minutes long and each distinct run will be repeated twice.

LANDING TASK

Start each approach with the aircraft trimmed for level flight at 800 feet altitude and on the localizer. You may have to make some minor trim corrections for computer offsets. Maintain constant altitude (800 feet), airspeed, and control to the localizer until the glide slope needle comes off the peg. Acquire the glide slope and follow while maintaining localizer and airspeed. At 60 feet altitude you will begin the flare maneuver. Information for flare control will be presented on the flight director. You will be required to fly the flight director needle to zero. Pitch attitude at touchdown should correspond approximately to the initial pitch attitude during the level flight portion of the run. Sheet E-1 gives the evaluation maneuver and pilot comment check list for this task.

GENERAL HANDLING QUALITY EVALUATION

Start each run in straight and level flight. Some minor trim adjustments may be necessary for computer offsets. In this evaluation you will be asked to make certain specified maneuvers. Sheet E-2 gives the evaluation maneuver and pilot comment check list for this task.

TERRAIN FOLLOWING

Start each run in straight and level flight. Some slight retrimming may be necessary for computer unbalances. After the aircraft has been trimmed you will fly some simulated terrain following task. A random flight path command signal will be generated and summed with the aircraft flight path. This signal will be presented on the flight director. You will be asked to fly the flight director to zero. Sheet E-3 gives the evaluation maneuver and pilot comment check list for this task.

IN-FLIGHT REFUELING

Start each run in straight and level flight. Some slight retrimming may be necessary for computer unbalances. The error between the drogue altitude and your altitude and drouge altitude rate and your altitude rate will be displayed on the flight director. You are to zero this needle while maintaining a constant heading. Sheet E-4 gives the evaluation maneuver and pilot comment check list for this task.

COOPER RATING AND CONFIGURATION DEFINITION

Sheet E-5 gives the Cooper rating scale that will be used and an identification of the control configurations.

PILOT EVALUATION SHEET

Sheet E-6 gives the pilot questionnaire that will be used for each series of runs.

SHEET E-1

TASK CARD -- LANDING

EVALUATION MANEUVERS

1. (a) Trim aircraft for straight and level flight at 800 feet.
   (b) Localizer needle - zero.

2. (a) Glide slope needle - acquire and maintain to zero.
   (b) Localizer needle - zero.
   (c) Reference airspeed (C-5A--112 knots, F-104--220 knots).

3. Flare - flare will automatically start at 60 feet altitude - continue to maintain horizontal needle to zero.

4. Touchdown - touchdown pitch attitude should correspond to level flight pitch attitude.

PILOT COMMENT CHECK LIST

1. Was it difficult to trim and maintain constant altitude?

2. Was the glide slope difficult to acquire and track?

3. Was the localizer difficult to track?

4. Did you consider presentation for glide maneuver adequate for evaluation?

5. Was the flare maneuver difficult?

6. Did you consider presentation for flare maneuver adequate for evaluation?

7. Was aircraft damping satisfactory?

8. Was airspeed difficult to maintain?

9. Do you have any comments on the stick force and displacement characteristics?

10. Was the total task difficult or easy?

11. Was sink rate easy to control?

12. Would it be advantageous to have a separate DLC control?

SHEET E-2

TASK CARD -- GENERAL HANDLING QUALITY EVALUATION

EVALUATION MANEUVERS

1. Trim aircraft for straight and level flight:
   (C-5A -- 15,000 feet and 370 knots)
   (F-104 -- 15,000 feet and 500 knots).

2. (a) Climb 1000 feet at 4000 feet per minute.
   (b) Stabilize altitude.
   (c) Descend at 4000 feet per minute to 15,000 feet and stabilize altitude.

3. (a) Bank 30 degrees and change heading 30 degrees; maintaining 15,000 feet altitude.
   (b) Roll out and stabilize new heading and altitude.

4. (a) Bank 45 degrees and change heading 60 degrees; maintaining 15,000 feet altitude.
   (b) Roll out and stabilize new heading and altitude.

5. In the F-104:
   (a) Bank 70 degrees and change heading 90 degrees maintaining 15,000 feet altitude.
   (b) Roll out and stabilize new heading and altitude.

6. (a) Make a rapid 1-g pull-up, stabilize g's.
   (b) Hold for two seconds.
   (c) Return rapidly to zero incremental g's and stabilize g's.

PILOT COMMENT CHECK LIST

1. Is the aircraft difficult to trim?

2. Is attitude control satisfactory?

3. Is your vertical acceleration response satisfactory?

4. Is altitude difficult to hold in turns?

5. Was lateral control a problem?

6. Was there a tendency toward pilot-induced oscillation (PIO)?

SHEET E-2--CONCLUDED

7. Was aircraft damping satisfactory?
8. Do you have any comments on stick force and displacement characteristics?
9. Was task difficult or easy?
10. Would it be advantageous to have a separate DLC control?

SHEET E-3

TASK CARD -- TERRAIN FOLLOWING

EVALUATION MANEUVER

1. Trim aircraft for straight and level flight.
2. When simulated terrain is introduced, track by driving flight director needle to zero.
3. Maintain constant heading and airspeed.

PILOT COMMENT CHECK LIST

1. Were you able to perform task easily?
2. Was airspeed difficult to maintain?
3. Was heading difficult to maintain?
4. Was there any tendency toward pilot-induced oscillation (PIO)?
5. What effect did turbulence have on your ability to perform the task?
6. Do you have any comments on stick force and displacement characteristics?
7. Was information presented on display adequate?

SHEET E-4

TASK CARD -- IN-FLIGHT REFUELING

EVALUATION MANEUVER

1. Trim aircraft for straight and level flight.
2. Fly flight director needle to zero.
3. Maintain constant heading.

PILOT COMMENT CHECK LIST

1. Were you able to perform task easily?
2. Was heading difficult to maintain?
3. Was there any tendency toward pilot-induced oscillation (PIO)?
4. What effect did turbulence have on your ability to perform the task?
5. Do you have any comments on stick force and displacement characteristics?
6. Was information presented on display adequate?

SHEET E-5

COOPER PILOT RATING SYSTEM

Operating Conditions	Adjective Rating	Numerical Rating	Description	Primary Mission Accomplished	Can Be Landed
Normal operation	Satisfactory	1	Excellent, includes optimum.	Yes	Yes
		2	Good, pleasant to fly.	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics.	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics.	Yes	Yes
		5	Unacceptable for normal operation.	Doubtful	Yes
		6	Acceptable for emergency condition only.[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition.[1]	No	Doubtful
		8	Unacceptable - dangerous.	No	No
		9	Unacceptable - uncontrollable.	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape.	No	No

[1] Failure of stability augmenter

SHEET E-6
PILOT EVALUATION SHEET

DATE ____________________ PILOT ____________________

RUN NUMBER ______________ TEST ENGINEER ______________

COMBINATION ______________

TASK ____________________

COOPER RATING	HOW DID YOU DO?	WORK LOAD?
Pitch ________	1. Above Average	1. Light
Lateral ________	2. Average	2. Normal
Overall ________	3. Poor	3. Heavy
	4. Lousy	4. Extreme

COMMENTS:

APPENDIX VI
PILOT EXPERIENCE

INTRODUCTION

All pilots except one had military flying experience and were currently flying. The nonmilitary pilot had light aircraft experience and a large number of simulator hours. Pilot experience is summarized in Table XVII.

Table XVII. Pilot Experience

Type of Aircraft	Pilot Experience (Hours)						
	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7
Jet fighter or trainer	2000	2500	150	---	277	---	700
Jet bomber	---	---	---	---	1470	---	---
Jet cargo	---	---	---	1700	660	---	---
Reciprocating	1000	---	3200	1700	720	---	1400
Helicopter	---	---	---	---	21	---	---
Light aircraft	---	---	150	---	---	100	---
Total	3000	2500	3500	3400	3148	100	2100

PILOT RESUMES

Pilot 1

My previous aircraft experience has been mostly fighter F-86, and T-33. I have about 2000 hours jet and about 800 to 1000 hours of piston airplane, mostly small airplanes, some Dakota time, and some C-45 time.

Pilot 2

Personal experience has been limited to single-engine jet aircraft. I have a total of 2500 hours of which over 2000 are single-engine jet. The past 10 years I have been flying the F-84.

Pilot 3

I have approximately 3500 hours flying time. This includes about 600 hours of instrument time and 700 or 800 hours of night time. My experience has been in the T-33, T-37, and T-34 jet trainers, also about 1800 hours in the C-124, 1200 hours in HU-16's, 150 hours in light aircraft, and 200 hours in the C-47 which I am presently flying.

Pilot 4

Aircrafts experience includes KC-97, KC-135, C-45, C-123, T-39. Total time approximately 3300 to 3400 hours and 12 years of flying.

Pilot 5

I have a total of 3148 flying hours of which 277 are in single-engine jet; 226 are in the T-33; 48 are in the F-104; 2-1/2 are in the F-106; and 65 are in the T-38. I have 50 hours in the two-engine T-28. I have 700 hours of reciprocating engine time, in addition to power training time. This includes 682 hours in the T-47; 3 hours in the U-3; 3 hours in the Aero Commander; 7 hours in the B-26, and 5 hours in the B-25. I have 43 hours in the KC-97; 20 hours and 50 minutes in helicopters (the H-19 and the H-13); 6 hours and 30 minutes in a B-57; 10 hours in the C-141; 1460 hours in the B-47; 650 hours in the KC-135; and 20 or 30 hours in the UH-1 and T-39.

Pilot 6

I have about 100 hours of light aircraft time. I also have very large number of undocumented simulator hours; that is, flying different aircraft configurations in the AFFDL moving base simulator and in several of the other simulators located at Wright-Patterson Air Force Base. I have about 800 hours total time in simulators in the past four years.

Pilot 7

My flight experience consists of about 300 hours of F8U-type aircraft, 300 hours of B-26s, and approximately 800 hours in training command-type aircraft, both single-engine jet and single-engine prop, 150 hours in A5A (?) aircraft and 700 hours in C-47 and transport-type aircraft.

APPENDIX VII
PILOT COMMENTS

These edited comments, in chronological order, were taken primarily from a tape recorder. There were 112 pilot evaluation sheets, some of which had written comments in addition to Cooper ratings. These written comments are included here. The Cooper ratings are summarized in Appendix VIII.

Questions or comments by persons other than the pilot are enclosed in parentheses. Titles or other information added for identification are capitalized. The term "PIO" refers to pilot-induced oscillation. Run number codes are defined in Figure 43.

PILOT 1, INITIAL COMMENTS ON THE SIMULATION (9/12/67)

First of all I think the simulation seems quite realistic. It feels like a real large sluggish airplane as far as the controls are concerned. There is some question in my mind about the motion of the simulator. I noted that going into a bank was fine, that the simulator tipped; but then coming out, the simulator actually tipped the other way when the horizon was still indicating the bank in the initial direction, which is a little bit confusing. I haven't resolved in my own mind whether this is really good or bad, it seems a little unusual to me. (As a result of these comments, the simulation roll input to the moving base was changed from 10:1 rate-to-attitude ratio ratio.)

PILOT 2, C-5A GENERAL TASK (9/12/67)

25G2015, 16 (elevator with turbulence)

No difficulty experienced in trim of the aircraft. Didn't appear too far from normal. The attitude control seemed satisfactory when considering longitudinal pitch control only. A little difficult when I was combining the attitude control along with turn. Normal acceleration response seemed satisfactory except in rapid pull-ups, where it looks like a tendency to over-control. In other words, it is difficult to lead the point where I should stop the pitch in the rapid climb-up maneuver. Lateral control did not appear a problem. Altitude in the turns is difficult if you have to roll in rapidly or roll out rapidly. If you are given sufficient time to roll into a turn or roll out, there should be no difficulty in holding altitude. Is there any tendency toward PIO? It's this point of proficiency with the trainer. There seems to be a lot of that.

This could be damped out somewhat with practice with this particular trainer. The displacement characteristics are difficult depending on whether or not the maneuver gives you sufficient time to, for instance, roll in or to roll out of a bank after going through a required amount of "heading in a turn". The main difficulty in the total task was due to the turbulence which limited the amount of feel you could develop for the maneuvers that were required.

25G3018, 19 and 28 (elevator -- no turbulence)

The aircraft does not appear difficult to trim. The attitude control is somewhat easier without the turbulence factor thrown in. Normal acceleration appears to be satisfactory. Without the turbulence factor thrown in again, attitude or altitude is much easier to hold in turns. Lateral control presented no problem. There is still a tendency toward PIO in the 45-degree bank in maintaining altitude. Displacement characteristics appeared to be somewhat more normal than what I'm used to without the turbulence factor thrown in. The task was easier than with the turbulence factor thrown in.

25G5020, 21 (closed-loop DLC with turbulence

Attitude control is a little improved over the last run. Lateral control is no problem. PIO is reduced as I get more practice in the trainer. The task difficulty was less as more practice is achieved. I noticed very little difference, if any, over the no direct lift control mode without turbulence.

25G6022, 023 (closed-loop DLC -- no turbulence)

Attitude control appeared improved. Acceleration response is okay. Lateral control no problem. With practice, PIO decreases. Aircraft damping appeared normal. The tasks presented no problem. It appears that direct lift control does present advantages over a normal system. I'm trying to remember how it was without direct lift control. It seems like it's easier to hold or establish a satisfactory 45-degree steep turn, and the initial execution of that maneuver, if begun correctly, is much easier to maintain throughout the rest of the turn.

25G8024, 25 (open-loop DLC with turbulence)

With turbulence present, attitude control is much more satisfactory with DLC than without DLC. As I have more positive normal acceleration response, the altitude is much easier to hold in turns than that without DLC control. Lateral control is no problem. There is definitely less tendency toward PIO. The task was less difficult than without DLC.

25G9026, 27 (open-loop DLC -- no turbulence)

Trim is okay. Attitude control is definitely more satisfactory than without DLC, with good normal acceleration response. Altitude is less difficult to hold in turns. Direct lift control appears to help in initiating steeper turns such as the 45-degree bank maneuver. There is definitely less tendency toward PIO. Whether that is because of being more familiar with this trainer here or not is hard to tell as compared with the DLC versus no DLC mode. The task is becoming more easy to perform with the added assistance given by the direct lift control.

25G3028 (elevator -- no turbulence)

There is no difficulty in trim. In attitude control there is a difference between the DLC mode and the no DLC mode. It appeared that overcontrol on the other control (elevator control?) was occurring, especially in the steeper turns. This is also apparent in the rapid climb where there is more tendency to overshoot the given altitude. The normal acceleration response still appeared satisfactory. Again the altitude was a little more difficult to hold in the initial portion of the bank. Lateral control was no problem. The tendency toward PIO returned without the direct lift control. Damping appeared satisfactory. Stick displacement characteristics are okay. The task is a little more difficult without DLC when you depart from straight, level conditions or constant maneuvers. The DLC appears to give an advantage in smoothing out your maneuvers when rapid pull-ups or roll-ins into steep banks are required.

PILOT 3 C-5A GENERAL TASK (9/13/67)

35G2029, 30 (elevator with turbulence)

Stick force is light. Following through the maneuvers, first of all we made an altitude change of 1000 feet at 4000 feet a minute rate of climb; then we stabilized and descended back to 15, 000 feet at 4000 feet a minute and stabilized again. Then we made a 30-degree turn at a bank angle of 30 degrees. The fourth maneuver is a 45-degree bank angle to a change of 60 degrees in heading, and the last maneuver is a pull-up for two seconds after which we obtained level flight and reverted back to initial conditions. The aircraft is not difficult to trim in normal flight. It's a little touchy in the control. I think it reacts quite fast, so I haven't been trimming well in a turn because of the response that is there already. Altitude is not hard to hold in a turn. I would say there is moderate turbulence, with the needle fluctuating 80 to 100 feet at the peak gust as it is now. Lateral control is not hard to maintain because there is no side load. At least it feels like there is no side load with no rudder control. I think that's quite easy because of the sensitivity of the control to get part of the yaw oscillation if one is abrupt on the controls. I would rate the task as not hard, although not easy either.

35G3031, 32 (elevator -- no turbulence)

Without turbulence it was a lot easier to handle. The stick force is still extremely light. It doesn't take much of a movement to change one- to two-thousand feet rate of climb, which seems a little too light compared with the aircraft I've flown. Maintaining altitude and heading is much easier. I average about ±50 feet on altitude during both 30 degrees and 45 degrees of bank. Airspeed doesn't fluctuate as much either direction. The aircraft is quite easy to trim, and it doesn't take any trim going in the turn. The stick force is probably quite light. Attitude control is satisfactory. Lateral control tends, even when it looks like it's straight level flight, to drift a little to the right, but I think it's this one needle offset that gives a false indication of left turn anyway. Because of the light stick force, I think probably it's still possible to put in pilot-induced isolations. It doesn't take much stick movement to get 4000 feet a minute, either climb or descend, maybe something like one to two inches at the most. I would say the task was relatively easy with no turbulence.

35G5033, 34 (blended closed-loop DLC with turbulence)

The turbulence appeared to be less. There was less fluctuation on the altimeter and it was easier to control. The stick force is still light and still a little sloppy in the neutral position. The mission is getting easier. The directional control was easy. The altitude control was, I think, more rapid. In other words, it gained 1000 feet quicker than before. On descending, it was easier to control the rate of descent than it was the rate of climb. I think DLC probably damps the turbulence a little bit, and the task, I think, is rather simple. I think the aircraft was easier to handle as far as the climbs and descents are concerned. It is quite easy to get to steady rates and to hold. I have been holding about 14,000 feet until about 150 feet prior to level-off altitude and coming on back; it seems to blend through quite well. I am still not trimming while turning or climbing because it takes a thousand feet just to put the trim in. By the time the trim is in, you take it back out. Altitude is quite easy to hold within ±50 feet. The task is quite easy, and I think that if it were possible to put more force on the stick, it would probably be more realistic, although the aircraft simulator handles quite well. Lateral control is better, now that I've become used to the one needle sticking off at an angle.

35G6035, 36 (closed-loop DLC -- no turbulence)

This was very easy to handle, although pitch is still sensitive.

35G8037, 38 (open-loop DLC with turbulence)

With turbulence, I think there is a tendency to get a slight pilot-induced oscillation with light stick force. This tends to make an altitude control a little bit unstable. Other than that, it was a pretty good run. Lateral control is no problem at all. There wasn't quite as much damping on the turbulence this time, as with the closed-loop DLC, and the stick force is still light. The task is the same with or without turbulence; it is quite easy. Compared with the closed-loop DLC mode, the turbulence is more effective -- at least there tends to be more oscillation on the altimeter, probably twice as much. I think closed-loop DLC tends to damp out the turbulence, whereas the open loop is either lagging behind or is not damping at all. Concerning control of the aircraft, the biggest factor is the turbulence itself. With the open loop, the turbulence being more effective, the altitude is more critical to hold. Therefore, it is harder to maintain altitude and heading with open loop as compared with the closed loop. I think the time to get to a 1000-foot altitude change is probably quicker. I think it's easier to stabilize with either closed loop or open loop than it is with just elevator control.

35G9039, 40 (blended open-loop DLC -- no turbulence)

There seemed to be some oscillation at the 4000 feet per minute rate of climb. This appeared to be pilot-induced about 600 feet plus or minus either side. Descent was better. Altitude control was a little sloppier that time, mostly pilot-induced. Altitude in the turn is still easy to control. Lateral control is easy. I think as time goes on the tendency toward pilot-induced oscillation will probably increase as time staring at the gages increases. I would still rate the task as easy, and stick force is light. (Do you think you would have this PIO if you didn't have this low force gradient around center on stick?) I don't think so. I think you would be faster on the control, and you can watch a little closer. As it is now, you just think about a climb and you have a tendency to maybe just pull it back or think you're pulling it back and it's already climbing up maybe one or at least a thousand feet per minute, or maybe 1500. It's kind of like flying a helicopter. You think about moving to the left and it moves. (How would you compare the three configurations that you have just flown?) Okay, meaning open loop, closed loop, and conventional elevator only. The closed loop was by far the easiest to fly and maintain both rate of climb and altitude, and altitude in the turns. The closed loop is much preferred over the open loop and both are preferred over elevator alone. It takes less time to climb (1000 feet) with DLC. At least I think it does. I haven't been timing it, but it appears that it doesn't take as long.

35G11041, 42 (separate DLC -- no turbulence)

It keeps one very busy centering; first of all you bring in the control and bleed it off to zero, maintaining let's say 4000 feet a minute rate of climb. Then you bring the control back in as you start down to level off and again bleed it off to zero as you come back with the elevator control. It's hard to coordinate and to know how much control you need for such a short or small change in (1000 feet) altitude. For 2000- or 3000-foot altitude change it might be easier to know how much to blend in. The DLC is not needed for turns. Elevator control is plenty effective. You can't tell from degree or increment on our dial the effect of DLC as compared with elevator alone. I did not use DLC for the turns and only used it for altitude changes. When one has to keep an eye on the dial for DLC and on the rate of climb in the altimeter, as well as trying to watch the airspeed, I think it's easier to get pilot-induced oscillations. Once you get up to 4000 feet a minute rate of climb, you then take out the DLC, starting the rate of climb back down. By the time it starts down and you start back on the elevator control again, you are little bit behind it, and it tends to produce an oscillation. DLC was not used to hold altitude in turns. The task goes from an easy task to a moderate one, as far as work to be done all at once. I think a good configuration would probably be to have the DLC spring-loaded to a neutral position so that it could be bled off automatically, and not have to watch the dial to find out if it did go or if you have to zero DLC when you would hope to have it there. In other words, start back on the elevator control, get 4000 feet a minute rate of climb, release the control, and give it a rate bleedoff back to zero. Then one just has to worry about the elevator maintaining the 4000 feet per minute rate of climb.

Concerning having an independent control, I don't see any advantage. I think it was much easier when it was in the closed loop. It's a lot easier to fly. I would say that it's at least twice as hard to fly with a separate control. Maybe with more practice one could see a greater benefit in it. Right now I would say it's much easier to have a blended control.

PILOT 2, C-5A GENERAL TASK (9/13/67)

25G11043, 44 (separate DLC -- no turbulence)

There was no difficulty in trimming the aircraft. The attitude control is unsatisfactory when using the separate direct lift control, in that throttle control is required almost simultaneously when you make pitch changes such as climb or rolling in turns. In order to maintain altitude, and then being required to move from throttle to the separate DLC control, makes for unsatisfactory operation. Normal acceleration responds satisfactorily. If separate DLC is used, it is difficult to hold altitude in turns, especially at the start of the turn where coordination between throttle and control stick is required. Lateral control did not appear to be a problem. There was a tendency toward PIO when attempts were made to use separate DLC. Damping is satisfactory. Stick displacement characteristics are okay. The task was somewhat more difficult when attempts were made to use DLC separately. If some method of providing the separate direct lift control, such as has been devised for our normal trim operation on a control stick, can be devised to be combined with the control stick, it would help the operator quite a bit in smoothing out and coordinating any maneuvers such as rapid climb or rapid roll in due to a turn. Any device that does not require additional hand movements would help tremendously.

2516045, 46 (closed-loop DLC -- no turbulence)

The task was relatively easy. No problem arose in maintaining heading. There was little to no tendency toward PIO.

2515047, 48 (closed-loop DLC with turbulence)

The task was relatively easy, with no difficulty in maintaining heading. There was just a slight tendency, when attention was relaxed, toward PI0, and corrections were made back to stabilized conditions. The effect of turbulence was that it took a little more concentration to maintain attitude, but other than that, it didn't present any major difficulty.

2518049, 50 (open-loop DLC with turbulence)

The task was a bit more difficult to perform than with closed-loop DLC and still maintain the horizontal needle zero. There was no problem on heading. There was a slight tendency toward PIO in trying to maintain the horizontal needle zero. The turbulence in this case required more concentration and more work to maintain the stabilized condition.

2512051, 52 (elevator with turbulence)

The task was difficult in that much more concentration was required to maintain the zero horizontal needle zero deflection. The heading did not present a problem. There was a tendency toward PIO in trying to maintain the zero horizontal deflection. The turbulence increased the tendency toward PIO, which made it a little more difficult to maintain the horizontal needle in zero deflection.

2513053, 54 (elevator -- no turbulence)

The task was performed easily, without much difficulty. There was no problem in maintaining heading. There is still a tendency toward PIO if the deflections on the horizontal needle would be three to four bar widths from the center dot.

2519055, 56 (open-loop DLC -- no turbulence)

The task was performed without difficulty as long as the corrections to zero needle deflections were maintained two bar widths or less. Beyond that, the task tended to be a little more difficult. Heading was maintained without difficulty. There was a tendency toward PIO if the deflections were more than approximately ±3 bar widths. The turbulence required more concentration on the part of the operator to maintain the desired accuracy.

25I11057, 58 (separate DLC -- no turbulence)

The task was more difficult with separate DLC. In this case, the hand motion to feel the effect was greater than the hand motion of the control stick, which felt somewhat awkward. There was no difficulty in maintaining heading. There was a tendency toward increasing IPO when separate DLC was used. Stick force and displacement characteristics appeared okay. Separate lift DLC may prove advantageous if a means is found to reduce the hand movements that are necessary in the setup in the simulator and also a means of determining how much DLC is being applied visually and located so it will not distract from the primary instruments that are being monitored to maintain the proper attitude.

Comments on Four as a Group

The choice would go to blended open-loop DLC. Separate DLC was, I felt, at the bottom as far as any advantages to the operator. No DLC with just elevator alone was better than having separate DLC in the simulator as it exists. Correcting my ratings, my first preference is blended closed-loop DLC. Second choice is blended open-loop DLC, and third choice is elevator alone. Separate DLC is the last choice.

PILOT 4, C-5A IN-FLIGHT REFUELING TASK (9/14/67)

45I5059, 60 and 61

I didn't find any difficulty in maintaining position on the bar itself. However, the airspeed, I think, is unusual and peculiar to the simulator, and in a normal flight situation, it wouldn't vary that much with that small of an altitude change. At one time there was about 50 knots variation, and not quite 100 feet of altitude throughout the whole three-minute period. I think this is an unusual situation, and, at first, it was a little annoying that you couldn't pin down the airspeed. At first it shocked me because it was holding level for some time. Then all of a sudden it shot up and, because it did shock me, I was distracted from the pitch control. The pitch control, itself, seemed to be no problem at all.

45I3062, 63

This is the second in the series; I believe the first was better. The task wasn't difficult at all. The pitch horizontal bar seemed to be less sensitive than the first two runs that we made, and the aircraft response seemed to be slower, not as effective, but it did seem smoother -- apparently not as much turbulence. Heading was no problem at all. I was told that there wasn't any turbulence in these last two runs, although there seemed to be. The information displayed was okay. They say the aircraft seemed to respond a bit more slowly, but again perhaps more smoothly too. So how do you rate pitch in that situation, I don't know. I think it's still very good.

45I2064, 65 (elevator with turbulence)

I think maintaining pitch and heading was relatively simple and not much of a task at all. There were no PIO tendencies. Turbulence doesn't seem to effect it that much. I don't think I have a tendency to chase the needle that much. I think the information displayed was okay. Perhaps I'm slowing down my cross checks somewhat. I feel that I should be able to maintain a closer relationship with the pitch bar.

45I6066, 67 (closed-loop DLC -- no turbulence)

All conditions and responses were satisfactory.

45I9068, 69 and 45I8070, 71 (open-loop DLC)

I think the task was fairly simple; it didn't require much effort. I think perhaps the cross check is a little slower, and it seems that perhaps the flight controls were a little less responsive on that run. Then again, this might be my own reaction that is slowing down too.

45I11072, 73 (separate DLC -- no turbulence)

I didn't see any advantage in separate DLC. In fact, at times it was a handicap when speed had to be adjusted. I tried to ease it in conjunction with the elevators and I found that actually my attempts to maintain the horizontal pitch attitude on the bar was a little more difficult. I think by concentrating on elevators alone, I could have maintained the relative motion more easily. Certainly airspeed could have been handled better. Speaking of airspeed, I think again it was out of proprotion. I was climbing and maintaining 62.5 percent and still the airspeed remained at 385 for a period of, I would say, greater than a minute, which shouldn't have been the case. Other than that, I see no advantage to the flaps, at least not on this test. (Would you comment now on all four -- comparatively?)

I didn't know which was which at the time. The difference, I think, is so slight. I think your difference would have to be seen from the means of absolute value data. I didn't think that I could really tell the difference. At times, I was getting a little more tired. Other times, I just wasn't interested in getting right to the pitch bar. At other times I was interested in getting to that point immediately; at other times my cross check was slow. I think that probably would have been my best run, but then, again, your results indicate that it was not.

My opinion of the overall ease of handling and the results you get out of it is that it is satisfactory. I found no difficulty at all. I think if you were flying in ILS with that pitch bar with that sensitivity, some other things demanding exactness wouldn't have any difficulty at all. (Did you find any advantage of one control configuration over another?) From the feel of the control, no. As I say, the difference among them is so slight that I can't see the advantage of one over the other. That doesn't mean there isn't an advantage. You have to check the mean of absolute value results on that. I don't think there is any extreme workload on any one of them. The pitch bar, I thought, was easily handled.

PILOT 3 F-104 GENERAL TASK (9/15/67)

34G6074, 75 (closed-loop DLC -- no turbulence)

Aircraft altitude is hard to maintain. Pitch attitude is very sensitive to stick movement, especially at these airspeeds. Altitude in a turn over 30 degrees is quite hard to hold as is airspeed. I think the throttle lags a little bit for putting in airspeed. Airspeed is hard to keep up with. Lateral control is not too hard to maintain for pitch changes only, and the vertical velocity is quite sensitive in all modes, both in turns and in altitude changes. The stick force is very light again, and the task has gone to a moderate task, I believe, because of the airspeed in this configuration. It's quite easy to get a pilot-induced oscillation in the pitch axis. Altitude is rather difficult to hold in turns.

34G3076, 77 (elevator -- no turbulence)

In the 70-degree bank angle, it was not possible to hold airspeed and maintain altitude, even with full throttle. Altitude is still hard to hold in turns. Pitch is very sensitive. As you increase the bank angles, pitch becomes even more critical. It is not logically possible to end up at the correct heading turning to the left, although to the right there seems to be no great problem. There might be a slight overshoot, but yet the angle changes as much as 10 degrees on the heading. Lateral control during pitching maneuvers is not difficult to maintain, but airspeed is very sensitive, as is pitch. In all conditions, I think, PIO is quite prevalent. (These next runs were made to see if, by flying out-of-trim, the stick stop at zero force could be avoided.)

34G3078 and 34G6079 (elevator and closed-loop DLC -- no turbulence)

These last two runs were made with an in-trim condition. We actually had to hold back stick pressure to maintain altitude. This was to alleviate the sloppy position of the stick and to see if we could get rid of some of the oscillation that was due to the sloppiness of the stick. Altitude changes were easier, I think, because setting a rate of 4000 feet a minute appeared to be easier than before, although now it comes down through zero. At least I had a tendency to think, "okay it's going to be neutral", and it wasn't. Because of that, I think, I had some oscillation in maintaining an altitude. With direct lift control blended in, it was possible to maintain 70 degrees of bank and altitude and also to maintain about 500 knots airspeed, which was not possible without DLC. I made two runs with the 70 degrees of bank because I really messed up the first one. I did not trim the aircraft though, either in the turns or in altitude, but just held steady the trim that was set in the beginning to keep it out of the neutral position. Vertical velocity and pitch are still quite sensitive, and any movement at all tends to create a little oscillation. Lateral control is a bit of a problem. I can now see that pitch tends to change attitude somewhat, maybe three or four degrees, when you go into about 45 degrees of bank. Just by changing the pitch while in a bank, you can see that the rate of change in the heading also changes a little bit. Of course, there is quite a bit of stick force pressure coming up to get a positive rate of climb and to go down to a negative rate of climb when there is also no stick force pressure -- that's about how much trim is in there. The task is still about moderate, and blended DLC seemed to be easier to control than with conventional elevator. (Pilot 3 did not complete this task on this date. Task was completed on 18 September 1967.)

PILOT 5 C-5A TERRAIN FOLLOWING (9/16/67)

55T5080, 81 (closed-loop DLC with turbulence)

I found that it was a little difficult to maintain airpseed because the pitch and acceleration commands I received on the pitch steering bar were of moderate intensity, and I was found climbing and diving at 20 degrees. Therefore, airspeed varied considerably, and I found that I was spending a lot of time cross checking the airspeed with appropriate power settings and, of course, this being a big airplane, a power lag was evident because of the requirements to accelerate the mass. This seemed to detract somewhat from the ability to center the pitch turn bar. The task wasn't difficult. I think I made an average run.

55T2082, 83 (elevator with turbulence)

This run was, I would say, considerably more difficult if you want to differentiate between considerable and extreme. It was more difficult to control pitch because I had to integrate the pitch rate to stop the steering bar on the dot. Therefore, I tended to be slower in responding in order to alleviate a tendency to overshoot. If the condition was more difficult to fly than the other, it was not nearly as accurate as the other. I wouldn't consider it unacceptable performance. I think that you could complete a mission like that, but certainly the performance was degraded from the initial performance, primarily due to the tendency to overshoot or to slow in correcting to the pitch bar so you wouldn't overshoot. When trying to respond to corrections on the pitch steering bar, the airplane has a tendency to overshoot. (By pitch do you mean the ball?) The dot. For example, in a pitchover, the pitch steering bar would show in some cases a considerable deflection, and I would abruptly pitch over. But I would have to begin the recovery from the pitchover in some cases before the pitch steering bar moved the correction to center the dot (with the pitch steering bar) because I knew that I would overshoot if I held the correction in until it came up. There are two ways to fight that. One is to let the pilot learn how to anticipate it, and the other is to change the gain in the pitch steering bar so that you can see the response sooner -- then in minor corrections you have a tendency to overcontrol.

55T8084, 85 (open-loop DLC with turbulence)

Probably the workload was considerably reduced here because overshoot was not as apparent, although I did see overshoot. I had a tendency to disregard it, and correct from the error after a large response. In other words, I would make a correction to what would seem to be the proper value and, although I know there would be some overshoot, I was too busy to try to integrate it since it didn't seem to be sufficient magnitude. I could make a second correction back to the center of the board and the dot. Attention to the pitch steering task was not as great a magnitude as in the previous task, and therefore I was able to pay more attention to heading and airpseed than I did before. I think with practice you could probably tighten up the pitch loop and make a flight very accurately. This task was more difficult than the first one, slightly more than the first one, I thought. (The first task was blended closed-loop DLC, and the task just prior to this one was the conventional elevator. This was the open-loop DLC task.)

Of the three turbulence runs, closed-loop DLC was by far the easiest to fly, and the response of the pitch steering bar relative to the dot on the attitude indicator was easier to control. It seemed that I could directly place the pitch steering bar on the dot without having to consider the ramifications of overshoot or undershoot. The next easiest system to control was open-loop DLC. It was more like that of the closed loop than it was of the straight C* (elevator control) system without any DLC. It seemed that in the second system, open loop, I noted some tendency for the dot to overshoot after I had removed control pressures. In the third setup without DLC, there was a considerable tendency to have the dot overshoot the pitch steering bar or, if you wish, overcontrol, and I had to ease up on the gain so that I would not do this.

55T9086, 87 (open-loop DLC -- no turbulence)

In this task, I tried to tighten the pilot's loop since the turbulence was out. I was able to make direct response from what I saw in the attitude indicator pitch steering bar and, in addition, to the seat of the pants. I found that I could fly fairly accurately by using the magnitude of the distance between the dot and the pitch steering bar as an indication of the magnitude of the input required and then removing the input as soon as the pitch steering bar started to move. With practice this task could be flown much more accurately with turbulence.

55T3088, 89 (elevator -- no turbulence)

The learning curve for this task had a rather large slope initially. The pilot loop could be tightened considerably such that, with one more practice run, I would estimate that maximum deviations from the pitch steering bar would probably be two or three units, with a mean of one, and airspeed control could be controlled within five knots or less, except for the very large attitude deviations where you don't have enough power to control it.

55T6090, 91 (closed-loop DLC -- no turbulence)

This was a very easy task when compared with the rest of them. The pitch steering bar was flown within approximately one bar width except for very large changes in attitude or when attention was diverted from the pitch task for such things as times when I caught myself staring at airspeed and roll attitude. I thought this was a very easy task and, of course, I have learned the system much better now than I had initially. I think that has a lot to do with the more accurate flying.

55T11092, 93 (separate DLC -- no turbulence)

As you stated, this task is not designed properly. Unsatisfactory mechanization of the task makes it even more difficult than it would normally be. A better configuration, one for two-handed people though, would require a lot of practice so that the cross check could be improved. Even then, I would estimate that a moderate to poor response would be obtained because you have attention divided into several additional areas. I think perhaps a mechanization which would incorporate lift response with the stick for this task would be more satisfactory. (Would you comment now on the group which you have done without turbulence?) Okay, if you wanted to optimize the learning curve, it would be best to let the pilot fly the non-turbulence group first. That way, you could evaluate his experience more easily. When you add turbulence, there are other factors that you have to consider in response. He could learn to fly without turbulence and then take that experience and add it to turbulence. I think you should do it both ways. I now find that the task was not difficult at all without turbulence. Disregarding the task with separate lift stick, all three modes were easy to control and, with practice, you could become quite accurate with it. I did not notice the tendency to overshoot to be as great, even with the manual mode. Although I could distinguish between the three, I thought that closed-loop DLC was by far the easiest to fly of the three. The second best was open-loop DLC and the third was complete manual.

(How does this motion simulator feel to you in this task?) I think the initial accelerations are too big. While we were practicing after the apparent malfunction, just a very small movement of the stick would give me a pretty good size acceleration feeling, and I think maybe you could slow that down so that you get more realistic feel. I was getting all my movement from the play in the stick. After I went through the sloppy zone and into the zone where there were increased forces, the thing had already washed out and that's where I think you would begin to feel more acceleration.

PILOT 6 C-5A TERRAIN FOLLOWING (9/16/67)

65T6094, 95 (closed-loop DLC -- no turbulence)

Heading was not sensitive enough. I question the power change required to maintain airspeed while following terrain. I'm putting some lead into pitch command while tracking bar. Longitudinal motion is okay but lateral doesn't seem natural.

65T9096, 97 (open-loop DLC -- no turbulence)

Pitch required slightly greater work concentration. Autothrottle leading attitude change commands would probably make holding constant airspeed easier in following terrain.

65T3098, 99 (elevator -- no turbulence)

Pitch excursions (command signals) seemed larger. I still feel too much throttle is required to hold airspeed. It's more difficult to track the bar -- transients occurred during the run.

65T11100, 101 (separate DLC -- no turbulence)

(Motion system malfunction after run 100. Run 101 was fixed-base.) Lack of motion makes it slightly more difficult to fly. I do not like this configuration -- it's too difficult to hold airspeed, I get behind it. It's easier to track the bar than with elevator only.

(You've had a chance to try all four combinations without turbulence. How would you compare the four?) The task with closed-loop DLC was relatively easy. I would say it was not easy, but it was easier than it was with the other configurations. Airspeed was somewhat difficult to maintain, but I feel that was due more to the amount of throttle travel required from stop to stop, to hold it, rather than to a fault in the system. Heading wasn't difficult to maintain. There was no tendency toward PIO. Stick force and stick displacement seemed okay, although there was a little more stick pressure than I personally like. I think the displayed information was suitable and apparently had some lead in it, since there wasn't too much overshoot occurring. Perhaps the lead was due to my tendency to lead instruments after spending a lot of time in simulators. I have that habit. I don't think, based on the task flown, that a separate direct lift control does anything or would be worth having. I prefer not to have it. I would rate the configuration in the first pair of flights as significantly improved over any of the others. I would say that the second configuration flown is perhaps half way between the first and the last two, and I would say the last two are about equal and not very good. (The first was closed-loop DLC, the second was open-loop DLC, the third was conventional elevator, and the last was separate DLC.)

65T8102, 103 (open-loop DLC with turbulence)

This was essentially equivalent to same case with no turbulence, but had greater excursions in bar and slightly greater difficulty holding airspeed.

65T104, 105 (elevator with turbulence)

A great deal of concentration is required in order not to get too far behind the bar or airspeed. If other simultaneous tasks were introduced, I feel this condition would be difficult to fly.

65T106, 108 (closed-loop DLC with turbulence)

This was significantly easier to control than other configurations with turbulence. On the first run I got behind airspeed and couldn't bring back. I feel this is the throttle setup. It appeared that commanded attitudes were much larger than other runs without turbulence.

(Would you compare these three configurations you've just flown in turbulence?) Again, I would say that the configuration with DLC was significantly easier to fly than the other configurations. I far preferred the setup with the normal acceleration feedback as part of the DLC loop. I still feel that I question the amount of throttle movement required to track airspeed. To me, the problem became quite severe in this setup where turbulence was also included. Several times I had to throttle against either stop for a significant period of time. I couldn't keep up with airspeed. Perhaps it's my piloting technique, but in tracking airspeed it seems to be difficult not to get behind it. It may be due to slow throttle response on my part, I'm not sure. There is a generally noticeable difference in workload; let's say flying turbulence against the no turbulence conditions. There is more to do with turbulence introduced. In maintaining heading, I didn't really notice much difference between any of the three different modes. With me in the loop, there were times when I felt I was on the verge of coupling with the long-period motions of the aircraft. As I said, turbulence just made it harder to fly. Again, I felt that stick forces were higher than I personally like, although I guess they are satisfactory for a big heavy airplane. Information on the display was adequate. I think the significant thing is that there is obviously a difference between DLC, especially with the accelerometer feedback, versus just pure elevator control. I think it's significantly easier to fly with DLC.

PILOT F-104 GENERAL TASK CONTINUED FROM FRIDAY, 9/15/67. THIS IS MONDAY, 9/18/67

(First runs will be 34G6109, 110, which repeats runs made on 9/15/67. No comments.)

34G9111, 112

I just finished combination nine. This was done with a trimmed aircraft as compared to the other day working the complete run and flying it out-of-trim to get rid of the neutral condition. Today it is the trimmed aircraft and all flight conditions are flown with this in-trim situation. I was unable to maintain airspeed in the 70-degree bank angle with this open loop, whereas in the closed loop it is possible to maintain airspeed. When stabilizing at either ±4000 feet rate of climb, one tends to put in PIO at the limits because of the fast acceleration to these limits. In other words, you're going to 4000 feet rate of climb quite rapidly and tend to overshoot, and then the stick being as sensitive as it is in the pitch mode, there is a tendency to put in some PIO. I think the task without turbulence here is light, easy to normal, and in the open-loop heading tends to be more critical than it was either in the closed loop or in the elevator only. It takes more power to fly open loop than it did closed loop, but this might be something with the trainer, I don't know.

Commenting on the configurations without turbulence, I think that the closed-loop DLC has many possibilities. For instance, I think it takes less power to fly. This may be because one does not tend to throw the controls back and forth quite as much; therefore, this does not induce quite so much drag. Airspeed is easier to maintain in closed loop; heading is also easier to maintain in closed loop. Altitude is as easy to maintain, and I think that rate of climb and descent are easier to stabilize in closed loop. I would say that the task is easier in closed loop also because of being able to maintain the limits that you are trying to set. The throttle is a bit slow. I think for an F-104, if you shove it 20 percent, that you should get more response in airspeed; you should get it immediately.

34G113, 114 (open-loop DLC with turbulence)

The turbulence, with the slight stick force, tends to set up a PIO. In other words, when you try to establish a 4000-feet-per-minute rate of climb, it will tend to set up PIO every time you try to change into a new stabilized condition. The turbulence probably varies about 50 to 75 feet on the altimeter at peak gust, and with turbulence, airspeed went completely wild in the 70-degree turn. I think it went as low as 400 knots. That's with full throttle and maintaining altitude. The aircraft is just as easy to turn, turbulence or not, and the altitude tends to jiggle around a bit, but it maintains a rather steady 15,000 feet. I think the altitude becomes more critical in turns with turbulence mostly because the induced oscillation tends to make you overcorrect or undercorrect and the pitch force, being light, tends to make it easier to do this. The task, with turbulence, is more difficult, I would say, than without, only because of the PIO that is induced.

34G5115, 116 (closed-loop DLC with turbulence)

The aircraft handles better with closed loop than open loop. Bank angles are hard to hold over 45 degrees -- very sensitive. I was unable to maintain airspeed at 70-degree bank angles -- it is worse to the right. The task is light to normal and the aircraft is quite easy to trim in all attitudes and altitude control is not too hard.

34G2117, 118 (elevator with turbulence)

The aircraft is very sensitive in pitch and heading with turbulence, and is very prone to PIO. I am still unable to turn to the right with banks of 70 degrees.

PILOT NUMBER 3 F-104 GENERAL TASK (9/18/67)

24G3119, 120 (elevator -- no turbulence)

Attitude is more sensitive than what I'm used to, so I would have a tendency toward PIO on attitude changes where a large displacement is required. Vertical acceleration response seems satisfactory. Lateral control did not appear to be a problem. Regarding the stick force and displacement characteristics, they are slightly different than what I'm used to, but I'll have to assume that they are close to what the F-104 requires. The tasks did not appear to be too difficult.

24G6121, 122 (closed-loop DLC -- no turbulence)

Attitude control is significantly improved. Vertical acceleration response is very satisfactory. Much less difficulty was experienced maintaining altitude during turns. Lateral control did not present a problem. The tendency toward PIO was decreased to the extent that there was very little. Stick force and displacement characteristics appeared favorable. The task was much easier than the previous task.

24G9123, 124 (open-loop DLC -- no turbulence)

The attitude control was just about the same as in the previous run. Vertical acceleration response was very satisfactory, as in the previous run. Altitude was somewhat difficult to hold in the last six percent of the steep turns. Lateral control about 90 percent of the time did not appear a problem. There was little tendency to overcontrol in steep turns. There was also a tendency toward PIO, especially in rapid pullups. Stick force and displacement characteristics appeared okay. The tasks did not appear difficult to perform.

Comments on Three Relative to Each Other

The first mode (elevator control) was more difficult than the last two. There was hardly any difference between the last two that I could detect in performing the maneuvers required.

24G8125, 126 (open-loop DLC with turbulence)

Attitude control is satisfactory, even though turbulence was thrown in. Vertical acceleration response was very satisfactory. Altitude was generally held without difficulty in turns, except during the last portion of the turn, say the last 40 percent or so. Lateral control was not a problem, except for overcontrolling slightly in rolling out of a steep turn. Turbulence produced a tendency toward PIO, somewhat more than without turbulence. Stick force and displacement characteristics appeared okay. The tasks did not appear to be too difficult to perform.

24G2127, 128 (elevator with turbulence)

Attitude control required more work to maintain the proper attitude. Vertical acceleration response was not as satisfactory during the recovery from a rapid climb or descent. Altitude was somewhat difficult to hold, especially in rolling in and rolling out of steep turns. Lateral control did not appear to be a problem, except when rolling in and rolling out of a steep turn. There was a tendency toward PIO during recovery or when initiating rapid climb or descent. Stick force and displacement characteristics appeared okay. The task did not appear too difficult to perform.

24G5129, 130 (closed-loop DLC with turbulence)

Attitude control wasn't too much of a problem for straight and level flight and for moderate turns of 30 to 45 degrees. Beyond that it was a little difficult to maintain a proper attitude, more so rolling out than rolling into a steep turn. Vertical acceleration response is very satisfactory as compared without the DLC mode. Altitude was again difficult to hold in the last portion of the turn and during rollout. Rolling in, in the first part of the turn, didn't seem to present any problem. Lateral control was generally no problem except when rolling out of a steep turn, I tended to overshoot or overcontrol. Tendency toward PIO was at a minimum. Stick force and displacement characteristics? Here again I have been describing them as okay or normal. I really have nothing to compare them with, other than the aircraft that I'm current in. In that regard they seem satisfactory. The task was relatively easy to perform. Little work was required except in rolling out of the steep turn. Other than that the task was relatively easy.

Comments on the Three Controllers in Turbulence

As far as open- or closed-loop DLC is concerned, I didn't feel too much difference, especially in turbulence. The main difference was between those two and the elevator control only. The difference was noted the most in establishing climbs and descents. It was much easier to establish the 4000-feet-per-minute rate of climb or descent using the DLC modes as opposed to the elevator alone. It was definitely easier to hold altitude in turns with DLC. Here again, I couldn't notice too much difference between the open- and closed-loop modes.

(How does the motion feel to you? Do you think that the motion you feel is adequate, is it a good cue as to what you are doing, and does it give you the feeling you should get as far as turbulence is concerned?) The turbulence induced in the simulator is normally not felt to a great extent. It appeared light to moderate. The longer you experience the turbulence the more you tend to describe it as moderate to heavy, whereas, for short periods of time, it will be light to moderate. I consider the motion of the simulator of secondary importance as opposed to the movement of the instruments, or response of the instruments with respect to throttle movement, stick movement, g application. This is the thing I look for to set myself in a realistic atmosphere. I try not to pay too much attention to the motion, because we're trained to disregard it to avoid spatial disorientation. I concentrate on instrument response with respect to throttle or stick movement. In fixed-base, I believe you can get just as good response from an operator, if given a realistic response from the instruments. To really get an effective overall feel, the simulator would have to bank to the extent that you are banking. In high banks, from 45 up to 70 degrees, you should probably have to experience the g-forces too. So just the bank alone for the high banks is, I believe, not sufficient, and I believe you can do just as well without the motion when you go into these high banks. If you are making shallow turns where you are not required to go in rapidly, the relative motion produced by this simulator does help.

PILOT 1 F-104 TERRAIN FOLLOWING TASK (9/19/67)

14T6131, 132 (closed-loop DLC -- no turbulence)

(According to the checklist, were you able to perform task easily?) I found the task quite difficult. In other words, the erratic movement of the horizontal bar was such that I was not able to anticipate where it was going or how far it would go, so that it was difficult to keep it at zero. (Was airspeed difficult to maintain?) Airspeed was not difficult to maintain except when there was a prolonged climb or descent. You would not know whether the climb or descent was going to be prolonged and, if it did turn out to be prolonged, then your airspeed would get off and throttle required a long time for it to build back to the desired speed. Heading was not difficult to maintain. I didn't notice any PIO tendencies. Stick force and displacement characteristics felt good, I think, for this kind of airplane at this kind of airspeed; they were just about right. Information presented on display is adequate for this purpose. Since this will be a factor with all other runs, I would think this was satisfactory. As to the advantages of having a separate direct lift control, I don't think it advisable on this kind of a task. You are extremely busy trying to keep the error as near zero as possible, and I don't think a separate control would help you in this case. I found this to be an airplane that responded quickly to both lateral and pitch inputs -- it is a very good airplane as far as response is concerned. The problem was just that the task was fiarly difficult in spite of a good responding airplane.

14T9133, 134 (open-loop DLC -- no turbulence)

This run I found very similar to previous runs with closed-loop DLC. I was rather hard-pressed to really note any significant difference. Overall though, I got the impression that the task was slightly more difficult this time, so I rated it a 3 rather than the previous 2.5. However, I was not at all sure of whether this was, in fact, not quite as good a configuration as the previous one. The difficulty was that as the task at various times was easy or difficult, it made me think one way or the other as to which was the best configuration. So I think they are very close. This one is perhaps slightly not as good. (Was airspeed difficult to maintain?) My comments are similar to the last one. Airspeed was not difficult to maintain, provided there was not a significant change in altitude. And, when this did happen, then airspeed would get low and the throttle took rather a long time to get it back to the desired amount. Lateral response was very good, and I found no significant difficulty with heading. I did not notice any PIO tendency. Stick force and displacement characteristics seemed about normal and information presented was as previously commented on -- it was adequate for this task. I found that perhaps the information displayed is more like close formation flying than I would expect for terrain following, although I have had no experience following terrain on radar.

14T3135, 136 (elevator -- no turbulence)

(Would you comment on the performance of the task?) One general comment on performance that applies to all of these runs is that it is difficult for me to say how I did on it as regards to average, poor, and so on, because I'm not quite clear as to the performance that is required. Therefore, I put these in the poor category. I think the comments on airspeed that I made in the previous runs apply also to this one. Airspeed is not difficult except when there is a prolonged climb or descent, and then airspeed is a little difficult to maintain. There was no particular in difficulty maintaining heading; it was the same as for the other runs. I thought stick force and displacement characteristics were quite satisfactory, as you would expect for this kind of an airplane in this flight condition. Some general comments on this particular run: I again found no significant change from the previous runs. I did think that I had more difficulty when an error was displayed in that when I corrected to zero the error, I tended to overshoot the bar more so than the other times. In other words, I kind of bobbled around the zero error. Perhaps pitch response was not quite as good as the previous one. There was no significant deterioration, but I think there was some deterioration. One other comment on these runs applies to all of them. It is the rather large amount of negative g's that are required when the pitch bar indicates a descent is required, that I go to more negative g's than I think a pilot would actually do in a flight. It would be uncomfortable to say the least, going up to, in some cases, an increment of two negative g's.

14T2137, 138 (elevator with turbulence)

This was run with turbulence; basically I found very little degradation due to turbulence. Even in the runs that had no turbulence, there was a certain amount of jerkiness to the simulator itself, and I think that is as significant as anything. With turbulence, I didn't really notice that the task was appreciably more difficult. Therefore, my comments for this particular run with just elevator are almost identical with the previous one without turbulence. I thought that the turbulence possibly made the task slightly more difficult but very, very slightly, if, in fact, at all.

14T8140, 141 (open-loop DLC with turbulence)

This run was with turbulence, and again I found no significant deterioration in the task. The turbulence possibly would be annoying and maybe more so in flight, but it seemed to have little significance on the ability to zero the error on the horizontal bar. This airplane generally felt very good and responsive and, as I noted before, there was less tendency to bobble around a zero error than there was with the previous elevator configuration.

14T85142, 143 (closed-loop DLC with turbulence)

Again, I found that turbulence did not significantly deteriorate performance. The turbulence might be slightly annoying, but I really couldn't tell that it made the task any more difficult. This combination is an improvement over the others, so I rated it a 2.0 in spite of the turbulence. The response was good, and the notable improvement in my mind was the ability, when the error is zero, to keep in on the zero rather than bobble around it as I did, particularly with the elevator alone configuration.

In flying the three combinations with and without turbulence, I found no deterioration due to turbulence. You could feel the simulator bump around a bit, but as far as the display instruments are concerned, there didn't seem to be any significant difference. With regard to the three combinations, I am fairly well convinced that closed-loop DLC was superior, primarily in that it gave a quicker initial response, primarily on the ability, once you have reduced your error to zero to maintain it on the zero. With open-loop DLC, I found it very similar but I thought not quite as good as the closed loop, though there was not any real difference between the two. I was quite satisfied with open-loop DLC; it gave a fairly quick response. I thought that you weren't able to zero out the error quite as readily as in this case. Going to the elevator alone made, it seemed slightly more sluggish although still a pretty good airplane, but I found that my tendency, when I had the error almost zero, was to overshoot it and go above it and below it. This was not really a PIO, but a tendency that you couldn't settle it right on zero. Regarding the task, I realize it's supposed to be terrain following. Although I've never done any terrain following on instruments, it seems to me that there was a lack of anticipation as to what was going to happen that you might more normally expect. I thought that part of it was more like close formation flying. When you are flying close formation you can see erratic movements of the other airplane and you attempt to follow them as quickly as you can, keeping the error zero. However, I think this was a good task to demonstrate the differences between the three and my only question was on the actual terrain following.

(On this task would you say there is a small difference between elevator and DLC, or am I incorrect? Would you say there is a large difference?) The difference I really couldn't call large. I thought there was a significant improvement but not really a large one.

(You checked heavy on workload on all of these runs. Would you say that workload was the same for all runs?) That's right. I thought the workload was the same for all of them -- heavy. I thought heavy in the sense that the movement of the bar was fairly erratic, that you couldn't anticipate it, and since it was moving quite rapidly, you had to work quite hard to keep it at zero. It was the same for each configuration. I found that DLC was of greater benefit as the workload became heavier. In other words, with elevator alone, when there was a very light workload, or smaller movement of the horizontal bar, then I could follow the task quite readily; but when it became more complex, DLC paid off more.

(Forgetting about the comparison evaluation that we're doing here now, what do you think of the motion simulator?) First of all, with regard to the turbulence, there is a certain amount of jerkiness to it anyway, without turbulence, and a little bit more with the turbulence, so I felt the turbulence simulation didn't come through very clear to me as turbulence. I could sense the rolling, but I'm not sure it really added anything to the evaluation.

I think the pitch helped a little more. You could tell, when you initiated say an up-command, that you could feel going down in the seat of it as you would expect. I think that the pitch movements added some although I'm more in question about the lateral. I don't think the lateral detracted though.

(Does this control system feel like a real airplane to you?) Yes, I thought the controls felt good. They were quite responsive and fairly light, although, as you would expect for an airspeed of 500 knots, they were fairly solid as well. I thought them quite realistic, much as you would expect this kind of airplane to be. I had no complaint at all with the control feel or displacement or forces.

PILOT 2 F-104 TERRAIN FOLLOWING (9/19/67)

24T6143, 144 (closed-loop DLC -- no turbulence)

The task was difficult to perform when the horizontal bar required the greatest movement. For slight movements the task was relatively easy. Airspeed was difficult to maintain due to trying to maintain zero bar deflection as close as possible. This required a lot of attention which detracted from keeping airspeed within limits. Heading was not too difficult to maintain. There was a tendency toward PIO, especially where the greatest corrections had to be made. Stick displacement characteristics appeared normal. Stick forces were not too much out of the ordinary. The information appeared adequately displayed.

24T3145, 146 (elevator -- no turbulence)

The task ranged from difficult to moderatley difficult to perform. The task was moderately difficult when small deflections were required to correct a zero needle and difficult when large deflections were required to correct to zero conditions. More attention was needed to maintain airspeed. Displacement characteristics appeared normal. Stick forces were abnormally heavy.

24T9147, 148 (open-loop DLC -- no turbulence)

The task was moderately difficult when correcting small to zero needle deflections, and became progressively more difficult when large deflections were required. Airspeed was difficult to maintain when attention was directed toward attitude. However, it seemed like it could be maintained within ±10 knots. Tendency toward PIO still occurred when large deflections had to be made to correct to zero needle. Stick displacement appeared okay. Stick forces, however, were heavy when large deflections had to be made for zero needle corrections.

24T8149, 150 (open-loop DLC with turbulence)

The task was moderately difficult. Airspeed could not be consistently maintained when large corrections to correct to zero needle deflection were required. The time devoted to the flight director detracted from maintaining from airspeed properly. Heading was maintained without any difficulty. A tendency still exists or occurs toward PIO when requiring large deflections for zero needle correction. Turbulence increased the workload which decreased the ability to maintain a proper instrument reading. Stick displacement characteristics were okay. However, stick force characteristics were a little on the heavy side, especially where making the larger control displacements.

24T5152 (closed-loop DLC with turbulence)

The task ranged from moderately difficult to a task of little difficulty, depending again on the amount of control displacement required to correct back to zero needle deflection. Airspeed varied as corrections were being performed with the flight direction. There was no difficulty maintaining heading. Tendency toward PIO occurred when the deflections were large and were presented by the flight director and corresponding large corrections had to be made with control stick to return to zero needle deflection. Turbulence increased the workload and decreased the ability to maintain the proper heading for the task. The control displacement characteristics were okay. The stick forces were still a little heavy when large control displacements were required.

24T2153, 154 (elevator with turbulence)

Most of the task was moderately difficult, again depending on the amount of control displacement required to achieve zero needle condition. Airspeed could only be maintained without difficulty when less time was devoted or required by the flight director during the cross check. I found the throttle movements a little excessive to maintain airspeed at times. Heading was maintained without too much difficulty. Tendency toward PIO occurred primarily when control displacements were high when correcting for large deflections in order to obtain zero needle deflection. Turbulence increased the workload with a corresponding decrease in ability to perform the task. Here again it applied primarily to correcting large zero needle deflections. Displacement characteristics were okay. Stick forces were somewhat heavy, which, in turn, I believe, were the major contributing factors toward PIO tendencies.

(May we have your general comments on comparing the three configurations that you tried this afternoon? How about comparing them first of all with turbulence which you just finished?) It was difficult to note any differences between open- and closed-loop modes when using DLC. Comparing the two with the elevator alone, there was a definite decrease in the workload in that the controls were more responsive in maintaining the zero needle condition. Lateral roll control was about the same on all three modes. It was still difficult to detect differences between the open- and closed-loop modes. There was, however, a definite difference between the DLCs and the elevator alone control. The task was much easier to perform with DLC than with elevator alone, especially when the deflections were large. I believe DLC also reduced the tendency toward PIO, whereas the elevator control, where the stick forces appeared heavier, contributed toward PIO more when correcting from large deflections.

PILOT 1 F-104 LANDING (9/20/67)

(How do you normally land an aircraft?) My normal technique would be to fly down the glide path, either ILS or visual, to an altitude on the order of 100 feet or so and, at this point, judging whether the landing looks good, whether you can start an initial flare, then touch down at your desired point. Part of this time you would have been carrying some throttle which would have been giving the right rate of descent that you wanted. Assuming the approach looked good, you would start the flare by elevator input, and I think your main reference in this case would be your pitch attitude. Then, if the landing looked like it was good, you would reduce the throttle and come back on the elevator so that the airspeed would bleed off at this time and you would hold off touching down by attitude, using depth perception to tell how high you were from the runway. In this case you would use an attitude. If the attitude was getting too high and you still were not touching down, then you would be concerned thinking the landing is not going right. In this case, you would add throttle, realizing that your airspeed was coming low, to reduce your rate of descent. That's about it.

(How do you control glide slope during an ILS approach?) Glide slope would be almost entirely controlled with elevator.

14L6155, 156 (closed-loop DLC -- no turbulence)

First of all, the impression I had was that the stick was very sensitive. In other words, it required very delicate handling to fly it. However, response to inputs was quite rapid and apparent so that precise control was possible with this configuration.

With regard to how much pitch to put in, I was afraid of putting in too much or not quite enough. It wasn't immediately apparent as to the exact amount. Aircraft damping seemed satisfactory. Airspeed remained constant by itself without throttle movement. Again, I thought stick force and displacement were very small for this kind of configuration. The total task, I would say, was about normal difficulty as you would expect for this kind of airplane. Sink rate was fairly easy to control. Elevator response was quite rapid so that sink could be altered quickly. I would see no advantage to a separate direct lift control.

14L9157, 158 (open-loop DLC -- no turbulence)

On this configuration, I found no significant differences from the previous one with closed-loop DLC. However, there seemed to be some difference in the pitch in that, putting in a small amount of elevator input, nothing would happen momentarily and then it would rather quickly take off to the amount that you would put in. Sort of an initial lag, followed by a quick response. This meant that while things were centered it stayed centered quite readily and tracked down very nicely. Whenever a correction was required it usually meant overcorrecting. So I thought this configuration, though not bad, was not quite as good as the previous one and, therefore, I rated it a four instead of a three. There was no need to trim, and maintaining constant attitude seemed quite easy to do. Glide slope was acquired without difficulty. Tracking was a little more difficult in that I wasn't able to track as smoothly and immediately correct an error as with the previous combination. The localizer was the same as before. I could easily track it. I didn't note any tendencies toward PIO. The flare maneuver seemed a little more difficult this time. Again it was hard to know how much you had flared and so you had to flare, then wait for the indications on the needles to tell you how much, and then, unless you weren't quite sure whether it was enough or too much, wait unitl it was rather late to make a correction. Do I consider the presentations the flare maneuver adequate for evaluation? I'm not too sure about this one. Flaring is not really the same as landing. However, it's the same for all configurations. I think really it makes a valid comparison between the different combinations. Aircraft damping was satisfactory. Stick force and displacement seemed rather delicate again, although it seemed to require only slightly more force in this configuration than the pitch movement than the previous run. The total task was, I would say, not difficult, but in the ILS landing phase, more difficult than in a normal visual landing. Sink rate seemed to be fairly readily controlled.

(This ended Wednesday's runs.)

THRUSDAY, 21 SEPTEMBER 1967

14L6159, 160 (closed-loop DLC -- no turbulence)

I rated this a three. I considered this good. The only thing slightly unpleasant about this which made me rate it a three rather than, say, a two was that again it was a very sensitive and very delicate control. It required control movements which were too small and too delicate. However, the aircraft seemed very responsive. It corrected almost immediately in the direction that you put an input and made it possible to perform the task reasonably well. Going down the checklist, I didn't have to trim it. It seemed trimmed to start with and not difficult to maintain constant altitude. Glide slope was acquired quite readily and was not particularly difficult to track. It became more difficult, as you might expect, when you got close to touchdown, but it still doesn't seem too bad. The localizer was about the same as the glide slope -- fairly sensitive but not too difficult to track. There was no tendency toward PIO. The flare maneuver was not difficult. The only difficulty in my mind was how much nose-up attitude to put in when starting the flare. It was a little hard to know if you were giving it too much or not enough. I think the flare maneuver was adequately presented for the evaluation. To me it was not really the same as landing where you have outside reference of the runway, but I think that is almost impossible to achieve in a simulation, and I think this was quite adequate for an evaluation. Aircraft damping seemed satisfactory. I didn't need to maintain airspeed with the throttle. Stick rather forces and displacement were rather small. The total task was not particularly difficult, although not exactly easy because of the very high sensitivity, but it was a task that could be readily accomplished. Sink rate seemed to be very readily controlled when the flare maneuver was initiated.

14L9161, 162 (open-loop DLC -- F-104 landing)

I can really detect very little difference between this and the previous runs as far as the performance of the aircraft. It seems very similar really. The tracking task in each case on the ILS seemed identical. It seemed to me that each time on the flare I did not do as well, but I think it was my own incorrect input that time. It didn't feel quite as nice on the flare. Each time I got a little too nose-high on attitude and then had to correct back down which wasn't the smooth flare that I would like, but I really feel that wasn't the fault of the input, it was just my initial overcorrection on pitch attitude. Therefore, I really can't make any other comments regarding this configuration as opposed to the previous one. All comments would equally apply to both.

14L3163, 164

No comments.

14L11165, 166, 167 (separate DLC)

I found that, particularly at long range, you could control the aircraft on the glide path quite precisely by just holding attitude constant and moving the DLC. When you got down to short range you would overcontrol the DLC, going from almost pull-up to pull-down. Also, for the actual flare I found again that if you put in both elevator and DLC, invariably you would overcontrol it. The best technique was to hold the attitude with the elevator apparently constant and put in DLC to make the flare. The difficulty here was how much DLC to put in so you didn't overdo it or didn't underdo it. I think with practice this could be accomplished quite readily. I rated this a four because of the different technique required. I think that with practice on this separate DLC, you could do a reasonable job on the landing approach and certainly better than with just the elevator. Going down the checklist, I found the aircraft in trim. I didn't need to trim. Maintaining constant altitude was not any problem. Glide slope could be quite readily acquired, and once acquired, the DLC could track it quite readily, particularly at the longer ranges. The localizer was the same as always. I found that, since I was using a different technique on the glide slope, perhaps I, through lack of concentration on the localizer, permitted it to wander more than I had on previous runs. I think it is a matter of training, though, to coordinate the whole thing together and do quite a reasonable job. I didn't notice any tendency toward PIO. With regard to the flare maneuver, I think once you got the technique down it would not be difficult in the learning process. It was a little difficult to know just how much DLC to put in to accomplish the flare. With regard to presentation of the flare maneuver, the same comments that I made before apply. Aircraft damping was satisfactory. I didn't control airspeed. Stick force and displacement again were rather small and sensitive as I commented previously. As for the total task, I found it difficult at first, but I think that learning comes into this. Once used to this technique as a separate DLC, it was not particularly difficult. Sink rate could quite readily be controlled. The difficulty was in knowing how much DLC to put in. This perhaps would be more peculiar to a simulator than an actual airplane. The sink rate might be more readily apparent by seeing outside and observing the runway. With regard to the advantages of having separate DLC control, I am kind of on the fence about this because I found DLC to be quite a different technique. Once that technique was mastered it appeared that the performance was comparable. I really think, though, that I would still prefer to have the DLC blended into the stick. As I say, that could change with training, using the control separately.

(Are you familiar with the Navy studies on DLC? Would you comment on separate DLC as we have it mechanized here? That is, is it adequate, or what changes would you recommend if it is not adequate?) DLC is, as it is used in this simulator, quite satisfactory provided, and this is a requirement, that you have at an autothrottle. That is, you couldn't be working both the DLC and your throttle with the left hand. So if you didn't have an autothrottle, I think it would be required to be on the stick so that you could control the DLC with your thumb of your stick hand, leaving your throttle hand available for the throttle. In a situation where you have an autothrottle, I think it works a little better to be able to use your other hand to control the DLC and save your right hand for the stick.

(Assuming we have autothrottle, do you think it would be better to have the separate DLC spring-loaded to center rather than having it stay where you leave it right now? What do you think about that?) Yes, although I'm not too sure about that. I found it not bad the way it is. At first, though, you would think maybe it would be better to have it spring-loaded to the center, but I didn't find any fault with it the way it is, that is, if it stays where you put it. There might be some tendency to leave it in a position that you're not really aware of. I'm not too sure about that. I think I would have to try it both ways.

(You have completed the block for the case of no turbulence. Would you comment comparatively on the four controls that you have tried for this task?) On the four controls that I have tried, I found that I liked closed-loop DLC the best. Open loop really was very little different. I think I had a slight preference for closed loop, but there was nothing very much wrong with open loop. As for separate DLC, my comments here indicate that a different technique is required. But, once this technique is mastered, it could well be that this could be considered as good as that of the closed loop or open loop. My opinion at this moment is that closed loop is a little better but I'm not sure. With training, separate DLC might be considered quite all right. Of course, I think the elevator is the worst of all because of the lack of response. DLC, whether open, closed, or separate, certainly improves on the elevator control.

(You have commented with regard to the task as a whole here. Could you comment on the devices for the flare maneuver and then separately for the glide slope following portions?) On the flare maneuver again I think I like closed-loop DLC the best because it is more normal to me to flare using the stick. Open-loop DLC seemed to be pretty much the same on flare. I don't recall any significant difference between flaring with open loop and closed loop. The elevator I found not so good because of the lag, and with the separate DLC in, the flare was a completely different technique. It was flaring with the DLC holding the attitude pretty much constant and, as it turned out, this worked out fairly good. At least the performance seemed satisfactory once you got on to the idea of flaring with the DLC. There was one trouble, though, flaring with the separate DLC, and that was how much to put in so that you were careful not to overdo it or underdo it. I tended to go from pull-up to pull-down rather rapidly in a bang-bang operation in order to get the right amount.

14L8168, 169 (open-DLC with turbulence)

First of all, the turbulence I thought was insignificant. I could hardly tell that there was any. In fact, if I had not been told, I doubt that I would have noticed any difference between that and other runs as far as turbulence was concerned. Consequently, my comments for open-loop DLC I think are identical with those already given. I noticed nothing different this time than from the previous runs with open-loop DLC and no turbulence, so I have no further comment at this time. (Turbulence increased from 0.5 degree to 1.0 degree angle of attack on subsequent runs.)

14L8170, 171 (open-loop DLC with turbulence)

In this case, the turbulence was doubled from the previous run. The turbulence this time became significant, at least on the instruments. I didn't notice that much difference as far as the motion simulator was concerned. However, turbulence definitely made the task more difficult. Because of the gust it would vary the vertical velocity of the aircraft so that it made it more difficult to track and flare because you could not depend on a particular pitch attitude to give you your desired attitude rate of descent. The aircraft I rated as a three still because the aircraft is really a good aircraft. It is responsive and performs as you would desire it. The only reason it is not higher than a three is because I feel it rather sensitive and rather delicate to fly. The turbulence, though, definitely decreased the performance and similarly made the workload a little heavier. On the checklist, I would say that I had no occasion to trim it.

Maintaining constant altitude was not too difficult, although perhaps a little more so than in smooth air. Glide slope was about the same as far as acquiring and tracking it. It became more demanding because of the changing vertical velocity of the aircraft. Localizer difficulty to track is the same as it has been, other than perhaps the fact that more concentration on the glide slope then gives you less time to look at the localizer. Flare I thought was more difficult, again because when the flare is initiated, if there is a gust at that time, it would give you either more than you intended or not as much, so it made it again a little more difficult to know how much to flare the aircraft to give you the desired touchdown. Aircraft damping seemed satisfactory. Airspeed maintained itself. Stick force and displacement were rather light and sensitive. The total task was more difficult with turbulence, although not a great deal more difficult, just somewhat more difficult. Sink rate was quite readily controlled.

14L5172, 173 (closed-loop DLC with turbulence)

There were no significant differences between this run and the previous run with open-loop DLC and turbulence. Turbulence seemed about the same in each case. It seemed fairly severe, I guess, in the sense that, on looking at the instruments, there were vertical gusts which seemed of quite strong velocity. The turbulence didn't made the simulator move that much. I think turbulence was about equal in either case, and aircraft responses also were quite good and rapid, pretty much as you would desire them to be. The turbulence, though, had the effect of making you work harder to fly accurately and at the same time decreasing the performance. In flare, turbulence can be quite hard to judge so that vou are not sure of how much to flare, and this could make your touchdown very significant. In both cases, turbulence simply makes the task more difficult, although the airplane itself responds quite well. With reference to the checklist, there is really very little difference from the ones that I mentioned before. I think turbulence makes it more difficult to track the glide slope and the localizer in the sense that spending more time concentrating on the glide slope leaves you less time for the localizer. There is no tendency toward PIO. Flare is more difficult because the vertical gust at the time makes it harder to know just the amount of flare, that is, the amount of pitch attitude to put in.

14L2174, 175 (elevator control with turbulence)

My major impression of this was that the turbulence seemed of greater intensity or that at least it had more effect on the airplane. I would probably expect that turbulence really wasn't much different but it had more effect in the sense that, when putting in an input to correct against a vertical gust, the airplane was slower in responding, hence giving the impression that the gust was of greater intensity or of longer duration. So I rated this configuration somewhat lower, and gave it a four. It didn't seem bad. I didn't have too much trouble tracking, at longer range at least. Flare, however, was rather an indefinite thing, and I really wasn't sure how much flare to put in. The lag and the control, and also the awareness of the turbulence, made the flare maneuver more difficult. Commenting on the checklist, maintaining constant altitude was about the same as always, not especially difficult. Glide slope required more effort to track it accurately. With more concentration on the glideslope, there was less tendency to concentrate on the localizer, and hence I allowed some localizer error that was undesirable. I did not note any significant tendency toward PIO. Flare was more difficult as previously commented on. Aircraft damping seemed satisfactory. Stick force and displacement were still rather sensitive. The total task was fairly difficult. Sink rate was not exactly easy to control with the lag there from an input that allowed you to keep sinking when you wanted to halt the sink rate.

(Would you comment now comparatively on these three configurations in turbulence?) It seemed to me that with open-loop DLC or closed-loop DLC there was no significant difference. I really couldn't detect much difference between the two. With the elevator alone, it seemed that turbulence was more severe, or that turbulence had greater effect on the airplane, so the task became more difficult and you had to work harder, particularly in the flare maneuver.

PILOT 2, F-104 LANDING

24L3176, 177 (elevator with turbulence)

There was no difficulty in acquiring and tracking glide slope. Localizer was not difficult to track. Tendency toward PIO occurred primarily during the flare portion. The flare maneuver was difficult, especially if you were several bar widths from the zero needle deflection position. The presentation for flare maneuver was inadequate. It was okay for evaluation, but it could use a warning light, for example, amber to standby to flare, then the red light for the actual flare itself. Airspeed was not difficult to maintain. Stick force and displacement characteristics were okay. The total task was not too difficult. Sink rate was easy to control if you could interprete the horizontal needle during the flare correctly. Otherwise, the sink rate was difficult to maintain and it tied in with the PIO tendencies.

24L6178, 179 (closed-loop DLC -- no turbulence)

PIO was significantly reduced as compared with the elevator alone control mode. The flare maneuver was moderately difficult to normal, once the (presentation) interpretation could be acquired during the flare. The presentation of the flare maneuver was adequate for evaluation. Airspeed was easy to maintain within three knots or less. Force and displacement characteristics were okay. The total task was easy to perform. Sink rate did not present too much difficulty.

24L9180, 181 (open-loop DLC -- no turbulence)

There was no problem acquiring glide slope and track and no problem in tracking the localizer. There was very little tendency toward PIO during this maneuver. The flare maneuver was performed without any difficulty during this particular task, even though I didn't have the rate of climb working. It was strictly following the horizontal needle. Presentations of flare maneuver was adequate for evaluation. There was no problem on airspeed. Stick force and displacement characteristics were near normal. The task was relatively easy. Sink rate was easy to control according to the needle.

24L11182, 183 (separate DLC -- no turbulence)

No difficulty was encountered in acquiring glide slope. The localizer was fairly easily tracked. Tendency toward PIO occurred during the flare out, trying to find a correction to zero needle deflection. The flare was difficult to perform. I didn't seem to be able to properly blend in the DLC to smooth out the flare the way it should have been. Presentation for the flare maneuver is adequate for evaluation. Airspeed was not difficult to maintain, except when having to leave the throttle to use the DLC independent control. Stick force and displacement characteristics were okay. The task was not too difficult to perform except for the last portion of the maneuver where the flare was concerned. The sink rate was hard to control when I tried to use the DLC where I tended to overcontrol and produce a tendency toward PIO. I don't think it would be advantageous to have a separate direct lift control.

(You have flown all four now without turbulence. Would you compare them?) The open- and closed-loop modes of the DLC were very similar in responses. They had a definite advantage over the elevator control. The tasks were performed easily and the corrections were significantly smoothed out as compared with the elevator alone control. As far as separate DLC is concerned, I would prefer to not have it at all. I would prefer elevator alone control.

24L8184, 185 (open-loop DLC with turbulence)

No difficulty was noted in acquiring glide slope. No difficulty was experienced in tracking the localizer until about the start of the flare. Tendency toward PIO appeared during the flare, especially when first initiated. The flare maneuver was moderately difficult. Presentation for the flare maneuver was adequate for evaluation. Airspeed deviated a little more this time because of the added workload due to the turbulence in trying to maintain the zero needle deflection. Stick force and displacement characteristics were okay. The total task was not too difficult except for the flare maneuver itself, which was moderately difficult. Sink rate was easily controlled during the glide portion. It tended to be a little difficult to control during flare.

24L5186, 187 (closed-loop DLC with turbulence)

There was no difficulty in acquiring glide slope. There was no difficulty with localizer except during the flareout portion and a little difficulty in trying to maintain track. There was a tendency toward PIO only during the flare maneuver. Possibly in this case it wasn't quite on the zero needle when the flare started. Presentation for the flare maneuver was adequate for evaluation. Airspeed was not too difficult to maintain. Stick force and displacement characteristics were okay. The total task was moderately difficult. The glide was easy except for the initial portion of the flare where I was overcontrolling somewhat. Sink rate was not too difficult to control.

24L2188, 189 (elevator with turbulence)

No difficulty with glide slope. No difficulty with localizer during the glide and a little difficulty to maintain it during the flare portion of the maneuver. Tendency toward PIO occurred during entry into, or just prior to, the flare or during the flare. The flare maneuver was difficult to perform as smoothly as it should have been. Presentation for flare maneuver was adequate for evaluation. No difficulty in airspeed. Stick force and displacement characteristics were okay. The task was moderately difficult to difficult during the flare maneuver. A consistent sink rate was not maintained. This was due to PIO, especially during flare portion of the maneuver.

(Would you now give a comparative evaluation of the three controllers in turbulence?) Again, I didn't notice too much difference between the open- and closed-loop DLC modes. However, the control response was significantly greater (better?) and the effort to maintain the proper instrument readings were more smoothly performed using DLC as opposed to the elevator control only. The tendencies toward PIO were damped considerably and it just made for a more comfortable maneuver transitioning from the glide to the flare portion of the maneuver.

74L6190, 191 (closed-loop DLC -- no turbulence)

No difficulty at all with trim. Glide slope was easy to control. Localizer was easy to track. No tendencies toward PIO. No difficulty with flare. There was adequate presentation of flare. Airspeed was easy to control and stick forces seemed normal. The total task, I would say, was quite easy. No difficulty with controlling the sink rate.

74L9192, 193 (open-loop DLC -- no turbulence)

No comments.

74L3194, 195 (elevator -- no turbulence)

No difficulty in maintaining altitude. Glide slope was a little more difficult to acquire and track under this condition. No difficulty in tracking localizer. There was a slight tendency toward PIO. Flare maneuver was not difficult, but more so than in condition 6. There was adequate presentation of the flare maneuver. Airspeed was not difficult to maintain. Stick forces and displacement appeared normal. The total task was not difficult but was a little harder than the other two conditions. Sink rate was a little more difficult to control in this condition.

(Separate DLC was not flown.)

(You have flown the three configurations now without turbulence. How would you compare them?... Relative to each other?) Conditions 6 and 9 were quite easy to control on glide slope and quite a bit easier to execute on the flare maneuver. Condition 3 I suppose you would consider as a normal glide slope control and flare.

74L8196, 197 (open-loop DLC with turbulence)

No difficulties were experienced in trim or in maintaining altitude. Glide slope was not difficult to acquire, but was rather difficult to track. No difficulties were experienced in tracking localizer. Didn't notice any tendency toward PIO. The flare maneuver was not difficult. Flare presentation was adequate. Airspeed fluctuated a lot more under turbulent conditions but was able to maintain it satisfactorily. Stick forces and displacement were normal. The total task was not difficult. Sink rate was considerably harder to maintain under turbulent conditions.

74L5186, 187 (closed-loop DLC with turbulence)

Altitude was easy to obtain and to maintain constant. Glide slope was easy to acquire and not at all difficult to track. Localizer was easy to track. There was no tendency toward PIO. The flare maneuver was easy. Flare maneuver presentation was adequate. Airspeed was easier to maintain under this condition. Stick force and displacement appeared normal. The total task was relatively easy. Sink rate was much easier to control under this condition.

74L2200, 201 (elevator with turbulence)

No difficulty was experienced in trim and maintaining constant altitude. Glide slope was fairly difficult to acquire and track. Localizer was not difficult to track. There was no noticeable tendency toward PIO. The flare maneuver was considerably more difficult. Flare maneuver presentation was adequate. Airspeed was more difficult to maintain but could easily be maintained within limits. Stick forces and displacement were normal. The total task was relatively difficult. Sink rate was relatively difficult to maintain.

(Would you compare the three configurations in turbulence?) Condition 5 (closed-loop DLC) was the easiest to control. There was relatively little indication of turbulence under those conditions. Conditions 8 (open-loop DLC) and 2 (elevator alone) were relatively difficult to maintain on glide slope, especially their rate of descent.

PILOT 3, C-5A GLIDE SLOPE (9/22/67)

35L11202 (separate DLC -- no turbulence)

On the first run, separate DLC was used only for flare. On the second run, it was used on the glide slope as well as on the flare. I think on the glide slope it can be seen that separate DLC tends to induce some PIO, whereas when used for flare only, I think it tends to help stabilize the aircraft. What I tried to do was to fly 112 knots until the light came on, indicating that the flare had started. At this point, I assumed that the aircraft would be landed. Therefore, the throttle was brought back and the flare continued until the altitude indicated zero and the airspeed had come down to about 90 knots when the computer simulation was automatically going into hold. So I think about 90 knots is a good landing airspeed, or maybe 95 or somewhere in there, but at least the power is available to decrease airspeed and to continue to flare until landing is made. Although the horizontal bar indicated that we were quite low or considerably below glide path on the flare, I think that flying with it at zero all the way down to about 20 or 30 feet and then flaring out using the power probably is more practical and achieves more what the aircraft would actually do.

I think that the aircraft is quite stable with this condition, and I think that DLC is advantageous for the flare.

35L6204, 205 (closed-loop DLC -- no turbulence)

The task was easy to normal. Maintaining the aircraft horizontal and vertical bars at zero was quite easy with closed-loop DLC. It was very beneficial as compared with separate DLC or just conventional elevator control. I think that the terminal conditions indicated that it was quite easy to maintain zero on both pitch and latitude (altitude?) even during flare. I didn't find any tendency toward PIO. I think this is due to the fact that the airspeed was lower than it was up at altitude, let's say 550 knots, when you just barely touch the stick and get behind the aircraft. Here on final approach and roundoff I think you will find that DLC really helps in maintaining stability of the aircraft.

35L9206, 207 (open-loop DLC -- no turbulence)

Again we are flying airspeed and the vertical and horizontal needles until the flare comes in and then pulling back the power and trying to flare to a landing. The aircraft is not hard to control in either pitch or latitude. I think that there is a slight tendency toward PIO in azimuth following the vertical needle, but the horizontal needle again is quite easy to maintain at zero. Airspeed is quite easy to control and the task is what I would call normal. I think the sink rate on flare is relatively good and, in general, it is only a bit more difficult to maintain than closed loop.

35L3208, 209 (elevator -- no turbulence)

I think the airspeed and needles were quite easy to maintain at zero, although when tending to correct azimuth as well as pitch, it tends to overshoot a little. Maybe this is again back to the light stick force around center. Either that or just the controls are effective enough to change the rate faster than what I'm used to. The flare is easy at first to keep up with, and then it tends to go quite rapidly up and the aircraft just cannot follow. Again the airspeed is probably down to about 90 knots so the pitch change does not affect altitude very much. As a general rule, I would say that the task is about normal and I did an average job in it.

(You have flown all four combinations now without turbulence. Would you comment on them comparatively?) First of all, I think separate DLC is not very good. At least with myself it tends toward PIO. I tend to overcorrect or undercorrect, so I don't bring it back to zero quick enough, and then I have to go to the throttle. It is difficult to keep up with. I would say that with conventional elevator control there might be a slight tendency toward PIO both in lateral and in pitch. Airspeed is not hard to maintain and the rate of descent is held rather constant. Into open-loop DLC there is perhaps a tendency on the pitch axis toward PIO, although it is not too great. In closed loop it is far superior to any of the other three, and it is easy to maintain and the task is a lot easier. Airspeed is easier to maintain, pitch and lateral-direction are also easier to maintain. The rate of climb is again held rather constant. I think you provably have less ground effect. At least the last 100 feet seem to fly a lot easier with DLC than without. We used DLC for just the flare maneuver when using separate DLC. I see where it probably will help if you had a fast rate of sink, to blend it out and gain control of the aircraft. Coming down the glide path the DLC is just an extra handle and you need three hands in the cockpit to operate it. Probably in the flare, once you have pulled back the power and you're just rounding out, there is a good use for it.

35L2210, 211 (elevator with turbulence)

Tends to introduce a little PIO both in glide path and especially in flare attitude. Airspeed is relatively constant but the horizontal bar is quite hard to follow. The latitude (altitude?) is not too hard to maintain. I think the biggest problem is maintaining the horizontal bar at zero conditions. The turbulence tends to help induce this PIO, especially with this moving base. Turbulence tends to add when you wish it would subtract. The sink rate is not really affected here, it is just a matter of trying to follow that horizontal needle. It's moving so rapidly during the flare portion that by the time you catch up with it, even when you try to anticipage reaching zero, it still tends to overshoot. The glide slope on the second run was better than on the first run down to about 100 to 150 feet. It was almost zero at all times. From 150 feet on I think PIO tended to shift it every direction. It is easier to fly trimming it down the glide slope, but once you hit the flare attitude it is best to leave the pitch knob alone.

35L5212, 213 (closed-loop DLC with turbulence)

This is blended closed-loop control. With this control it is relatively easy to maintain zero vertical and horizontal needles as compared with the conventional elevator. The localizer is quite easy to track as well, and the glide slope is quite easy to follow. As you get closer and closer to the ground, I think it is easier and easier to overcorrect because of the needle becoming more sensitive to even small changes. The sink rate is not large. I may tend to make the rate zero for touchdown, to grease it on rather than landing it at maybe four to five hundred feet a minute rate of descent. This tends to prolong the touchdown point another 500 feet down the runway. The total task I think is normal to easy, and even with turbulence it's relatively easy to keep up with the needle. In the flare I think it tends to get a little PIO, maybe right at the last phase. Again I think this is due trying to get the rate of climb down to zero for touchdown.

35L8214, 215 (open-loop DLC with turbulence)

There tends to be some PIO both in lateral and in pitch from 150 feet on down. I think the airspeed is effected by ground effect as well as the lift being effected, and, together with the PIO, the horizontal needle tends to oscillate maybe as much as a quarter of an inch above and below at the extreme values. The airspeed is easy to maintain if you keep your eye on it, as well as the rate of descent, and get the power back quick enough. Once you're low on airspeed, and this is on all runs, it is hard to build it back up, which is probably going to be the case in the C-5A. Once you dump the nose a little bit, the airspeed tends to build up quite rapidly, which again is going to be true of the C-5A. The directional control I would say in almost all runs was easy to maintain -- directional heading is probably the only fallacy with this simulation. In the true aircraft, if you're off maybe two or three degrees on heading you tend to correct with rudder rather than with ailerons, and I think this will probably tend to make the system more damped out because you're not throwing in the aileron and pulling back and getting direct lift control to maintain the altitude or the rate of descent that you were holding. Other than that, it is a fairly realistic setup. The flare with the light as an indicator I think is probably quite good, it gives you an idea of exactly where you are. You then check your airspeed, pull off your power, and you can complete what I would call a pretty good flare for an aircraft. In open-loop DLC there might be a little PIO both in lateral as well as pitch with turbulence on. This is not too hard to compensate, although it is there and you can see going by your zero values in both directions. I think in elevator control, as probably will be seen by the graphs, it was quite hard, almost impossible, to control the PIO that was there with turbulence on. It is a relatively difficult task to follow the two needles and airspeed and altimeter with turbulence. I don't know what the rate was for the turbulence, but I would say, just feeling the aircraft and watching the movements, it was probably light to moderate. Closed-loop DLC has a distinct advantage over all three. I would say that closed-loop DLC with turbulence on is probably easier to fly than the elevator control with no turbulence. With open-loop DLC I tend to get a little PIO on both runs. Maybe it is something in the simulation or in my flying, I don't know which. PIO is very prevalent in elevator only. In the closed loop there might be a little PIO in pitch, maybe the last 100 feet or so. Again, trying to change your rate of descent so you're landing with zero rate of descent probably gave you most of this. Airspeeds were not really difficult to control in any mode except elevator only. With turbulence on it was quite difficult.

(Does the moving base simulator add to the realism?) The motion I'm getting varies maybe five-six degrees of bank angle to maintain the heading. I think it is good that it is there because it actually adds a little more true simulation to what an aircraft would give you. With pitch I think it is very good because otherwise you have no feeling of g's whatsoever, and this at least tends to give you an idea that you have flared or that you're correcting the rate of descent. I think it is good.

I think probably you could do better because, with the stick being as sensitive as it is, this little bit of motion in the simulator tends to couple into the stick through me; as the motion simulator changes, the weight of your arm changes a little bit to give a little g. I think it is more realistic having motion rather than fixed-base.

(When you pull up, does the simulator give you the type of acceleration that you expected?) I think it does. It doesn't give as many g's, and it takes more force to pull up in an actual aircraft I believe. I think you would actually feel more backpressure and you would feel more seat pressure. Again you don't fly any of our aircraft to a zero condition so it wouldn't be on the gages so it is hard to tell. Here we are flying strictly gages to touchdown so I don't know. I think you would have more g-feel and more backpressure in an aircraft. This gives you a feeling of some g's, although the amount of g's is probably less than half a g or less.

I mentioned once before, I think turbulence feels probably light to moderate, probably even light. There is enough there to fluctuate the altimeter and the angle of attack and the rate of climb a little bit. Airspeed changes may be one or two knots in trim level flight.

(In summarizing, do you feel that the motion that we have simulated here helped in the evaluation of the various combinations tested?) Yes. I think it gives a more realistic view of what the aircraft is really doing, and it tends to bring in the other factors that would be there should you be in an actual aircraft. With turbulence on and banking, the weight of the body and the arms gives a little bit of motion, both side effect and backpressure.

PILOT 1

15L3216, 217 (elevator -- no turbulence)

First, my overall impression of the aircraft is that it was extremely sluggish, that is, very slow on response. The aircraft seemed, however, very stable provided large corrections weren't required. It seemed to track on the glide path quite well. I rated the overall pitch control a four, probably because of its sluggish and slow response. The flare I rated five because it was more difficult in this situation to know whether you were arresting your sink rate or not. Airspeed seemed very critical. If you could keep the airspeed about its proper figure the task was considerably easier. However, if you let it get up to 10 knots off your desired figure then it became very difficult to get it back to the proper reading. The throttle response as you might expect in this kind of airplane was extremely sluggish, and once it got low under you could hardly get it back at all. To go down the checklist, there was no need for me to trim the aircraft. Maintaining constant altitude was quite easy. Glide slope was not difficult to acquire, and in the initial part tracking was quite good. This is particularly so if you can keep the airspeed at its right value. When you get close in on the glide slope, it becomes more and more difficult to track as you might expect because the small error shows up larger on the artificial horizon. The localizer was not particularly difficult to track. The big thing here was to not let the error get very large. I didn't notice any tendency toward PIO. The flare maneuver I found rather difficult in that I didn't know how much to flare. At the same time you had to pull quite a lot of throttle off in order to touchdown or else have quite a float. As for the flare presentation, I think it is adequate for this evaluation, but it doesn't have near as much information input as an actual landing would, where you would have the visual reference outside. Aircraft damping seemed satisfactory. Airspeed I thought was rather difficult to maintain because of the extremely slow response in the throttles that, once it was off the desired value, you didn't know how much throttle to put in to correct it back, so you were overcorrecting or undercorrecting. Stick force and displacement were about right for this kind of an airplane. The total task I would say was reasonably difficult and the sink rate I thought was kind of hard to control. I'm not sure just how you can control it with the elevator. It is a combination of elevator and throttle.

15L9218, 219 (open-loop DLC -- no turbulence)

I found quite an improvement in this open-loop DLC configuration over the previous one that was straight elevator. The quick response both on the glide path and the flare enabled you to keep the errors very small so that you could track much more precisely. The secret seems to be in keeping a very small error and correcting that before it becomes large, and then the task is considerably less difficult. This seemed like a good configuration. It behaved quite well. Going down the checklist, there was no need to trim, and there was no difficulty maintaining constant altitude. The glide slope was not difficult to acquire, and it was much easier to track this time than the previous time. The localizer was not particularly difficult to track. The big thing there is to not let the error get very large. There were no tendencies toward PIO, and the flare maneuver seemed better this time. It is still a little indefinite as to how much to pull the throttle off and how much to go back on the elevator to give you the desired flare. The response being quicker this time gave you better feel for the proper flare maneuver. Regarding the presentation of the flare maneuver, the previous comments apply. Aircraft damping seemed satisfactory. Airspeed seemed less difficult to maintain this time. I'm not sure whether I'm becoming proficient in getting the right throttle setting or possibly the quicker response of the aircraft controls also helped in maintaining a more desired airspeed. Stick force and displacement seemed quite good. The total task this time was, I thought, much easier than the previous run. I still was not actually sure how much input you need to control the sink rate, but at least in this configuration a little quicker response from the elevator made it easier to control.

15L6220, 221 (closed-loop DLC -- no turbulence)

These two runs were by far the best I've had. They seemed very easy. Therefore, I rated this generally a two. It seemed very simple to center the cross pointers and keep them more or less centered for the run on the entire glide slope. The flare maneuver also seemed to go better this time. All in all, it seemed a very good run. I really have no adverse comments that I could make on this particular run. (We will skip this checklist.)

15L11222, 223 (separate DLC -- no turbulence)

Acquiring and maintaining the glide path seemed quite easy with this configuration. It presented no problem at all. The glide path can be controlled very precisely down to about the 200-foot altitude. One problem, when you change the DLC then it changes the airspeed as well, so you're rather hard pushed with your left hand to work both the throttle and the DLC to give you the right airspeed. On the glide path, however, airspeed changes are small so this doesn't present much of a problem. In a flare, however, I had considerable difficulty in coordinating the throttle and the DLC to give me the kind of flare that I wanted. It usually resulted in considerably overcontrolling. Usually, when the airspeed was a little bit low just before the flare, increasing the throttles would maintain the airspeed, but then, as the flare was initiated, the airspeed would be too high, requiring the throttle to come out and the combination of the two made it pretty difficult to track the bar. In fact, I found that I really couldn't track the bar satisfactorily at all. Going down the checklist, maintaining altitude was quite satisfactory. Glide slope was easy to acquire and easy to track. Localizer was also easy, but there was no tendency toward PIO. The flare maneuver was the difficulty, and I rated this configuration as low as a five. Aircraft damping was satisfactory. Airspeed was rather difficult to control. This wasn't too much of a problem on the glide path because the deviation airspeed was fairly small, but in the flare maneuver the airspeed was quite difficult to control. Stick force and displacement seemed all right. The glide slope task was easy and the flare was very difficult. Sink rate could be controlled quite easily, but the trouble was the big effect on airspeed when you put in full-up DLC that made the combination rather difficult.

(Would you now give a comparative evaluation of these four configurations flown without turbulence?) In comparing the four combinations, it seemed to me that closed-loop DLC was by far the superior. Open-loop DLC was nearly as good, and the elevator alone was not too bad except for the flare maneuver; it was hard to get the right kind of flare. With separate DLC the problem of coordinating the throttle and the DLC at the flare made it very difficult too. So I like closed-loop DLC best and open-loop DLC just about the same. The elevator alone was not as good and separate DLC was the worst of all, primarily because of the problem of controlling both airspeed and the flare at the same time.

15L8224, 225 (open-loop DLC with turbulence)

With the inclusion of turbulence, the main difficulty is maintaining airspeed. Tracking is more difficult because there is more variation. The airplane responds fairly well, but when fairly large elevator corrections are needed, then the airspeed changes quite substantially. It is hard to keep it at the desired value. This mades the glide path tracking workload higher. It wasn't too difficult, although I did have some trouble maintaining proper airspeed. To comment on the checklist, there was no need to trim. Maintaining constant altitude was not difficult, although a little more work was required. The glide slope also was not difficult to acquire or track, although again turbulence made the workload a little higher and, as I said, the problem of varying airspeed bothered me more than any other particular thing on the glide slope.

The localizer was as it had been as far as tracking. No special problem there. There was no tendency toward PIO that I noted, although I noted that in the flare maneuver there was a tendency to overcontrol, but it was not really PIO as such. The flare maneuver was the most difficult; this again was knowing the throttle setting for the airspeed that you want to make a proper touchdown. Aircraft damping seemed satisfactory. Airspeed was, I thought, the biggest problem. It was rather difficult to control. Stick force and displacement seemed satisfactory. The total task was more difficult due to the turbulence, and particularly the flare maneuver was more difficult. Sink rate could be quite readily controlled, but again, when you had to put large movements in to control the sink rate, it had quite an effect on the airspeed.

15L2226, 227 (elevator with turbulence)

With elevator alone, I found that again the turbulence detracted quite a lot to make the task much more difficult than without turbulence. I found that the glide slope wasn't too bad. The turbulence could be compensated for; it made you work harder, but it wasn't too hard to maintain the glide path. Larger corrections were required, and it meant more concentration on the airspeed, but this could be controlled with fair accuracy down to the order of 200 feet. The flare maneuver again was the difficult one.

With turbulence, it made it difficult to know how much throttle to pull off and howmuch up pitch to put in, and usually a gust then would mean that you go too high. You then have to put it down elevator, and this is an uncomfortable thing to do when you are very close to the ground. So turbulence, then, made it hard to know what control inputs you needed to make the desired flare maneuvers. I wouldn't like to land such an airplane in gusty conditions. Commenting on the checklist, maintaining constant altitude was not too bad. A little more concentration was all that was required. I didn't need to trim it. The glide slope was little more difficult to acquire and track, but this could be done with a little bit more concentration. Localizer tracking was about the same as always. There were no tendencies toward PIO, although there was a tendency to overcontrol both on the glide slope, and, more particularly, in the flare. Aircraft damping was satisfactory. Airspeed was considerably more difficult to maintain because of the turbulence. Stick force and displacement were satisfactory. The total task was more difficult and, in particular, the flare maneuver was quite a bit more difficult. Sink rate was rather difficult to control, the airplane being sluggish and slow on response.

15L5228, 229 (closed-loop DLC with turbulence)

With closed-loop DLC, turbulence didn't seem to have much detrimental effect as on the other runs, particularly the elevator runs. I found that the glide slope could be readily acquired and maintained and the turbulence caused a little more concentration, but the aircraft was such that a reasonably good job of tracking could be done. I found that with this configuration the flare was quite a bit better than it had been with the other with turbulence. There seemed to be a reasonable ability to initiate the control and maintain a proper attitude until touchdown, so I think that this combination is fairly superior in turbulence. Commenting on the checklist, glide slope could be acquired and tracked quite readily. Localizer was as before. There were no tendencies toward PIO, and the flare maneuver I thought was quite a bit better this time then in the previous configurations with turbulence. Aircraft damping still satisfactory. Airspeed was somewhat difficult to maintain, but there was less difficulty in this configuration than I had in the previous ones. Sink rate was also more readily controlled in the flare maneuver, and that helped quite a bit.

(Would you comment now, comparatively, on these three configurations in turbulence?) Comparing the three configurations in turbulence, I think that, very definitely, closed-loop DLC gave far better results than the others, particularly better than the elevator. The open loop was an improvement over the straight elevator, but I seemed to have some difficulty with airspeed in this case, particularly in the flare maneuver. With closed-loop DLC the turbulence seemed to have less effect, although I think the degree of turbulence was as much as for the others, but it didn't seem to effect the aircraft quite as much, and you could compensate for the turbulence more readily. So I definitely liked closed-loop DLC better with turbulence.

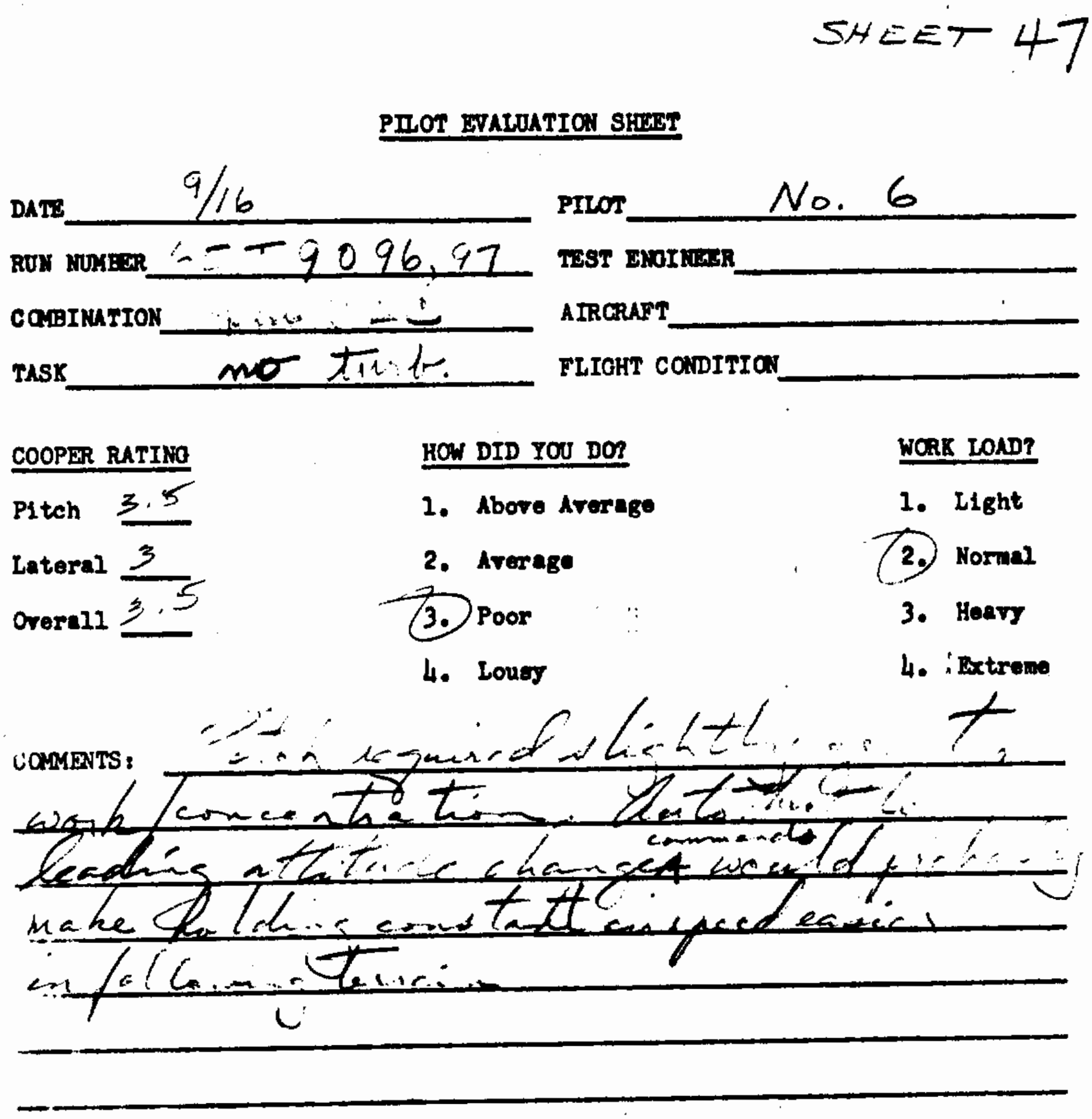
(Regarding the motion system, does this help you in any way in performing the task or do you think you could do as well without the motion?) I really don't think the turbulence aids the task very much. No, I really don't think there is much aid to the motion. Perhaps there is some in the pitch, and hence some in the flare. When you initiate a flare, then you can feel the whole thing move up. I think maybe in that situation there may be some, but I think that would be about the only case. I don't think there is much to the lateral motion. Of course, on this kind of run, there is not much lateral motion anyway. Possibly the motion of the simulator makes the turbulence seem a little more realistic, but I really couldn't say that aids you in doing the task any better.

(I guess maybe I asked the wrong question there. What I want to know is whether you feel the motion cues that you get in any way resemble these you would expect in an actual aircraft?) No, I'm afraid the motion cues really are not as much as in a real airplane; you don't really feel the sink or the stopping of the sink in the flare maneuver. I do not think the motion aids in the realism except in the turbulence, but other than that I don't really think there is much derived from the motion cues as far as the task is concerned.

APPENDIX VIII

COOPER RATINGS, WORKLOAD DATA

The pilots were asked to give Cooper ratings, workload ratings, and ratings on how well they did for each series of runs. Figure 42 is a sample of the Pilot Evaluation Sheet used to record this data. There were 112 such sheets; a few had comments as well as numerical ratings. These written comments are included in Appendix VII. The ratings from these evaluation sheets are summarized in Tables XVIII through XXIV.



SHEET 47

PILOT EVALUATION SHEET

DATE 9/16
PILOT No. 6
RUN NUMBER [illegible] T 9096, 97
TEST ENGINEER
COMBINATION [illegible]
AIRCRAFT
TASK no turb.
FLIGHT CONDITION

COOPER RATING
Pitch 3.5
Lateral 3
Overall 3.5

HOW DID YOU DO?
- **1. Above Average**
- **2. Average**
- [✓ **3. Poor**]
- **4. Lousy**

WORK LOAD?
- **1. Light**
- [✓ **2. Normal**]
- **3. Heavy**
- **4. Extreme**

COMMENTS: [illegible] required slightly more than normal work/concentration. Note that leading attitude ~~changes~~ commands would probably make holding constant airspeed easier in following terrain.

Figure 42. Sample Pilot Evaluation Sheet

Table XVIII. Evaluation Ratings -- C-5A General Qualities Handling Task

Runs	Controller	Turbulence	Pilot No.	Trials	Cooper Rating			How Did You Do?	Workload
					Pitch	Roll	Overall		
18 19 28	elevator	out	2	3	2	3	3	---	---
31 32			3	2	3	2	2	1.5	1
15 16 17		in	2	3	3	3	3	---	---
29 30			3	2	4	3	3	2	---
22 23	closed-loop DLC	out	2	2	1.75	2.5	2.0	---	---
35 36			3	2	2	1	1.5	1	1
20 21		in	2	2	2.5	2.5	2.5	---	---
33 34			3	2	2	2	2	2	1
26 27 28	open-loop DLC	out	2	3	2.0	2.0	2.0	---	---
39 40			3	2	3	2	3	2	1
24 25		in	2	2	2.5	2.5	2.5	---	---
37 38			3	2	3	1	2	2	1
43 44	separate DLC	out	2	2	5	2.5	4	---	---
41 42			3	2	4	3	4	2	2

Table XIX. Evaluation Ratings -- C-5A In-flight Refueling Task

Runs	Controller	Turbulence	Pilot No.	Trials	Cooper Rating			How Did You Do?	Workload
					Pitch	Roll	Overall		
53 54	elevator	out	2	2	3. 5	2. 5	3. 0	---	---
62 63			4	2	3	2	2	2	1
51 52		in	2	2	3. 5	2. 5	3. 2	---	---
64 65			4	2	2	2	2	2	1
45 46	closed-loop DLC	out	2	2	2	2	2	---	---
66 67			4	2	2	2	2	2	1
47 48		in	2	2	2. 5	2	2. 3	---	---
59 60 61			4	3	2	2	2	2	1
55 56	open-loop DLC	out	2	2	3. 75	2. 5	3. 5	---	---
68 69			4	2	2	2	2	2	1
49 50		in	2	2	3. 5	2	3. 0	---	---
70 71			4	2	2	2	2	3	1
57 58	separate DLC	out	2	2	5	2. 5	5	---	---
72 73			4	2	5	2	2	2	1

Table XX. Evaluation Ratings -- C-5A Terrain Following Task

Runs	Controller	Turbulence	Pilot No.	Trials	Cooper Rating			How Did You Do?	Workload
					Pitch	Roll	Overall		
88 89	elevator	out	5	2	2	3	2	1	1
98 99			6	2	4	3	3. 5	3	2
82 83		in	5	2	4	3	4	2. 5	2. 5
104 105			6	2	3. 5	3	3. 5	3. 5	2. 5
90 91	closed-loop DLC	out	5	2	1	3	2	1	1
94 95			6	2	3	3	3	3	1
80 81		in	5	2	3	2	3	2	2
106 108			6	2	2. 5	3	3	3	2. 5
86 87	open-loop DLC	out	5	2	2	3	3	1. 5	2
96 97			6	2	3. 5	3	3. 5	3	2
84 85		in	5	2	3	3	3	2	2
102 103 107			6	3	3. 5	3	3	3	2
92 93	separate DLC	out	5	2	5	3	4	3	3
100 101			6	2	4	3	4	3. 5	3. 5

Table XXI. Evaluation Ratings -- F-104 General Qualities Handling Task

Runs	Controller	Turbulence	Pilot No.	Trials	Cooper Rating			How Did You Do?	Workload	Remarks
					Pitch	Roll	Overall			
78	elevator	out	3	1	3	3	3	2	2	Pilot 3 fly out of trim
119 120			2	2	3.5	3	3.2	---	---	
117 118		in	3	2	4	3	3.5	2	2.5	
127 128			2	2	3.0	3.0	3.0	---	---	
79 109 110	closed-loop DLC	out	3	3	2	2	2	2	2	
121 122			2	2	2.2	3.0	2.8	---	---	
115 116		in	3	2	3	2	2.5	---	---	
129 130			2	2	2.5	2.8	2.7	---	---	
111 112	open-loop DLC	out	3	2	3	3	3	2	1.5	
123 124			2	2	2.5	2.8	2.75	---	---	
113 114		in	3	2	3	3	3	2	2	
125 126			2	2	2.9	3.0	3.0	---	---	
76 77	elevator		---	---	---	---	---	---	---	Fly in trim
74 75	closed-loop DLC		---	---	---	---	---	---	---	

Table XXII. Evaluation Ratings -- F-104 Terrain Following Task

Runs	Controller	Turbulence	Pilot No.	Trials	Cooper Rating			How Did You Do?	Workload
					Pitch	Roll	Overall		
135 136	elevator	out	1	2	3.5	3	3.5	3	3
145 146			2	2	4.75	3.0	4.5	3	3
137 138		in	1	2	3.5	3	3.5	3	3
153 154			2	2	4.8	3.5	4.7	2	3
131 132	closed-loop DLC	out	1	2	2.5	2.5	2.5	2	3
143 144			2	2	4	4	4	3	2
141 142		in	1	2	2	2	2	2	3
151 152			2	2	4	3	3.8	2.5	2.5
133 134	open-loop DLC	out	1	2	3	3	3	2.5	3
147 148			2	2	1.0	3.0	4.0	2.5	2
139 140		in	1	2	2.5	2.5	2.5	2.5	3
149 150			2	2	4	3	4	2.5	2.5

Table XXIII. Evaluation Ratings -- F-104 Landing Task

Runs	Controller	Turbulence	Pilot No.	Trials	Cooper Rating						How Did You Do?	Workload	Remarks
					Pitch		Roll		Overall				
					Glide	Flare	Glide	Flare	Glide	Flare			
163 164	elevator	out	1	2	3.5	4	3	3	3.5	4	3	2	
176 177			2	2	2.2	5	2.2	2.5	2.2	4.5	2	2	
174 175		in	1	2	4	4.5	3	3	4	4.5	3	2.5	
188 189			2	2	2.8	5	2.5	2.5	2.8	4.8	2	2.7	
159 160	closed-loop DLC	out	1	2	2	3.5	3	3	3	3	2	2	
178 179			2	2	1.5	2.6	2.0	2.5	1.75	2.6	2	2	
172 173		in	1	2	3	3.5	3	3	3	3.5	2.5	2.5	
186 187			2	2	2.5	3	2.5	2.5	2.5	2.8	2	2.5	
161 162	open-loop DLC	out	1	2	3	4	3	3	3	4	2.5	2	
180 181			2	2	2.0	2.5	2.0	2.5	2.0	2.5	1.5	2	
170 171		in	1	2	3	4	3	3	3	4	2.5	2.5	
184 185			2	2	2.8	3	2.5	2.5	2.7	2.9	2	2.4	
165 166 167	separate DLC	out	1	3	4	4	3	3	4	4	2	2	
182 183			2	2	2.5	4.5	2.5	2.5	2.5	4.5	2	2	
155 156	closed-loop DLC	out	1	2	3		3		3		2	2	Run day before complete task
157 158		in	1	2	4		3		3.5		2.5	2	

Table XXIII. Evaluation Ratings -- F-104 Landing Task -- Concluded

Runs	Controller	Turbulence	Pilot No.	Trials	Cooper Rating					How Did You Do?	Workload	Remarks
					Pitch		Roll		Overall			
					Glide	Flare	Glide	Flare				
194 195	elevator	out	7	2	2	3	2	3	---	2	2	
			---	---	---	---	---	---	---	---	---	
200 201		in	7	2	3	3	2	2	---	2	2	
			---	---	---	---	---	---	---	---	---	
190 191	closed-loop DLC	out	7	2	2	2	1	2	---	1	1	
			---	---	---	---	---	---	---	---	---	
198 199		in	7	2	2	2	1	2	---	1	1.5	
			--	--	---	---	---	---	---	---	---	
192 193	open-loop DLC	out	7	2	2	2	1	2	---	1	1	
			---	---	---	---	---	---	---	---	---	
196 197		in	7	2	3	2	2	3	---	2	2	
			---	---	---	---	---	---	---	---	---	

Table XXIV. Evaluation Ratings -- C-5A Landing Task

Runs	Controller	Turbulence	Pilot No.	Trials	Cooper Rating						How Did You Do	Workload
					Pitch		Roll		Overall			
					Glide	Flare	Glide	Flare	Glide	Flare		
216 217	elevator	out	1	2	4	4.5	3	3	4	4.5	---	---
208 209			3	2	3	3	2	3	2.5	3	2	2
226 227		in	1	2	3	4.5	3	3	3	4.5	3	3
210 211			3	2	3	4	3	3	3	3.5	2	2
220 221	closed-loop DLC	out	1	2	2	2.5	2	2	2	2.5	2	1.5
204 205			3	2	1.5	2	1.5	1.5	1.5	2	1.5	1.5
228 229		in	1	2	3	3.5	3	3	3	3.5	2	2.5
212 213			3	2	2	2.5	2	2	2	2.5	2	2
218 219	open-loop DLC	out	1	2	3	3	3	3	3	3	2	2
206 207			3	2	2	3	2	2	2	2.5	2	2
224 225		in	1	2	3	4	3	3	3	4	2.5	2.7
214 215			3	2	2.5	3.5	2	3	2.5	3	2	2
222 223	separate DLC	out	1	2	3	5	3	3	3	5	3	2.3
202 203			3	2	2	3	2	2	2	---	2	2

APPENDIX IX

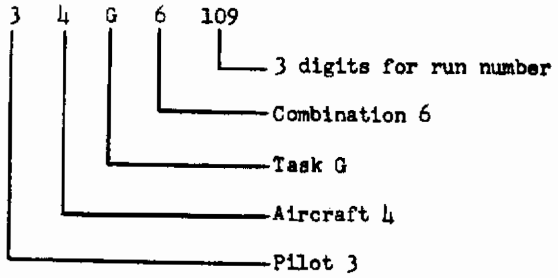
QUANTITATIVE DATA

During all tasks except the general task, quantitative data in the form of mean absolute values and final values for landing of parameters indicative of pilot performance was taken. This data is contained in Tables XXV through XXIX. Fifteen mean absolute values and six final values at landing were recorded. The units on HORIZ BAR, VERT BAR, and PITCH POINTER are $\frac{\%\ \text{FULL SCALE}}{100}$.

The distance to glide slope intercept is positive for long and negative for short at touchdown. The code for information contained in the run numbers is shown in Figure 43.

Run Number Code

Example:



Pilots

Seven pilots

Participated

Aircraft

4 - F-104

5 - C-5A

Tasks

G - General

T - Terrain following

I - In-flight refueling

L - Landing

Control Combinations

- 2 - elevator with turbulence
- 3 - elevator without turbulence
- 5 - closed-loop DLC with turbulence
- 6 - closed-loop DLC without turbulence
- 8 - open-loop DLC with turbulence
- 9 - open-loop DLC without turbulence
- 11 - separate DLC without turbulence

Figure 43. Run Number Code Identification

Table XXV. Quantitative Data -- C-5A Landing Task

DIRECT LIFT CONTROL PILOT IN THE LOOP STUDY

MEAN ABSOLUTE VALUES

RUN NUMBER	%HORIZ BAR	%VERT BAR	%PITCH POINTER	PITCH STICK (DEG)	PITCH ATTITUDE (DEG)	HEADING ATTITUDE (DEG)	ROLL ATTITUDE (DEG)	ROLL STICK (DEG)	C.G. ACCEL (GEES)	ALPHA GUST (DEG)	DELTA ELEVATOR (DEG)
15L3216	.15	.03	.16	1.64	8.16	.88	1.78	1.70	.03	1.51	3.07
15L3217	.12	.04	.14	1.25	8.63	.61	1.68	1.76	.02	1.17	3.17
35L3208	.18	.03	.17	2.75	4.82	.35	1.00	2.47	.06	1.20	4.01
35L3209	.14	.03	.15	1.80	5.01	.74	1.80	3.83	.03	1.39	3.20
15L2226	.14	.03	.14	1.78	3.47	.55	1.14	2.36	.05	.91	3.39
15L2227	.15	.03	.15	2.02	3.37	.37	.89	2.38	.06	1.33	3.86
35L2210	.30	.07	.26	4.98	5.98	1.80	4.30	6.12	.13	1.23	6.53
35L2211	.16	.03	.16	2.80	4.35	.43	1.34	1.88	.07	1.19	3.43
15L6220	.15	.04	.16	1.49	4.58	.58	1.37	2.14	.02	1.34	3.24
15L6221	.10	.03	.13	1.07	4.26	.72	1.61	1.68	.02	1.23	2.59
35L6204	.11	.04	.12	1.37	6.04	1.16	2.32	2.94	.03	1.25	1.86
35L6205	.12	.03	.13	1.94	5.65	.26	1.03	2.75	.04	1.20	2.96
15L5228	.11	.03	.13	1.63	2.43	.50	1.11	2.64	.05	1.20	3.98
15L5229	.19	.03	.21	1.60	4.51	.64	1.30	2.53	.05	1.56	2.93
35L5212	.16	.05	.17	2.01	2.90	.93	2.29	2.73	.06	1.25	4.33
35L5213	.14	.02	.15	2.06	3.62	.43	1.26	2.17	.06	1.20	4.21
15L9218	.10	.06	.12	1.07	5.30	1.41	3.40	2.96	.02	1.35	2.12
15L9219	.10	.05	.12	1.27	4.24	1.29	2.89	2.36	.02	1.44	2.33
35L9206	.10	.03	.11	1.65	4.48	.38	1.15	2.87	.03	.98	3.16
35L9207	.15	.04	.17	2.01	6.12	.37	1.58	3.65	.03	1.32	3.33
15L8224	.20	.02	.20	1.67	4.53	.48	1.22	2.16	.06	1.50	3.46
15L8225	.14	.03	.16	1.85	6.34	.40	1.28	3.12	.06	1.59	3.27
35L8214	.24	.04	.23	2.45	4.91	.60	1.49	2.68	.08	1.64	4.47
35L8215	.19	.04	.20	2.07	4.77	.76	1.65	3.49	.06	1.14	3.38
15L11222	.15	.03	.17	1.12	5.41	.68	1.41	1.59	.03	1.22	1.46
15L11223	.13	.02	.14	.67	6.23	.61	1.23	1.65	.03	1.37	.99
35L11202	.13	.02	.15	1.76	6.76	.26	.81	2.03	.03	1.26	2.23
35L11203	.19	.03	.17	2.60	6.00	.92	1.81	2.78	.07	1.42	3.42

RUN NUMBER	MEAN ABSOLUTE VALUES					FINAL VALUES				
	DELTA FLAP (DEG)	ELEVATOR RATE (DEG/SEC)	FLAP RATE (DEG/SEC)	PITCH RATE (DEG/SEC)	ALTITUDE RATE (FT/SEC)	DISTANCE TO GI (FT)	DISTANCE TO R CL (FT)	PITCH ATTITUDE (DEG)	ROLL ATTITUDE (DEG)	ANGLE ATTACK (DEG)
15L3216	.00	2.99	.00	.49	14.50	-282.00	2.00	25.66	1.12	20.52
15L3217	.00	2.91	.00	.34	18.40	-714.00	10.20	24.50	1.02	20.50
35L3208	.00	8.48	.00	.96	21.50	544.00	28.90	20.64	2.76	20.42
35L3209	.00	8.36	.00	.97	8.40	2926.00	52.80	16.00	2.88	15.60
15L2226	.00	6.87	.00	.64	19.50	-482.00	14.50	20.12	.72	19.42
15L2227	.00	8.02	.00	.76	6.80	160.00	10.20	11.00	.34	11.50
35L2210	.00	13.65	.00	1.80	21.50	294.00	66.20	3.52	4.34	10.04
35L2211	.00	10.74	.00	.65	8.40	1726.00	28.20	8.56	.66	10.80
15L6220	1.36	2.54	1.10	.44	13.70	128.00	67.70	25.04	.82	18.83
15L6221	.81	1.75	.65	.29	3.50	346.00	15.60	16.96	.58	14.00
35L6204	1.27	3.48	1.49	.37	3.40	1968.00	2.20	24.32	1.72	16.92
35L6205	2.00	6.29	2.71	.60	10.40	1234.00	1.10	29.42	1.86	19.87
15L5228	2.13	3.90	3.17	.48	3.50	1412.00	.80	7.42	1.48	8.19
15L5229	2.24	7.50	2.71	.50	5.90	1570.00	34.00	11.08	2.60	11.05
35L5212	2.56	9.72	3.90	.59	2.40	2546.00	1.30	1.66	2.72	2.50
35L5213	2.71	10.10	4.12	.62	4.50	522.00	9.90	1.74	1.52	.69
15L9218	.53	1.82	.39	.33	9.00	-258.00	79.50	23.62	2.62	18.42
15L9219	.56	2.20	.42	.34	10.20	1132.00	61.20	24.18	1.16	18.99
35L9206	1.01	4.73	.99	.52	10.00	470.00	23.40	29.36	.56	20.90
35L9207	1.17	5.80	1.20	.57	13.40	3350.00	18.10	32.36	3.46	21.84
15L8224	1.12	7.38	1.20	.60	11.20	696.00	27.20	17.86	2.96	16.24
15L8225	1.31	9.32	1.38	.62	4.90	2058.00	46.70	10.08	3.10	9.66
35L8214	1.64	11.57	1.94	.82	7.30	344.00	36.70	11.96	2.54	12.60
35L8215	1.44	10.98	1.55	.69	9.20	-726.00	38.90	6.78	2.92	9.52
15L11222	7.12	2.11	1.00	.27	13.90	370.00	57.10	16.48	1.98	14.91
15L11223	3.74	1.54	.97	.18	4.90	34.00	54.30	6.76	1.84	7.52
35L11202	.26	4.14	.11	.55	8.60	564.00	8.20	22.20	.68	17.92
35L11203	1.75	7.70	.43	.86	17.00	1050.00	16.70	17.70	.54	5.56

Table XXVI. Quantitative Data -- F-104 Landing Task

DIRECT LIFT CONTROL PILOT IN THE LOOP STUDY

RUN NUMBER	MEAN ABSOLUTE VALUES										
	%HORIZ BAR	%VERT BAR	%PITCH POINTER	PITCH STICK (DEG)	PITCH ATTITUDE (DEG)	HEADING ATTITUDE (DEG)	ROLL ATTITUDE (DEG)	ROLL STICK (DEG)	C.G. ACCEL (GEES)	ALPHA GUST (DEG)	DELTA ELEVATOR (DEG)
14L3163	.15	.03	.19	.89	7.31	1.03	1.35	.48	.05	.49	.69
14L3164	.18	.03	.21	.90	7.30	1.14	1.29	.32	.05	.51	.70
24L3176	.15	.03	.18	.75	9.31	.76	1.58	.68	.05	1.06	.55
24L3177	.30	.04	.33	1.47	16.60	1.52	2.69	.76	.09	1.60	1.08
14L2174	.18	.03	.20	.68	9.16	.96	1.96	.84	.06	1.08	.62
14L2175	.26	.03	.25	.97	11.28	1.91	3.17	1.34	.09	1.16	.84
24L2188	.33	.02	.34	1.64	13.59	.95	2.13	.79	.13	1.20	1.10
24L2189	.27	.03	.26	.92	7.39	.40	.70	.43	.07	.81	.59
14L6159	.10	.02	.14	.88	7.66	.63	1.08	.34	.05	.57	.67
14L6160	.12	.02	.16	.89	8.35	.89	1.68	.28	.05	.50	.73
24L6178	.09	.03	.12	.69	7.82	.55	1.28	.40	.06	.84	.41
24L6179	.12	.05	.15	.79	9.34	.84	1.86	1.01	.07	.98	.48
14L5172	.16	.02	.18	.68	9.07	.65	1.68	.71	.06	1.00	.55
14L5173	.21	.05	.21	.98	10.76	2.06	2.33	.66	.10	1.20	.76
24L5186	.13	.03	.14	1.31	8.33	1.04	2.54	1.16	.11	.97	.68
24L5187	.14	.05	.16	1.24	8.36	.75	1.58	.75	.11	.89	.57
14L9161	.13	.04	.15	.97	8.49	.76	1.87	.76	.05	.49	.72
14L9162	.13	.03	.16	.88	7.46	1.13	1.48	.47	.05	.47	.64
24L9180	.17	.07	.21	1.24	12.36	1.14	2.02	.73	.10	1.23	.65
24L9181	.11	.02	.14	.79	8.04	.48	1.22	.46	.06	.82	.30
14L8170	.14	.03	.17	.55	9.34	1.21	1.71	.57	.06	.71	.57
14L8171	.19	.03	.23	.59	11.85	.50	.82	.26	.08	.89	.75
24L8184	.16	.02	.17	1.50	7.31	.77	1.45	.74	.12	.73	.73
24L8185	.22	.04	.24	1.37	11.15	1.24	2.52	1.13	.12	1.10	.95
14L11165	.17	.08	.20	.89	8.85	2.94	2.54	.79	.06	.53	.76
14L11166	.13	.02	.17	.71	7.14	.49	1.23	.27	.04	.40	.42
14L11167	.12	.02	.18	.84	7.73	.59	1.19	.27	.05	.45	.67
24L11182	.19	.06	.22	1.53	11.76	.79	1.27	.44	.09	1.24	.83
24L11183	.23	.02	.25	1.25	10.63	.78	1.54	.71	.08	1.06	.69
14L6155	.14	.03	.18	.61	10.18	1.16	1.44	.50	.06	.53	.55
14L6156	.11	.01	.16	.56	10.39	.33	.92	.21	.06	.51	.57
14L9157	.16	.03	.19	.64	10.40	.52	1.17	.60	.06	.53	.64
14L9158	.16	.03	.21	.73	12.53	.53	1.36	.56	.07	.57	.83
74L3194	.22	.03	.21	1.47	8.80	.95	1.74	.87	.09	1.12	.84
74L3195	.25	.04	.27	1.41	9.22	1.86	2.44	1.08	.09	.97	.88
74L2200	.25	.03	.23	1.51	9.22	1.03	2.38	1.33	.10	.97	.97
74L2201	.23	.04	.23	1.18	10.00	1.71	1.99	1.08	.10	1.01	.88
74L6190	.16	.03	.20	.83	9.98	1.00	1.23	.35	.07	1.17	.45
74L6191	.16	.02	.20	.73	9.57	.70	2.16	.76	.06	.97	.36
74L5198	.23	.03	.24	1.23	10.49	1.21	2.44	1.05	.11	1.25	.79
74L5199	.16	.02	.19	1.03	10.12	.77	1.96	1.34	.09	.87	.67
7469192	.15	.08	.19	.90	9.17	2.92	4.71	1.06	.06	1.17	.36
74L9193	.20	.04	.24	.99	9.52	2.16	3.85	1.02	.06	.95	.50
74L8196	.25	.05	.26	1.40	10.20	1.97	4.25	1.64	.12	1.14	.96
7468197	.22	.05	.23	1.42	10.32	1.92	3.33	1.90	.11	.93	.88

RUN NUMBER	MEAN ABSOLUTE VALUES					FINAL VALUES				
	DELTA FLAP (DEG)	ELEVATOR RATE (DEG/SEC)	FLAP RATE (DEG/SEC)	PITCH RATE (DEG/SEC)	ALTITUDE RATE (FT/SEC)	DISTANCE TO GI (FT)	DISTANCE TO R CL (FT)	PITCH ATTITUDE (DEG)	ROLL ATTITUDE (DEG)	ANGLE ATTACK (DEG)
14L3163	.00	1.52	.00	.48	1.70	724.00	4.40	9.40	.00	.00
14L3164	.00	1.47	.00	.52	10.50	50.00	65.30	9.52	.00	.00
24L3176	.00	2.11	.00	.51	6.90	176.00	185.90	13.34	1.04	13.94
24L3177	.00	3.57	.00	1.08	2.40	5364.00	203.40	13.44	1.88	12.82
14L2174	.00	2.36	.00	.52	7.70	-318.00	102.20	17.56	3.86	17.49
14L2175	.00	3.22	.00	.75	6.50	1496.00	13.90	14.28	1.82	14.35
24L2188	.00	4.72	.00	1.44	8.70	5200.00	28.20	10.58	1.18	11.68
24L2189	.00	2.74	.00	.83	12.30	158.00	214.80	10.58	.00	12.75
14L6159	2.10	1.33	3.65	.32	1.60	1484.00	72.40	10.54	.00	.00
14L6160	2.09	1.26	2.82	.33	1.10	2936.00	58.00	10.34	.00	.00
24L6178	1.96	1.59	5.04	.40	4.00	3372.00	257.90	15.04	1.64	14.68
24L6179	2.46	2.12	6.12	.40	1.90	1590.00	343.00	13.42	5.42	13.07
14L5172	2.78	2.33	5.83	.49	8.80	-262.00	99.70	14.42	.68	15.02
14L5173	3.46	3.08	8.52	.61	1.00	1378.00	210.60	13.12	4.00	12.70
24L5186	4.88	3.40	11.14	.93	4.60	448.00	84.50	14.76	3.40	14.83
24L5187	4.14	3.47	10.30	.80	8.00	140.00	277.20	10.08	3.96	11.44
14L9161	1.40	1.27	1.99	.38	1.40	3268.00	149.50	9.88	.00	.00
14L9162	1.85	1.21	2.20	.42	4.90	1456.00	112.20	9.16	.00	.00
24L9180	3.31	2.92	7.73	.75	2.60	4348.00	366.90	12.72	3.30	12.32
24L9181	2.02	1.86	4.83	.44	2.20	1950.00	89.20	11.70	.68	11.87
14L8170	1.39	2.37	2.02	.43	4.20	648.00	207.70	13.24	2.22	13.26
14L8171	1.39	2.97	2.55	.44	6.30	1750.00	173.50	14.54	1.04	14.49
24L8184	4.60	3.88	9.76	1.14	1.80	1072.00	132.50	11.82	1.44	11.93
24L8185	4.18	3.65	7.63	1.03	3.50	1218.00	177.20	11.62	1.70	12.06
14L11165	3.29	1.70	.54	.42	8.80	2370.00	486.50	7.54	2.68	.00
14L11166	2.29	1.29	.50	.20	3.20	386.00	66.90	8.44	3.92	.00
14L11167	2.73	1.29	.66	.14	5.00	486.00	64.20	7.42	2.80	.00
24L11182	1.95	2.97	.53	1.36	4.80	4120.00	272.50	17.80	.62	17.66
24L11183	2.04	2.36	.12	1.04	5.70	4646.00	25.00	13.14	3.12	13.30
14L6155	1.62	1.08	2.34	.25	3.70	572.00	3.30	.00	.00	.00
14L6156	1.26	1.17	2.51	.22	2.00	812.00	71.00	.00	.00	.00
14L9157	1.04	1.19	1.49	.36	5.20	570.00	145.40	.00	.00	.00
14L9158	1.06	1.40	1.61	.39	2.00	3528.00	90.70	.00	.00	.00
74L3194	.00	2.86	.00	1.13	14.50	-298.00	129.80	14.28	4.88	16.37
74L3195	.00	2.81	.00	1.06	3.80	-170.00	139.50	15.12	3.32	15.01
74L2200	.00	4.38	.00	1.27	6.00	1642.00	40.50	12.60	.90	13.11
74L2201	.00	4.65	.00	1.06	9.40	1734.00	85.00	11.26	.62	12.55
74L6190	2.37	1.39	3.80	.38	4.10	2108.00	243.70	12.28	3.60	12.43
74L6191	1.88	1.67	3.77	.35	5.50	2028.00	28.60	11.64	4.10	11.96
74L5198	4.49	3.32	9.60	.91	7.80	5102.00	85.50	7.96	3.14	9.17
74L5199	3.90	3.41	8.98	.70	4.00	306.00	27.90	14.02	4.06	13.57
7469192	1.95	1.54	3.32	.48	9.30	.00	473.50	11.72	4.26	12.82
74L9193	2.51	1.69	3.65	.60	5.00	368.00	17.50	13.14	2.58	13.30
74L8196	3.60	3.58	5.83	1.13	8.70	602.00	299.80	16.90	13.44	17.16
7468197	4.11	4.55	7.99	1.15	6.50	2810.00	236.70	12.20	8.14	12.54

Table XXVII. Quantitative Data -- C-5A Terrain Following Task

DIRECT LIFT CONTROL PILOT IN THE LOOP STUDY

MEAN ABSOLUTE VALUES

RUN NUMBER	%HORIZ BAR	%VERT BAR	%PITCH POINTER	PITCH STICK (DEG)	PITCH ATTITUDE (DEG)	HEADING ATTITUDE (DEG)	ROLL ATTITUDE (DEG)	ROLL STICK (DEG)	C.G. ACCEL (GEES)	ALPHA GUST (DEG)	DELTA ELEVATOR (DEG)
55T3088	.10	.00	3.33	2.37	4.66	1.10	1.67	2.37	.52	.71	2.19
55T3089	.09	.00	3.44	2.83	7.85	.59	.85	.70	.63	.68	2.44
65T3098	.15	.00	3.93	2.11	5.21	1.63	1.33	1.24	.46	.59	1.77
65T3099	.15	.00	1.51	1.78	3.12	1.89	1.31	.92	.39	.67	1.53
55T2082	.11	.00	2.74	2.17	6.11	1.00	1.49	1.11	.53	.69	1.96
55T2083	.14	.00	2.79	3.00	8.96	1.25	2.22	2.00	.68	.76	2.53
65T2 104	.16	.00	3.10	2.24	5.75	1.84	1.40	.87	.53	.65	2.00
65T2 105	.15	.00	3.58	2.37	6.54	1.88	.75	1.07	.56	.70	2.09
55T6090	.05	.00	3.19	1.82	5.35	.84	1.02	.79	.44	.66	.87
55T6091	.06	.00	3.07	1.97	5.44	.86	1.55	1.75	.47	.73	1.08
65T6094	.08	.00	2.56	1.70	4.63	2.29	.91	.99	.40	.68	1.01
65T6095	.08	.00	3.43	1.47	5.08	2.33	1.89	1.56	.35	.71	.86
55T5080	.08	.00	3.02	2.14	6.80	.66	1.10	1.07	.52	.77	1.19
55T5081	.06	.00	3.24	2.02	5.82	.92	1.42	1.16	.49	.67	1.15
65T5106	.11	.00	4.07	1.91	5.55	1.52	.81	.71	.49	.61	1.60
65T5108	.10	.00	3.76	1.54	6.18	1.34	.85	.85	.37	.71	.93
55T9086	.10	.00	3.79	2.03	3.63	.49	.49	.34	.47	.65	1.46
55T9087	.09	.00	3.33	2.00	5.13	.62	1.16	.84	.45	.74	1.56
65T9096	.12	.00	3.96	2.04	5.95	1.46	1.60	1.55	.46	.64	1.47
65T9097	.17	.00	4.77	2.09	5.05	2.28	1.48	1.48	.47	.72	1.49
55T8084	.09	.00	4.05	2.15	4.40	.42	1.42	2.00	.55	.76	1.83
5TT8085	.10	.00	3.03	2.17	5.41	.68	1.52	1.63	.54	.66	1.69
65T8102	.12	.00	4.35	1.38	4.31	1.57	.92	1.14	.44	.59	1.41
65T8103	.14	.00	3.06	2.38	6.81	1.98	.94	1.43	.61	.61	1.93
65T8107	.10	.00	3.24	1.70	5.81	1.23	1.36	1.49	.42	.77	1.02
55T11092	.11	.00	3.00	1.99	4.65	.90	.51	.18	.46	.65	2.08
55T11093	.14	.00	3.77	2.14	4.79	.44	.64	.34	.54	.60	1.98
65T11100	.15	.00	3.76	1.67	6.61	1.66	1.17	.56	.41	.63	2.22
65T11101	.15	.00	3.67	1.30	3.89	1.00	.94	.82	.32	.56	1.90

MEAN ABSOLUTE VALUES

RUN NUMBER	DELTA FLAP (DEG)	ELEVATOR RATE (DEG/SEC)	FLAP RATE (DEG/SEC)	PITCH RATE (DEG/SEC)
55T3088	.00	7.01	.00	1.94
55T3089	.00	6.23	.00	2.22
65T3098	.00	4.23	.00	1.55
65T3099	.00	4.07	.00	1.32
55T2082	.00	7.38	.00	1.80
55T2083	.00	7.57	.00	2.27
65T2 104	.00	6.98	.00	1.64
65T2 105	.00	7.61	.00	1.93
55T6090	3.35	4.12	5.90	1.18
55T6091	3.42	4.43	6.23	1.28
65T6094	3.15	4.22	5.40	1.10
65T6095	2.61	3.12	4.09	.96
55T5080	3.61	5.67	8.16	1.38
55T5081	3.51	5.96	8.45	1.34
65T5106	1.28	7.01	1.60	1.55
65T5108	2.63	4.12	6.31	1.04
55T9086	1.50	4.36	1.57	1.43
55T9087	1.46	5.75	1.52	1.42
65T9096	1.39	4.33	1.33	1.41
65T9097	1.56	4.75	1.59	1.47
55T8084	1.45	8.78	1.99	1.68
5TT8085	1.53	8.27	1.93	1.60
65T8102	1.05	7.21	1.68	1.34
65T8103	1.65	7.75	2.05	1.89
65T8107	3.26	4.92	7.31	1.19
55T11092	3.09	5.56	.78	1.61
55T11093	5.04	3.84	1.84	1.47
65T11100	5.58	3.59	.88	1.17
65T11101	3.71	3.39	.78	.92

Table XXVIII. Quantitative Data -- C-5A In-flight Refueling Task

DIRECT LIFT CONTROL PILOT IN THE LOOP STUDY

MEAN ABSOLUTE VALUES

RUN NUMBER	%HORIZ BAR	%VERT BAR	%PITCH POINTER	PITCH STICK (DEG)	PITCH ATTITUDE (DEG)	HEADING ATTITUDE (DEG)	ROLL ATTITUDE (DEG)	ROLL STICK (DEG)	C.G. ACCEL (GEES)	ALPHA GUST (DEG)	DELTA ELEVATOR (DEG)
2513053	.10	.00	.08	.67	.53	.76	.79	.60	.11	.51	.88
2513054	.10	.00	.08	.74	.56	1.25	1.34	1.34	.12	.53	.98
4513062	.12	.00	.14	.68	.68	.84	.42	.16	.12	1.40	.82
4513063	.11	.00	.15	.75	.73	.97	1.07	.82	.13	1.44	.88
2512051	.14	.00	.10	1.12	.86	1.18	1.04	.92	.21	.56	1.46
2512052	.15	.00	.08	1.64	1.07	.90	1.17	1.29	.29	.54	2.00
4512064	.14	.00	.12	.89	1.52	.85	1.02	.53	.19	1.44	1.13
4512065	.18	.00	.17	1.07	2.07	.66	.86	.68	.21	1.60	1.28
2516045	.12	.00	.11	.37	.40	.89	.93	.74	.07	.51	.38
2516046	.10	.00	.10	.31	.28	.70	.72	.49	.05	.54	.46
4516066	.06	.00	.17	.54	.56	.84	.77	.43	.10	1.64	.49
4516067	.09	.00	.13	.60	.61	.99	1.09	.89	.11	1.31	.48
2515047	.11	.00	.10	.39	.63	.71	.92	.87	.09	.55	.53
2515048	.09	.00	.09	.31	.41	1.50	1.10	.86	.08	.50	.54
4515059	.08	.00	.15	.73	1.88	.60	.55	.24	.14	1.51	.84
4515060	.09	.00	.16	.67	2.07	1.08	1.31	.84	.13	1.64	.78
4515061	.07	.00	.16	.65	1.97	1.23	1.19	.61	.13	1.50	.80
2519055	.10	.00	.08	1.26	.55	.31	.91	.70	.22	.54	1.83
2519056	.11	.00	.09	1.00	.51	.73	1.00	.99	.18	.54	1.41
4519068	.09	.00	.25	.58	.63	.81	.92	.41	.11	1.50	.62
4519069	.09	.00	.16	.48	.60	.97	.96	.41	.09	1.63	.51
2518049	.14	.00	.11	.88	.68	1.02	1.11	.93	.21	.54	1.15
2518050	.12	.00	.08	.78	.63	1.40	.84	.65	.18	.55	1.00
4518070	.14	.00	.15	.55	1.48	1.50	.67	.21	.17	1.20	.63
4518071	.15	.00	.21	.65	2.06	1.06	1.01	.42	.18	1.56	.73
25111057	.12	.00	.10	.73	.49	1.04	1.33	1.82	.12	.54	1.02
25111058	.15	.00	.10	1.55	1.35	.66	1.18	1.21	.26	.53	1.91
45111072	.15	.00	.15	.57	1.29	.79	.89	.55	.11	1.36	1.04
45111073	.22	.00	.20	.67	1.09	1.53	1.11	.75	.13	1.63	1.06

MEAN ABSOLUTE VALUES

RUN NUMBER	DELTA FLAP (DEG)	ELEVATOR RATE (DEG/SEC)	FLAP RATE (DEG/SEC)	PITCH RATE (DEG/SEC)
2513053	.00	6.22	.00	.65
2513054	.00	7.04	.00	.74
4513062	.00	3.96	.00	.57
4513063	.00	4.08	.00	.63
2512051	.00	10.56	.00	1.19
2512052	.00	13.66	.00	1.70
4512064	.00	6.74	.00	.91
4512065	.00	6.96	.00	1.01
2516045	.84	2.83	2.25	.22
2516046	.67	2.83	2.17	.18
4516066	1.19	3.04	2.80	.32
4516067	1.36	2.92	2.92	.36
2515047	1.29	4.47	4.09	.30
2515048	1.12	4.02	3.80	.25
4515059	2.34	5.05	5.21	.58
4515060	2.24	4.50	4.71	.55
4515061	2.18	5.51	5.41	.52
2519055	.99	11.55	2.95	1.30
2519056	.88	9.34	2.30	.96
4519068	.74	2.80	1.10	.47
4519069	.61	2.30	.89	.38
2518049	.96	9.06	1.80	.80
2518050	.84	8.16	1.57	.74
4518070	.71	4.11	.94	.61
4518071	.81	4.37	1.07	.72
25111057	1.05	7.27	.03	.71
25111058	2.82	10.98	.41	1.59
45111072	3.10	2.39	.53	.46
45111073	2.98	2.38	.40	.50

Table XXIX. Quantitative Data -- F-104 Terrain Following Task

DIRECT LIFT CONTROL PILOT IN THE LOOP STUDY

MEAN ABSOLUTE VALUES

RUN NUMBER	%HORIZ BAR	%VERT BAR	%PITCH POINTER	PITCH STICK (DEG)	PITCH ATTITUDE (DEG)	HEADING ATTITUDE (DEG)	ROLL ATTITUDE (DEG)	ROLL STICK (DEG)	C.G. ACCEL (GEES)	ALPHA GUST (DEG)	DELTA ELEVATOR (DEG)
14T3135	.13	.00	2.83	1.84	5.78	.97	2.85	.56	1.18	.18	.59
14T3136	.12	.00	3.34	1.77	5.98	1.01	2.19	.47	1.11	.20	.54
24T3145	.13	.00	3.54	1.82	4.79	1.06	2.93	.44	1.14	.18	.54
24T3146	.14	.00	3.38	1.81	6.39	.95	3.50	.53	1.14	.18	.56
14T2137	.13	.00	2.41	1.66	4.93	.76	1.95	.37	1.02	.19	.50
14T2138	.13	.00	2.27	1.63	5.75	.73	2.13	.39	1.01	.20	.50
24T2153	.15	.00	3.68	1.63	5.26	.77	2.59	.36	1.01	.22	.50
24T2154	.14	.00	2.65	1.63	5.25	.86	3.07	.40	1.01	.19	.49
14T6131	.12	.00	3.59	1.60	5.87	1.04	2.19	.30	.97	.19	.40
14T6132	.10	.00	3.16	1.62	6.23	1.41	2.33	.42	.98	.19	.42
24T6143	.14	.00	4.42	1.74	7.31	.68	3.94	.56	1.07	.19	.46
24T6144	.14	.00	3.26	1.68	7.06	1.18	4.93	.51	1.02	.19	.44
14T5141	.11	.00	4.36	1.65	6.78	.77	1.97	.34	1.01	.20	.43
14T5142	.11	.00	3.63	1.59	6.50	.75	2.05	.32	.96	.19	.42
24T5151	.14	.00	1.93	1.12	1.72	1.18	1.06	.92	.21	1.41	1.46
24T5152	.15	.00	1.59	1.64	2.15	.90	1.17	1.29	.29	1.36	2.00
14T9133	.12	.00	2.49	1.81	6.19	1.11	3.08	.56	1.19	.19	.49
14T9134	.12	.00	3.18	1.74	6.28	1.15	3.03	.56	1.12	.20	.46
24T9147	.12	.00	4.09	1.71	6.88	1.01	3.07	.45	1.11	.20	.45
24T9148	.11	.00	4.16	1.98	8.39	1.07	2.87	.44	.99	.19	.41
14T8139	.10	.00	3.29	1.42	6.45	.71	2.27	.40	.86	.18	.35
14T8140	.10	.00	3.19	1.56	6.37	.78	2.80	.50	.98	.20	.41
24T8149	.12	.00	3.65	1.45	4.91	1.20	2.67	.49	.91	.20	.38
24T8150	.13	.00	1.94	1.56	4.41	.95	2.48	.35	1.01	.19	.41

MEAN ABSOLUTE VALUES

RUN NUMBER	DELTA FLAP (DEG)	ELEVATOR RATE (DEG/SEC)	FLAP RATE (DEG/SEC)	PITCH RATE (DEG/SEC)
14T3135	.00	2.58	.00	3.37
14T3136	.00	2.49	.00	.51
24T3145	.00	3.27	.00	3.82
24T3146	.00	2.99	.00	3.58
14T2137	.00	2.79	.00	3.07
14T2138	.00	2.54	.00	3.0
24T2153	.00	2.91	.00	2.97
24T2154	.00	2.97	.00	3.21
14T6131	3.83	1.64	8.64	2.18
14T6132	3.76	1.74	9.29	2.24
24T6143	3.92	2.67	12.86	2.62
24T6144	3.84	1.82	10.27	2.29
14T5141	3.89	2.01	9.99	2.29
14T5142	3.75	2.06	10.25	2.17
24T5151	.00	10.56	.00	1.19
24T5152	.00	13.66	.00	1.70
14T9133	4.04	2.35	8.31	2.69
14T9134	3.87	2.36	8.24	2.55
24T9147	3.66	2.50	8.68	2.65
24T9148	3.34	2.44	8.30	2.38
14T8139	3.00	2.37	6.39	2.03
14T8140	3.22	2.43	7.39	2.25
24T8149	3.12	2.69	7.33	2.17
24T8150	3.41	2.92	8.09	2.50

APPENDIX X

LANDING TRAJECTORIES

Landing trajectory plots (ranges versus altitude) were made for all landing runs. These are given in Figures 44 through 49. Touchdown sink rates are also given on the trajectory plots for each landing run.

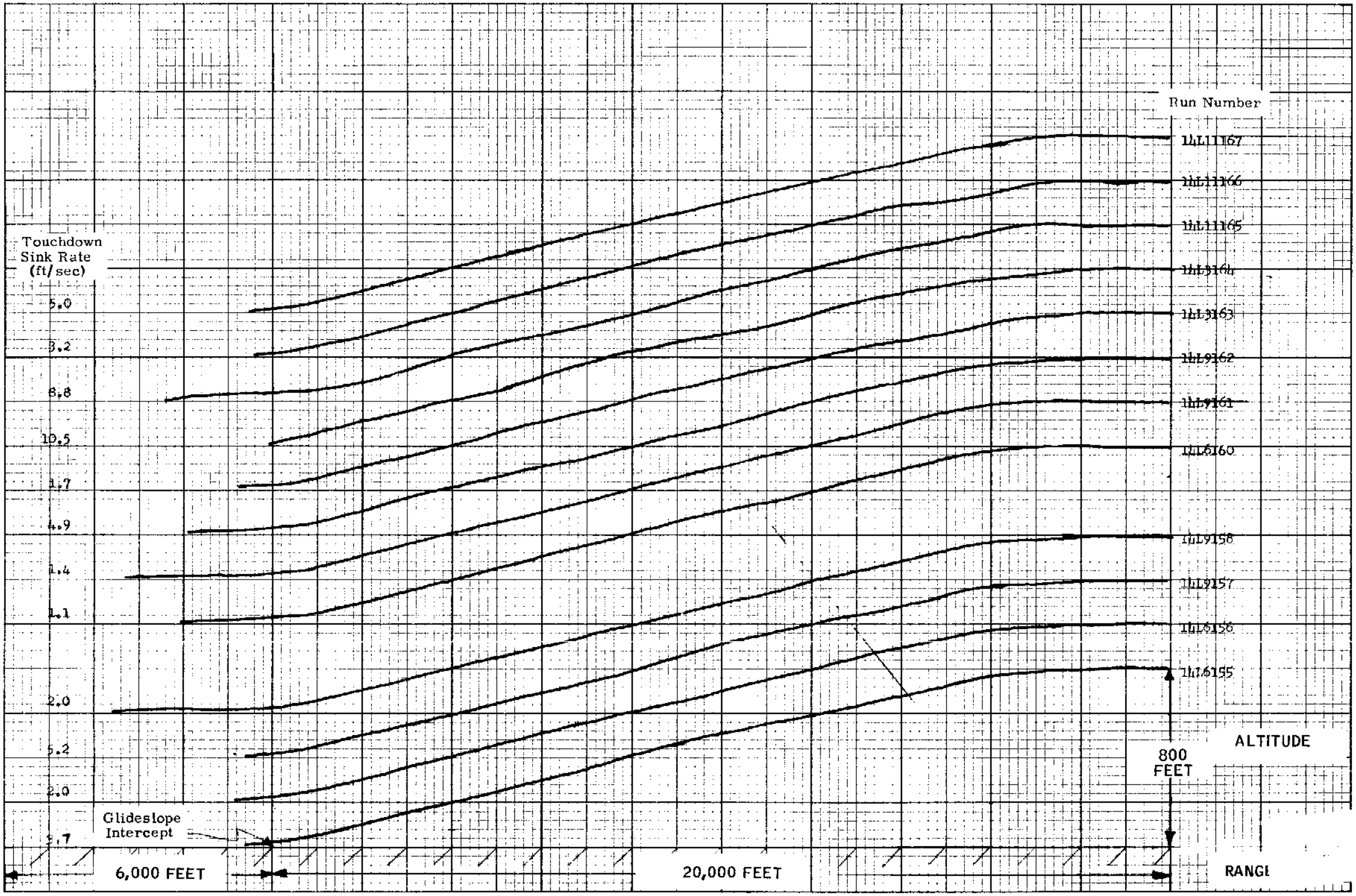


Figure 44. Landing Trajectory Plots -- Runs 155 Through 158 and 160 Through 167

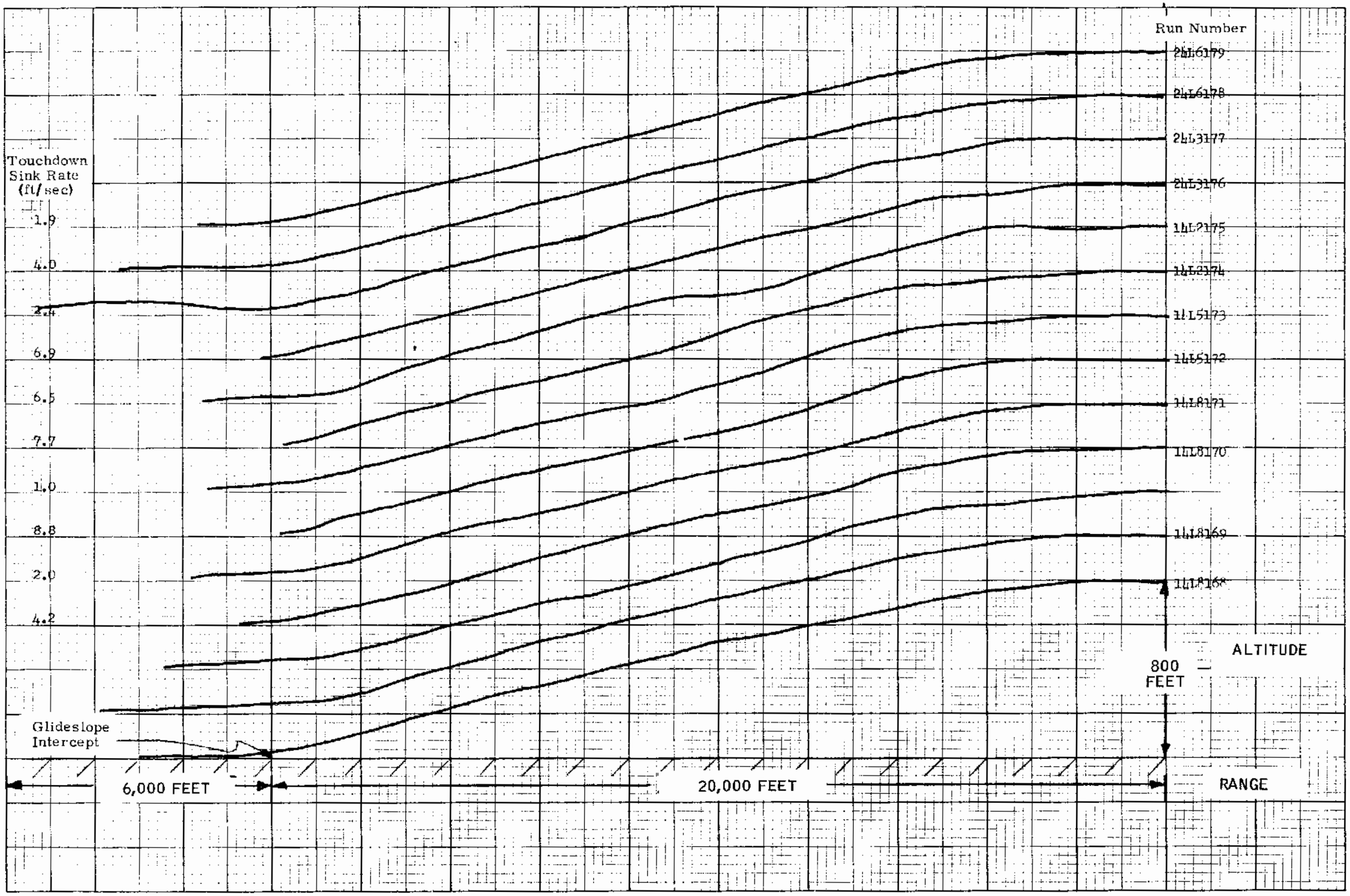


Figure 45. Landing Trajectory Plots -- Runs 168 Through 169

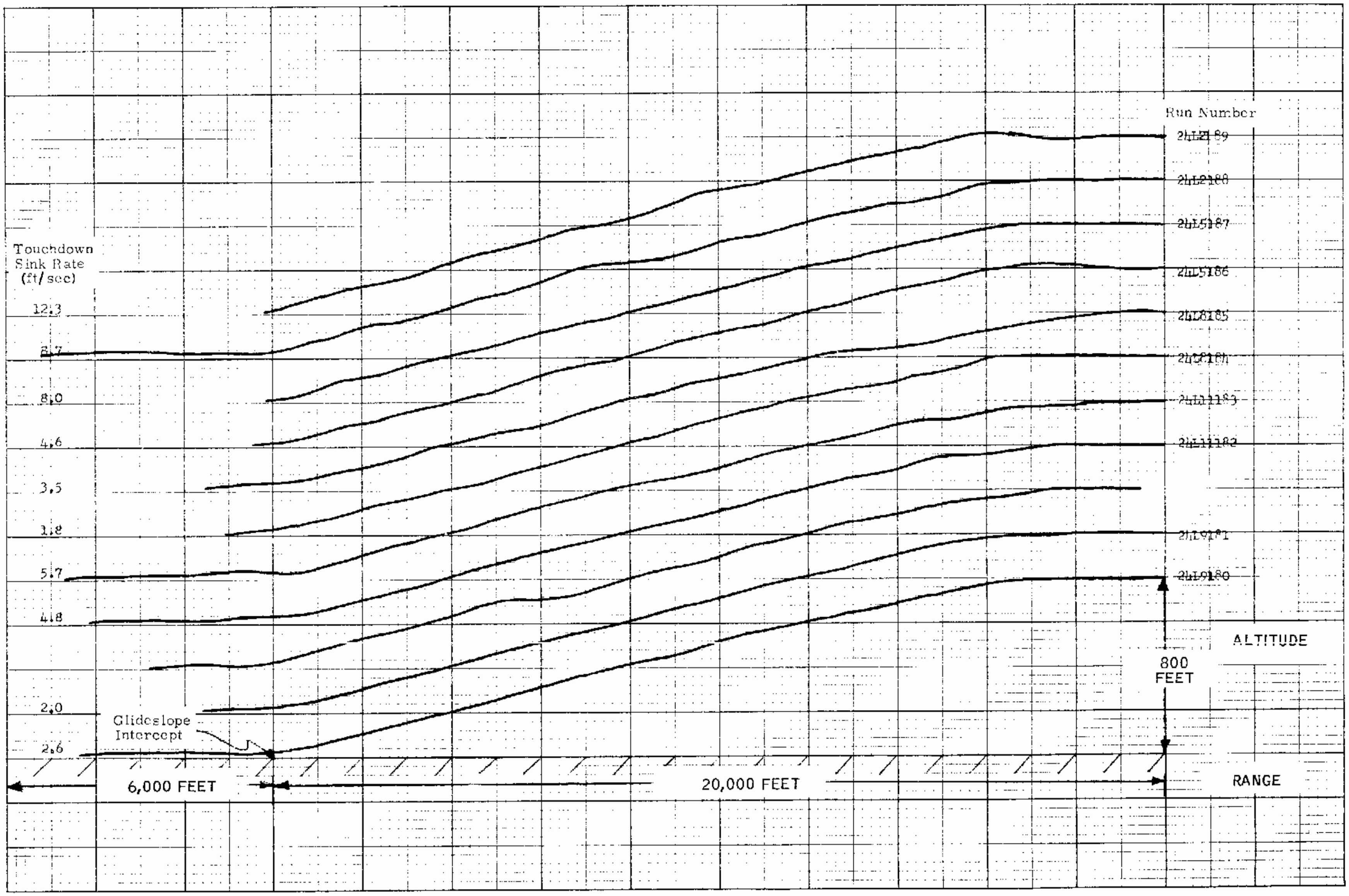


Figure 46. Landing Trajectory Plots -- Runs 180 Through 189

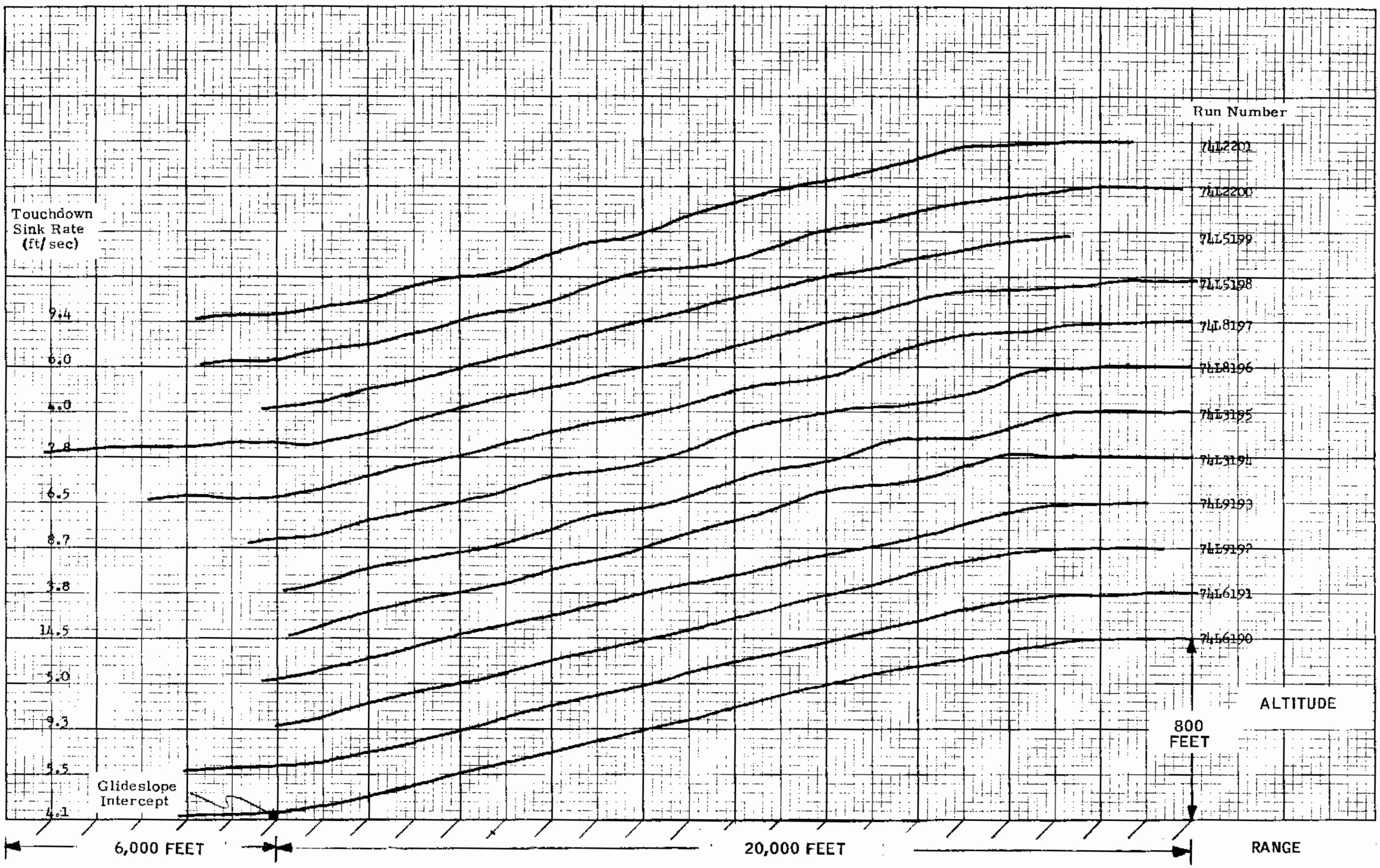


Figure 47. Landing Trajectory Plots -- Runs 190 Through 201

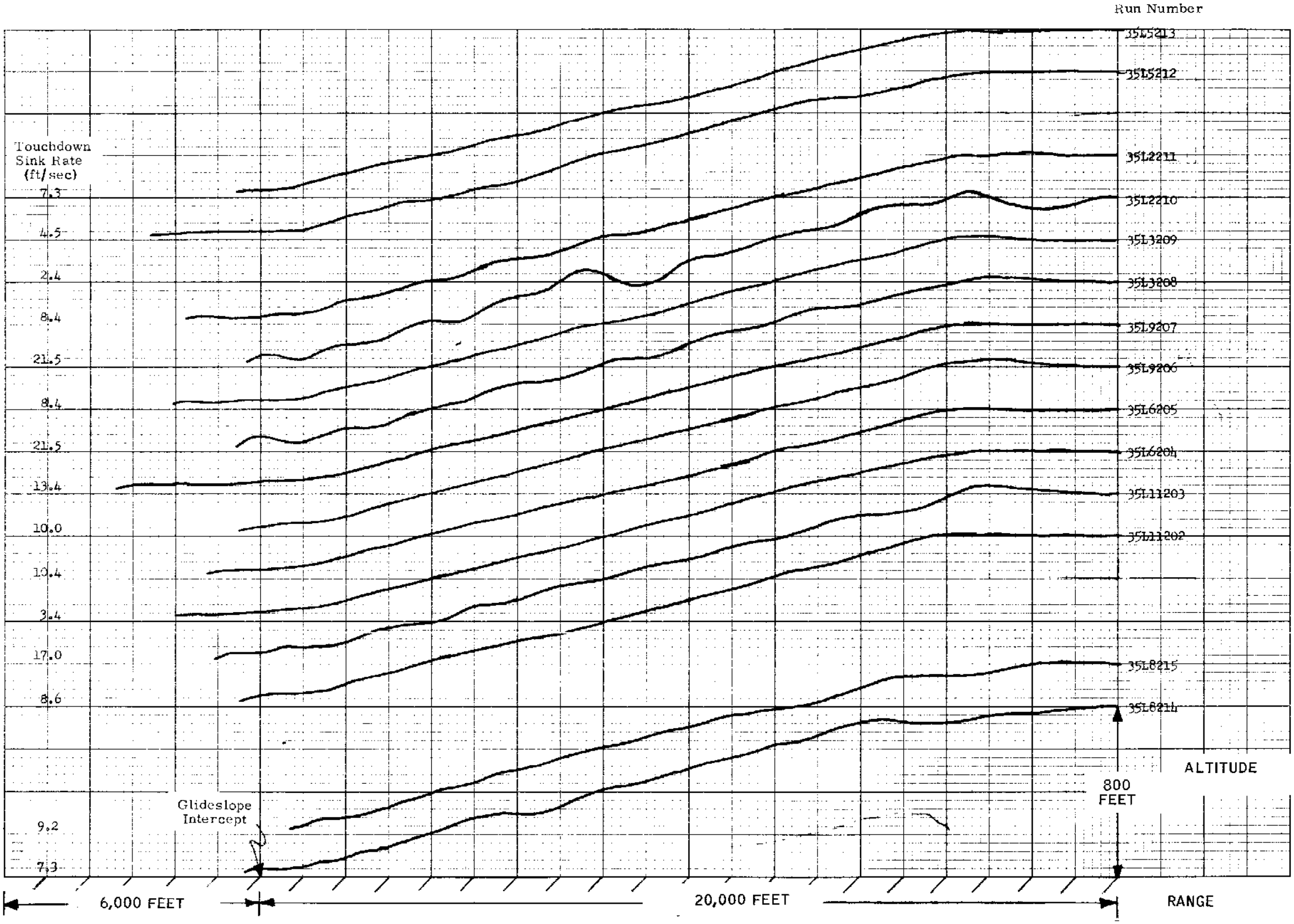


Figure 48. Landing Trajectory Plots -- Runs 202 Through 215

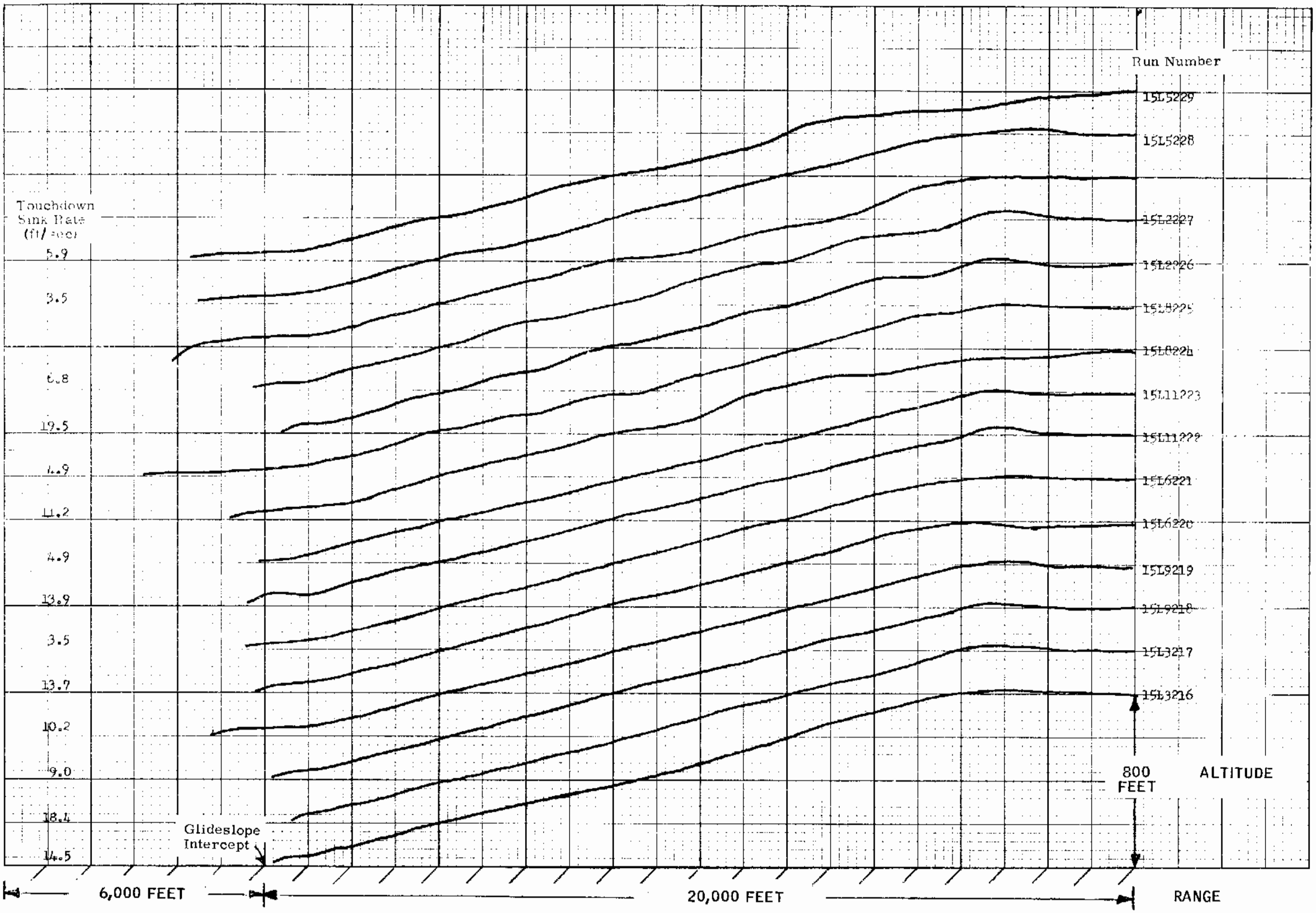


Figure 49. Landing Trajectory Plots -- Runs 216 Through 229

APPENDIX XI

SIMULATION DESCRIPTION

GENERAL

The AFFDL moving base simulator cockpit is shown in Figure 2. The following instruments were used for the visual presentation:

- Attitude direction indicator (ADI) (roll, pitch and heading on the ball, horizontal needle and left side meter for glide slope, and vertical needle and bottom meter for localizer)
- Sideslip
- Angle of attack
- Incremental g's
- Rate of climb, feet per minute
- Engine rpm (for thrust simulation)
- A small side meter (for flap deflection in separate DLC mode)
- Airspeed
- Altitude
- Flare light

CONTROL STICK

Control stick force-displacement characteristics were generated with a pneumatic system that allowed adjustable force-displacement characteristics. A schematic of the feel system is shown in Figure 50. The mechanical arrangement of this feel system allowed considerable play around center in both pitch and roll. Both pitch and roll stick displacements could be made with little or no stick force. This characteristic was annoying to the pilots, especially since a force pickoff was not available and a stick position pickoff was used.

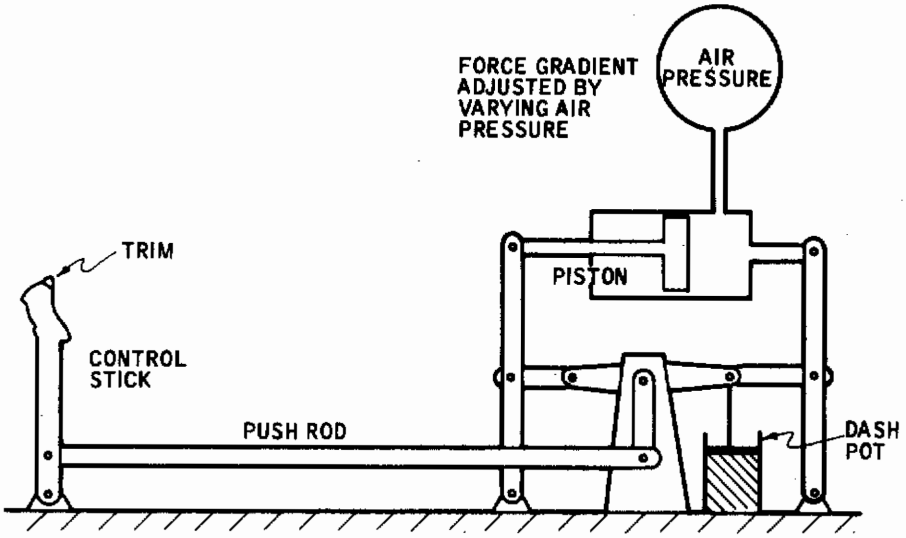


Figure 50. Schematic of Pitch Stick and Feel System (Roll Similar)

Figure 51 shows stick force and electrical characteristics versus stick displacement. Comparing pitch voltage with force, 0. 3 volt is obtained with zero force (at 0. 125-inch displacement). This made precise control difficult. For example, 0. 4 g could be pulled within the stick play during F-104 general handling qualities evaluation. The pitch trim was therefore disabled, and diodes added at the pitch stick error amplifier, thereby introducing a ±1-volt electrical dead zone at the stick. The stick had a 24-inch radius to grip center. It was desired to adjust the C-5A and typical fighter force-displacement characteristics to this 24-inch stick. The desired characteristics are listed in Table XXX.

All DLC configurations investigated used stick force displacement characteristics of the C-5A and F-104 fighter. Electrical gradients, K_{nzF} and K_{C*F} to flap and elevator, respectively, assumed a stick force pickoff and were in g's per pound. This simulator used a stick position pickoff rather than a force pickoff. In addition, the length of the stick did not correspond to that of a C-5A or a typical fighter. It was therefore necessary to convert force gradients to displacement gradients. Conversion factors used are shown in Table XXX.

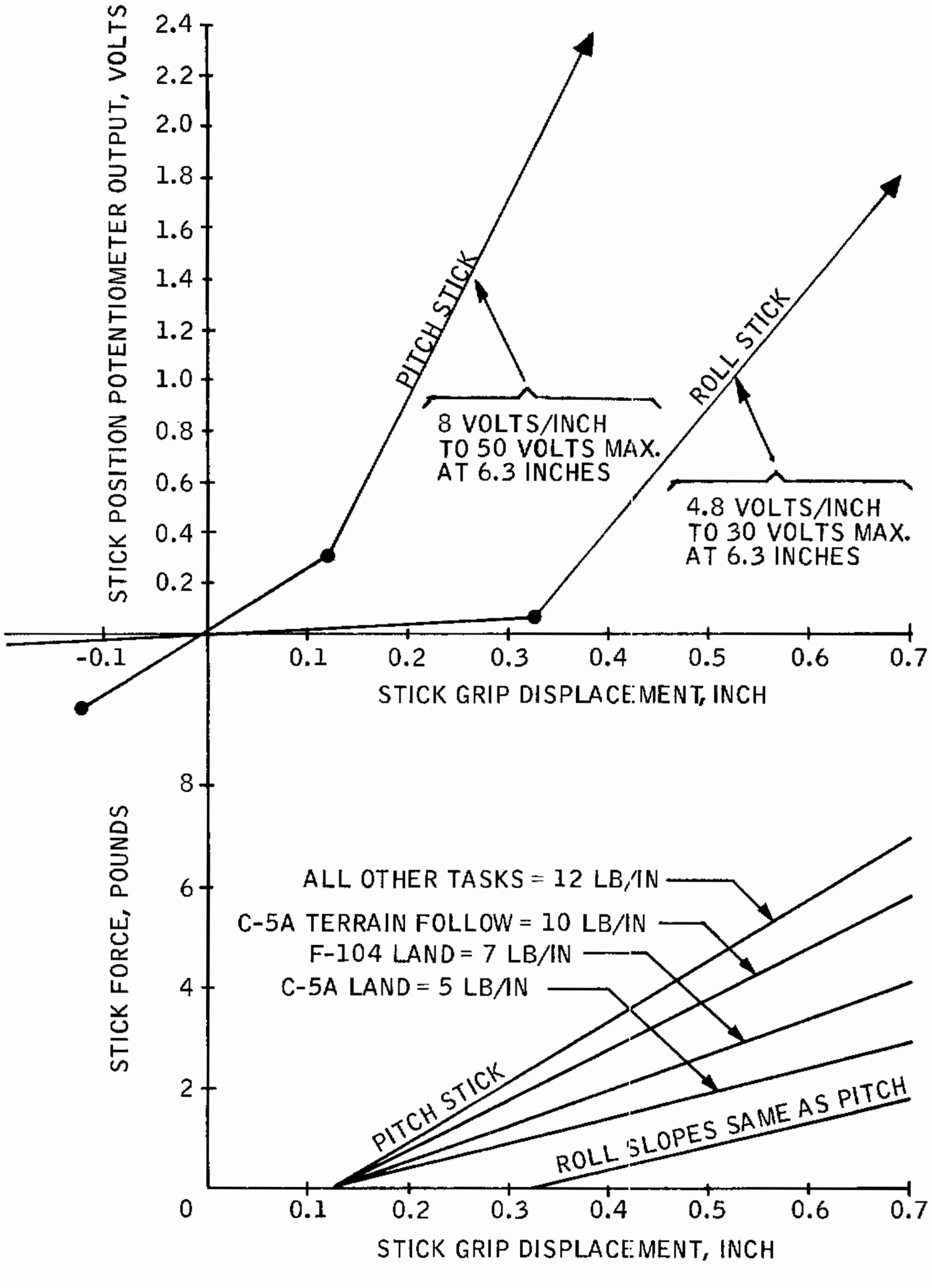


Figure 51. Stick Force and Electrical Characteristics

Table XXX. Force-Displacement Characteristics and Conversion Factors

Description	C-5A Aircraft			F-104 Aircraft		
	Landing Task	M = 0.6 at 5000 ft	M = 0.6 at 20,000 ft	Landing Task	M = 0.9 at 5000 ft	M = 0.9 at 35,000 ft
① Column displacement, deg/lb	0.5	0.15	0.177	1.0	0.27	0.27
② Column length, inches	---	31.3	---	---	18.8	---
③ Desired simulator stick displacement, deg/lb, 24-inch column $= \frac{①\times②}{24}$	0.65	0.20	0.23	0.78	0.21	0.21
④ Desired simulator force gradient, lb/inch $= \frac{57.3}{①\times②}$	3.7	12.4	10.3	3.1	11.5	11.5
⑤ $K_{n_{z_F}}$, design stick force to normal acceleration gradient, g/lb	0.06	0.06	0.06	0.2	0.2	0.2
⑥ Desired simulator electrical flap gradient, n_z/deg = ⑤/③	0.093	0.31	0.26	0.26	1.04	1.04
⑦ $K_{C^*_F}$, design stick force to C^* gradient, g/lb	0.08	0.08	0.08	0.28	0.28	0.28
⑧ Simulator electrical gradient, C^*/deg = ⑦/③	0.12	0.4	0.35	0.36	1.35	1.35

The desired stick gradients could not be used due to the poor centering characteristics. Table XXXI gives the actual pitch characteristics used, and also the roll gradients which could not be independently adjusted.

Table XXXI. Pitch Characteristics and Roll Gradients

Aircraft	Flight Condition		Desired Pitch (lb/in)	Actual Used (lb/in)	Resulting Roll (lb/in)
	Mach No.	Altitude (ft)			
C-5A	0. 17	sea level	3. 7	5. 0	3. 0
	0. 6	sea level	12. 4	11. 7	6. 0
	0. 6	20, 000	10. 3	10. 0	4. 5
F-104	0. 3	sea level	3. 08	7. 0	3. 0
	0. 9	5000	11. 5	11. 7	6. 0
	0. 9	35, 000	11. 5	11. 7	6. 0

MOTION SYSTEM GEOMETRY

The motion system geometry is shown in Figure 52, and the analog computer mechanization used to drive the motion system is shown in Figure 53. Using Figures 52 and 53, the actual motion drive equations can be determined.

Desired Pilot Motions

The desired pilot motions are given by:

$$\theta_q = f(\theta, q) \quad \text{(pitch)}$$

$$\phi_q = f(\phi, p) \quad \text{(roll)}$$

$$Z_p = f(z_p) \quad \text{(heave)}$$

Actual Inputs to Motion Drive

The actual inputs to the motion drive are given by the following equations:

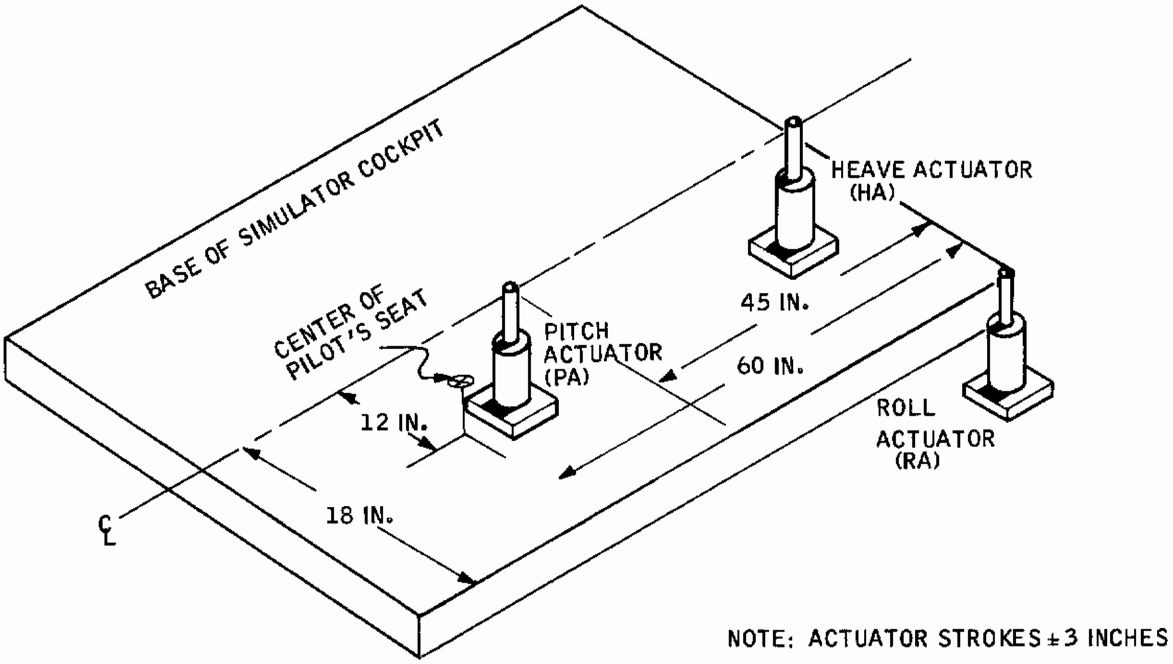


Figure 52. Motion Simulator Geometry

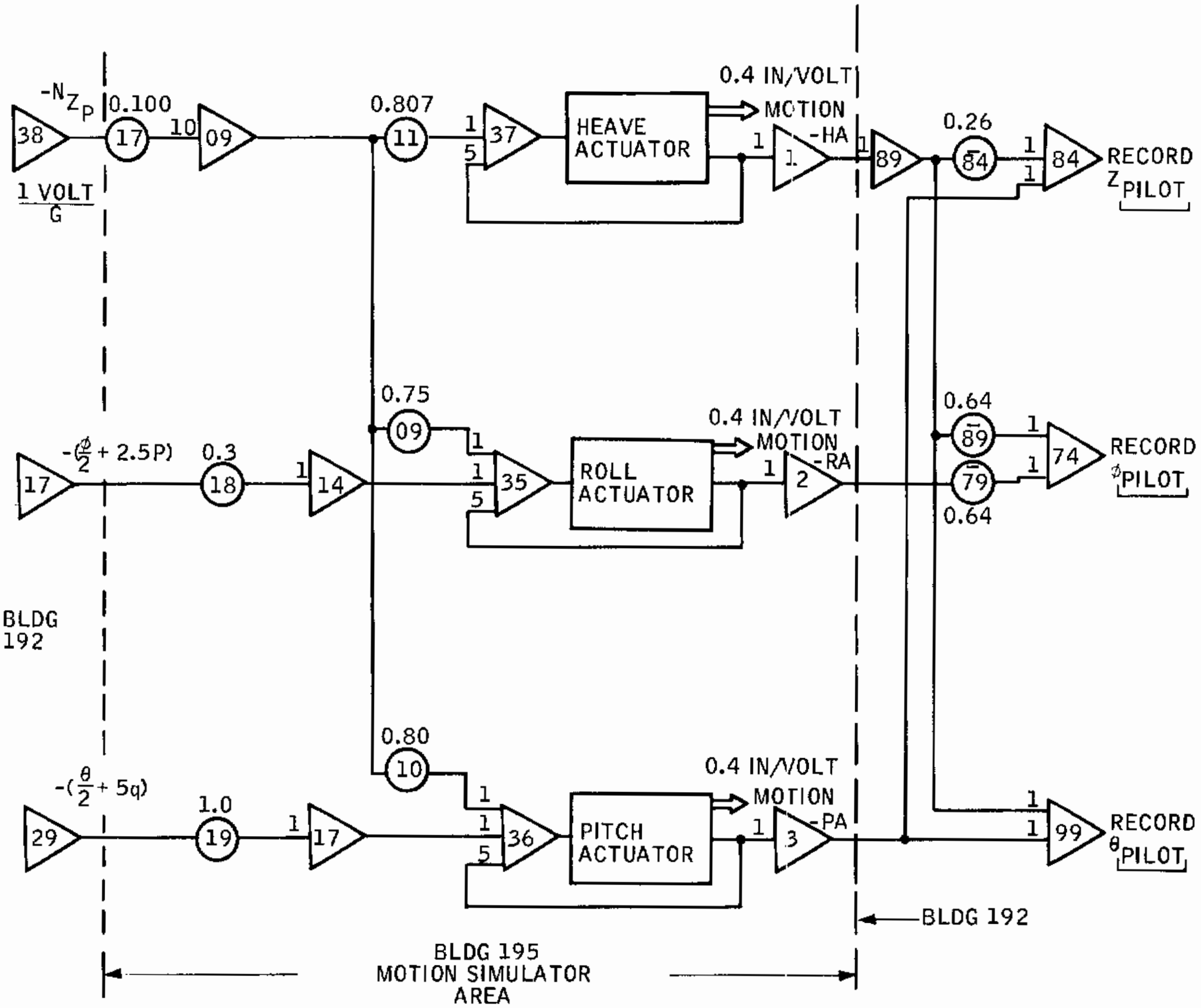


Figure 53. Motion Simulator Drive and Recording

$$\theta_p = 0.04\ (\theta + 10q) \text{ -- [C-5A]} \tag{60}$$

$$\theta_p = 0.04\ (\theta + 5p) \text{ -- [F-104]} \tag{61}$$

$$\phi_p = 0.038\ (\phi + 5p) - 0.012\ n_{z_p} \text{ -- [C-5A]} \tag{62}$$

$$\phi_p = 0.038\ (\phi + 2.5p) - 0.012\ n_{z_p} \text{ -- [F-104]} \tag{63}$$

$$Z_p = 0.064 n_{z_p} + 0.022\ (\phi+5p) + 0.055(\theta+10q) \text{ -- [C-5A]} \tag{64}$$

$$Z_p = 0.064\ n_{z_p} + 0.022\ (\phi+2.5p) + 0.055\ (\theta+5q) \text{ -- [F-104]} \tag{65}$$

Actual Motion Drive Equations

1) Actuator feedback responses:

$$HA = 0.16\ N_{z_p} \text{ volts} \tag{66}$$

$$RA = 0.15\ N_{z_p} + 0.06\ \left(\frac{\phi}{2} + 2.5p\right) \text{ volts} \tag{67}$$

$$PA = 0.16\ N_{z_p} + 0.20\ \left(\frac{\theta}{2} + 5q\right) \text{ volts} \tag{68}$$

2) Actuator Motions were 0.4 inch/volt.

3) Pilot motions:

$$\theta_p = \left(\frac{57.3 \text{ deg}}{45 \text{ in.}}\right) \left(PA - HA\right) \left(0.4 \frac{\text{in.}}{\text{volt}}\right) \tag{69}$$

$$= 0.08\ \left(\frac{\theta}{2} + 5q\right) \text{ degree}$$

$$\phi_p = \left(\frac{57.3 \text{ deg}}{18 \text{ in}}\right) \left(RA - HA\right) \left(0.4 \frac{\text{in.}}{\text{volt}}\right)$$

$$= -0.012\ N_{z_p} + 0.076\ \left(\frac{\phi}{2} + 2.5p\right) \text{ degree} \tag{70}$$

$$
\begin{aligned}
Z_p &= \left(\frac{60 \text{ in.}}{45 \text{ in.}}\right) \text{PA} - \left(\frac{15 \text{ in.}}{47 \text{ in.}}\right) \text{HA} + \left(\frac{12}{18}\right) \left(\text{RA-HA}\right) \\
&= 0.064\, N_{z_p} + 0.045 \left(\frac{\phi}{2} + 2.5p\right) + 0.11 \left(\frac{\theta}{2} + 5q\right) \text{ inches}
\end{aligned}
\tag{71}
$$

4) Analog recording of pilot motion:

$$
\begin{aligned}
Z_p &= (\text{PA} - 0.26\ \text{HA}) \text{ volts} \quad \text{(roll neglected)} \\
&= (1.33)(0.4) = 0.53\, \frac{\text{inch}}{\text{volt}}
\end{aligned}
\tag{72}
$$

$$
\begin{aligned}
\phi_p &= 0.64\ (\text{RA-HA}) \text{ volts} \\
&= \left(\frac{0.4}{0.64}\right)\left(\frac{57.3}{18}\right) = 2.0\, \frac{\text{deg}}{\text{volt}}
\end{aligned}
\tag{73}
$$

$$
\begin{aligned}
\theta_p &= (\text{PA-HA}) \text{ volts} \\
&= \left(\frac{57.3}{45}\right)\left(\frac{0.4}{1.0}\right) = 0.51\, \frac{\text{deg}}{\text{volt}}
\end{aligned}
\tag{74}
$$

5) Individual maximum displacements:

$$
\begin{aligned}
\theta_p &= \left(\frac{57.3}{45}\right)\left(3 \text{ in.} + 3 \text{ in.}\right) \\
&= \pm 7.6 \text{ degrees}
\end{aligned}
\tag{75}
$$

$$
\begin{aligned}
\phi_p &= \left(\frac{57.3}{18}\right)\left(3 \text{ in.} + 3 \text{ in.}\right) \\
&= \pm 19 \text{ degrees}
\end{aligned}
\tag{76}
$$

$$
\begin{aligned}
Z_p &= \left(\frac{60}{45}\right)\left(3\right) - \left(\frac{15}{45}\right)\left(-3\right) \\
&= \pm 5 \text{ inches}
\end{aligned}
\tag{77}
$$

Rate-to-Attitude Ratios

The ratios of rate to attitude were determined by pilot preference in previous experiments with the AFFDL moving base simulator. The pilot's vertical motion, Z_p, includes pitch and roll inputs, as well as pilot's acceleration, N_{z_p}. Since N_{z_p} was in g's, and pitch and roll in degrees, it can be seen that the pilot's vertical motion was due mainly to pitch and roll inputs, i.e., N_{z_p} rarely exceeded 2 g's, calling only for 0.13 inch vertical motion.

STATIC AND DYNAMIC RESPONSE OF MOTION SYSTEM

At the conclusion of the formal test program the static (low-frequency) and dynamic response of the motion system was investigated. The following results were obtained:

- Heave Static and Dynamic

  For $-n_{z_p} = +34$ volts drive:

	Calculated	Measured
Z_p	$= PA - 0.26\ HA = 4.1$ volts	-4.2 volts
ϕ_p	$= 0.64\ (RA - HA) = +0.25$ volts	0.5 volt
θ_p	$= PA - HA = 0$ volts	-2 volts

  For one-third maximum amplitude at low frequency:

  -3 db at 0.4 cps

  -11 db at 1.0 cps

- Roll Static and Dynamic

  For $\phi^* = -40$ volts drive:

	Calculated	Measured
ϕ_p	$= 0.64\ (RA - HA) = 1.54$ volts	1.6 volts

  For one-third maximum amplitude at low frequency:

  -3.6 db at 0.4 cps

  -9.8 db at 1.0 cps

- Pitch Static and Dynamic

For θ^* = -20 volts drive:

	Calculated	Measured
θ_p	= (PA - HA) = 4 volts	4 volts
Z_p	= (PA - 0.26 HA) = 4 volts	4 volts

For one-third maximum amplitude at low frequency:

-2 db at 0.4 cps

-8 db at 1.0 cps

The predicted static performance (low-frequency data) was obtained for pitch and roll inputs, but pilot's acceleration input (N_{z_p}) calling for heave produced large pitch and roll, as well as vertical displacement. It was suspected that the heave actuator static gain was low.

APPENDIX XII

DIRECT LIFT CONTROL POWER REQUIREMENTS

Mean absolute values of control surface rates and positions were obtained in all piloted runs and are presented in Appendix IX. This data may be used to estimate the power required to operate the direct lift controllers. The horsepower required is obtained by:

(1) Assuming that flap null (or trim) position, δ_T, must be at least three times the mean observed value to provide adequate DLC authority.

(2) Assuming that the required flap rate must be three times the mean observed value of flap rate, δ.

The mean aerodynamic hinge moment is assumed proportional to the trimmed flap position and angle of attack. The horsepower required is then:

$$\text{H. P.} = \frac{\left(H_\delta \, \delta_T + H_\alpha \, \alpha_T \right) \quad 3 \, \dot{\delta}_{RHS}}{550} \qquad (78)$$

Note that with these assumptions (with angle of attack contribution small) power required is about nine times the power consumed.

C-5A flap rates and positions are available for landing, terrain following, and in-flight refueling. F-104 data is available for landing and terrain following. Before estimating terrain following DLC requirements, note the mean absolute value of normal accelerations of approximately 0. 42 g for the C-5A and 1. 0 g for the F-104. These are excessive; the tracking task did not impose the g-limits normally present in a terrain following system. Honeywell analysis of another aircraft with a terrain following system has shown that, with ±0. 9-g limits, the rms value of normal acceleration was 0. 2 g; the mean absolute value (for comparison with the data in this study) would be about 80 percent of this, or 0. 16 g. If the simulation had been scaled to result in these rates, both the mean positions and rates would be reduced proportionately. In estimating terrain following power then, the C-5A mean values are reduced by the ratio (0. 16/0. 42), and the F-104 values by the ratio (0. 16/1. 0).

Table XXXII presents mean absolute value data from Appendix IX. Table XXXIII has estimates of C-5A hinge moment derivatives H_α and H_δ in foot-pounds per degree. Table XXXIV contains similar data for the F-104. Table XXXV uses data from Tables XXXII and XXXIII to estimate DLC power required in the C-5A. Seventy horsepower (delivered) is indicated for in-flight refueling. Table XXXVI uses data from Tables XXXII and XXXIII to estimate F-104 DLC power. Three horsepower must be delivered to the flaps for approach.

Table XXXII. Mean Absolute Values of Flap Position and Rates -- Closed-Loop Direct Lift Control in Turbulence

Parameter	Landing Task	Terrain Following Task	In-flight Refueling Task
F-104 flap position, deg	3.95	0.65	---
F-104 flap rate, rad/sec	0.16	0.029	---
C-5A flap position, deg	2.4	1.06	1.8
C-5A flap rate, rad/sec	0.061	0.038	0.065

Table XXXIII. C-5A Estimated Hinge Moment Coefficients and Moments, Using Reference 4

Parameter	Landing Task	Flight Condition	
		M=0.6 at 5000 ft.	M=0.6 at 20,000 ft.
q	43	533	245
qS_FC_F	343,000	4,260,000	1,960,000
H_α, ft-lb/deg	1380	17,100	7900
H_δ, ft-lb/deg	3680	45,500	20,800

NOTE: $C_{h_\alpha} = -0.004/\text{deg}$; $S_F = 1040\ \text{ft}^2$

$C_{h_\delta} = -0.011/\text{deg}$; $C_F = 7.7\ \text{ft}$

Table XXXIV. F-104 Estimated Hinge Moment Coefficients and Moments

Parameter	Control Task	
	Landing	Terrain Following
q, lb/ft^2	133	998
$q S_F C_F \times 10^{-4}$ (ft-lb)	0.88	6.5
H_α, ft-lb/deg	-33	-250
H_δ, ft-lb/deg	-100	-730

NOTE: C_{h_α} = -0.004/deg; S_F = 23 ft^2

C_{h_δ} = -0.011/deg; C_F = 2.7 ft

Table XXXV. C-5A Flap Power Required in Turbulence

Parameter	Control Task		
	Landing	Terrain Following	Inflight Refueling
① Mean flap variation from Table XXXII, degrees	2.4	1.06	1.8
② Minimum trim position = 3 x ①	7.2	3.1	5.4
③ Selected trim, degrees	30.0	3.1	5.4
④ Z_α per degree	1.75	18.6	9.6
⑤ Z_δ per degree	0.73	3.4	2.3
⑥ $\alpha_T = \frac{1}{Z_\alpha}[32.2 - Z_\delta \delta_T]$	5.8	1.1	1.8
⑦ H_α, ft-lb/deg	1380	17,100	7900
⑧ H_δ, ft-lb/deg	3680	45,500	20,800
⑨ Trim hinge moment = ③ x ⑧ + ⑤ x ⑦, ft-lb	119,000	199,000	126,000
⑩ Mean flap rate from Table XXXII, rad/sec	0.061	0.038	0.065
⑪ Power required (horse power) = 3 x ⑩ x ⑨/550	61.0	41.0	70.0

Table XXXVI. F-104 Flap Power Required in Turbulence

Parameter	Control Task	
	Landing	Terrain Following
① Mean flap position, (Table XXXII), deg	3.95	0.65
② Selected trim position, δ_T, deg	33	2
③ Z_α per degree	2.7	31.6
④ Z_δ per degree	0.59	6.1
⑤ $\alpha_T = \frac{1}{Z_\alpha}\left[g - Z_\delta \delta_T\right]$	4.7	0.63
⑥ H_α, ft-lb/deg (Table XXXIV)	-33	-250
⑦ H_δ, ft-lb/deg (Table XXXIV)	-100	-730
⑧ Trim hinge moment, ft-lb	-3420	-1620
⑨ Mean flap rate (Table XXXII)	0.16	0.029
⑩ Power required = $\frac{3 \times \textcircled{9} \times \textcircled{8}}{550}$	3.0	0.85

APPENDIX XIII

ANALYSIS OF VARIANCE

An order of magnitude improvement in performance with the use of direct lift control was not expected. Therefore, it was desired to know that if differences in performance resulted, were these differences significant or could these differences be attributed to chance. An analysis of variance was performed on the quantitative performance given in Appendix IX. A three-factor analysis was used: controller (three), turbulence (in and out), pilot (two, except three for F-104 landing). Results are summarized in Table XXXVII, where only the levels of significance are given for the main effects and interactions for the parameters of interest within the five different control tasks. The results generally show that improvements in pilot performance and reduction in pilot work load with DLC were significant.

C-5A ALTITUDE RATE TRACKING TASK

First- and second-order interactions are not significant for pitch director tracking error. Controllers and pilot main effects are significant at the 0. 1 percent level. With blended closed-loop DLC the mean tracking error is 7. 75 percent. With blended open-loop DLC it is 11. 63 percent. With conventional elevator it is 13. 12 percent.

First- and second-order interactions are not significant for pitch rate. The controller main effect is significant at the 0. 1 percent level. Pilot and turbulence main effects are significant at the 5 percent level. Closed-loop DLC has a mean of 1. 23 degrees per second. Open-loop DLC has a mean of 1. 53 degrees per second and conventional elevator has a mean of 1. 86 degrees per second. Pitch rate is higher with turbulence, as expected.

Controller and pilot main effects are significant at the 5 percent level for the pitch stick position. Closed-loop DLC has a mean of 1. 82 degrees,open-loop DLC has a mean of 2. 03 degrees,and conventional elevator has a mean of 2. 36 degrees.

F-104 ALTITUDE RATE TRACKING TASK

The controller-pilot first-order interaction is significant at the 1 percent level for the pitch director tracking error. The turbulence-pilot first-order interaction is significant at the 5 percent level. With closed-loop DLC, one pilot improved performance, while the other pilot had reduced performance compared with conventional elevator. Both pilots had improved performance with open-loop DLC compared with conventional

Table XXXVII. Variance Analysis Summary

Aircraft/Control Task	Parameter	Source of Variation[a]						
		Controller	Turbulence	Pilot	Controller Turbulence	Controller Pilot	Turbulence Pilot	Controller Turbulence Pilot
C-5A altitude rate tracking	tracking error	0.1	---	0.1	---	---	---	---
	pitch rate	0.1	5.0	5.0	---	---	---	---
	stick position	5.0	---	5.0	---	---	---	---
F-104 altitude rate tracking	tracking error	0.1	---	0.1	---	1.0	5.0	---
	pitch rate	5.0	---	---	---	---	---	---
	stick position	---	1.0	---	---	---	---	---
C-5A altitude tracking	tracking error	0.1	0.1	---	1.0	5.0	---	---
	altitude error	---	---	0.1	---	---	---	---
	stick position	0.1	5.0	---	1.0	0.1	---	5.0
C-5A landing	tracking error	---	5.0	---	---	---	---	---
	pitch rate	---	5.0	5.0	---	---	---	---
	stick position	5.0	5.0	1.0	---	---	---	---
	touchdown dispersion	---	---	---	---	---	---	---
	touchdown rate	5.0	---	---	---	---	---	---
F-104 landing	tracking error	0.1	1.0	5.0	---	---	---	---
	stick position	---	5.0	1.0	---	---	5.0	---
	touchdown dispersion	---	---	---	---	---	---	---
	touchdown rate	5.0	---	---	---	---	---	---
	pitch rate	0.1	0.1	0.1	---	---	---	---

[a] Figures shown indicate 0.1, 1.0, or 5.0 percent level of significance.
--- denotes varriation is not significant.

elevator. One pilot improved performance with turbulence. These two interactions do not seem likely ones. Controller and pilot main effects are significant at the 0.1 percent level. Blended open-loop DLC resulted in the best performance, followed by blended closed-loop DLC and conventional elevator.

The controller main effect is significant at the 5 percent level for pitch rate. Closed-loop DLC has a mean pitch rate of 2.085 percent followed by 2.403 percent for open-loop DLC and 2.941 percent for conventional elevator.

The turbulence main effect is significant at the 1 percent level for pitch stick position. The mean stick position is less with turbulence than without turbulence.

C-5A ALTITUDE TRACKING TASK

The controller-turbulence first-order interaction is significant at the 1 percent level, and the controller-pilot first-order interaction is significant at the 5 percent level for the pitch director tracking error.

Controller and turbulence main effects are significant at the 0.1 percent level. Blended closed-loop DLC has a mean of 9.25 percent; blended open-loop DLC has a mean of 11.75 percent. Conventional elevator has a mean of 13 percent of full-scale error.

For this task altitude error was not displayed to the pilot. Altitude error was a result of tracking the sum of attitude and altitude rate. The first- and second-order interactions were not significant for the altitude error. The controller main effect was not significant. The mean data indicates that altitude error was less with conventional elevator.

First-order interactions of controller-turbulence and controller-pilot are significant at the 1 percent and 0.1 percent levels, respectively, for pitch rate. The probable explanation for the controller-pilot interaction is use of a different piloting technique between pilots using blended closed-loop DLC. The controller main effect was significant at the 0.1 percent level. The mean stick position with blended closed-loop DLC was about one-half that of the other two controllers.

C-5A LANDING TASK

Only the turbulence main effect was significant and only at the 5 percent level for the pitch director tracking error. Without turbulence the error was less.

Turbulence and pilot main effects were significant at the 5 percent level for pitch rate. Without turbulence the mean pitch rate was 0.485 percent. With turbulence the mean pitch rate was 0.731 percent.

Controller and turbulence main effects were significant at the 5 percent level for pitch stick position. The pilot main effect was significant at the 1 percent level. The mean for blended closed-loop DLC was 1.646 degrees. The mean for blended open-loop DLC was 1.755 degrees and for conventional elevator 2.377 degrees.

None of the main effects or first- and second-order interactions were significant for the touchdown longitudinal dispersions.

The controller main effect was significant at the 5 percent level for touchdown rates. Mean touchdown rates for blended closed-loop DLC were 5.9 feet per second; for blended open-loop DLC they were 9.4 feet per second and for conventional elevator 14.83 feet per second.

F-104 LANDING TASK

The controller main effect was significant at the 0.1 percent level for pitch director tracking error. The mean error for blended closed-loop DLC was 14.83 percent full scale, for blended open-loop DLC 17.25 percent, and for conventional elevator 23.08 percent. First- and second-order effects were not significant.

The three main effects were significant at the 0.1 percent level for pitch rate. The mean pitch rate with blended closed-loop DLC was 0.55 degree per second; with open-loop DLC pitch rate was 0.699 degree per second. With conventional elevator, pitch rate was 0.8875 degree per second.

The controller main effect was not significant for pitch stick position. The turbulence main effect was significant at the 5 percent level, and the pilot main effect was significant at the 1 percent level.

None of the main effects or first- and second-order interactions were significant for touchdown longitudinal dispersions.

Only the controller main effect is significant and only at the 5 percent level for touchdown rates. The mean touchdown rate for blended closed-loop DLC is 4.37 feet per second, for blended open-loop DLC 4.7 feet per second, and for conventional elevator 7.53 feet per second.

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A moving base pilot-in-the-loop simulator study was conducted to evaluate the effectiveness of direct lift control systems in improving the mission effectiveness of two types of aircraft. The missions considered were in-flight refueling, terrain following, and landing. The aircraft considered were the C-5A heavy cargo plane and the F-104 fighter-bomber. Improved performance was obtained for all missions with direct lift control augmentation systems when compared with conventional stability augmentation systems utilizing elevator control alone. This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Flight Dynamics Laboratory (FDCL), Wright-Patterson AFB, Ohio 45433.

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