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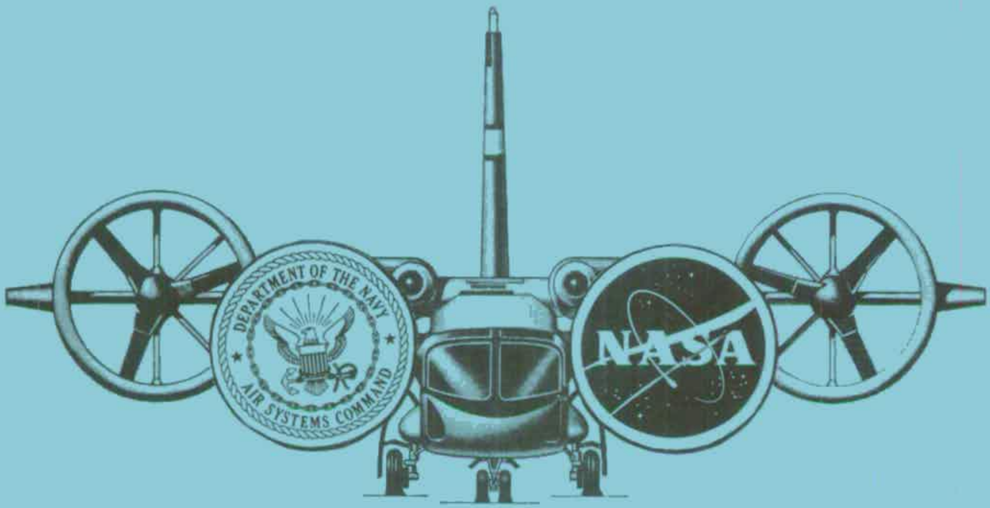
A FLIGHT INVESTIGATION OF CONTROL, DISPLAY, AND GUIDANCE REQUIREMENTS FOR DECELERATING DESCENDING VTOL INSTRUMENT TRANSITIONS USING THE X-22A VARIABLE STABILITY AIRCRAFT

VOLUME II: BACKGROUND INFORMATION AND SUPPORTING DATA

Final Report
September 1975

By
J. V. Lebacqz
E.W. Aiken



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VTOL Control Systems
VTOL Electronic Displays
Instrument Landings
Flight Directors
VTOL Terminal Guidance
V/STOL Aircraft
VTOL Aircraft Flying Qualities
VTOL Flight Test
VTOL Stability and Control Augmentation Systems

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

The third flight research program using the variable stability X-22A aircraft was undertaken to investigate control, display, and guidance requirements for VTOL instrument transitions. The primary purpose of the experiment was to provide meaningful data related to the interaction of aircraft control system and displayed information characteristics on pilot rating and performance during a steep decelerating descending transition from a representative forward velocity (100 Kt) to the hover completely under instrument conditions. Thirty-eight in-flight evaluations were performed of combinations of five

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generic display presentations, ranging from position-information-only to four-axis control directors, and five levels of control augmentation systems, ranging from rate-augmentation-only to decoupled longitudinal and vertical velocity responses and automatic configuration changes. In addition, new guidance developments of fundamental importance to VTOL instrument terminal area operations, including an Independent Thrust Vector Inclination Command (ITVIC) and a procedure for automatically switching between airspeed and ground speed tracking to account for headwinds and crosswinds, were conceived, designed, and demonstrated during the experiment. Primary results of the program include the demonstration of an inverse relationship between control complexity and display sophistication, as was hypothesized in the experiment design, and the definition of acceptable and satisfactory control/display combinations. In particular, it was found that the explicit display of translational velocities is required for a satisfactory system, regardless of control system complexity or automation, and that rate-augmentation-only may be acceptable (though still unsatisfactory) only if full control director commands are provided in addition to velocity status information. Analysis of the results in terms of simple pilot-in-the-loop considerations and measured performance and workload provide initial guidelines for the design of future VTOL control-display characteristics.

A FLIGHT INVESTIGATION OF CONTROL, DISPLAY, AND GUIDANCE REQUIREMENTS FOR DECELERATING DESCENDING VTOL INSTRUMENT TRANSITIONS USING THE X-22A VARIABLE STABILITY AIRCRAFT

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VOLUME II

APPENDIX I

MASTER DATA SUMMARY

The appendices to this report contain background information and supporting data relevant to the Technical Discussion and Results presented in Volume I. This appendix (I) is contained in both volumes, and summarizes the most pertinent data for ready reference; the contents of the remaining appendices (Volume II) are listed below:

Appendix II: Frequency responses of all control systems, selected time history responses to step inputs.

Appendix III: Summary of the ground simulation investigations used in the experiment design.

Appendix IV: Documentation of digital identification used to estimate achieved dynamic characteristics from flight data.

Appendix V: Complete documentation of pilot comments for each evaluation.

Appendix VI: Documentation of performance and workload analyses.

Appendix VII: Documentation of estimation of winds and turbulence.

Appendix VIII: Description of equipment.

Table I-1 is the master summary, listed according to control system, of all the evaluations performed in this experiment. The classification of the evaluations into primary (P), crosswind (CW), and NO-ITVIC (NI) matrices is given in the table. For the performance analyses given in Section X, a separation according to turbulence level is also made on the basis of turbulence effect rating (TER); as can be seen from the table, a TER of A through C generally corresponds to a turbulence level index of ≤ 3.2 ft/sec. The table also gives values of headwind and crosswind components estimated from aircraft measurements of airspeed and ground speed; in general, the values are biased relative to the winds called out by the airport tower during each evaluation (which are also included in the table) but do indicate in general the existing conditions. The estimation of wind and turbulence levels is discussed in Appendix VIII.

Table I-2 summarizes the longitudinal and lateral-directional stability and control derivatives in aircraft body axes at three flight conditions. These values are obtained by a digital identification technique from flight data; this procedure is discussed in Appendix IV. It is noted that the deriva-

TABLE I-1

MASTER DATA SUMMARY

CONTROL AUG.	ED FORMAT	ITVIC	ADI NEEDLES	DUCT ROTATION	PILOT RATING	FLIGHT NUMBER	MEASURED WINDS (FPS): HEADWIND†	CROSSWIND‡	TURBULENCE	TOWER WIND DIR./KTS	SPN-42 COURSE	EVAL. MATRIX
RATE	ED3	ON	OFF	MAN	4B	F-108	25.0	4.4(R)*	—	210°/15	220°	P
	ED3	ON	OFF	MAN	4C	F-121	17.6*	10.1(L)*	2.8	270°/12	300°	P
	ED3	ON	OFF	MAN	7B	F-130	-9.9	10.8(R)	2.3	010°/10	300°	CW
	ED3	ON	OFF	MAN	7C	F-140	-4.5	6.9(R)	3.2	350°/13	300°	CW
	ED2+	ON	OFF	MAN	7A	F-130	-5.6	11.8(R)	2.6	360°/08	300°	CW
	ED2+	ON	OFF	MAN	8E	F-132	19.0	6.0(R)	3.4	290°/20	255°	P
	ED2+	ON	OFF	MAN	8-1/2F	F-134	21.3	1.8(L)	3.6	230°/15	255°	P
	ED2	ON	OFF	MAN	7A	F-124	16.0*	7.6(R)	2.0	250°/11	220°	P
	ED1	ON	FD	MAN	7-1/2B	F-130	-9.4	14.0(R)	2.7	360°/05	300°	CW
ATT/RATE	ED3	ON	OFF	MAN	3D	F-128	22.4	13.2(L)	3.3	250°/15	280°	P
	ED3[x]	ON	OFF	MAN	6B	F-133	7.8	3.9(L)	2.2	250°/15	280°	P
	ED3	ON	OFF	MAN	3C	F-142	0.0	8.7(R)	3.2	330°/09	300°	P
	ED2+	ON	OFF	MAN	4D	F-128	15.5	9.2(L)	3.3	250°/15	280°	P
	ED2+	ON	OFF	MAN	4D	F-132	22.5	7.7(R)	4.1	270°/20	255°	P
	ED2	ON	OFF	MAN	5D	F-127	25.0	4.4(R)*	—	270°/15	280°	P
	ED2	ON	OFF	MAN	4-1/2B	F-133	9.3	6.5(L)	1.9	250°/15	280°	P
ATTITUDE	ED3	ON	OFF	MAN	3D	F-120	25.4*	9.2(R)*	3.7	320°/16	300°	P
	ED3	ON	OFF	MAN	2A	F-131	3.5	3.6(L)	2.5	200°/08	220°	P
	ED3	ON	OFF	MAN	3D	F-139	-6.3	12.5(R)	3.3	010°/07	300°	CW
	ED2+	ON	OFF	MAN	3A	F-131	11.0	4.7(L)	2.0	210°/10	220°	P
	ED2+	ON	OFF	MAN	3E	F-134	24.8	9.1(L)	4.0	250°/15	255°	P
	ED2+	ON	OFF	MAN	2-1/2C	F-140	4.2	13.6(R)	3.2	360°/10	300°	CW
	ED2	ON	OFF	MAN	5D	F-121	17.6*	10.1(L)*	3.4	270°/12	300°	P
	ED2	ON	OFF	MAN	4B	F-123	6.5*	5.4(L)*	2.4	180°/05	220°	P
	ED1	ON	FD	MAN	7D	F-121	17.6*	10.1(L)*	4.0	270°/12	300°	P
	ED3	OFF	OFF	MAN	6D	F-123	7.6*	9.1(R)	3.0	230°/08	220°	NI
	ED2	OFF	OFF	MAN	6C	F-128	19.0	11.2(L)	3.0	250°/15	280°	NI
AUTO λ	ED3	ON	OFF	AUTO	2B	F-126	22.0	12.7(R)*	—	250°/15	280°	P
	ED2+	ON	OFF	AUTO	2A	F-131	10.9	0.5(L)	2.3	210°/10	220°	P
	ED2+	ON	OFF	AUTO	3D	F-134	22.0	4.6(L)	3.5	250°/15	255°	P
	ED2	ON	OFF	AUTO	3C	F-123	13.3*	2.3(R)*	3.0	230°/08	220°	P
	ED2	ON	OFF	AUTO	2-1/2A	F-133	9.4	5.0(L)	2.0	250°/15	280°	P
	ED1	ON	OFF	AUTO	7B	F-124	16.0*	11.8(R)	2.8	250°/11	220°	P
DVC	ED3	ON	OFF	AUTO	2C	F-142	0.0	12.5(R)	3.0	330°/09	300°	P
	ED2+	ON	OFF	AUTO	2C	F-142	0.0	10.9(R)	3.6	330°/09	300°	P
	ED2	ON	OFF	AUTO	2B	F-141	12.7	7.6(R)	2.6	340°/15	300°	P
	ED2	ON	OFF	AUTO	2B	F-141	11.4	9.7(R)	2.7	340°/15	300°	P
	ED1	ON	OFF	AUTO	7B	F-141	15.2	12.7(R)	2.3	340°/15	300°	P

†NEGATIVE SIGN INDICATES TAILWIND
‡LETTER INDICATES DIRECTION AS SEEN FROM AIRCRAFT
*MEASURED VALUES INVALID, TOWER VALUES RESOLVED
[x]DIFFERENT VBAR GAIN, NOT INCLUDED IN ANALYSES

TABLE I-2

BASIC AIRCRAFT STABILITY DERIVATIVES

		λ = 90 deg (0 Kt)	λ = 50 deg (65 Kt)	λ = 15 deg (100 Kt)
X_u	(1/sec)	-0.15	-0.18	-0.19
X_w	(1/sec)	0.0	-0.030	0.087
$X_{\delta_{es}}$	(ft/sec^2/in)	-0.143	-0.356	0.147
$X_{\delta_{cs}}$	(ft/sec^2/deg)	0.0	0.52	1.12
Z_u	(1/sec)	0.0	-0.20	-0.26
Z_w	(1/sec)	-0.12	-0.55	-0.65
$Z_{\delta_{es}}$	(ft/sec^2/in)	-0.16	0.0	0.61
$Z_{\delta_{cs}}$	(ft/sec^2/deg)	-1.50	-1.00	-0.36
M_u	(rad/ft-sec)	0.015	-0.010	-0.0066
M_w	(rad/ft-sec)	0.000875	-0.0177	-0.0049
M_q	(1/sec)	0.23	-0.09	-0.5
$M_{\delta_{es}}$	(rad/sec^2/in)	0.348	0.33	0.30
$M_{\delta_{cs}}$	(rad/sec^2/deg)	0.0	0.021	0.037
Y_v	(1/sec)	-0.060	-0.267	-0.30
Y_p	(ft/rad-sec)	1.67	0.573	0.347
Y_r	(ft/rad-sec)	-1.68	-0.108	-1.49
L'_v	(rad/ft-sec)	-0.015	-0.037	-0.0386
L'_p	(1/sec)	+0.07	-0.75	-1.05
L'_r	(1/sec)	0.0	1.24	1.85
$L'_{\delta_{as}}$	(rad/sec^2/in)	0.40	0.382	0.398
$L'_{\delta_{rp}}$	(rad/sec^2/in)	0.095	-0.150	-0.102
N'_v	(rad/ft-sec)	0.0011	0.001	-0.00118
N'_p	(1/sec)	0.0	-0.110	-0.178
N'_r	(1/sec)	-0.17	-0.21	-0.10
$N'_{\delta_{as}}$	(rad/sec^2/in)	0.043	0.052	0.068
$N'_{\delta_{rp}}$	(rad/sec^2/in)	0.23	0.15	0.058

tive estimates are all obtained for steady flight; the unsteady effects caused by the decelerating transition are therefore not included in the values for λ =50° (65 kt), and these values should therefore be interpreted as useful primarily to indicate the trends in the derivatives and modal characteristics.

A complete listing of all the transfer functions for the five control augmentation systems investigated is given in Table I-3. These modal characteristics were calculated using the basic aircraft derivatives listed in Table I-2 and the feedback-feed forward gains given in Section V. The pitch, roll, and/or yaw prefilters, as appropriate, are indicated by enclosing the aircraft transfer functions for those cases in brackets ({ }). The format used is as follows:

$$K\left(s+\frac{1}{\tau_1}\right)\left(s^2+2\zeta\omega_n s+\omega_n^2\right) \Longrightarrow K\left(\frac{1}{\tau_1}\right)\left[\zeta;\ \omega_n\right]$$

Finally, Tables I-4 and I-5 summarize the electronic display symbol sensitivities and control director gains (in terms of full scale values), respectively; these tables are a compilation of the information presented in Section VI.

TABLE I-3a

TRANSFER FUNCTIONS--RATE AUGMENTATION CONTROL SYSTEM

	λ = 90 deg (0 kt)	λ = 50 deg (65 kt)	λ = 15 deg (100 kt)
LONGITUDINAL			
$\Delta(s)$	(.12)(2.94) [.10;.405]	(.18)(-.092) [.94;1.95]	(.93)(2.89)(.31)(-.12)
$N^{u}_{\delta_{es}}$	-.18(.12) [-.012;8.84]	-.447(.48) [.03; 5.86]	.185(-69.08) [.73;.78]
$N^{w}_{\delta_{es}}$	-.201(.78) [-.53;.79]	41.54 [.38;.25]	.766(+83.55) [.52;.20]
$N^{\theta}_{\delta_{es}}$	.437(.12)(.14)	.414(.17)(.58)	.377(.24)(.58)
$N^{u}_{\delta_{cs}}$	-.0021(-25.33)	.65(1.63)(2.56)(.43)	1.4(-.33) [.96;1.53]
$N^{w}_{\delta_{cs}}$	-1.875(2.94) [.10;.405]	-1.25(-.30) [.62;1.22]	-.45(-12.35) [-.35;.29]
$N^{\theta}_{\delta_{cs}}$	-.00164(.15)	.0263(.16)(1.17)	.046(.12)(.565)
LATERAL-DIRECTIONAL			
$\Delta(s)$	(1.62)(2.71) [-.025;.45]	(.73)(3.04) [.59;.81]	(.14)(3.14) [.42;1.35]
$N^{v}_{\delta_{as}}$	.60(1.72)(21.8)	-4.87(-3.85)(1.07)	2.1(.51)(12.13)
$N^{\phi}_{\delta_{as}}$	.403(.063)(1.74)	.388 [.92;1.02]	.4 [.59;1.10]
$N^{\psi}_{\delta_{as}}$	$\frac{.043}{(0)}$ (.90) [-.50;.95]	$\frac{.052}{(0)}$ (1.18) [-.46;1.10]	$\frac{.0685}{(0)}$ (.73) [-.17;1.18]
$N^{v}_{\delta_{rp}}$	-.278(-9.50)(.0045)	-18.69(-.091)(3.97)	-54.8(.072)(4.1)
$N^{\phi}_{\delta_{rp}}$	.116 [.126;.25]	-.183(-2.47)(1.60)	-1.24(-.41)(1.12)
N^{ψ}_{rp}	$\frac{.281}{(0)}$ (2.39) [-.02;.46]	$\frac{.183}{(0)}$ (3.69) [.17;.56]	$\frac{.071}{(0)}$ (1.4)(.22)

TABLE I-3b

TRANSFER FUNCTIONS--PITCH ATTITUDE/ ROLL RATE COMMAND CONTROL SYSTEM

	λ = 90 deg (0 kt)	λ = 50 deg (65 kt)	λ = 15 deg (100 kt)
LONGITUDINAL			
$\Delta(s)$	(.12)(.17) [.74;4.29]	(.16)(.50) [.72;4.45]	(.23)(.55) [.76;4.1]
$N^{u}_{\delta_{es}}$	$\frac{[.7;4.0]}{[.7;2.0]}$ {-.18(.12) [-.012;8.84]}	$\frac{[.7;4.0]}{[.7;2.0]}$ {-.447(.48) [.03;5.86]}	$\frac{[.7;4.0]}{[.7;2.0]}$ {.185(-69.06) [.73;.78]}
$N^{w}_{\delta_{es}}$	$\frac{[.7;4.0]}{[.7;2.0]}$ {-.201(.78) [-.53;.79]}	$\frac{[.7;4.0]}{[.7;2.0]}$ {41.54 [.38;.25]}	$\frac{[.7;4.0]}{[.7;2.0]}$ {.766(83.55) [.52;.20]}
$N^{\theta}_{\delta_{es}}$	$\frac{[.7;4.0]}{[.7;2.0]}$ {.437(.12)(.14)}	$\frac{[.7;4.0]}{[.7;2.0]}$ {.414(.17)(.58)}	$\frac{[.7;4.0]}{[.7;2.0]}$ {.377(.24)(.58)}
$N^{u}_{\delta_{cs}}$	-.0044(-9.14)	.65(.51) [.76;4.41]	1.4(.54) [.63;4.02]
$N^{w}_{\delta_{cs}}$	-1.875(.17) [.74;4.29]	-1.25(.26) [.49;4.30]	-.45(.49) [.87;5.43]
$N^{\theta}_{\delta_{cs}}$	-.00164(.15)	.0263(.16)(1.17)	.046(.12)(.565)
LATERAL-DIRECTIONAL*			
$\Delta(s)$	(.17)(1.67)(2.60) [.52;2.15]	(.48) [.48;2.38] [.97;1.70]	(.52) [.44;2.53] [.83;1.49]
$N^{v}_{\delta_{as}}$	$\frac{(2)}{(0)}$ { .60(22.19) [1.0;1.96] }	$\frac{(2)}{(0)}$ { -5.07(1.83)(-4.10)(.062)}	$\frac{(2)}{(0)}$ { 2.13(14.71)(.11)(.75)}
$N^{\phi}_{\delta_{as}}$	$\frac{(2)}{(0)}$ { .403(1.83)(2.16)(.060)}	$\frac{(2)}{(0)}$ { .385(.73) [.89;1.48]}	$\frac{(2)}{(0)}$ { .401(.55) [.51;1.61] }
$N^{\psi}_{\delta_{as}}$	$\frac{(2)}{(0)}$ { .043(.92) [-.49;.94] }	$\frac{(2)}{(0)}$ { $\frac{.052}{(0)}$ (.50)(1.95)[-.46;1.90]}	$\frac{(2)}{(0)}$ { $\frac{.068}{(0)}$ (.50)(.82) [-.14;1.91]}
$N^{v}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ { -1.04(-.71)(-8.89)(0) }	-28.67(.50) [.83;2.31]	-24.39(.50) [.78;2.19]
$N^{\phi}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ { .433(0) [.43;.27] }	-.273(1.66)(-2.42)(.50)	-.186(.50)(1.76)(-2.41)
$N^{\psi}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ { 1.05(.165) [.51;2.20] }	$\frac{.273}{(0)}$ (.50)(.55) [.75;2.22]	$\frac{.11}{(0)}$ (.50)(.44) [.81;2.77]

*ATC FOR λ = 15°,50°;HH FOR λ = 90°

TABLE I-3c

TRANSFER FUNCTIONS--ATTITUDE COMMAND AND AUTOMATIC λ CONTROL SYSTEMS

	λ = 90 deg (0 kt)	λ = 50 deg (65 kt)	λ = 15 deg (100 kt)
LONGITUDINAL			
$\Delta(s)$	(.12)(.17) [.74;4.29]	(.16)(.50) [.72;4.45]	(.23)(.55) [.76;4.1]
$N^{u}_{\delta_{es}}$	$\frac{[.7;4.0]}{[.7;2.0]}$ {-.18(.12) [-.012;8.84]}	$\frac{[.7;4.0]}{[.7;2.0]}$ {-.447(.48) [.03;5.86]}	$\frac{[.7;4.0]}{[.7;2.0]}$ {.185(-69.06) [.73;.78]}
$N^{w}_{\delta_{es}}$	$\frac{[.7;4.0]}{[.7;2.0]}$ {-.201(.78) [-.53;.79]}	$\frac{[.7;4.0]}{[.7;2.0]}$ {41.54 [.38;.25]}	$\frac{[.7;4.0]}{[.7;2.0]}$ {.766(83.55) [.52;.20]}
$N^{\theta}_{\delta_{es}}$	$\frac{[.7;4.0]}{[.7;2.0]}$ {.437(.12)(.14)}	$\frac{[.7;4.0]}{[.7;2.0]}$ {.414(.17)(.58)}	$\frac{[.7;4.0]}{[.7;2.0]}$ {.377(.24)(.58)}
$N^{u}_{\delta_{cs}}$	-.0044(-9.14)	.65(.51) [.76;4.41]	1.4(.54) [.63;4.02]
$N^{w}_{\delta_{cs}}$	-1.875(.17) [.74;4.29]	-1.25(.26) [.49;4.30]	-.45(.49) [.87;5.43]
$N^{\theta}_{\delta_{cs}}$	-.00164(.15)	.0263(.16)(1.17)	.046(.12)(.565)
LATERAL-DIRECTIONAL*			
$\Delta(s)$	(.16)(1.70)(2.48) [.30;2.20]	(.49) [.31;2.44] [.96;1.63]	(.52) [30;2.66] [.74;1.41]
$N^{v}_{\delta_{as}}$	1.45(22.19) [1.0;1.96]	-12.2(-4.1)(1.83)(.062)	5.14(14.71)(.11)(.75)
$N^{\phi}_{\delta_{as}}$	.97(1.83)(2.16)(.060)	.928(.73) [.89;1.48]	.967(.55) [.51;1.61]
$N^{\psi}_{\delta_{as}}$	.104(.92) [-.49;.94]	$\frac{.126}{(0)}$ (.50)(1.95) [-.46;1.90]	$\frac{.165}{(0)}$ (.50)(.82) [-.14;1.91]
$N^{v}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ {-1.04(-.59)(-10.6)(0)}	-28.67(.50) [.60;2.31]	-24.4(.50) [.56;2.19]
$N^{\phi}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ {.433(0) [.43;.27]}	-.273(1.66)(-2.42)(.50)	-.186(.50)(1.76)(-2.41)
$N^{\psi}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ {1.05(.16) [.29;2.22]}	$\frac{.273}{(0)}$ (.50)(.51) [.49;2.30]	$\frac{.106}{(0)}$ (.50)(.43) [.57;2.80]

*ATC FOR λ = 15°, 50°, HH FOR λ = 90°

TABLE I-3d

TRANSFER FUNCTIONS--DECOUPLED VELOCITY CONTROL SYSTEM

	λ = 90 deg (0 kt)	λ = 50 deg (65 kt)	λ = 15 deg (100 kt)
LONGITUDINAL			
$\Delta(s)$	[.90;3.54] [.96;.58]	(1.45)(.43) [.86;3.42]	(2.04)(.83) [.88;2.47]
$N^{\dot{x}}_{\delta_{es}}$	.82(.90) [-.013;8.85]	2.04(1.30) [.07;6.38]	-.84(-8.84) [.93;4.40]
$N^{\dot{h}}_{\delta_{es}}$	.92(4.13)(-10.99)(-.033)	-4.27(-18.16)(.091)	-3.50(-6.29)(7.25)(.21)
$N^{\theta}_{\delta_{es}}$	1.99(.14)(.90)	1.89(1.03)(.27)	1.72 [.93;.61]
$N^{\dot{x}}_{\delta_{cs}}$	-.092 [-.018;8.9]	-.57(-1.66)(1.20)(13.30)	-3.00(-1.25) [.92;3.63]
$N^{\dot{h}}_{\delta_{cs}}$	3.39(.386) [.89;3.45]	2.26(.349) [.57;5.07]	-1.14(-12.16)(8.09)(.38)
$N^{\theta}_{\delta_{cs}}$	-.227(.14)	.61(.32)(.88)	1.04 [.95;.62]
$N^{\dot{x}}_{\lambda}$	$\frac{2.44}{(0)}$ (.89) [.73;4.12]	$\frac{4.18}{(0)}$ (1.33) [.70;4.06]	$\frac{2.09}{(0)}$ (4.02) [.78;3.58]
$N^{\dot{h}}_{\lambda}$	$\frac{-.93}{(0)}$ (-.12) [.91;4.81]	$\frac{1.53}{(0)}$ (-.13) [.58;5.07]	$\frac{5.60}{(0)}$ (.17) [.77;4.44]
N^{θ}_{λ}	$\frac{.348}{(0)}$ (-.36)(1.06)	$\frac{.39}{(0)}$ (-.33)(.90)	$\frac{.30}{(0)}$ (-1.35)(.66)
LATERAL-DIRECTIONAL			
$\Delta(s)$	(.16)(1.70)(2.48) [.30;2.20]	(.49) [.31;2.44] [.96;1.63]	(.52) [.30;2.66] [.74;1.41]
$N^{v}_{\delta_{as}}$	1.45(22.19) [1.0;1.96]	-12.2(-4.1)(1.83)(.062)	5.14(14.71)(.11)(.75)
$N^{\phi}_{\delta_{as}}$	.97(1.83)(2.16)(.060)	.928(.73) [.89;1.48]	.967(.55) [.51;1.61]
$N^{\psi}_{\delta_{as}}$	.104(.92) [-.49;.94]	$\frac{.126}{(0)}$ (.50)(1.95) [-.46;1.90]	$\frac{.165}{(0)}$ (.50)(.82) [-.14;1.91]
$N^{v}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ { -1.04(-.59)(-10.6)(0) }	-28.67(.50) [.60;2.31]	-24.4(.50) [.56;2.19]
$N^{\phi}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ { .433(0) [.43;.27] }	-.273(1.66)(-2.42)(.50)	-.186(.50)(1.76)(-2.41)
$N^{\psi}_{\delta_{rp}}$	$\frac{(1)}{(0)}$ { 1.05(.16) [.29;2.22] }	$\frac{.273}{(0)}$ (.50)(.51) [.49;2.30]	$\frac{.106}{(0)}$ (.50)(.43) [.57;2.80]

TABLE I-4

ELECTRONIC DISPLAY SYMBOL SENSITIVITIES*

DISPLAY FORMAT	ATTITUDE	POSITION		VELOCITY		CONTROL DIRECTORS
		VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL	
ED-1	Artificial horizon and fixed indices (10° increments); one-to-one with real world. Tail of A/C symbol: one-to-one with real world.	Altitude error diamond and fixed indices (50 ft increments): .015 cm/ft ±1.5 cm full scale Landing pad symbol: Diameter = 1 cm @ 875 ft AGL Diameter = 2 cm @ 100 ft AGL	Fixed A/C symbol and moving landing pad/approach course symbol: $\frac{6}{600+\hat{X}_e}\left(\frac{cm}{ft}\right)$ where $\hat{X}_e$ = range (ft)	None	None	None
ED-2	Same	Same	Same	Altitude rate error circle: $.15\ \frac{cm}{ft/sec}$ @ $\lambda = 90°$ $.03\ \frac{cm}{ft/sec}$ @ $\lambda = 0°$ ±1.5 cm full scale	Velocity vector/velocity command diamond: $.0296\ \frac{cm}{ft/sec}$ (approach mode) $.118\ \frac{cm}{ft/sec}$ (Hover mode) Velocity error circle: $.02\ \frac{cm}{ft/sec}$ ±1 cm full scale	None
ED-2+	Same	Same	Same	None	Same	VTAB: ±1.5 cm full scale
ED-3	Same	Same	Same	None	Same as ED-2 with no velocity command diamond	HBAR } ±1 cm VBAR } full scale VTAB ±1.5 cm full scale

*A symbol deflection of 1 cm is equivalent to 0.85 degree of arc at the pilot's eye.

TABLE I-5

CONTROL DIRECTOR LOGIC

		FULL SCALE SIGNAL				
DIRECTOR ELEMENT	VARIABLE	RATE AUGMENTATION	ATT/RATE AUGMENTATION	ATTITUDE AUGMENTATION	AUTO λ	DECOUPLED VELOCITY CONTROL
HBAR	$\epsilon_{\dot{X}_h}$	± 33 (ft/sec)	33	33	33	33
	θ_{wo}	± 37 (deg)	75	75	75	--
	q	±130 (deg/sec)	230	230	230	--
VBAR	$\epsilon_{\dot{Y}_h}$	± 42 (ft/sec)	42	42	42	42
	ϕ	± 20 (deg)	20	110	110	110
	p	± 67 (deg/sec)	38	296	296	296
VTAB	ϵ_z	±100 (ft)	100	100	100	100
	$\epsilon_{\dot{z}}$ ($\lambda = 0$) ↓	± 50 (ft/sec) ↓	50 ↓	50 ↓	50 ↓	250 ↓
	($\lambda = 90^\circ$)	± 10 (ft/sec)	10	10	10	50

APPENDIX II

CONTROL SYSTEM FREQUENCY RESPONSES

This appendix presents amplitude and phase frequency responses for the five control augmentation systems investigated in this experiment; in addition, time histories of the attitude responses for hover and 100 kt are given to provide additional information. The frequency responses correspond to the transfer functions listed in Appendix I, and are based on the identified aircraft characteristics (Appendix IV) and the feedback gains given in Section V. The attitude responses are for one-inch step inputs to facilitate correlation with some of the MIL-F-83300 requirements discussed in Section V. Since the longitudinal stick transfer functions for the pitch-attitude/roll-rate command system (ATT/RATE) are the same as for the attitude command system (ATT), and the lateral stick transfer functions for the decoupled velocity control system (DVC) are the same as for the attitude command system (ATT), these two sets of frequency responses are not repeated; similarly, the attitude command (ATT) and automatic duct rotation (AUTO) control system implementations are identical in all regards except duct rotation, and hence separate AUTO responses are not given. For all the frequency responses, the amplitude is indicated by a solid line and is referred to the ordinate at the left of the figure, while the phase is indicated by the square symbols and is referred to the ordinate at the right of the figure.

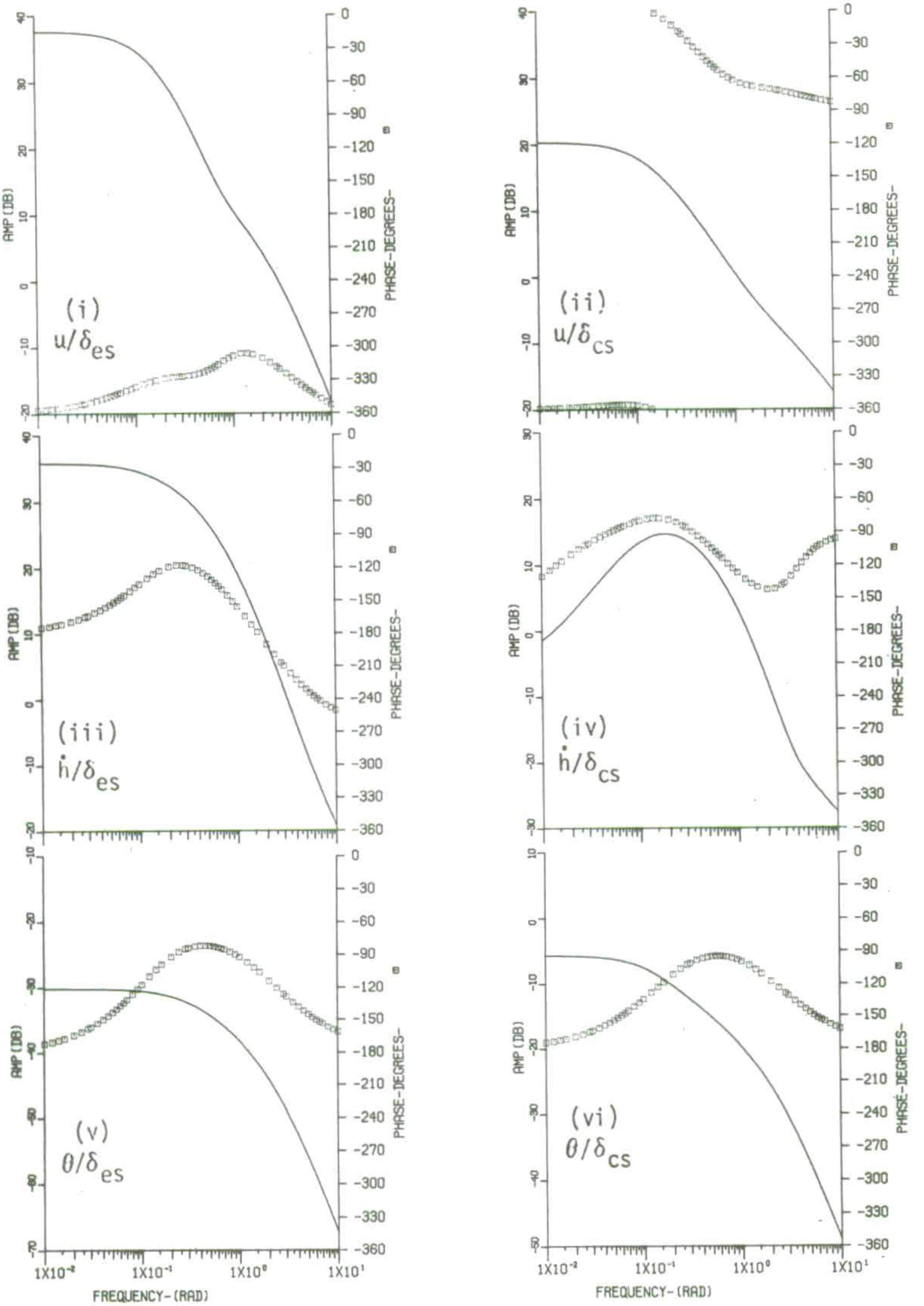


Figure II-1a LONGITUDINAL FREQUENCY RESPONSES FOR RATE AUGMENTATION SYSTEM AT 100 KT (λ = 15°)

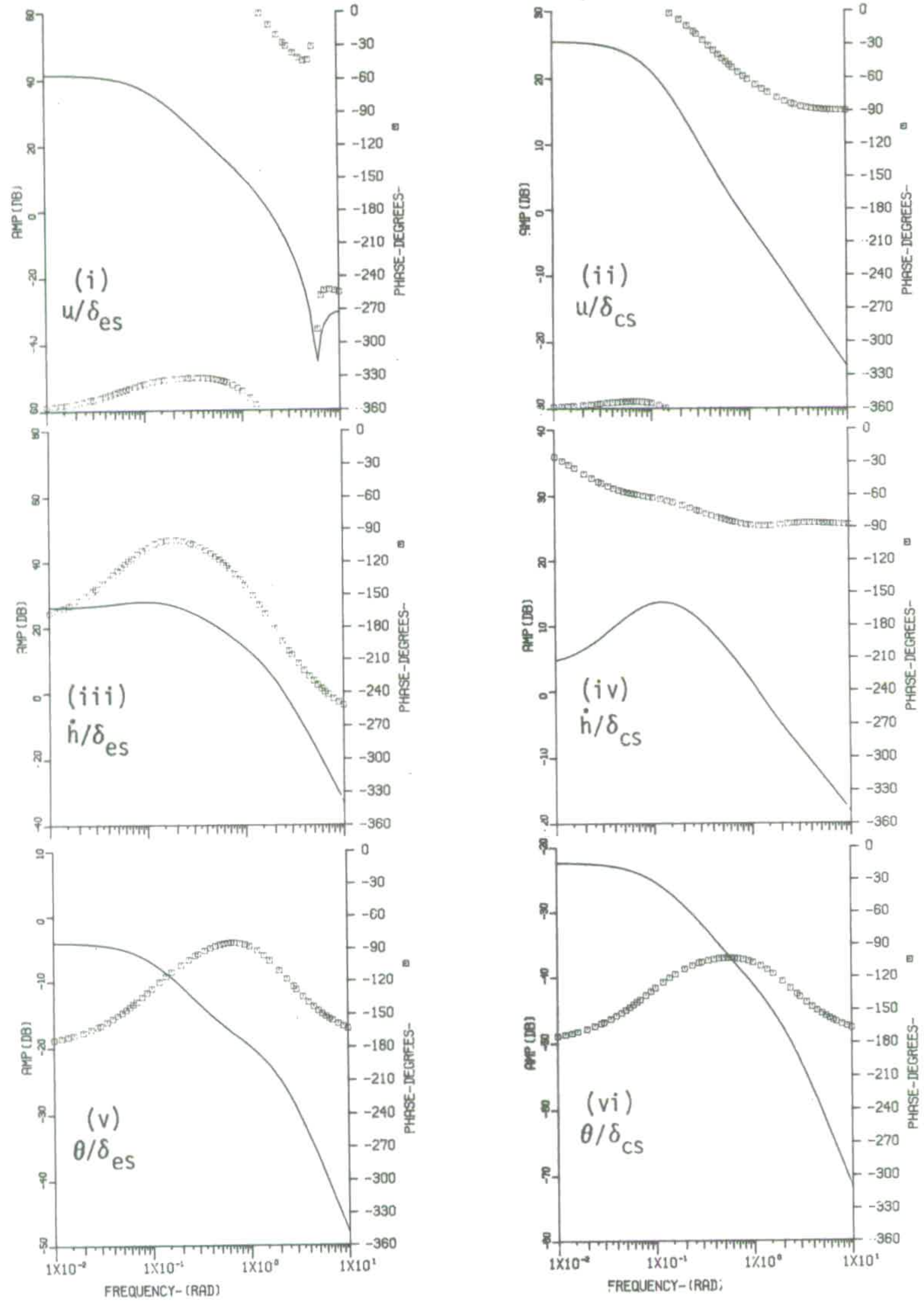


Figure II-1b LONGITUDINAL FREQUENCY RESPONSES FOR RATE AUGMENTATION SYSTEM AT 65 KT ($\lambda = 50°$)

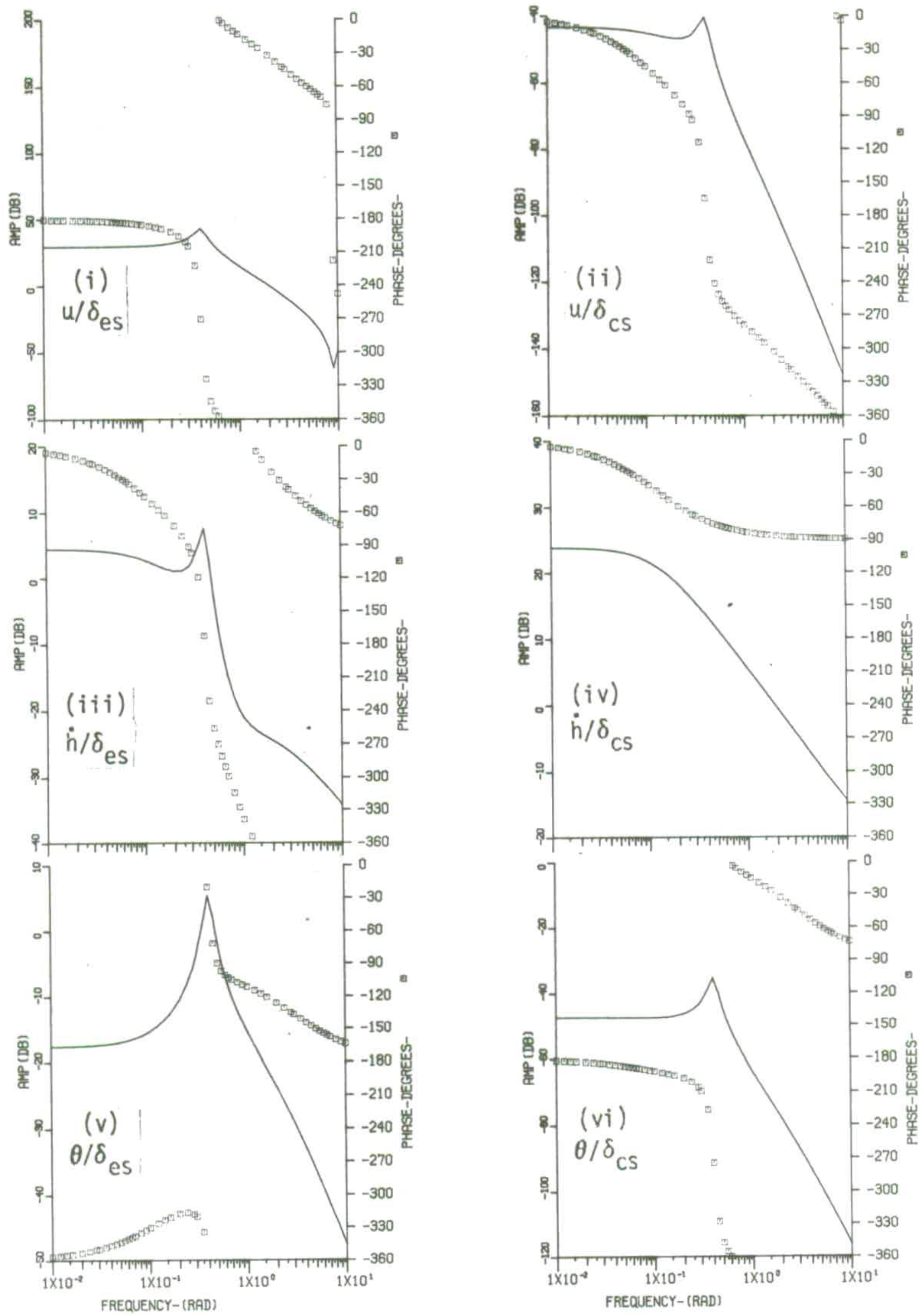


Figure II-1c LONGITUDINAL FREQUENCY RESPONSES FOR RATE AUGMENTATION SYSTEM AT 0 KT ($\lambda = 90°$)

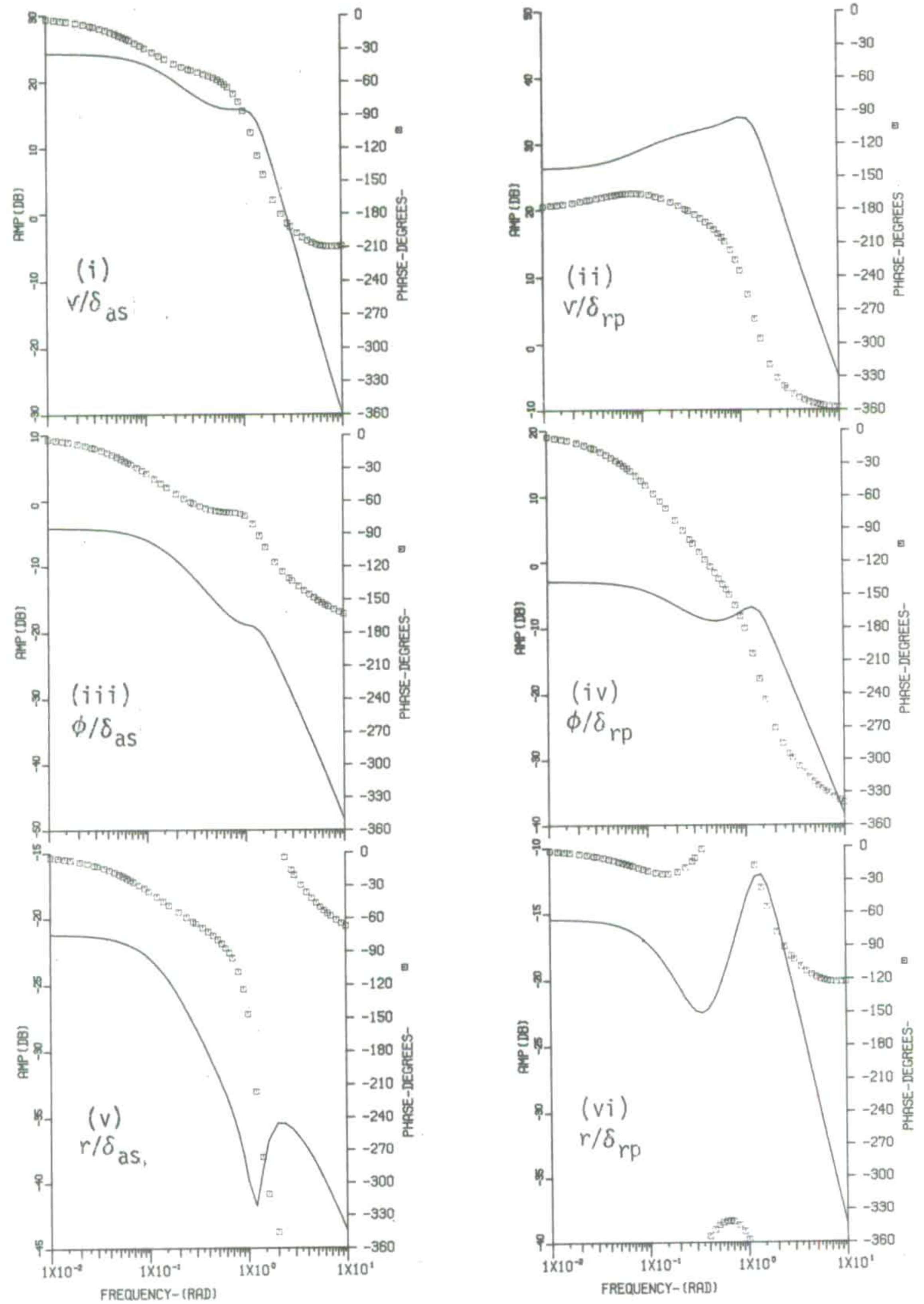


Figure II-2a LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR RATE AUGMENTATION SYSTEM AT 100 KT ($\lambda = 15°$)

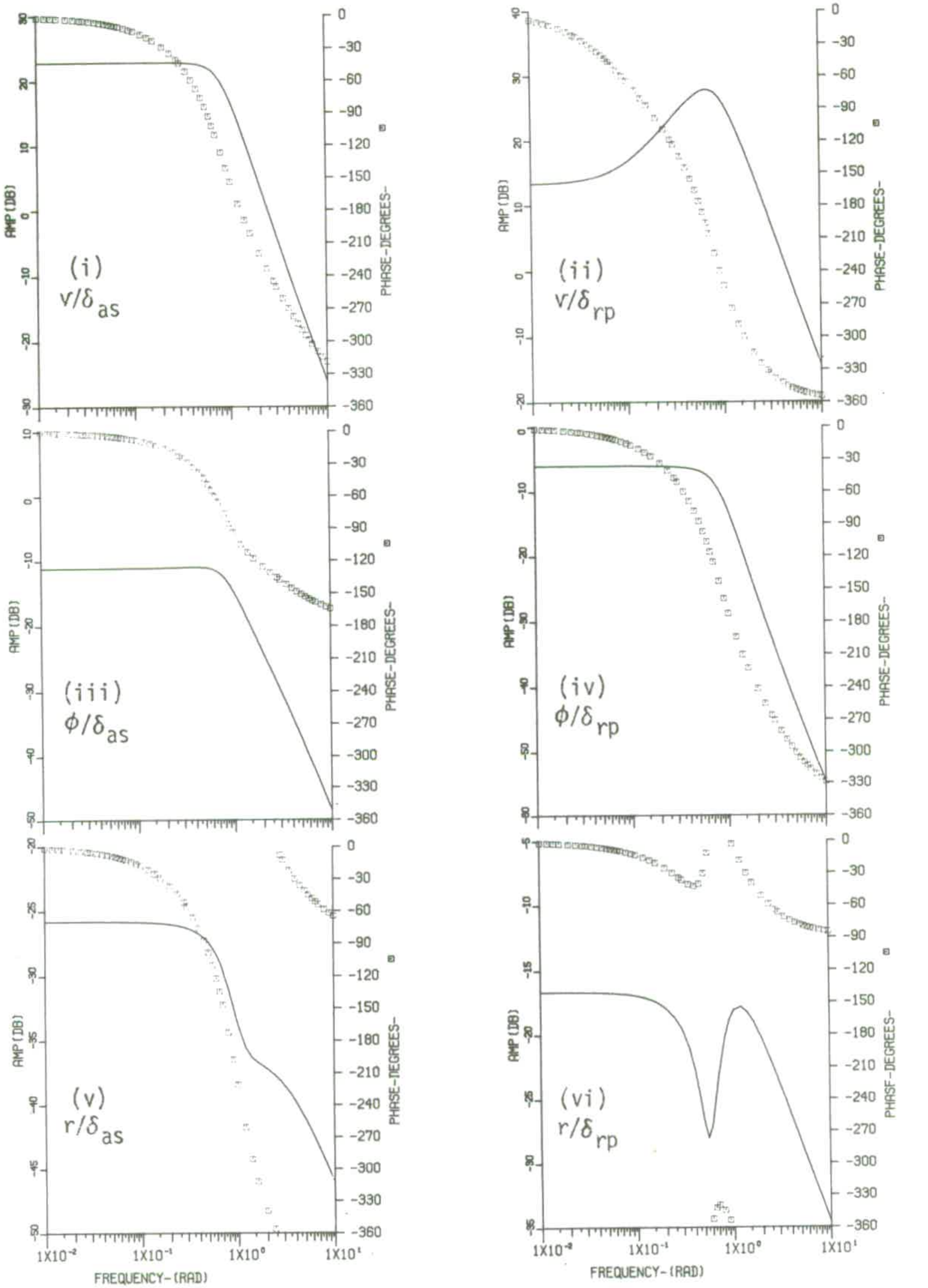


Figure II-2b LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR RATE AUGMENTATION SYSTEM AT 65 KT ($\lambda = 50°$)

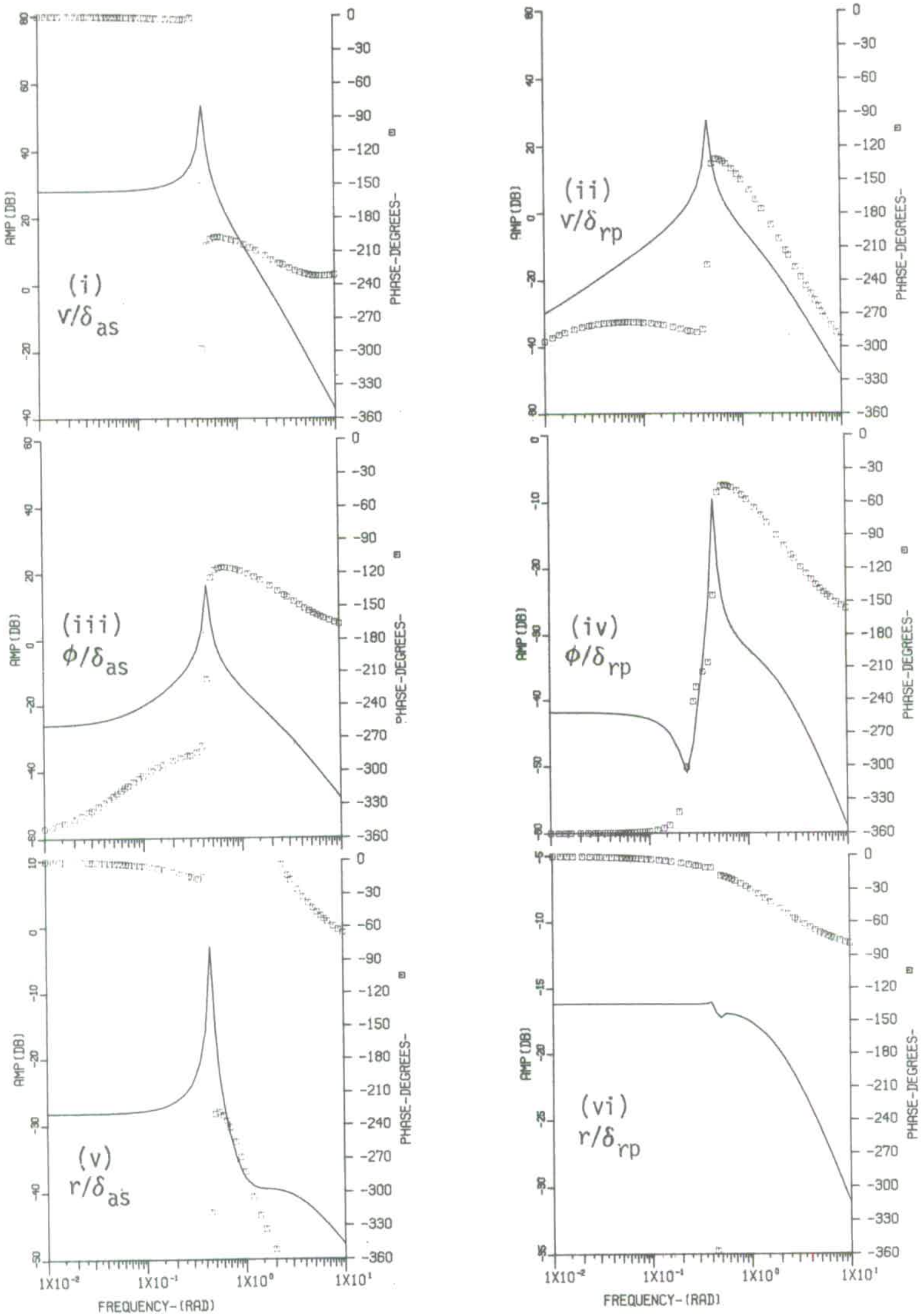


Figure II-2c LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR RATE AUGMENTATION SYSTEM AT 0 KT (λ = 90°)

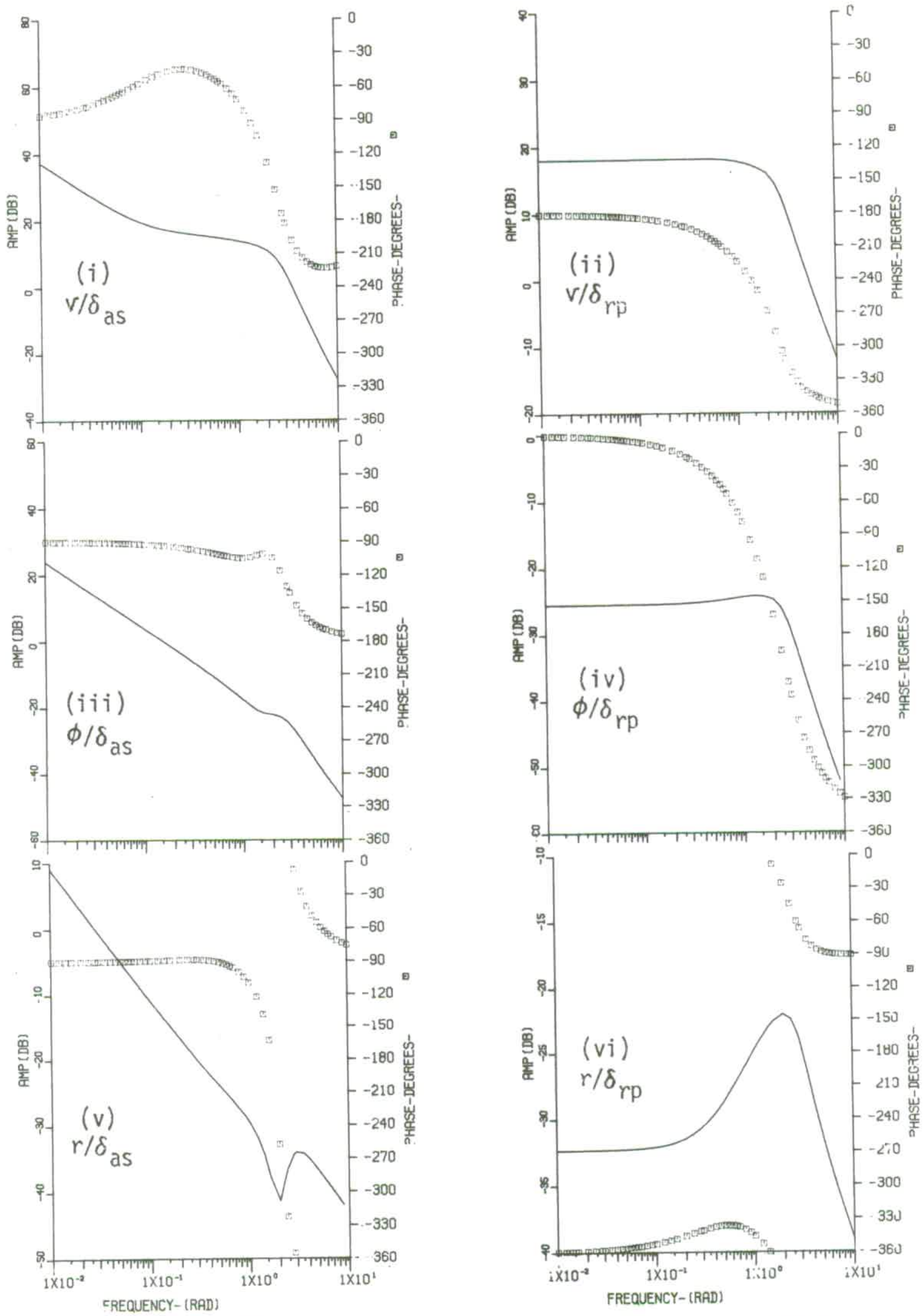


Figure II-3a LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR ATTITUDE/RATE COMMAND SYSTEM (ATC) AT 100 KT ($\lambda = 15°$)

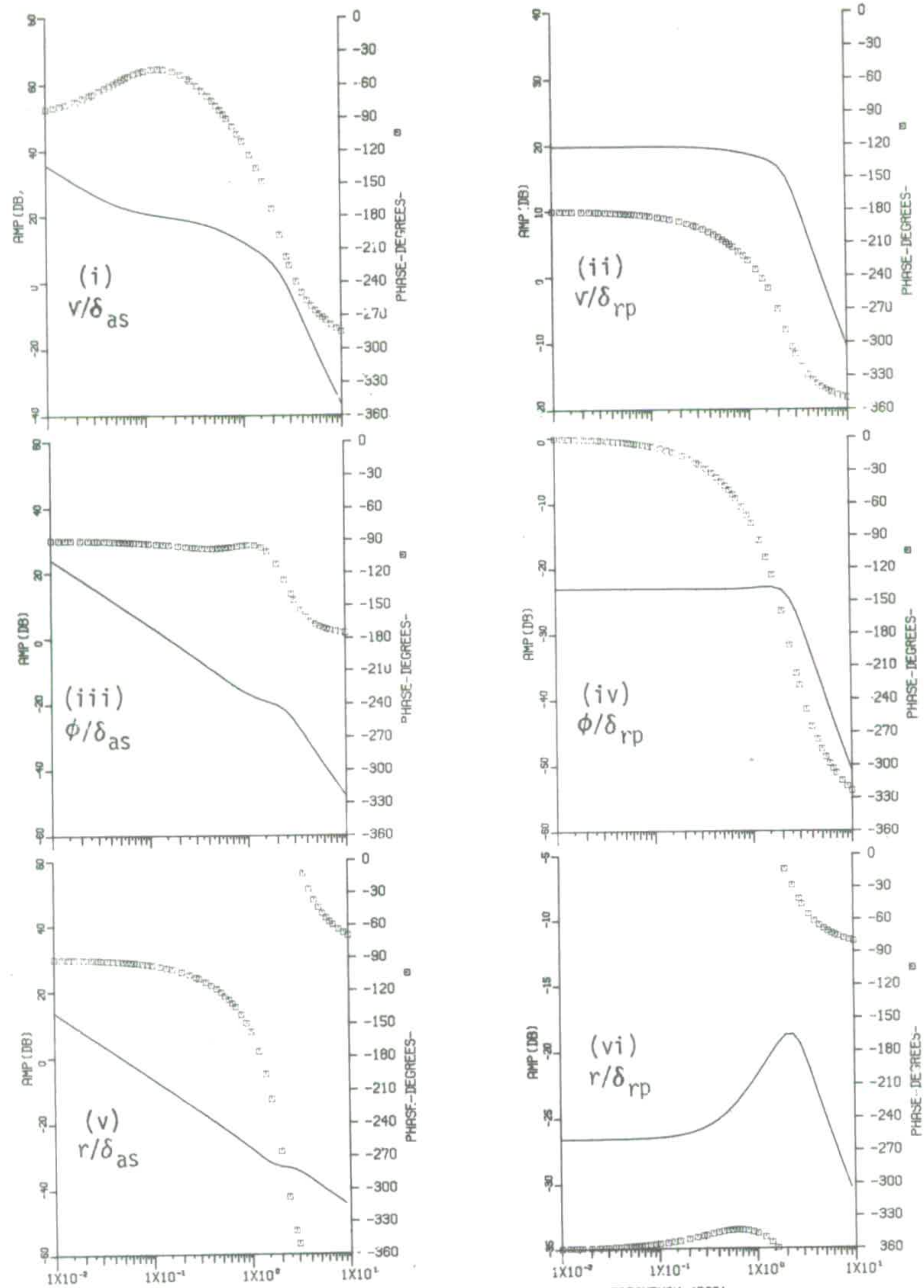


Figure II-3b LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR ATTITUDE/RATE COMMAND SYSTEM (ATC) AT 65 KT ($\lambda = 50°$)

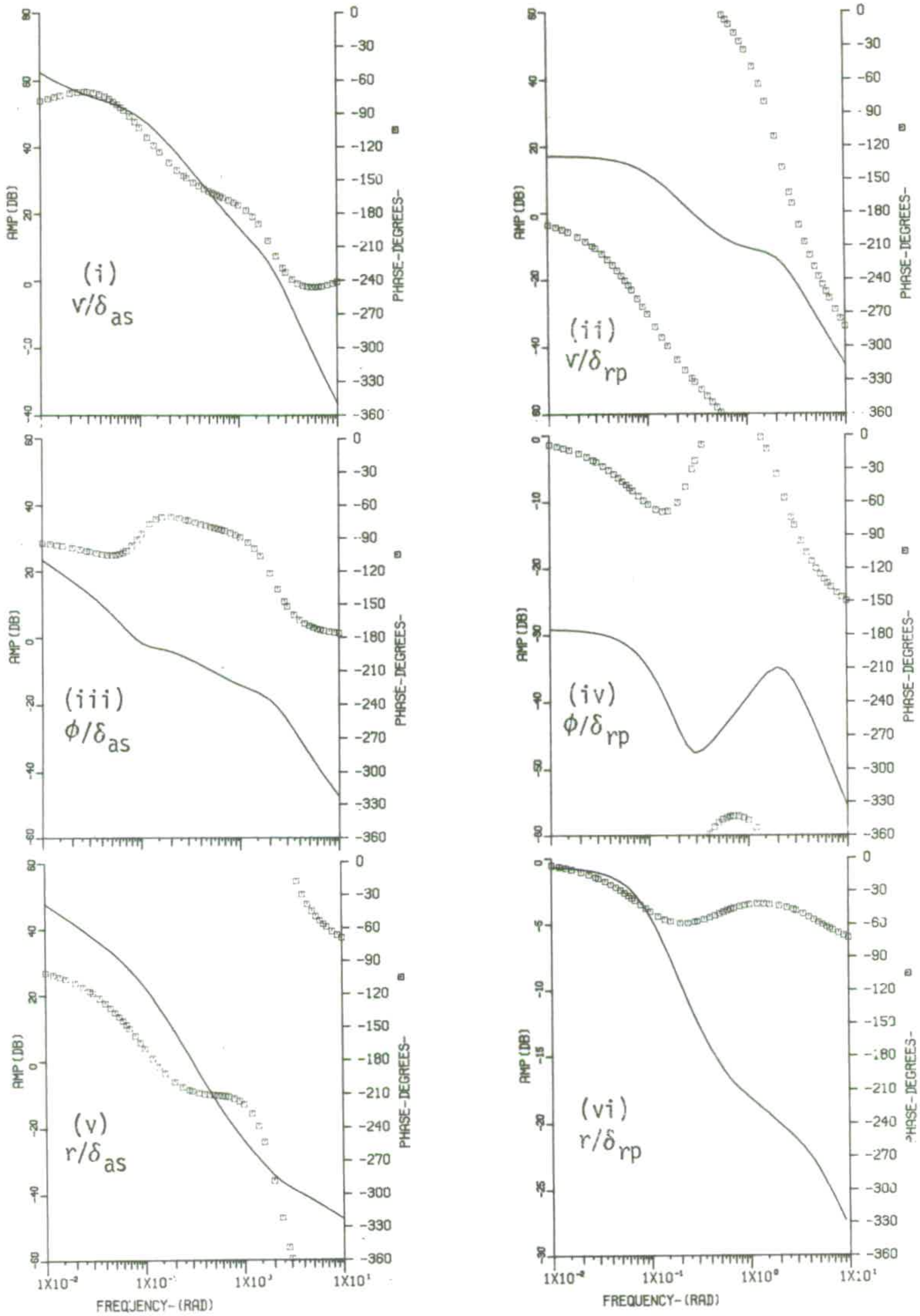


Figure II-3c LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR ATTITUDE/RATE COMMAND SYSTEM (ATC) AT 0 KT (λ = 90°)

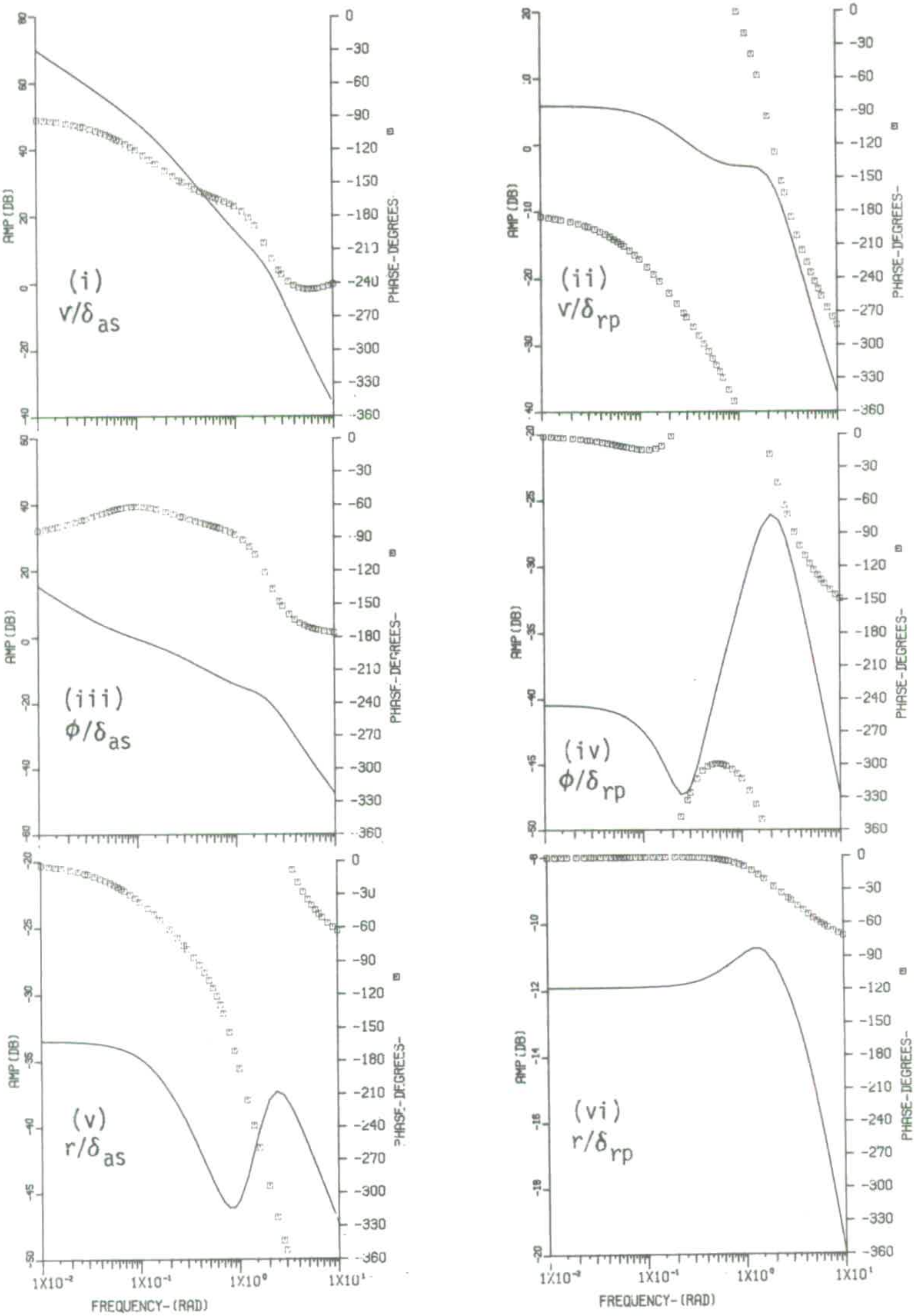


Figure II-3d LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR ATTITUDE/RATE COMMAND SYSTEM (HH) AT 0 KT ($\lambda = 90°$)

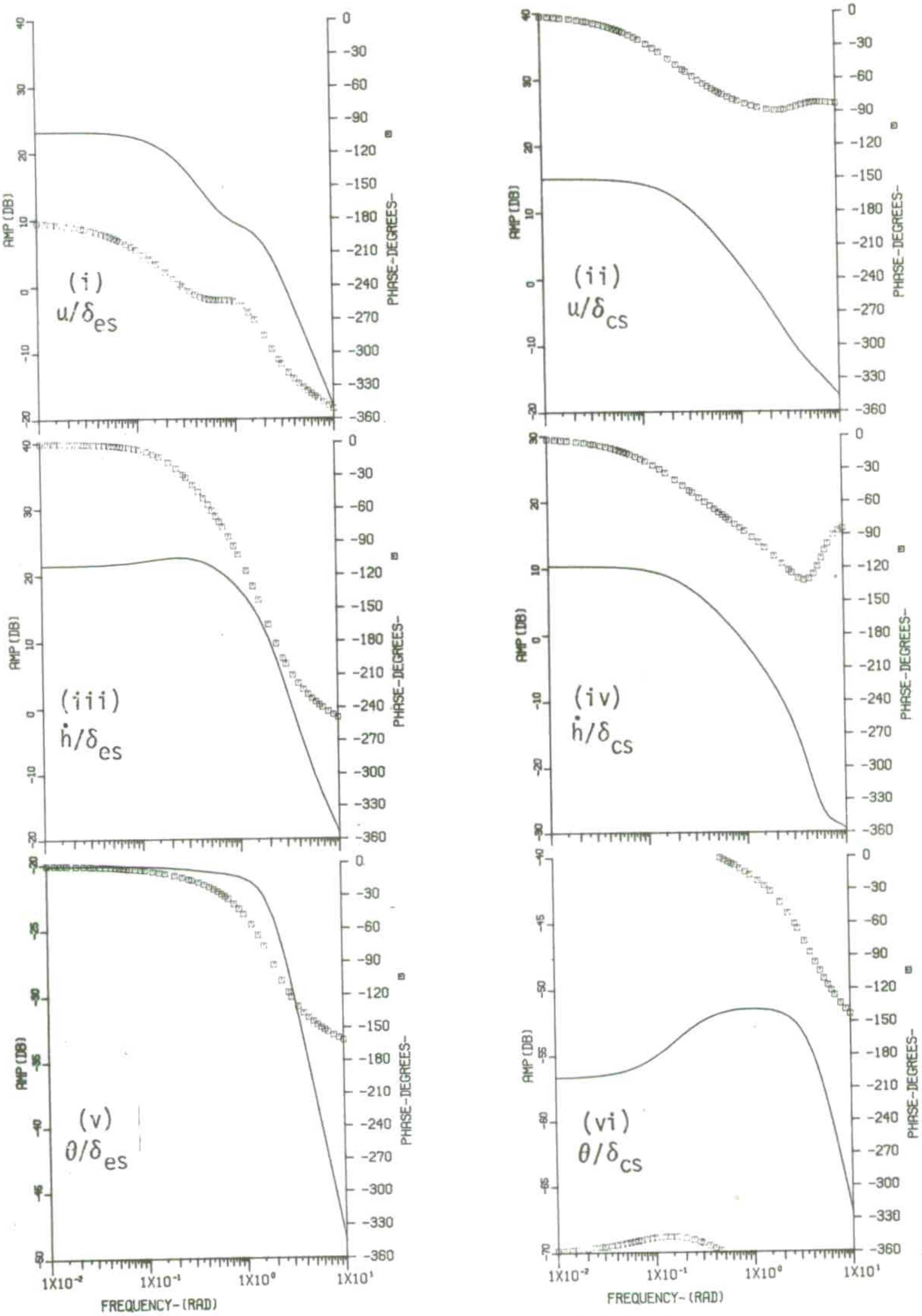


Figure II-4a LONGITUDINAL FREQUENCY RESPONSES FOR ATTITUDE/RATE, ATTITUDE COMMAND, AND AUTOMATIC λ SYSTEMS AT 100 KT ($\lambda = 15°$)

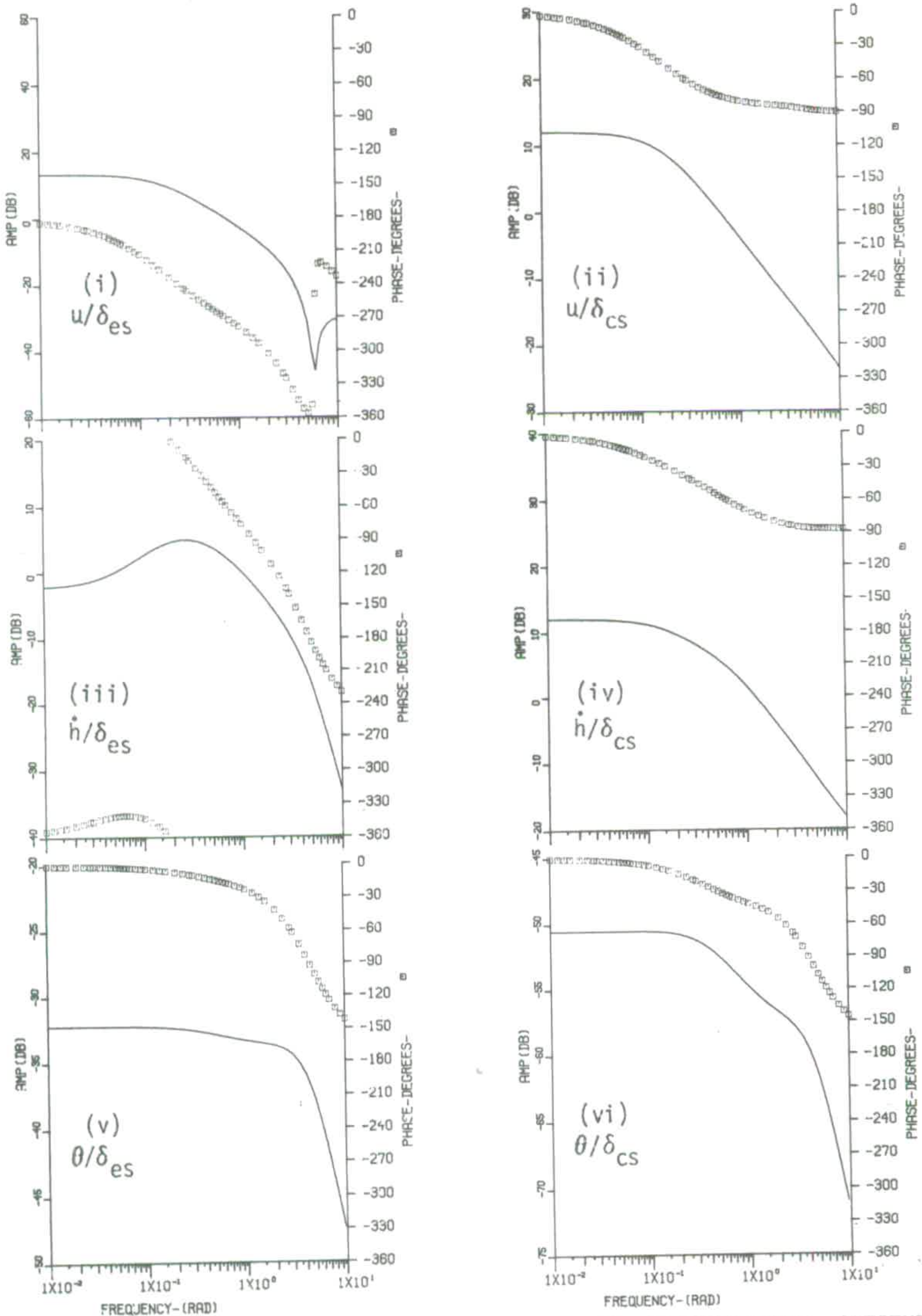


Figure II-4b LONGITUDINAL FREQUENCY RESPONSES FOR ATTITUDE/RATE, ATTITUDE COMMAND, AND AUTOMATIC λ SYSTEMS AT 65 KT (λ = 50°)

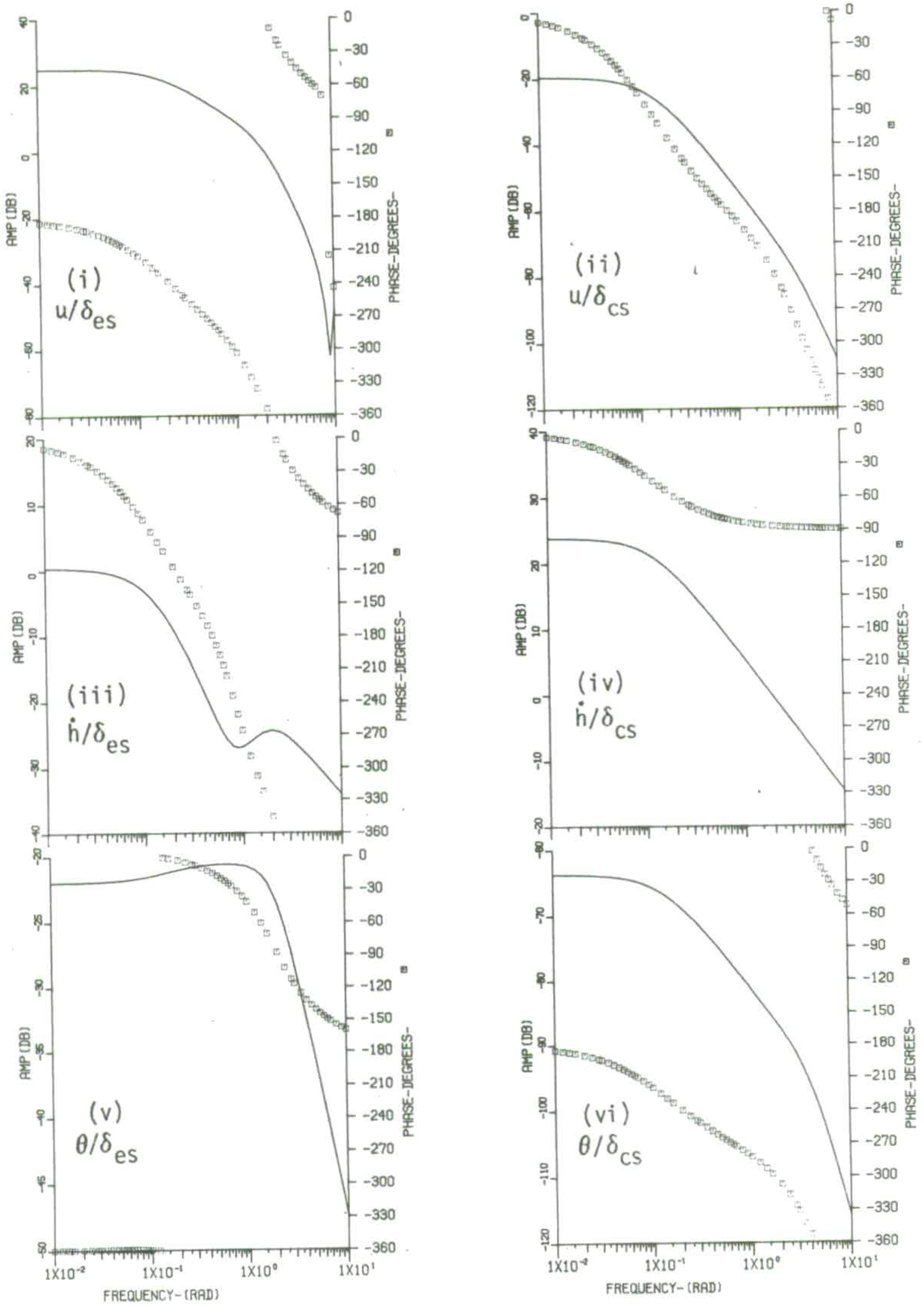


Figure II-4c LONGITUDINAL FREQUENCY RESPONSES FOR ATTITUDE/RATE, ATTITUDE COMMAND, AND AUTOMATIC λ SYSTEMS AT 0 KT (λ = 90°)

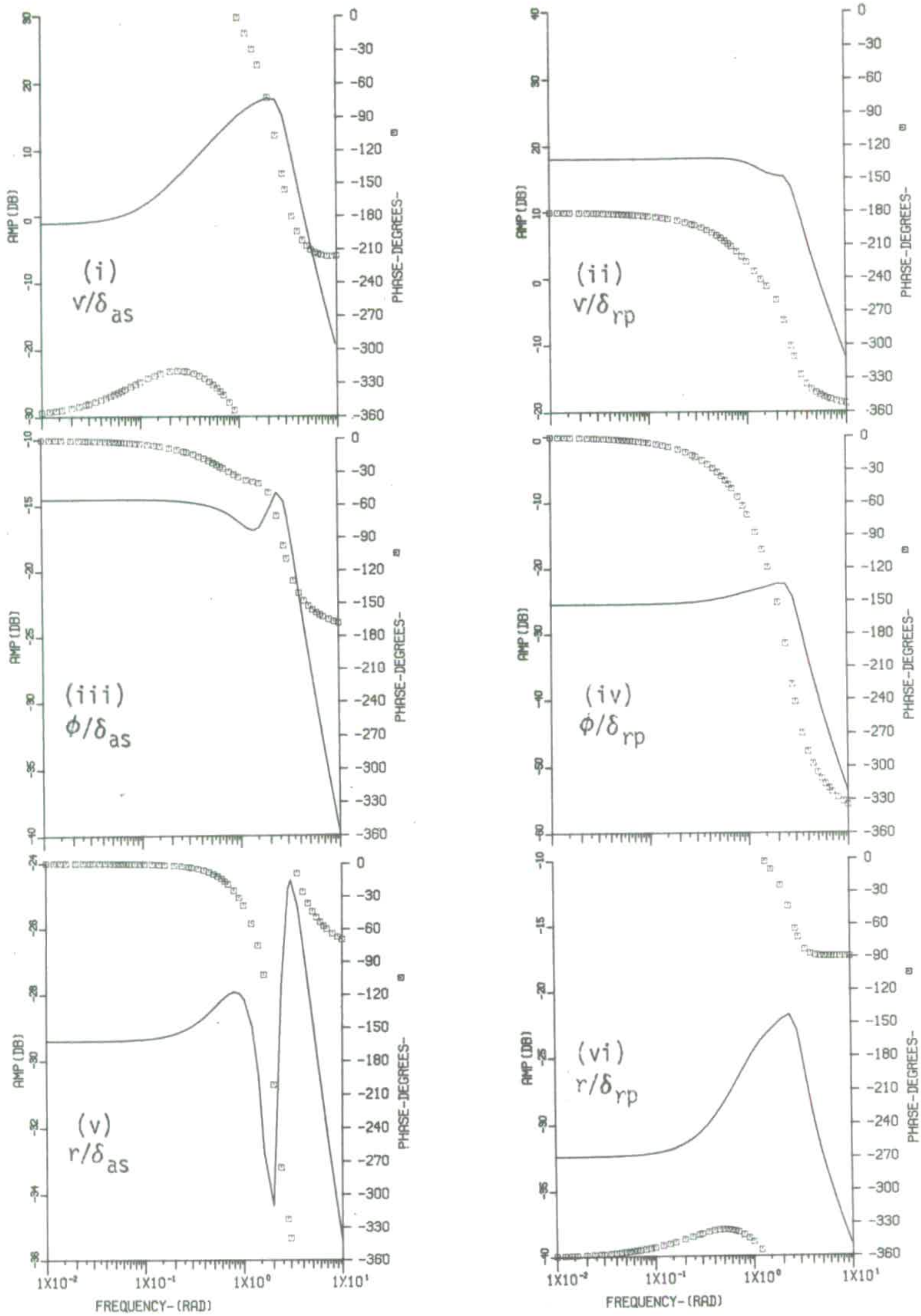


Figure II-5a LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR ATTITUDE COMMAND, AUTOMATIC λ, AND DECOUPLED VELOCITY CONTROL SYSTEMS (ATC) AT 100 KT (λ = 15°)

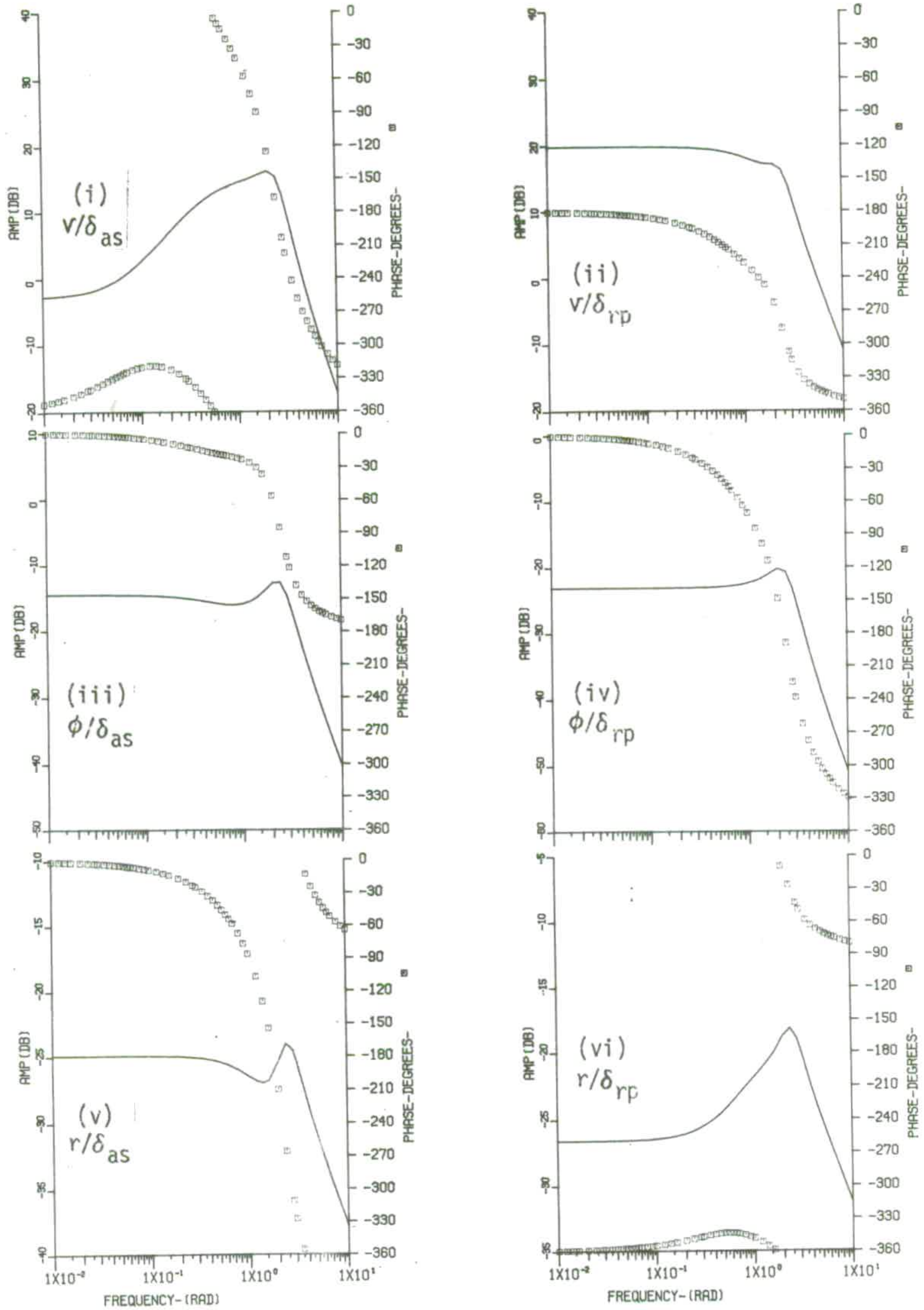


Figure II-5b LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR ATTITUDE COMMAND, AUTOMATIC λ, AND DECOUPLED VELOCITY CONTROL SYSTEMS (ATC) AT 65 KT (λ = 50°)

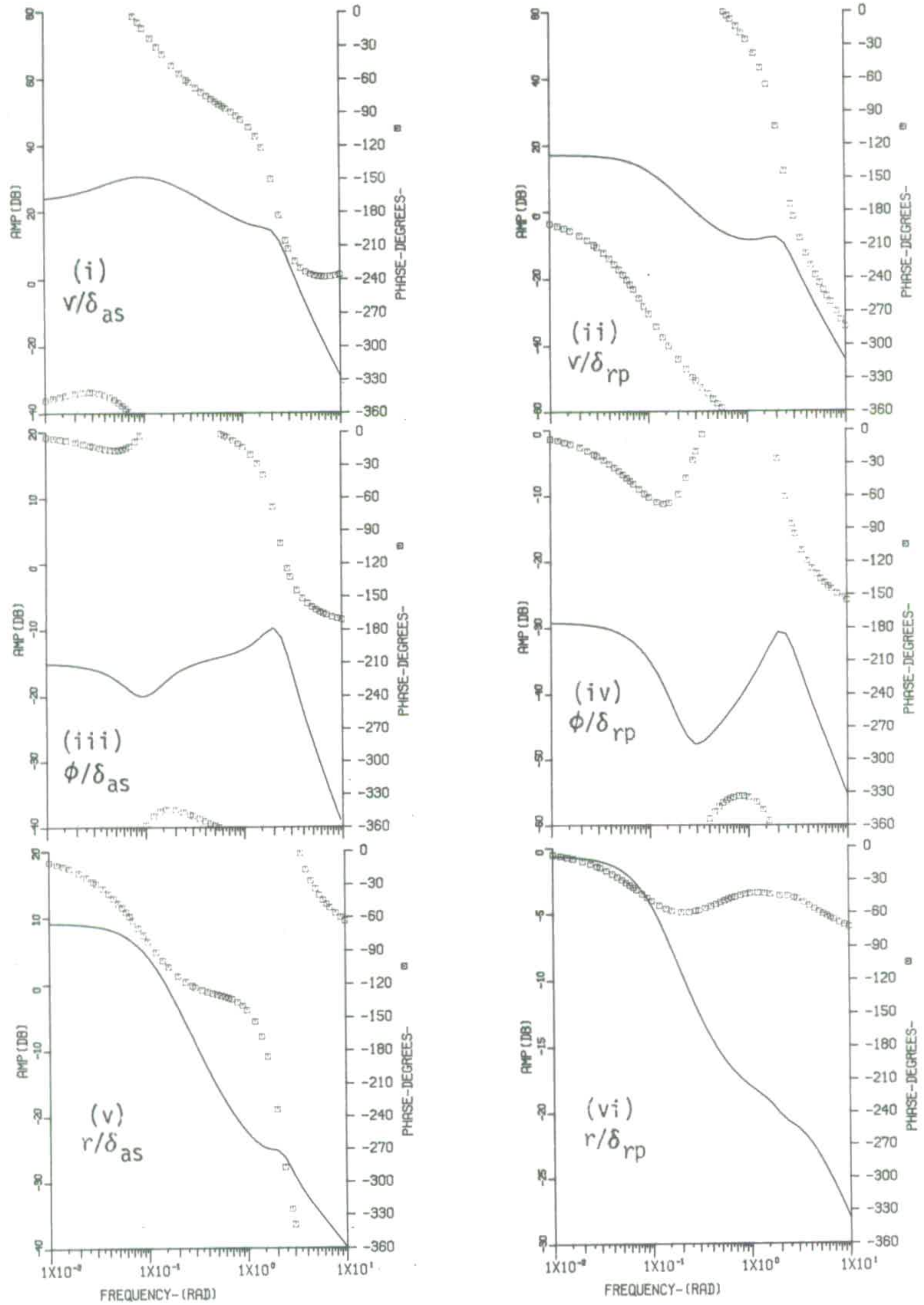


Figure II-5c LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR ATTITUDE COMMAND, AUTOMATIC λ, AND DECOUPLED VELOCITY CONTROL SYSTEMS (ATC) AT 0 KT (λ = 90°)

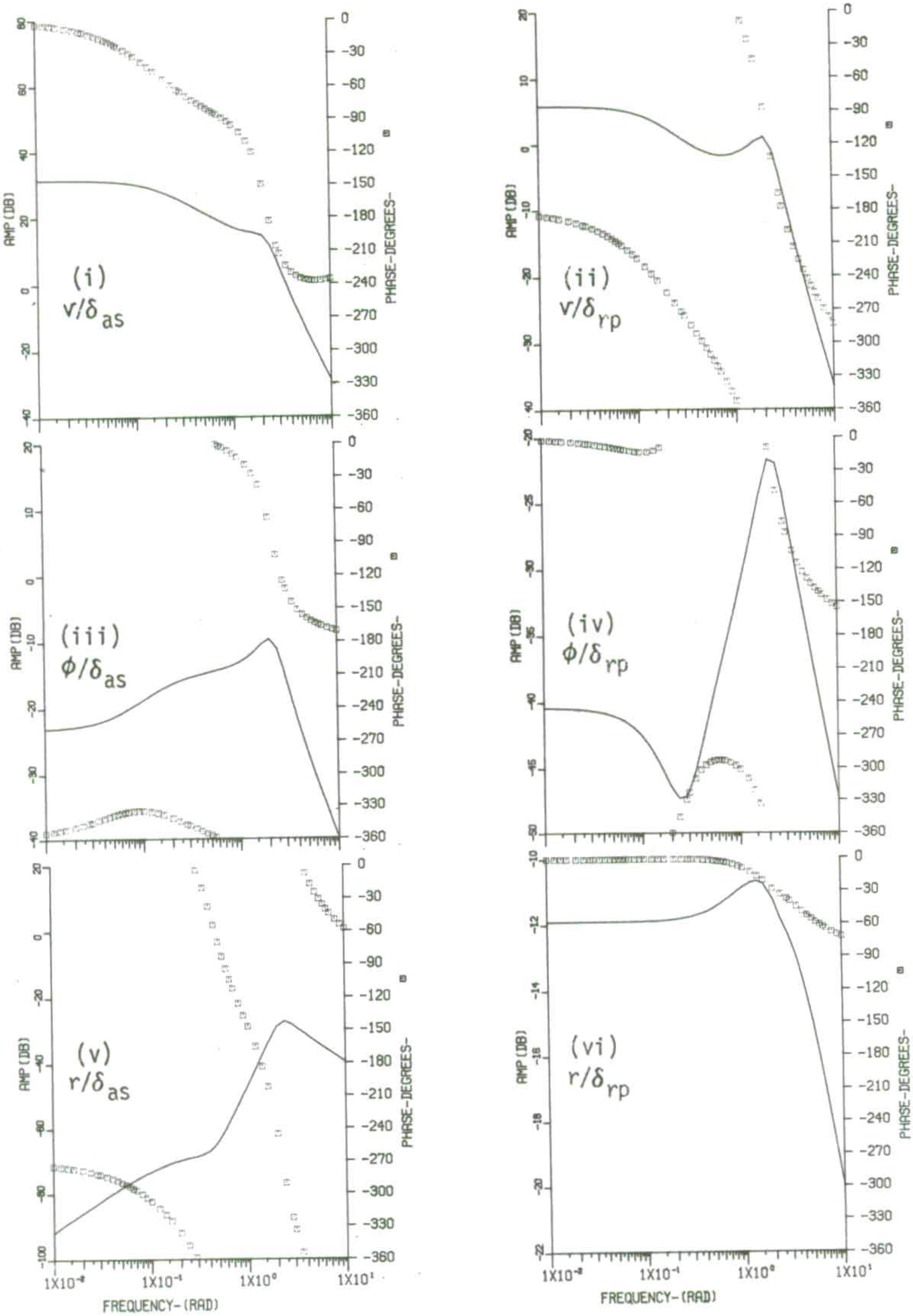


Figure II-5d LATERAL-DIRECTIONAL FREQUENCY RESPONSES FOR ATTITUDE COMMAND, AUTOMATIC λ, AND DECOUPLED VELOCITY CONTROL SYSTEMS (HH) AT 0 KT (λ = 90°)

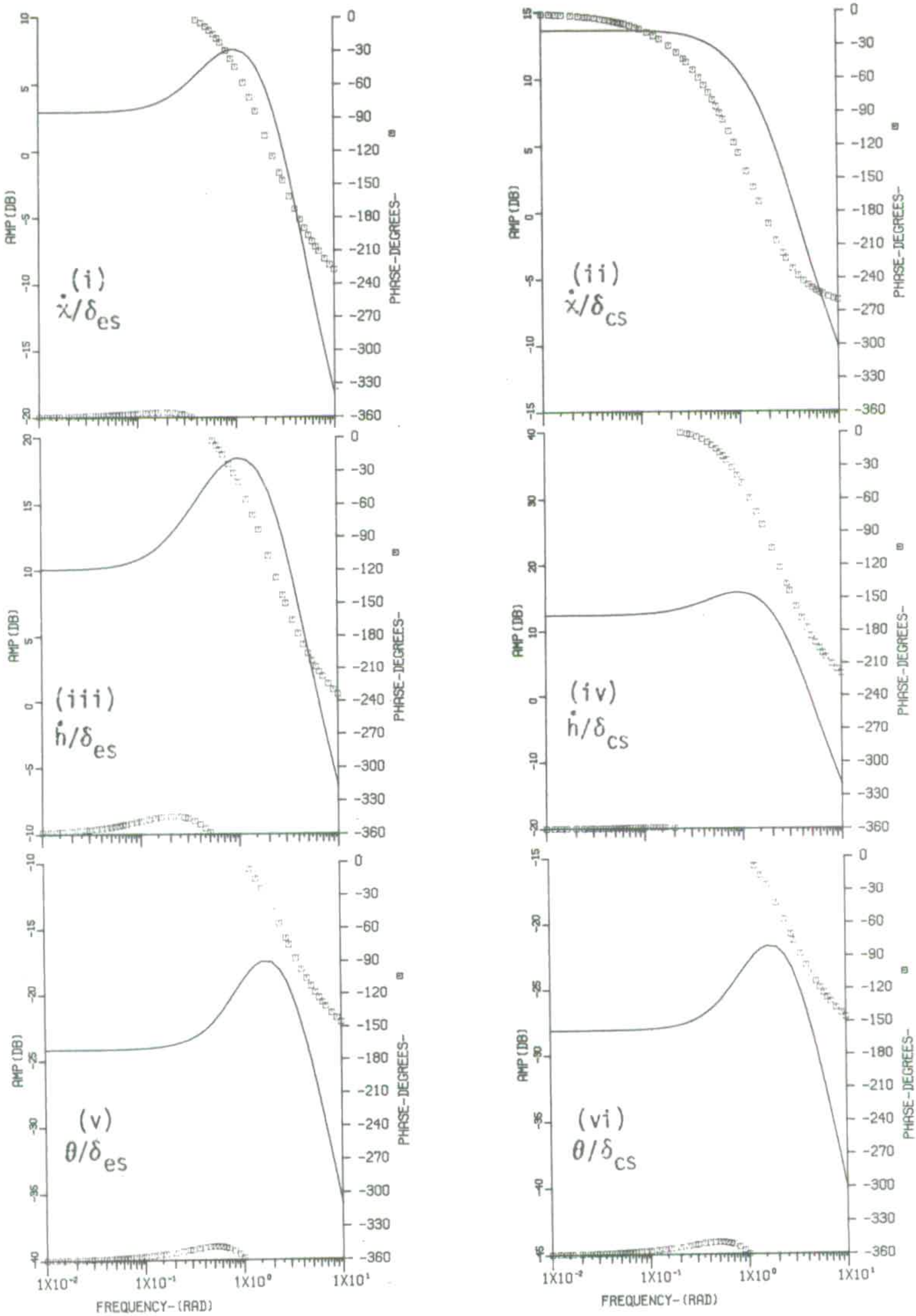


Figure II-6a LONGITUDINAL FREQUENCY RESPONSES FOR DECOUPLED VELOCITY CONTROL SYSTEM AT 100 KT (λ = 15°)

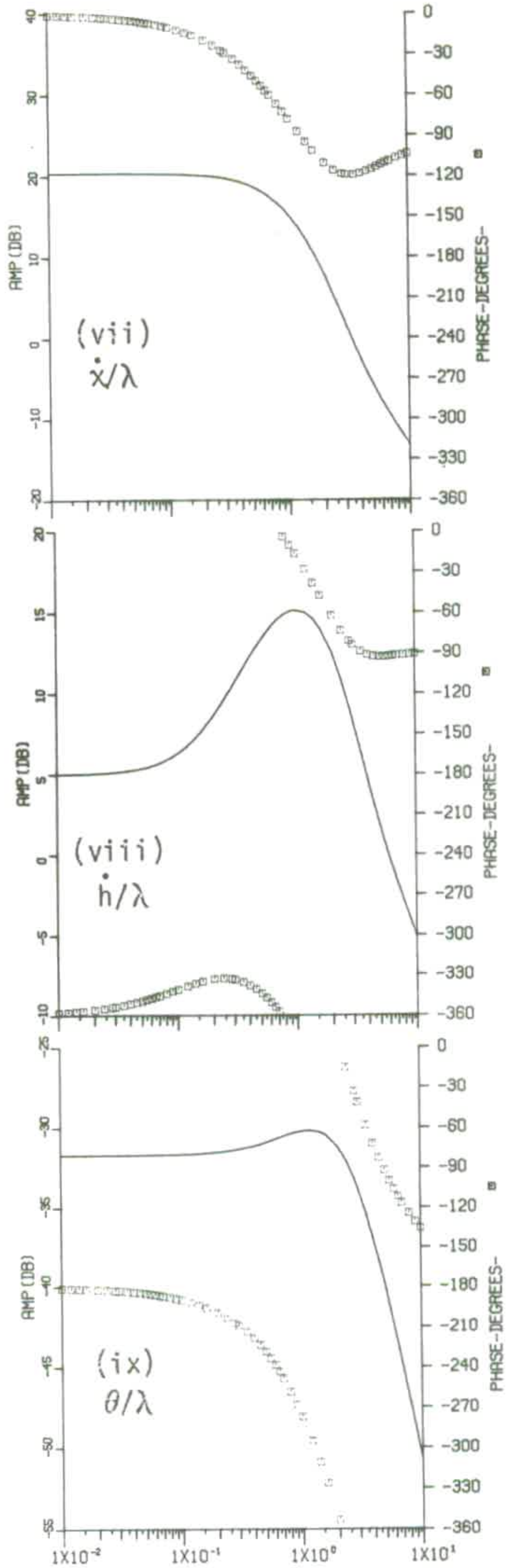


Figure II-6a (Cont.) LONGITUDINAL FREQUENCY RESPONSES FOR DECOUPLED VELOCITY CONTROL SYSTEM AT 100 KT (λ = 15°)

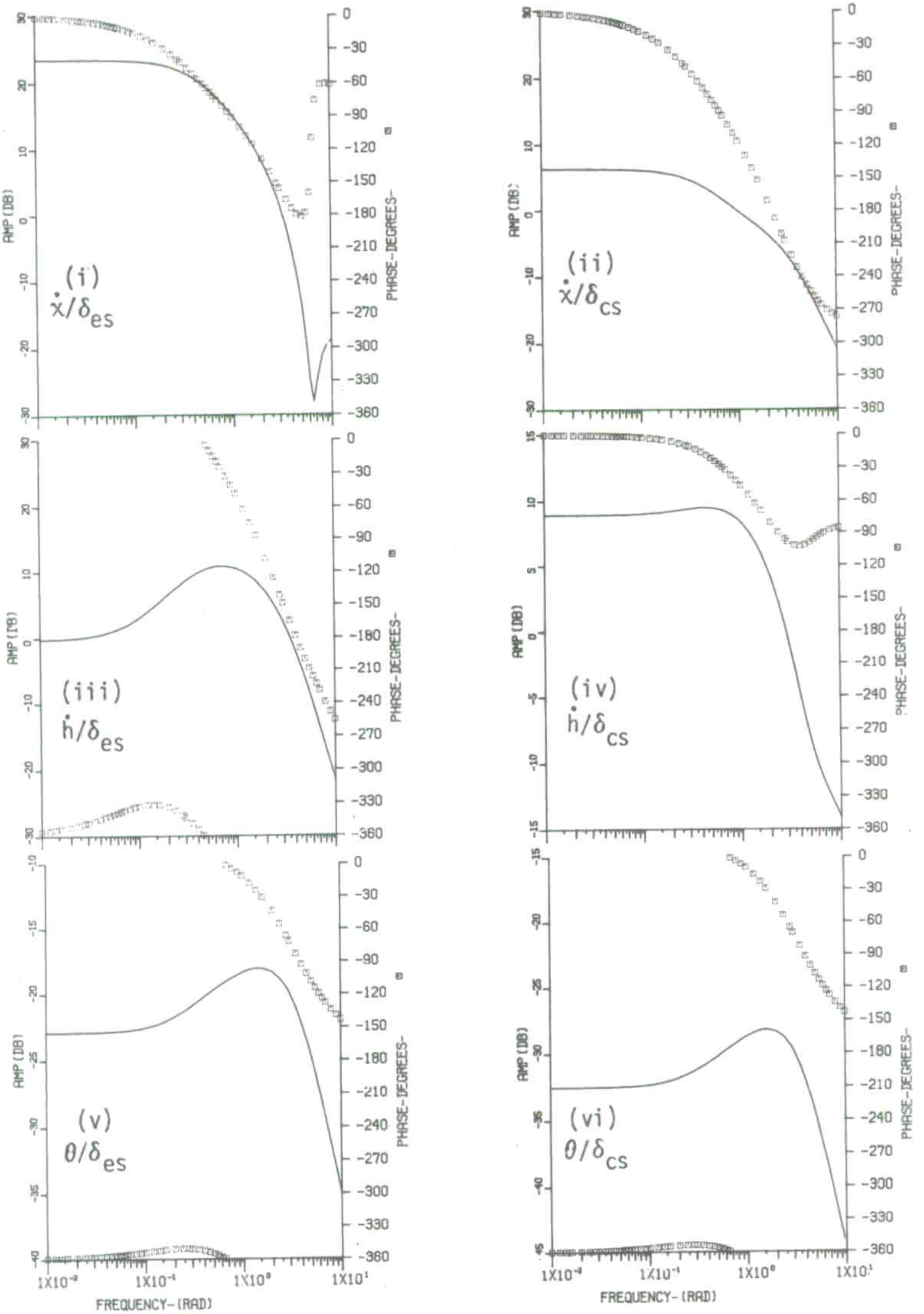


Figure II-6b LONGITUDINAL FREQUENCY RESPONSES FOR DECOUPLED VELOCITY CONTROL SYSTEM AT 65 KT ($\lambda = 50°$)

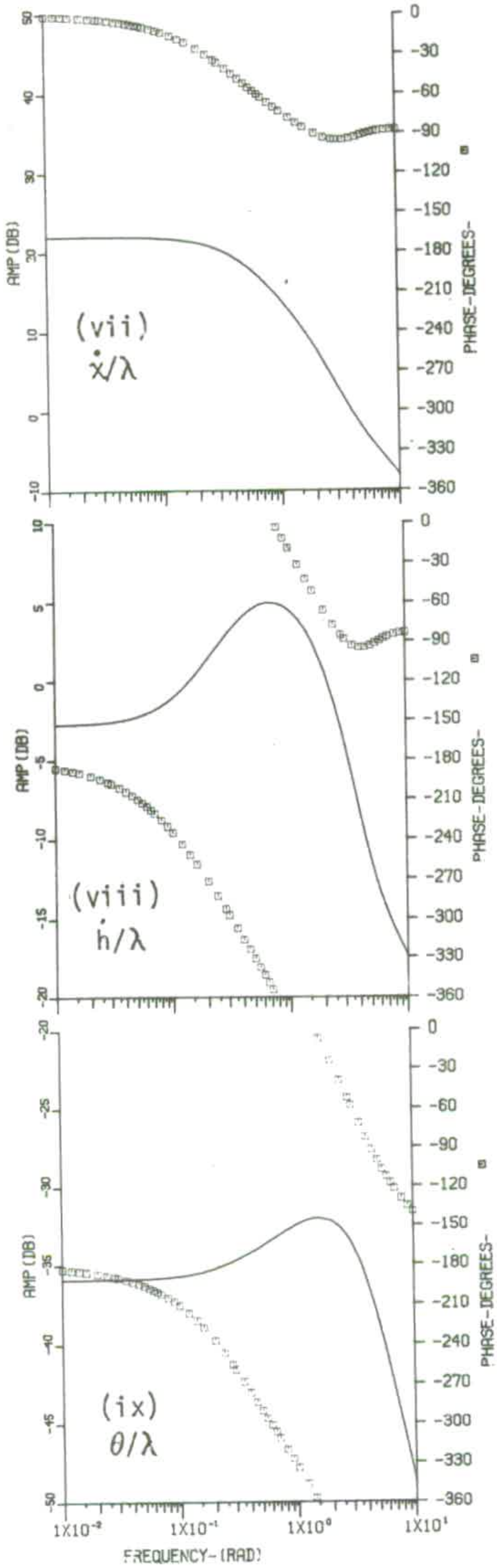


Figure II-6b (Cont.) LONGITUDINAL FREQUENCY RESPONSES FOR DECOUPLED VELOCITY CONTROL SYSTEM AT 65 KT (λ = 50°)

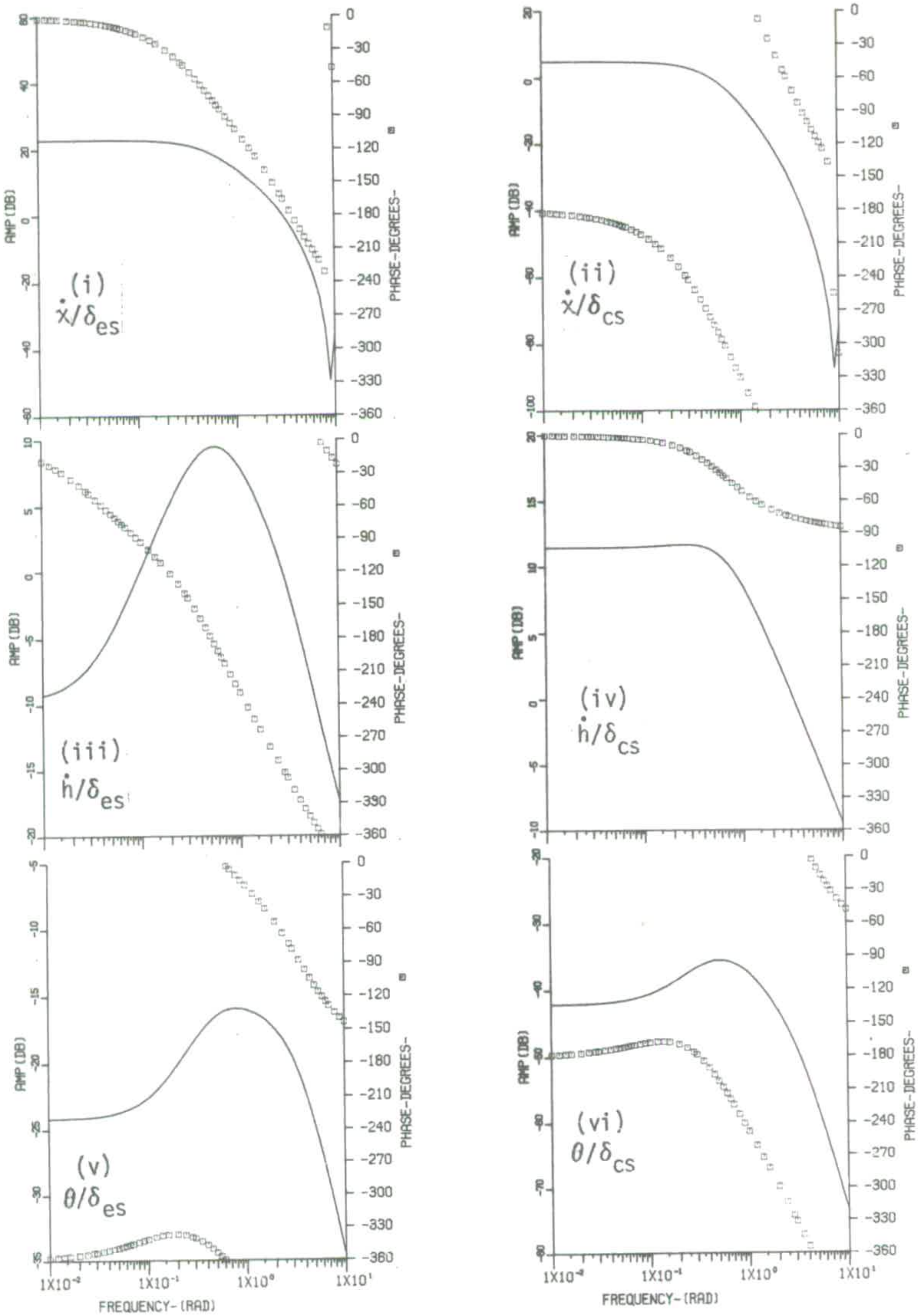


Figure II-6c LONGITUDINAL FREQUENCY RESPONSES FOR DECOUPLED VELOCITY CONTROL SYSTEM AT 0 KT ($\lambda = 90°$)

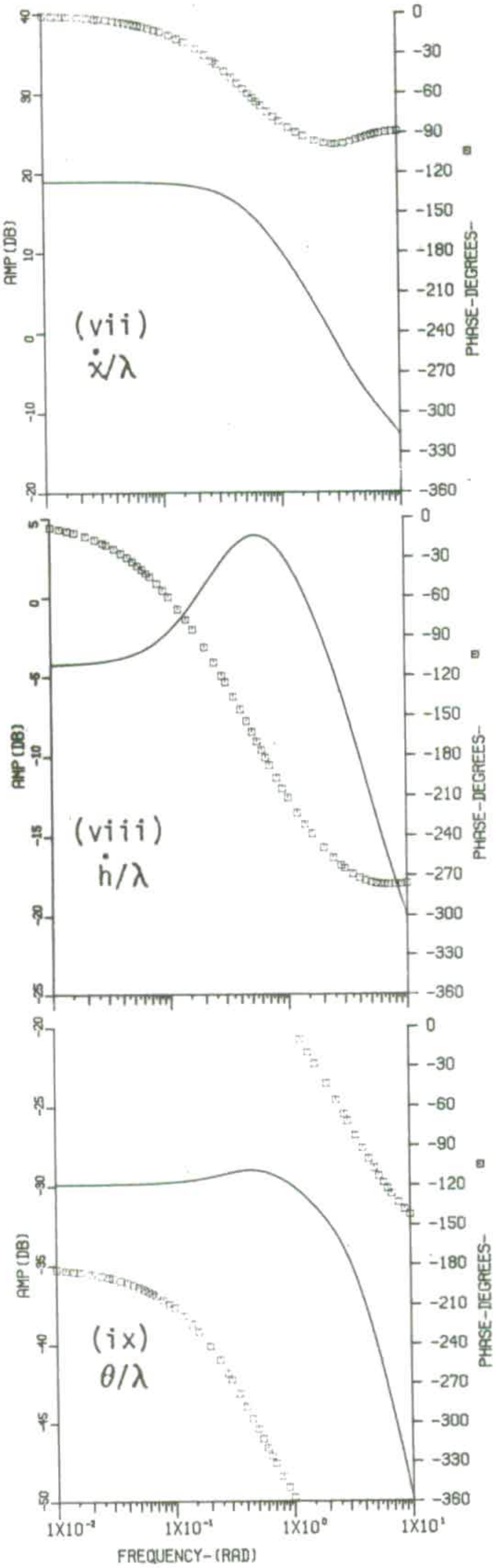


Figure II-6c (Cont.) LONGITUDINAL FREQUENCY RESPONSES FOR DECOUPLED VELOCITY CONTROL SYSTEM AT 0 KT ($\lambda = 90°$)

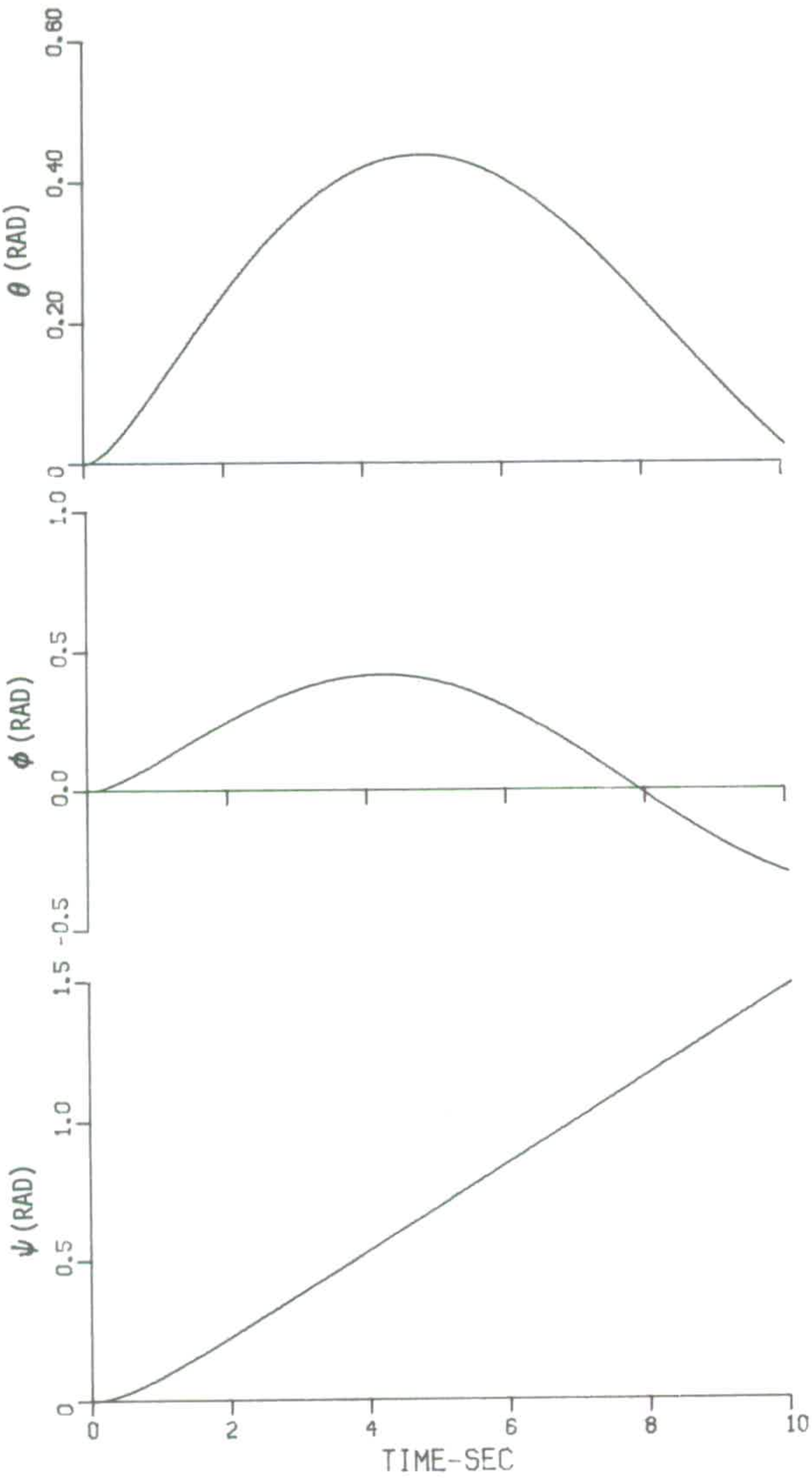


Figure II-7a HOVER ATTITUDE RESPONSE TIME HISTORIES FOR RATE AUGMENTATION CONTROL SYSTEM

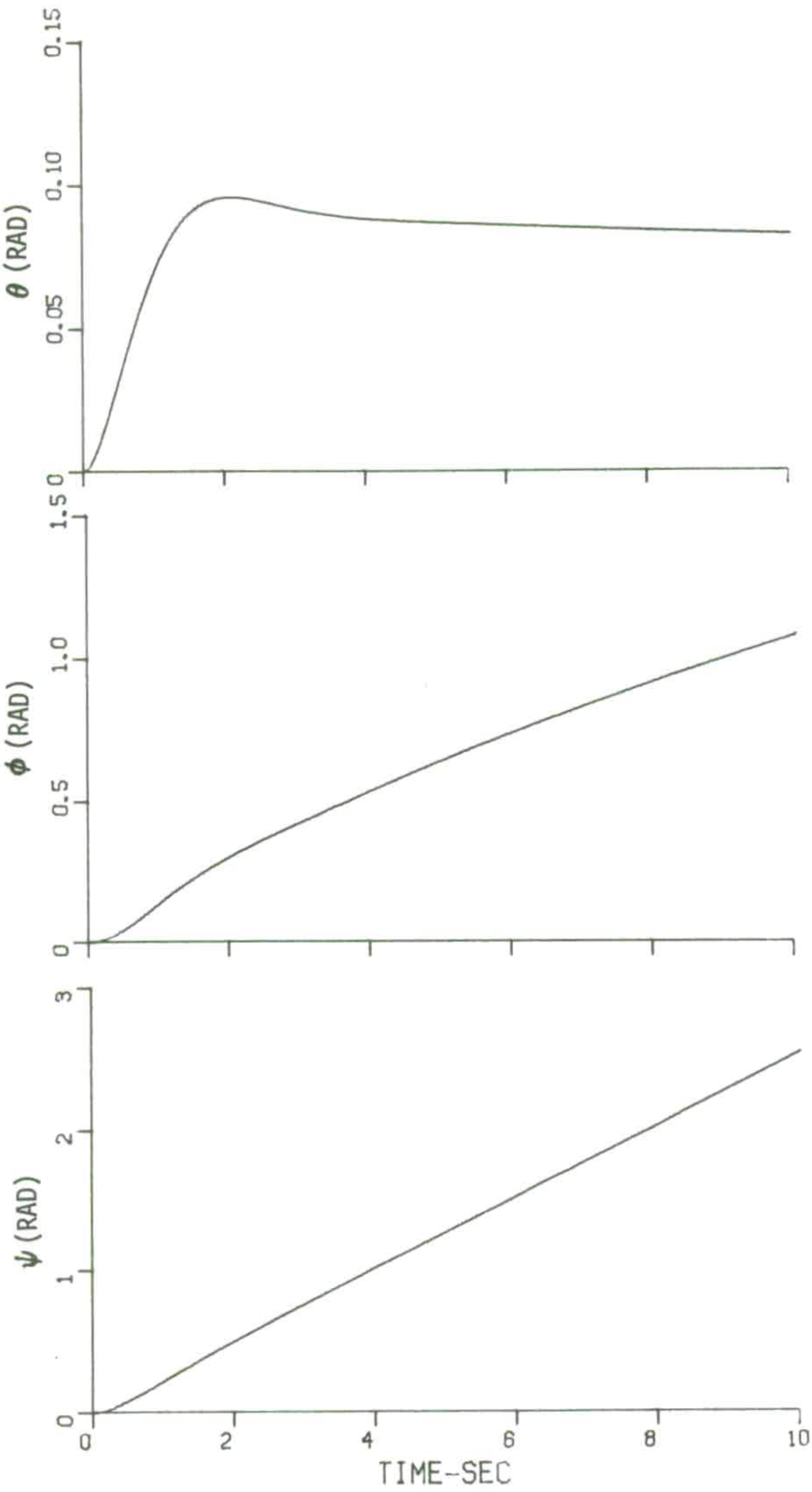


Figure II-7b HOVER ATTITUDE RESPONSE TIME HISTORIES FOR ATTITUDE/RATE COMMAND CONTROL SYSTEM

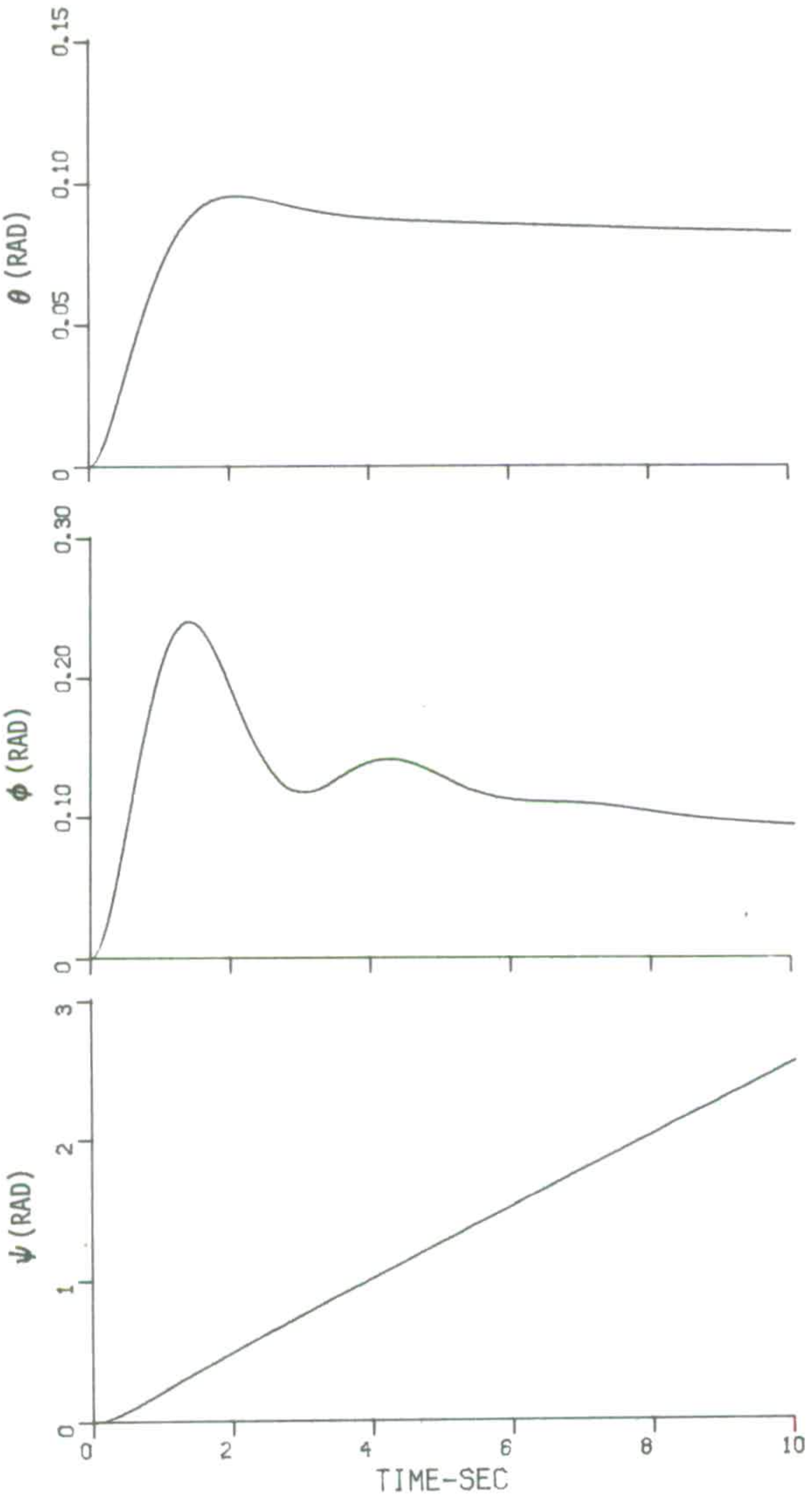


Figure II-7c HOVER ATTITUDE RESPONSE TIME HISTORIES FOR ATTITUDE COMMAND AND AUTOMATIC λ CONTROL SYSTEMS

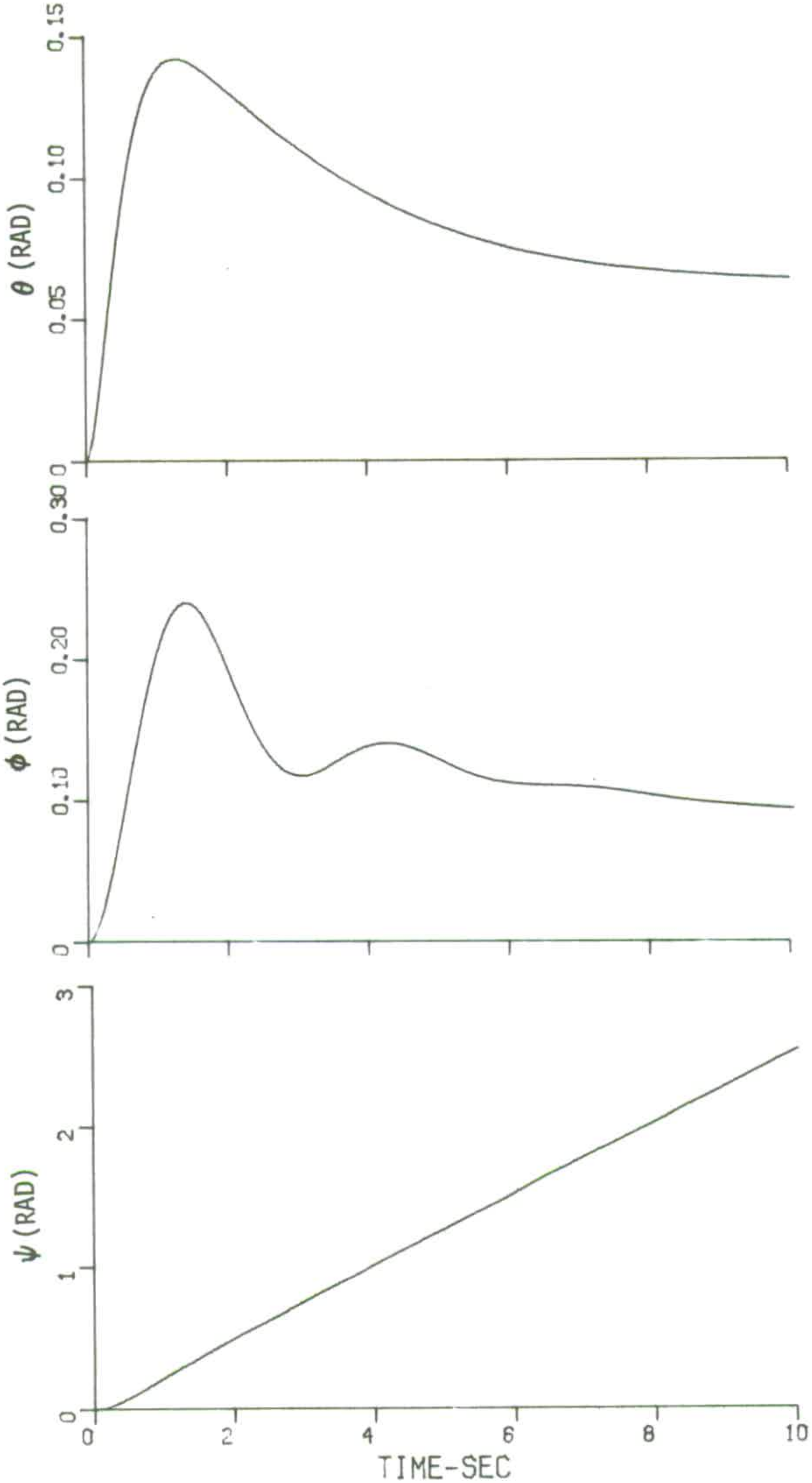


Figure II-7d HOVER ATTITUDE RESPONSE TIME HISTORIES FOR DECOUPLED VELOCITY CONTROL SYSTEM

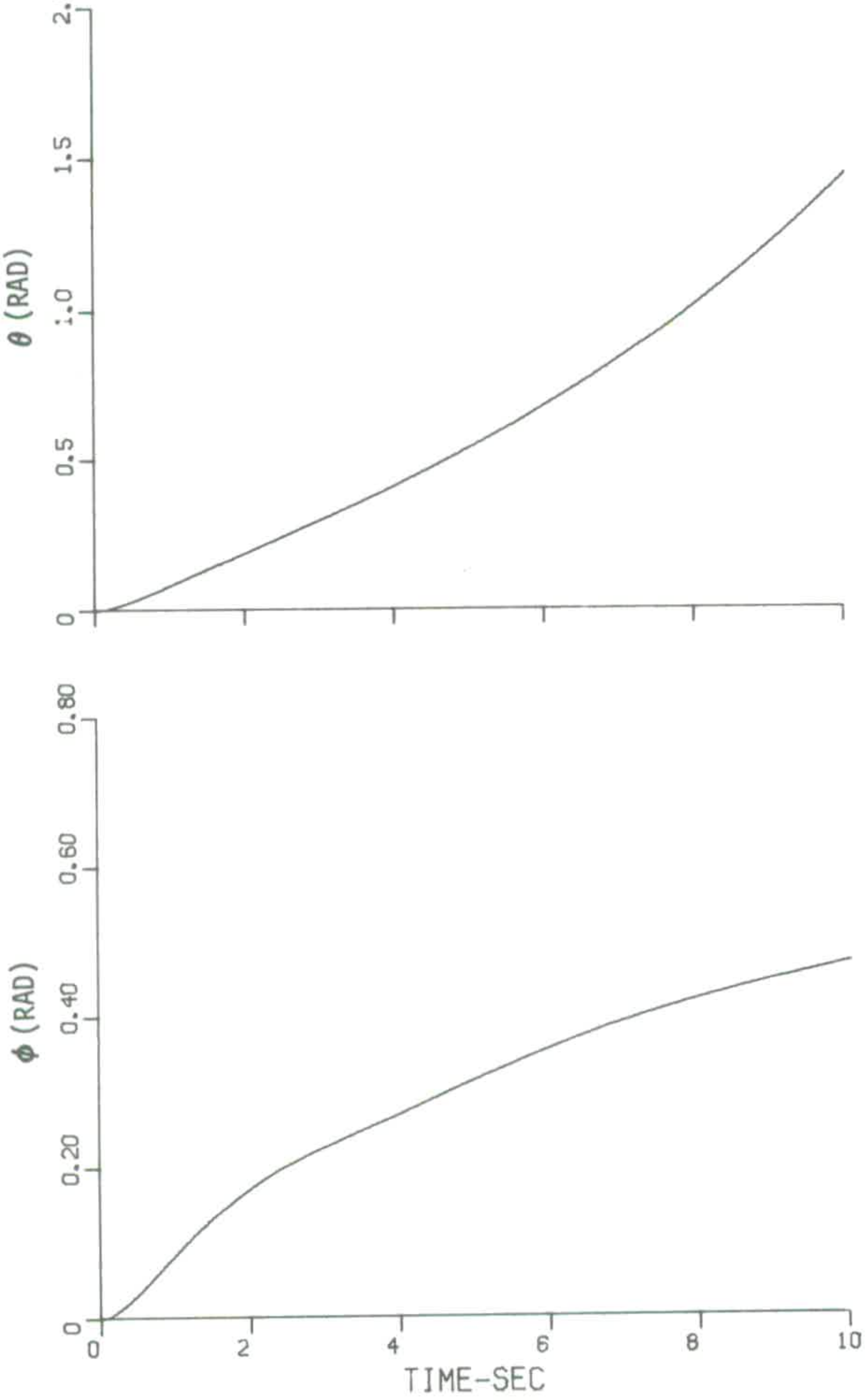


Figure II-8a 100 KT ATTITUDE RESPONSE TIME HISTORIES FOR RATE AUGMENTATION CONTROL SYSTEM

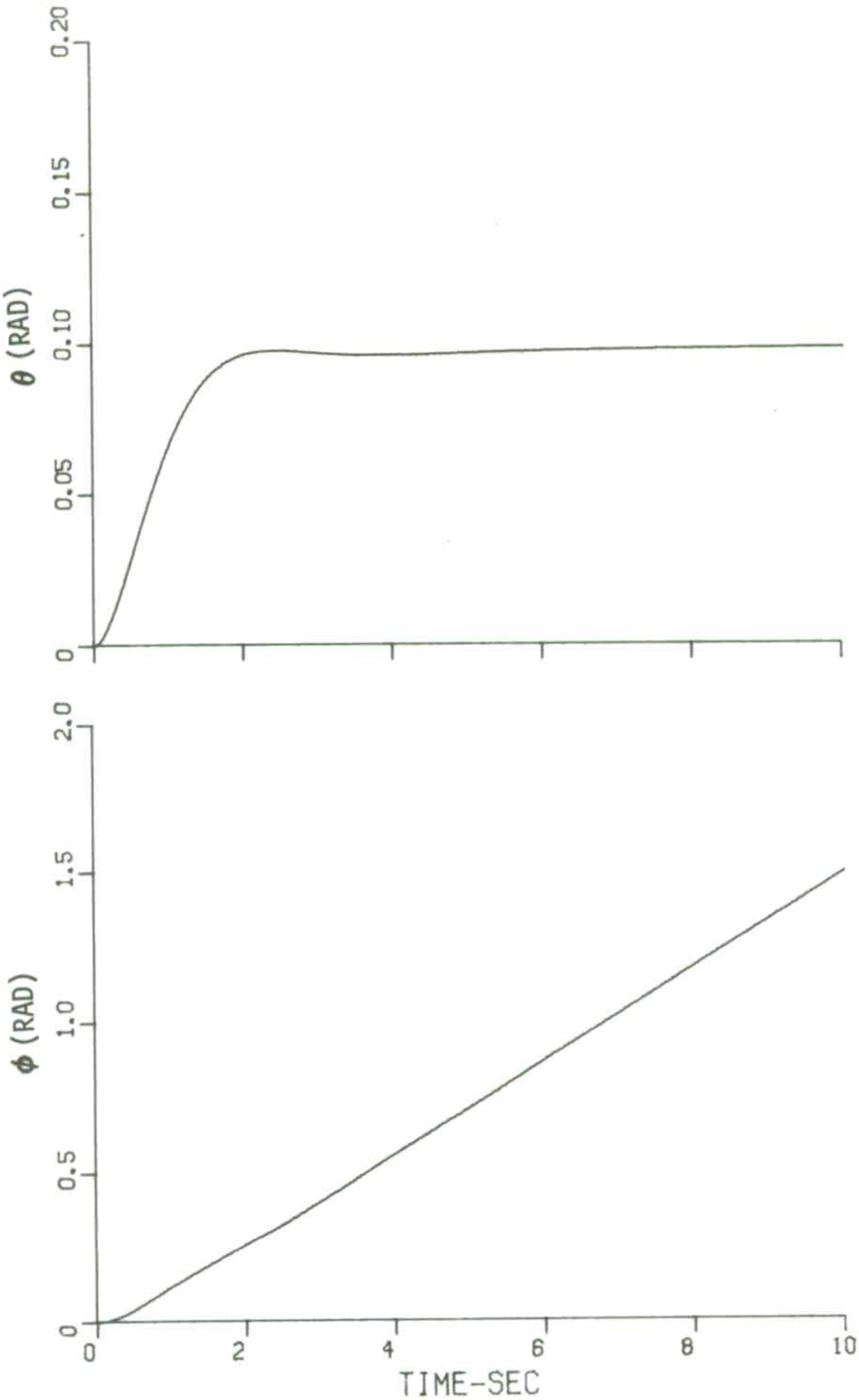


Figure II-8b 100 KT ATTITUDE RESPONSE TIME HISTORIES FOR ATTITUDE/RATE COMMAND CONTROL SYSTEM

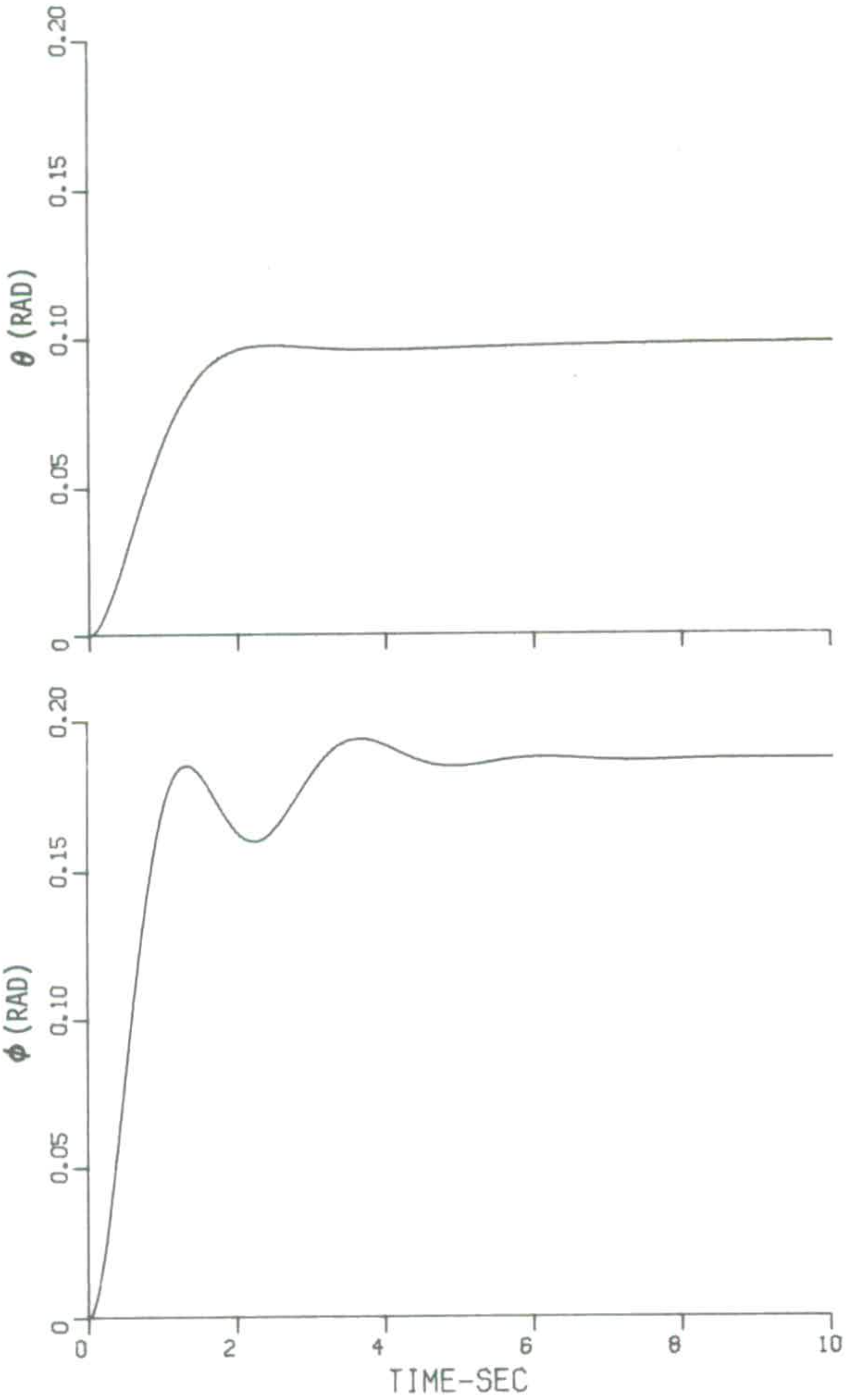


Figure II-8c 100 KT ATTITUDE RESPONSE TIME HISTORIES FOR ATTITUDE COMMAND AND AUTOMATIC λ CONTROL SYSTEMS

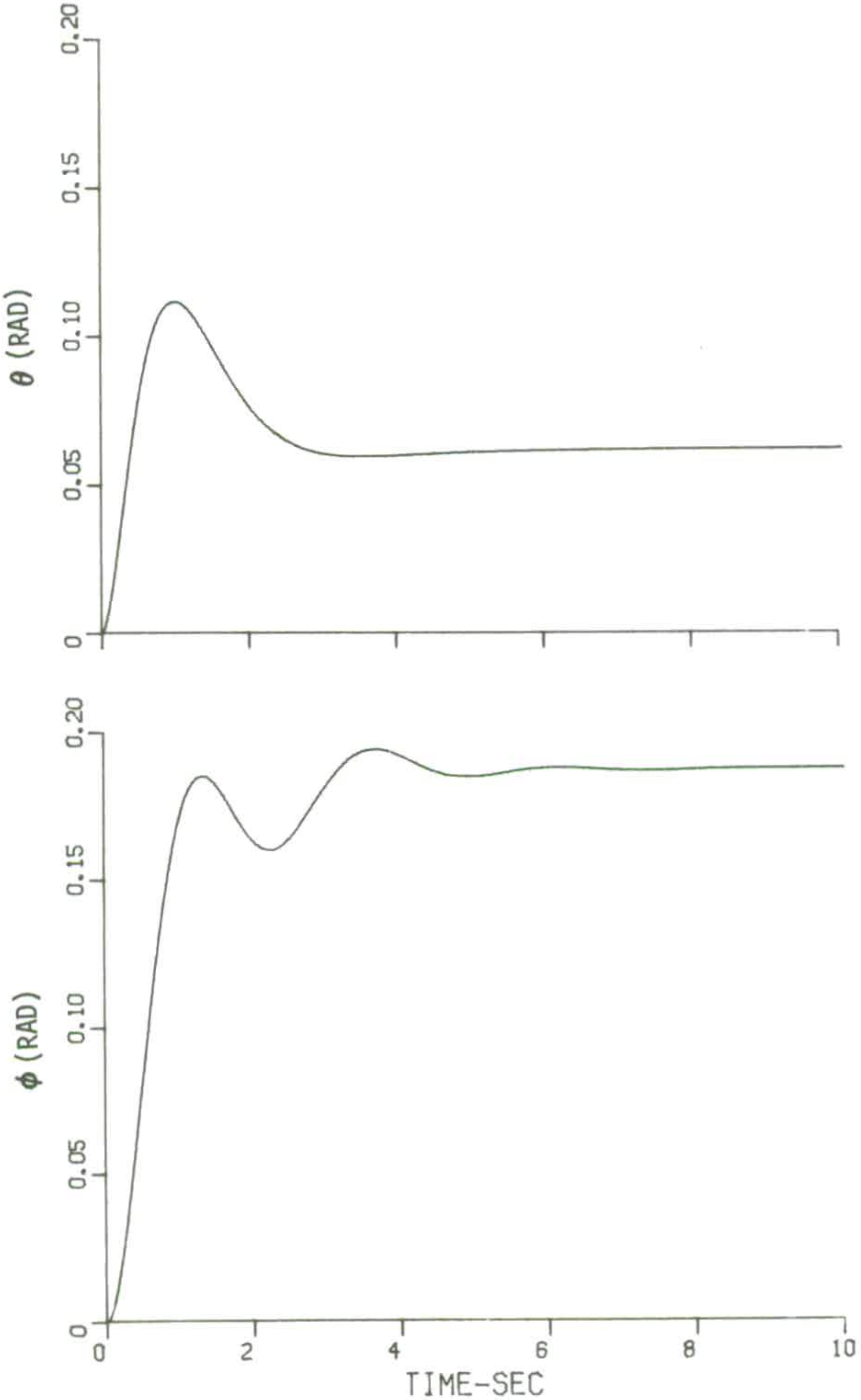


Figure II-8d 100 KT ATTITUDE RESPONSE TIME HISTORIES FOR DECOUPLED VELOCITY CONTROL SYSTEM

APPENDIX III

PRELIMINARY GROUND SIMULATOR INVESTIGATIONS

Introduction and Summary

The X-22A fixed-base ground simulator facility (Reference 12) was used extensively in support of the flight program described in this report with the following objectives:

- to aid in the design of the flight experiment for increased flight testing efficiency
- to develop new control/display system concepts and designs into forms which were at once acceptable to the pilot and feasible to implement in the aircraft
- to ground test new experimental equipment before installation in the aircraft
- to ensure evaluation pilot proficiency before the commencement of flight testing and to maintain that proficiency between evaluation flights.

The purpose of this appendix is to describe the simulator investigations devoted to the first two objectives; the design of the flight experiment and the development of the control/display systems. The third function of the simulator facility was to test and calibrate both the analog symbol generator and the airborne analog computer function generators used to produce the guidance commands (Appendix VIII) prior to flight testing. Finally, the evaluation pilot underwent a familiarization program in the simulator cockpit both prior to and during the flight program; this program consisted of training in the use of the various electronic display formats during the evaluation task and in the procedures to be used for the actual evaluation, in particular the use of the comment card.

The emphasis of the initial ground simulator experiment (Reference 12) was placed upon the control system aspects of the VTOL instrument approach problem; in particular, the investigation centered on several attitude command systems and a simple "direct" velocity control system. The evaluation pilot's information display remained constant for that experiment; the primary instruments were an electromechanical ADI including three-axis control director information and an electromechanical moving map which conveyed only horizontal position and orientation information to the pilot. The various control systems were evaluated for the descending deceleration to the hover only; the localizer acquisition and glide slope intercept phases were not considered as elements of the evaluation task. The efforts involved in the preliminary simulator investigations were devoted primarily to expanding the results of that initial experiment thereby aiding in the design of the flight experiment. The results of the simulator investigations are presented in three categories:

- Display Investigation

    1. electronic display formats
    2. duct rotation director
    3. control director logic

- Control System Investigation

    1. RATE system
    2. ATT system prefilter model
    3. AUTO system duct drive logic
    4. Roll rate command/attitude hold system
    5. DVC system

- Task Investigation

    1. localizer capture and glide slope intercept
    2. "smoothed" flare to level flight
    3. exponential final deceleration to hover
    4. steady winds

Display Investigations

The initial portion of the simulator investigations were involved with the evaluation and modification of the electronic display formats which were eventually to be implemented for the flight program. This phase of the display format design process was made possible by the use of a programmable analog symbol generator developed by Dukes of Princeton University and loaned to the X-22A program. The display formats which were the direct result of these investigations are, with few exceptions, the ED-1, 2, and 3 formats described in Section VI of this report. Changes in the formats as originally conceived which were deemed necessary as a result of the display evaluations were:

- an improved pitch and roll attitude presentation - the original "peripheral" display of attitude was not sufficiently compelling and resulted in confusion concerning aircraft orientation when artificial attitude stability was not provided; the artificial horizon bar was implemented.

- improved horizontal position scaling - the original automatic discrete scale change near hover as used in the initial simulator experiment was found to be disconcerting; a continuous scale change was required.

- velocity vector/command diamond sensitivity - the scaling of the vector and diamond for the approach (20 kts/cm) was found to be too coarse for the hover element of the task; as a result the "hover mode" scaling was implemented for the flight program.

- earth/heading axis system - no particular preference in position/velocity reference system was expressed for the final approach to the hover; however, the earth-referenced system was found to be preferable for the localizer acquisition because of the occasional disorientation which occurred when the heading axis approach course symbol rotated in response to aircraft heading changes.

The conclusions of this phase of the experiment which served to broaden the scope of the flight experiment were:

- With an attitude command system, satisfactory performance and pilot workload are obtained with the ED-2 format; a control director display (ED-3) is not required.

- Satisfactory performance and pilot workload are obtained with an angular rate augmentation system with a control director format (ED-3); the velocity display format (ED-2) is unacceptable for this control system.

The duct rotation director light described in Section VI was developed in the simulator in an effort to simplify the longitudinal control problem for the pilot of a vehicle which was not "adequately" stabilized in attitude. The command light was in fact required for a satisfactory RATE:ED-3 combination but was also found to improve pilot opinion of any of the control-display combinations which required manual duct rotation.

The final display investigation was an extensive evaluation of various control director design philosophies:

- Classical control theory design-based upon the STI "crossover" pilot model (see Section VI).

- Optimal control theory design with no compensation for effective pilot time delay.

- Optimal control theory design compensated for pilot time delay.

The results of this investigation are reported in Reference 35. A separate "quick look" investigation of the "frequency separation" technique of control/display design (Reference 22) was also conducted. Based upon the results of this phase of the experiment it was decided to implement the "classical" control director design for the flight experiment; director gains which remained constant for all flight conditions but varied with generic controlled vehicle characteristics were found suitable in the simulator and hence were implemented for preliminary flight testing. The simulations also revealed that, for the evaluation task, the guidance errors which were part of the director logic were required to be presented in the aircraft heading-referenced axis system to ensure valid commands with large heading offsets from the desired approach course.

Control System Investigations

Prior to these simulator investigations it was generally believed that pitch attitude stabilization was a requirement for the VTOL instrument landing task. The RATE system implemented in the simulator, with angular rate feedback gains held constant at the value of the X-22A full SAS gains in hover, and a properly designed control director display format (ED-3) including the configuration change director resulted in a satisfactory control/display combination for the task. This particular result caused the expansion of the flight test configuration matrix to include generic control systems less complex than attitude command systems.

The pitch attitude command prefilter (Section V) was developed in the simulator. Three different feedforward command schemes were evaluated: 1) pitch attitude command only, 2) pitch rate and attitude commands, and 3) pitch acceleration, rate, and attitude commands. The latter two schemes were found to be acceptable for flight testing, with the third scheme providing the best "model-following". The first scheme was found to be unacceptable because of the relatively slow response in attitude caused by the cascading of a second-order prefilter with the attitude-stabilized aircraft dynamics.

The feasibility of using the configuration change director logic to rotate the ducts for the automatic configuration change (AUTO) system was investigated by using the simulator to activate the aircraft's duct drive system. Initially, a simple deadband of $\sim 3^o$ of duct angle error was applied to the ITVIC signal (Section IV); that is an error of greater than 3^o would cause the ducts to rotate until the error was reduced to less than 3^o. A hysteresis circuit was found to be more suitable than the deadband because fewer individual duct rotations were commanded through the transition; a 3.3^o turn-on point and a 0.75^o turn-off point were found to be acceptable in terms of both pilot performance/workload and duct hydraulic system fatigue due to pressure transients.

Based upon preliminary flight test results, it was decided to implement the ATT/RATE system which involved a roll rate command/attitude hold system; the roll channel of the ATT/RATE system was also developed in the simulator. Simple roll rate feedback to the lateral stick was rejected because of the unstable spiral mode which resulted when automatic turn coordination was selected. Instead an integral plus proportional lateral stick feedforward $(\frac{s+2}{s})$ with a roll-attitude stabilized plant $(\omega_n = 2; \zeta = 1.0)$ was implemented and found suitable for the task although some difficulty in holding a constant bank attitude was encountered because of the lack of a deadband on the lateral stick signal.

The most complex control system designed for this experiment, the DVC system, underwent careful evaluation in the simulator and was modified somewhat as a result of these evaluations. An initial attempt was made to create a two-controller (δ_{es} and δ_{cs}) longitudinal DVC system by blending duct angle control into the pitch controller in a manner similar to that used in the initial simulator experiment. However, the changing trim stick position through the transition created a situation where excessively large aft stick motions (and hence large nose-high pitch attitudes) were required to cause duct rotation at low airspeeds ($\lambda = 60 \sim 70^{o}$, V = 30~40 Kts). Solutions to this particular problem which were investigated were: 1) the use of actual attitude rather than commanded attitude to rotate the ducts and 2) the use of an automatic trim device to allow the "trim" position of the pilot's stick to remain at zero through the transition. The controlled vehicle characteristics which resulted from these solutions were, however, found to be unacceptable for the task; hence, the three-controller DVC system was adopted for flight. Modifications to the system as originally designed which were implemented as a result of the preliminary simulations are:

- increase of the time constant of the longitudinal velocity response to duct angle from ~1 sec to ~2 sec.

- the use of the AUTO duct drive logic to achieve an automatic coarse control of duct angle; the pilot was then able to control longitudinal velocity with manual duct angle inputs about the "nominal" value of duct angle for each point in the approach.

Task Investigations

The guidance commands described in Section IV of this report were all developed in simulator investigations. The initial simulator experiment had verified the decision to use a constant deceleration level for the approach. The localizer acquisition and glide slope intercept problems were included as part of the evaluation task for the preliminary investigations; the guidance commands for these tasks, resulting in an exponential localizer capture and a smoothed glide slope intercept, were verified in the simulator and are described in Section IV. The "instantaneous" flare to level flight used in the initial experiment was replaced with a 10-second smoothed flare for the preliminary investigation and the flight testing. Finally, because of the recommendations of Reference 12, a final exponential deceleration to the hover was substituted for the constant deceleration used in that experiment; the revised deceleration law was found to be acceptable and was implemented for the flight program.

Because steady winds had not been included in the evaluation task of the initial experiment, a digital program modification which allowed the investigation of the effects of headwind and crosswind components was implemented. As a result of these investigations, the required compensation of the guidance commands for the effects of steady winds described in Section IV was initiated. In addition, the importance of the use of heading-referenced control director error signals and the heading-referenced display of position and velocity information near hover (Section VI) was realized as a result of simulator evaluations with crosswind components.

Concluding Remarks

The X-22A ground simulator facility proved to be an invaluable research tool for the flight experiment described in this report. Its role in the design of the flight experiment and the development of new control/display systems resulted in the expansion of the configuration matrix from that originally conceived (i.e. the matrix investigated in the initial simulation experiment) to the final matrix described in Section VII. The quality and efficiency of this flying qualities research program were also enhanced by the use of the simulator as a test bed for the new experimental equipment and as an evaluation pilot training device. The integration of theoretical analysis and in-flight simulation provided by the ground simulator has resulted in a well-designed flying qualities research program from which valid and meaningful experimental results may be derived.

APPENDIX IV

IDENTIFICATION OF EVALUATION CONFIGURATIONS

The conduct of flying qualities experiments using response-feedback variable stability aircraft is strongly dependent on the capability to estimate dynamic characteristics from flight data. For the experiment described in this report, identification of the longitudinal and lateral-directional basic X-22A stability and control derivatives, both in forward flight and at hover, was required to determine the dynamic characteristics that resulted from implementing the control augmentation designs discussed in Section V of this report. This appendix discusses in some detail how this identification was performed: included in the discussion will be a brief review of the digital identification technique used, a summary of the data processing required, a description of the procedures involved, and the presentation of the results.

Kalman Filter Digital Identification Technique

The primary identification method used on this flight program was the locally iterated Kalman filter technique developed by Calspan for the X-22A. The development of this technique is given in Reference 30, and a summary of its application in previous X-22A flight programs is contained in References 31 and 32.

The Kalman filter technique is an advanced method which is capable of treating both process and measurement noises for systems that may be described by general nonlinear equations. Referring to Figure IV-1, the method employs a three-stage refining process to perform the identification.

(1) Initial estimates of the parameters, and their variances, in the assumed equations are obtained by a method that is essentially an equation-error technique. Since the variances obtained by this method are somewhat under-estimated, an improved variance estimate, employing the parameters estimated above, may be obtained by a Cramer-Rao lower bound computation if desired.

(2) An extended Kalman filter, utilizing a "local iteration" or "multi-correction" algorithm, is used to refine the initial estimates of the parameters. Although the extended Kalman filter gives biased estimates when applied to a nonlinear problem, which is inherent to parameter identification, it can be shown that the multi-correction scheme reduces biases due to nonlinearities by improving the reference trajectory between data points.

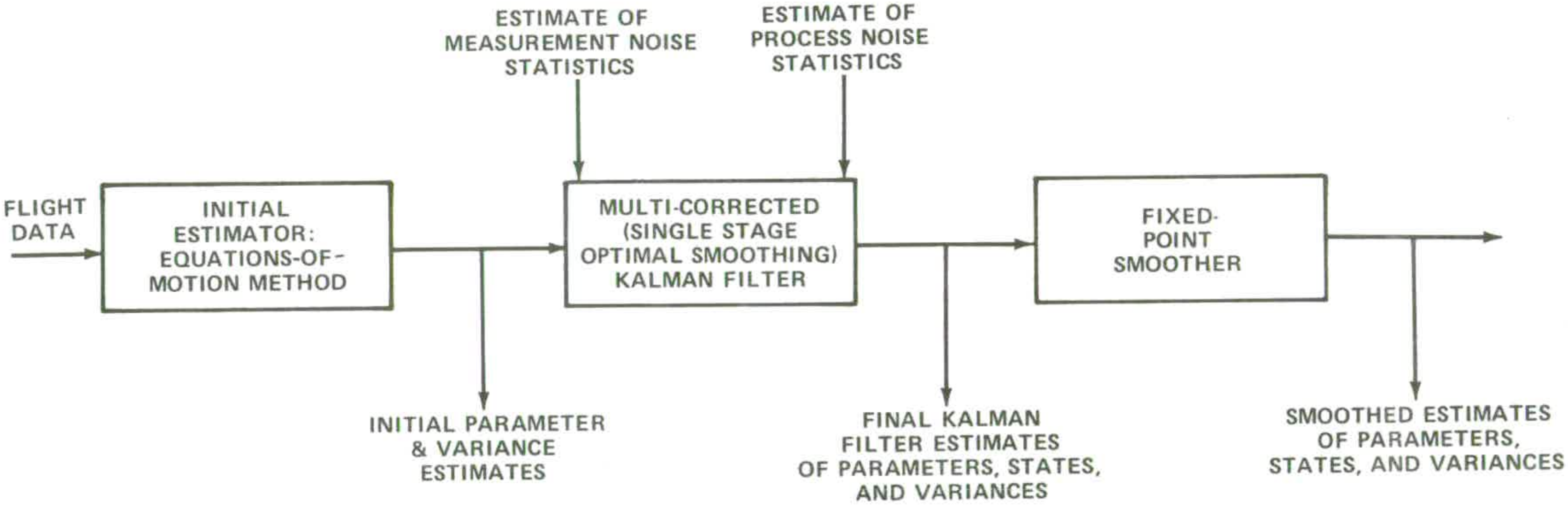


Figure IV-1 SCHEMATIC DIAGRAM OF KALMAN FILTER DIGITAL IDENTIFICATION PROCESS

(3) A fixed-point smoothing algorithm, which actually works in conjunction with the multi-corrector at each data point, may be used to further refine the parameter estimates and separate out the effects of process noise. This step is extremely important as a first attempt at determining the mathematical modeling error, as well as improving the parameter estimates. Also, a more accurate variance computation of the parameter estimate is obtained.

In the previous X-22A programs (References 10, 11) it was found that suitable assumed equations of motion consisted of linear aerodynamics and nonlinear kinematic and gravitational terms. These equations, as used in this experiment, are (in aircraft body axes):

Longitudinal:

$$\dot{u} + wq + g\sin\theta = X_0 + X_u(u-u_0) + X_w(w-w_0) + X_\theta(\theta-\theta_0) + X_{\delta_{es}}(\delta_{es}-\delta_{es_0}) + X_{\delta_c}(\delta_c-\delta_{c_0})$$

$$\dot{w} - uq - g\cos\theta = Z_0 + Z_u(u-u_0) + Z_w(w-w_0) + Z_\theta(\theta-\theta_0) + Z_{\delta_{es}}(\delta_{es}-\delta_{es_0}) + Z_{\delta_c}(\delta_c-\delta_{c_0})$$

$$\dot{q} = M_0 + M_u(u-u_0) + M_w(w-w_0) + M_q q + M_\theta(\theta-\theta_0) + M_{\delta_{es}}(\delta_{es}-\delta_{es_0}) + M_{\delta_c}(\delta_c-\delta_{c_0})$$

Lateral-Directional:

$$\dot{v} - wp + ur - g\sin\phi = Y_0 + Y_v(v-v_0) + Y_p p + Y_r r$$

$$\dot{p} = L'_0 + L'_v(v-v_0) + L'_p p + L'_\phi \phi + \left(L'_r + K_L \frac{q}{57.3}\right) r + L_{\delta_{as}}(\delta_{as}-\delta_{as_0}) + L_{\delta_{rp}}(\delta_{rp}-\delta_{rp_0})$$

$$\dot{r} = N'_0 + N'_v(v-v_0) + \left(N'_p + K_N \frac{q}{57.3}\right) p + N'_\phi \phi + N'_r r + N_{\delta_{as}}(\delta_{as}-\delta_{as_0}) + N_{\delta_{rp}}(\delta_{rp}-\delta_{rp_0})$$

$$\dot{\phi} = p + \frac{\theta q}{57.3}\sin\phi + \frac{\theta r}{57.3}\cos\phi$$

Implicit in these equations are the following assumptions:

- Longitudinal and lateral-directional motions may be considered essentially decoupled
- Calibration records are obtained in trimmed, steady flight ($q_0 = r_0 = p_0 = \phi_0 \triangleq 0$).

- Roll and yaw control inputs contribute a negligible amount to the side force equation ($Y_{\delta_{as}} = Y_{\delta_{rp}} \triangleq 0$)

- Attitude derivatives (e.g. M_θ, L_ϕ) are included to permit identification of records in which angular attitude augmentation was used.

Digital Data Processing

To perform digital identification with the Kalman filter using the equations given above, a fairly extensive data processing procedure is required to transform the recorded flight data into a suitable format. A description of the general process is given in Appendix VIII, and those details pertinent to the identification procedure are summarized below.

For use with the assumed equations, the digital data are transformed from measured variables to equations-of-motion variables at the center of gravity. Strictly speaking, it is preferable to perform these transformations within the identification algorithm using appropriate measurement equations; to provide more efficient (i.e. less costly) identification, however, these transformations are used in the preparation of a final data tape for identification, which permits the use of simple measurement equations in the identification algorithm. The primary transformations required are on the aerodynamic motions, since relative wind and velocity sensors are located either on a nose boom (α, β, w) or the top of the tail(u , v). In addition, the accelerometer package is displaced above the aircraft center of gravity, and hence the n_x and n_y measurements must be corrected for angular accelerations. The appropriate transformations as used in this experiment are:

$$w = \frac{u \tan \alpha_m}{K_\alpha} + q_m \ell_{x_n} - u \tan \alpha_0 \qquad (\lambda = 15^\circ, 50^\circ)$$

$$= w_m + q_m \ell_{x_n} \qquad (\lambda = 90^\circ)$$

$$v = \frac{v_m}{K_v} + r_m \ell_{x_t} - p_m \ell_{z_t}$$

$$u = u_m + q_m \ell_{z_t}$$

$$n_z = n_{z_m}$$

$$n_y = n_{y_m} - \dot{p}_m z_y$$

$$n_x = n_{x_m} + \dot{q}_m z_y$$

where:
ℓ_{x_n} = 22.5 ft
ℓ_{x_t} = 16.7 ft
ℓ_{z_t} = 15.5 ft
z_y = 1 ft

K_α, K_v, α_0 depend on flight condition

Applying these transformations to the recorded data and performing suitable editing to allow processing by an IBM 370/65 computer (see Appendix VIII) result in the final data tape for the identification procedure. In common with any technique based on Kalman filter theory, the following input information is required:

1. Initial estimates of the parameters.

2. Variances of the initial estimates.

3. Reference conditions of the states.

4. Measurement noise variances.

5. Process noise variances.

The initial parameter estimates are obtained from a conventional least-squares equation error method, which also produces estimates of the parameter variances. It has been observed experimentally that the variance estimates obtained by this method do not correctly represent either the absolute or the relative accuracy of the initial parameter estimates. Two alternatives may be taken. The first is to multiply the initially estimated variances equally by an arbitrary factor. The second, which is more appealing theoretically, is to use an independent technique to calculate them. Since it is clear that the initial variances should reflect the identifiability of the parameters to some extent, which is in turn dependent on the control input used, one means of obtaining the variances is to obtain the Cramer-Rao lower bound on the covariance of the parameter estimates for the given data. The variances obtained by this method would be expected to be more correct in their ratios to each other, and again can be multiplied by an arbitrary factor and used as the initial variances. For the results obtained during this program, the method of multiplying the equation-error computed variances by a constant factor was used. This choice was dictated by operational considerations: the need to process large quantities of data in a rapid fashion during calibration flights results in eliminating, if possible, intermediate computing steps, such as the separate calculation of the Cramer-Rao lower bound. In general, experimental experience has demonstrated that, for the type and quality of the identification records for the X-22A, the more direct method of uniformly increasing the equation-error method variances appears to be adequate.

The measurement noise statistics are obtained by visual examination of the flight records. Generally, the "hash" on the records is assumed to equal the variance of the measurement noise, which provides a conservative value. This estimate is then checked qualitatively by comparing plots of the residual sequences of the filter operation with the assumed noise statistics, and readjusting the statistics if required. The X-22A data acquisition system provides data with excellent signal-to-noise ratios in general, and therefore this method of estimating the measurement noise variances is sufficiently precise. The values used for the results presented herein are:

Longitudinal:

	σ_u (ft/sec)	σ_w (ft/sec)	σ_θ (deg)	σ_q (deg/sec)	σ_{n_x} (ft/sec^2)	σ_{n_z} (ft/sec^2)	$\sigma_{\dot{q}}$ (deg/sec^2)
$\lambda = 15^\circ$	1.5	2.0	0.2	0.1	0.2	0.7	1.0
$\lambda = 50^\circ$	1.0	1.0	0.2	0.1	0.2	0.4	1.0
$\lambda = 90^\circ$	0.5	0.5	0.1	0.1	0.2	0.5	1.0

Lateral-Directional:

	σ_v (ft/sec)	σ_p (deg/sec)	σ_r (deg/sec)	σ_ϕ (deg)	σ_{n_y} (ft/sec^2)	$\sigma_{\dot{p}}$ (deg/sec^2)	$\sigma_{\dot{r}}$ (deg/sec^2)
$\lambda = 15^\circ$	2.0	0.2	0.2	0.2	0.4	2.0	1.0
$\lambda = 50^\circ$	2.0	0.2	0.2	0.2	0.4	2.0	1.0
$\lambda = 90^\circ$	0.5	0.1	0.1	0.2	0.2	1.0	1.0

In addition to selecting the measurement noise statistics from visual examination of the data, the reference (or initial) conditions of the states are chosen to be the first datum points ($t \triangleq 0$) on each record tape. Since calibration identification records of the evaluation configurations are usually obtained about trimmed flight, the first point on the data tape is generally a valid reference condition. The fixed point smoother may be used to obtain an estimate of the initial conditions if necessary, but this computation is not generally required for the X-22A data.

The most difficult choice of required input information is that of the process noise statistics. To some degree, the process noise covariance matrix Q is a "fiddle parameter" in the algorithm which may be used to improve its performance for a given data record. On the other hand, the requirement for rapid post-flight identification as nearly automatic as possible leads to a desire to hold these statistics at a fixed value for all flight records. To make this tradeoff, then, it is important to define precisely what the sources of process noise might be. For the X-22A data, there are essentially three sources of process noise:

1. Gust or turbulence inputs.
2. The variable stability system.
3. Modeling errors.

Of these, the gust inputs are of the least significance for the records that are analyzed, because the majority of calibration identification records are obtained in turbulence-free air to facilitate rapid checks on the frequency and damping of prevalent rigid-body modes of motion. The variable stability system is the source of "noise" both as a result of its dynamics not being included in the model and through its operation on noisy measurement signals, particularly if feedback of aerodynamic quantities is employed (e.g. angle of attack). The primary source of modeling errors, however, is the fundamental restriction that we seek the best linear model for the aircraft dynamics that will fit the data, as most flying qualities parameters are defined in terms of linear systems.

With regard to the choice of process noise statistics, therefore, the following considerations are relevant. For simulated aircraft that are highly augmented with regard to the X-22A (e.g., higher rigid body frequencies and dampings), the assumption of a linear model becomes increasingly valid, but the process noise added by the variable stability system increases. For simulated aircraft whose rigid body motions are similar to the X-22A (very little augmentation), the effects of the variable stability system are reduced but nonlinearities may start to become important. The magnitude of the process noise in these two cases may be considered approximately the same. The worst case is one in which the X-22A must be highly de-augmented, as linear aerodynamic terms may approach zero, thereby accentuating nonlinearities, and the variable stability system effects again become larger. For this case, it may be necessary to assume more process noise, particularly if the configuration is sensitive to turbulence.

For this experiment, the flight records used in the identification process were generally for situations in which both angular rate and angular attitude augmentation were added to the basic X-22A dynamics; this procedure validates the linearization assumption without adding significantly to VSS-induced process noise (the rate and attitude measurements are much less noisy than those of the aerodynamic quantities). Hence, the level of process noise could generally be assumed low, particularly in forward flight when some of the modeling assumptions (i.e. decoupled lateral-directional and longitudinal motion) are most valid. In addition, more than one data record for each flight condition of interest was generally available, which means that increased confidence in the derivative estimates and model validity is obtained; in these cases, the process noise can be assumed even smaller. For the time history matches to be presented herein, the actual process noises used to obtain the results are:

Longitudinal:

	$\dot{u}$ (ft/sec^2)	$\dot{w}$ (ft/sec^2)	$\dot{q}$ (ft/sec^2)
$\lambda = 15^\circ$	0.0	0.0	0.0
$\lambda = 50^\circ$	0.0	0.0	0.0
$\lambda = 90^\circ$	2.0	2.0	0.5

Lateral-Directional:

	$\dot{v}$ (ft/sec^2)	$\dot{p}$ (deg/sec^2)	$\dot{r}$ (deg/sec^2)
$\lambda = 15^o$	0.0	0.0	0.0
$\lambda = 50^o$	0.5	0.5	0.5
$\lambda = 90^o$	2.0	1.0	1.0

Identification Results

Time history matches and identified derivatives for longitudinal and lateral-directional dynamics at three flight conditions (15^o/100 Kt, 50^o/65 Kt, and 90^o/0 Kt) are given in Figures IV-2 through IV-7. The feedback and gearing gains used for the dynamics being identified are summariezed below.

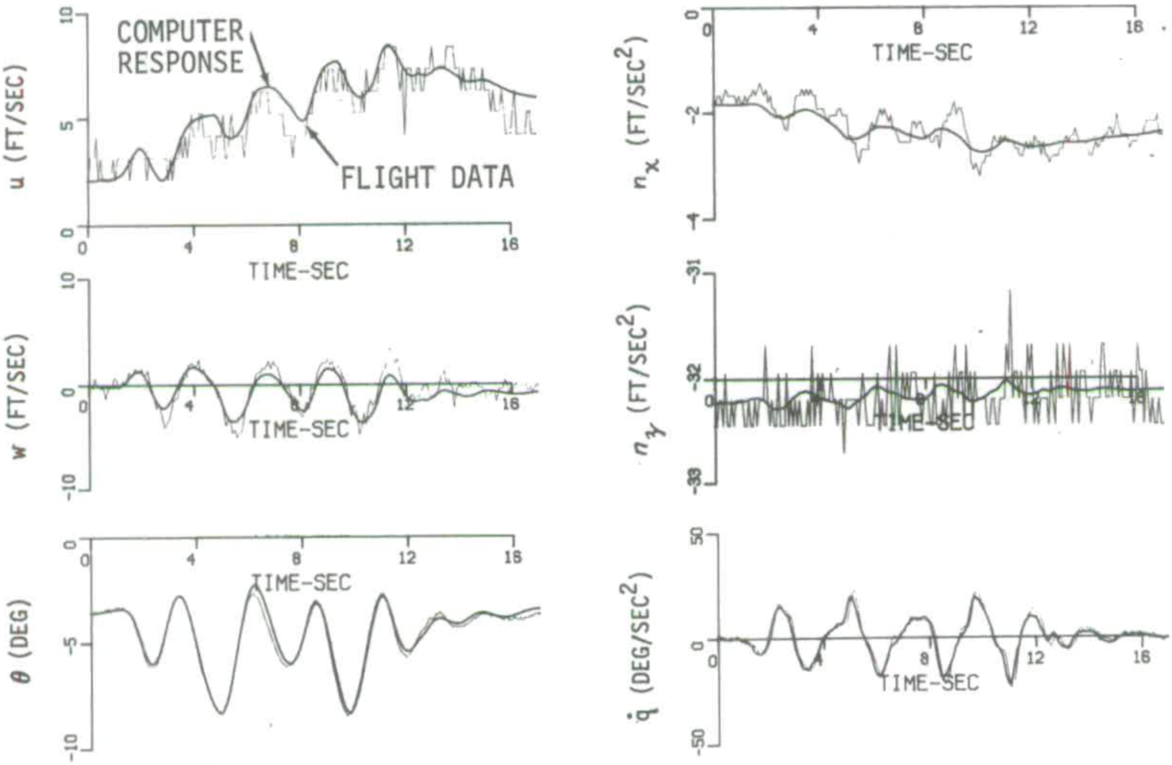
Longitudinal:

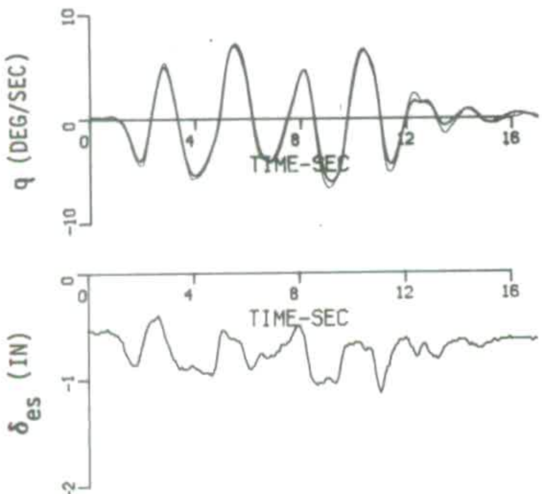
	Δ_{es}/q (in/rad/sec)	Δ_{es}/θ (in/rad)	Δ_{es}/δ_{es} (in/in)	Δ_{cs}/δ_{cs} (deg/deg)
$\lambda = 15^o$	- 8.9	0.0	1.256	1.25
$\lambda = 50^o$	- 3.97	-12.03	1.05	1.25
$\lambda = 90^o$	- 3.97	-12.03	1.05	1.25

Lateral-Directional:

	Δ_{as}/p (in/rad/sec)	Δ_{as}/ϕ (in/rad)	Δ_{as}/δ_{as} (in/in)	Δ_{rp}/r (in/rad/sec)	Δ_{rp}/δ_{rp} (in/in)
$\lambda = 15^o$	-3.72	-7.33	1.14	-3.2	2.11
$\lambda = 50^o$	-3.72	-7.33	1.42	-3.2	2.11
$\lambda = 90^o$	-3.72	-7.33	1.42	-3.2	2.11

Using these gains and the identified derivatives listed in the figures, the basic X-22A stability and control derivatives as tabulated in Appendix I may be computed.

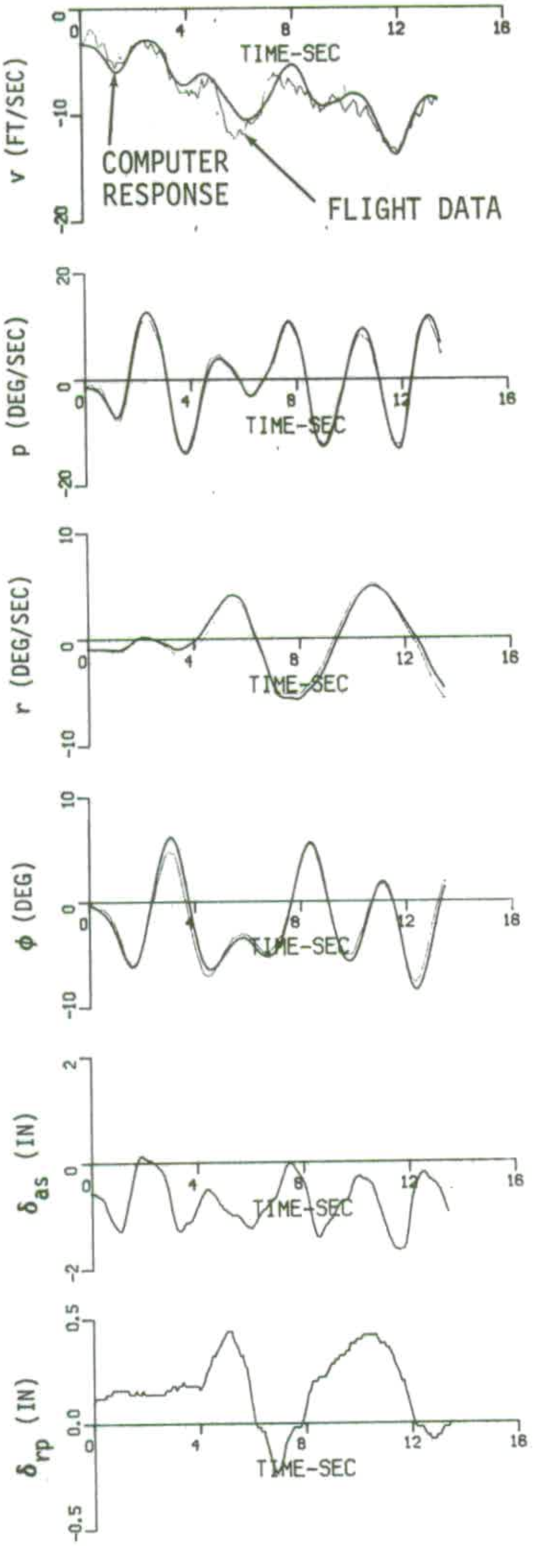


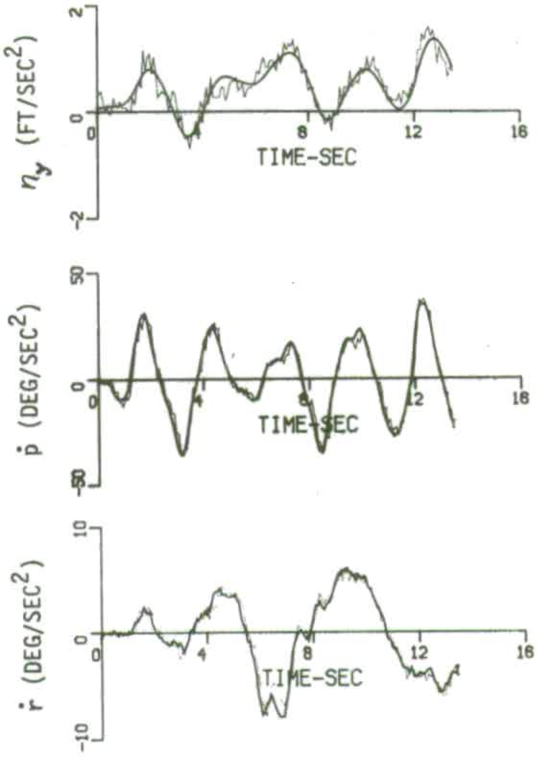


IDENTIFIED DERIVATIVES

M_u	= 0.015	X_u	= -0.15
M_w	= 0.000875	X_w	= 0.0
M_q	= -1.15	X_θ	= 1.81
M_θ	= -4.21	$X_{\delta es}$	= -0.150
$M_{\delta es}$	= 0.365	Z_u	= 0.0
		Z_w	= -0.12
		Z_θ	= 2.40
		$Z_{\delta es}$	= -0.170

Figure IV-2 IDENTIFICATION OF LONGITUDINAL CHARACTERISTICS, 90°/0 KT





IDENTIFIED DERIVATIVES

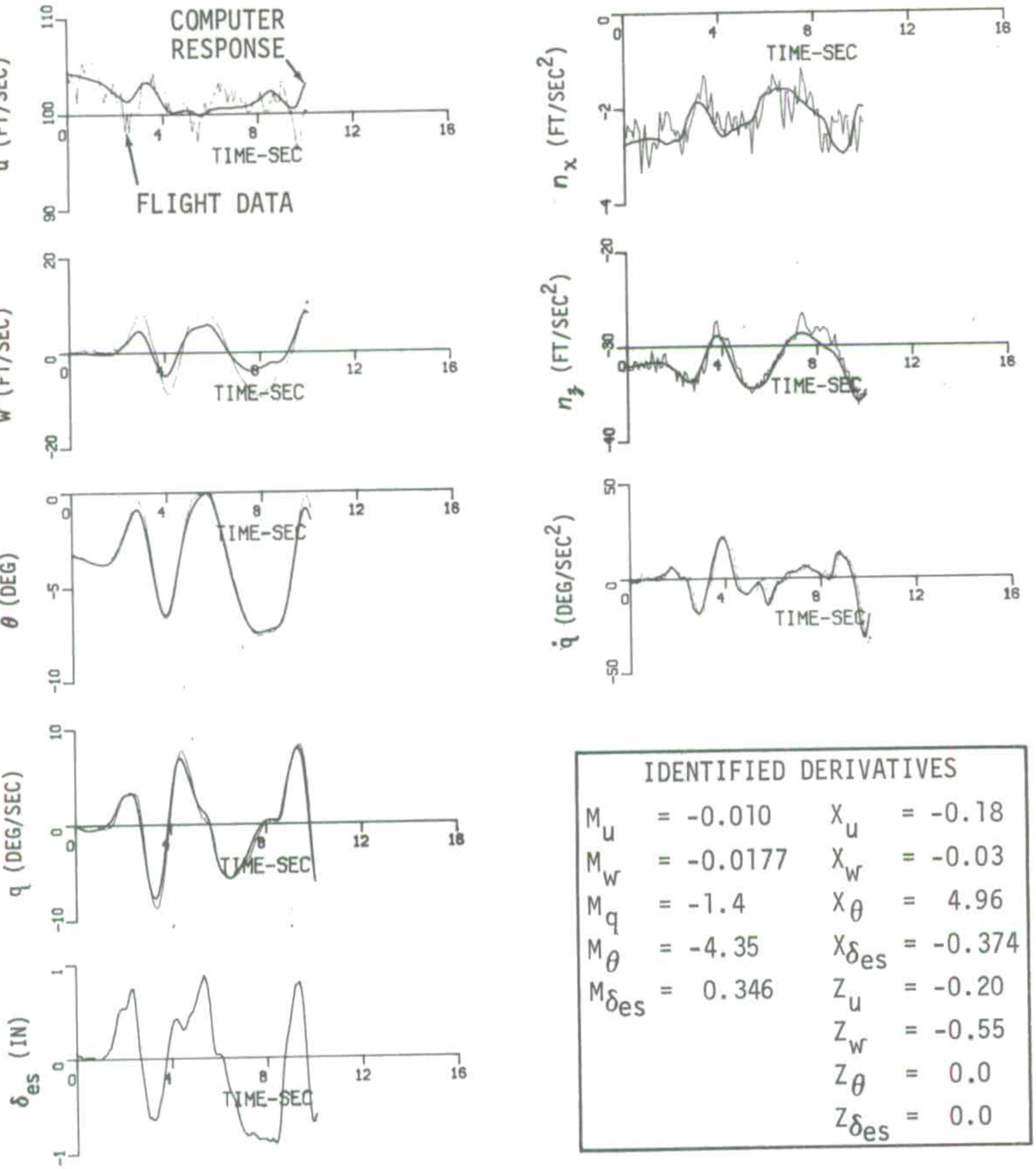
$Y_v = -0.060$

$Y_p = 1.67$

$Y_r = -1.68$

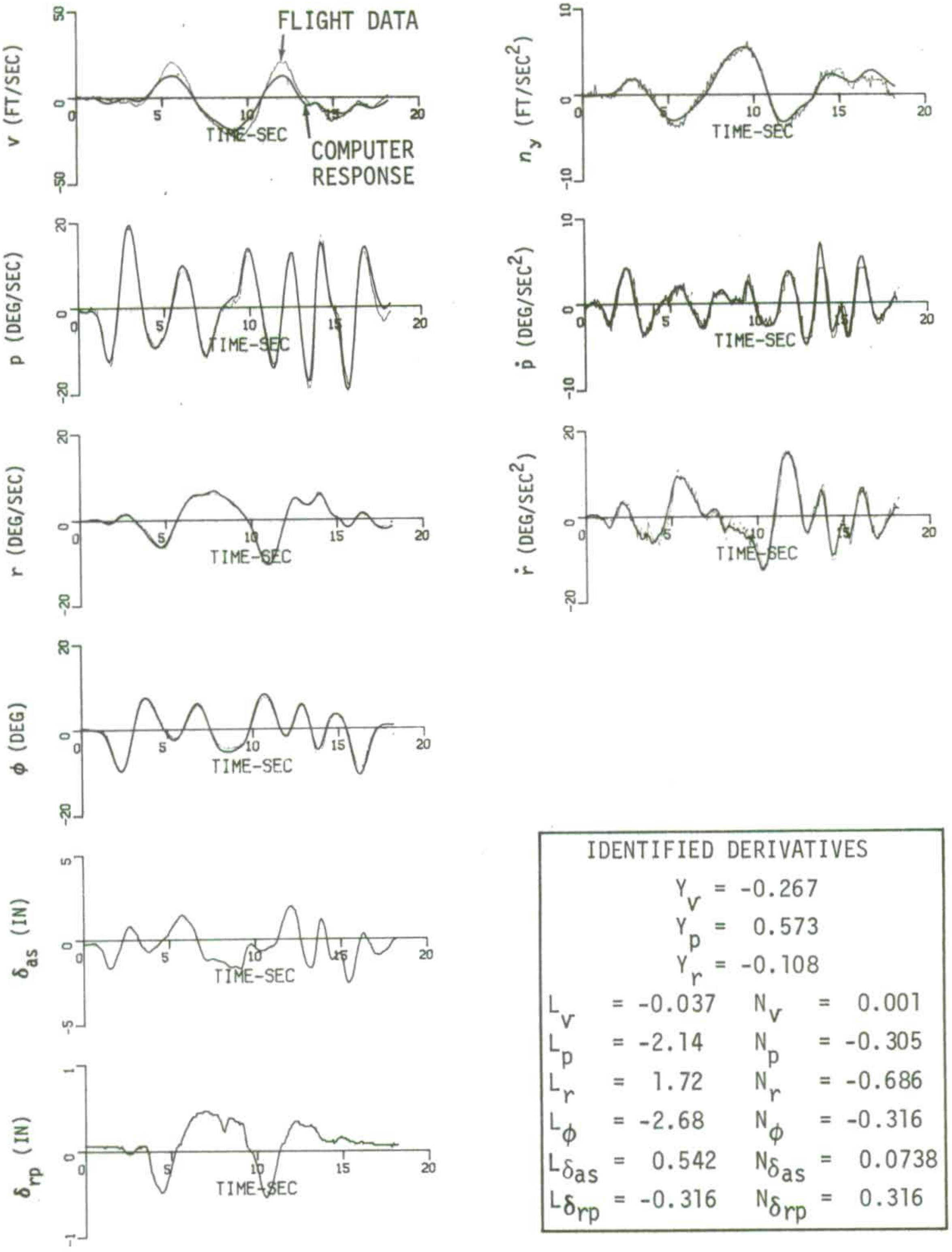
L_v	= -0.0151	N_v	= 0.00107
L_p	= -1.40	N_p	= -0.156
L_r	= -0.389	N_r	= -0.904
L_ϕ	= -2.83	N_ϕ	= -0.135
$L_{\delta as}$	= 0.562	$N_{\delta as}$	= 0.0605
$L_{\delta rp}$	= 0.199	$N_{\delta rp}$	= 0.481

Figure IV-3 IDENTIFICATION OF LATERAL-DIRECTIONAL CHARACTERISTICS, 90°/0 KT



IDENTIFIED DERIVATIVES			
M_u	= -0.010	X_u	= -0.18
M_w	= -0.0177	X_w	= -0.03
M_q	= -1.4	X_θ	= 4.96
M_θ	= -4.35	$X_{\delta_{es}}$	= -0.374
$M_{\delta_{es}}$	= 0.346	Z_u	= -0.20
		Z_w	= -0.55
		Z_θ	= 0.0
		$Z_{\delta_{es}}$	= 0.0

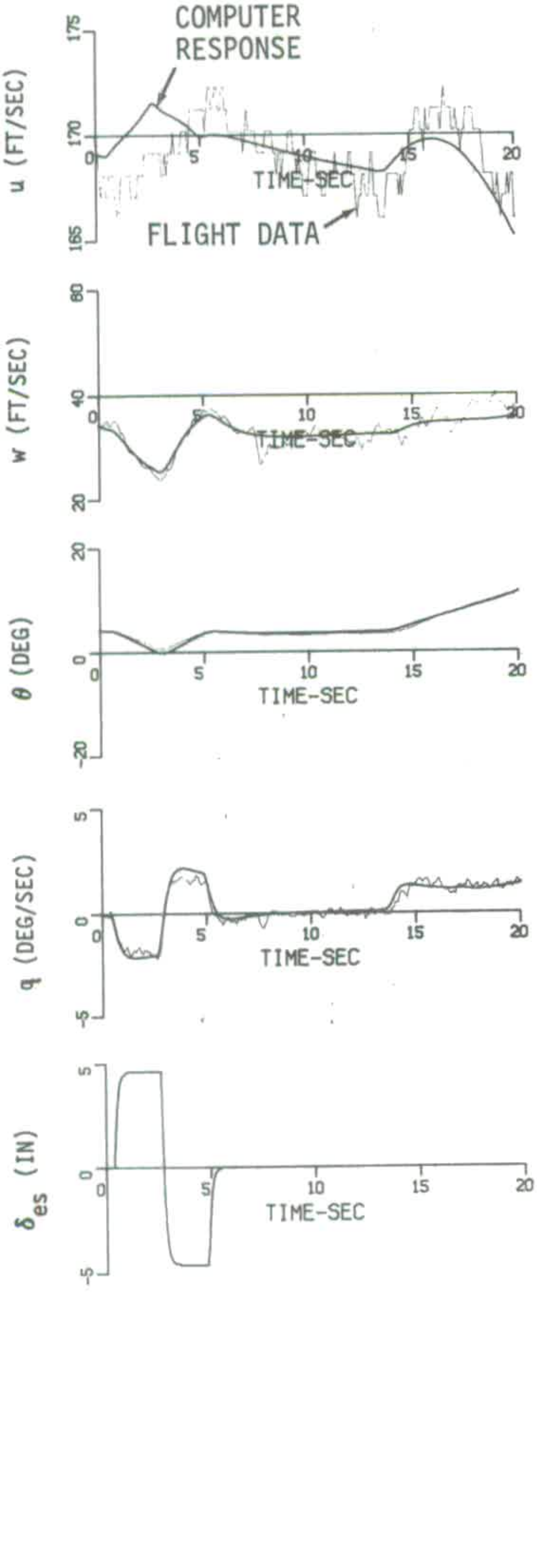
Figure IV-4 IDENTIFICATION OF LONGITUDINAL CHARACTERISTICS, 50°/65 KT

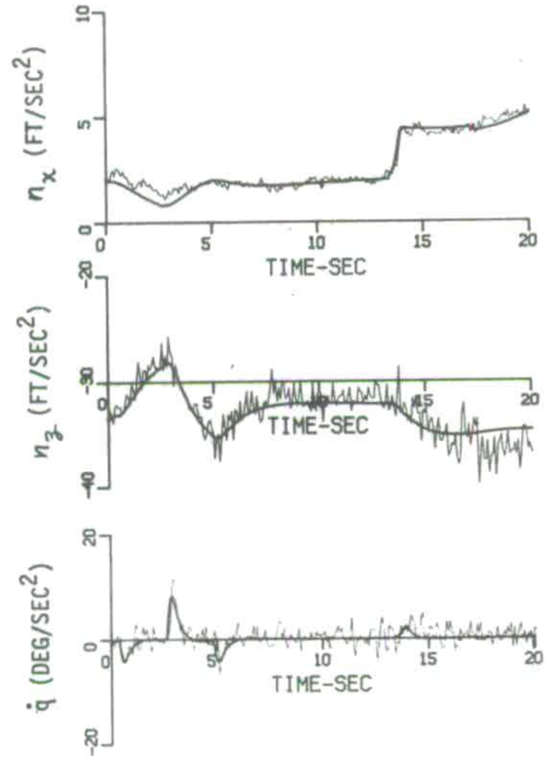


IDENTIFIED DERIVATIVES

	$Y_v = -0.267$		
	$Y_p = 0.573$		
	$Y_r = -0.108$		
L_v	$= -0.037$	N_v	$= 0.001$
L_p	$= -2.14$	N_p	$= -0.305$
L_r	$= 1.72$	N_r	$= -0.686$
L_ϕ	$= -2.68$	N_ϕ	$= -0.316$
$L_{\delta_{as}}$	$= 0.542$	$N_{\delta_{as}}$	$= 0.0738$
$L_{\delta_{rp}}$	$= -0.316$	$N_{\delta_{rp}}$	$= 0.316$

Figure IV-5 IDENTIFICATION OF LATERAL-DIRECTIONAL CHARACTERISTICS, 50°/65 KT

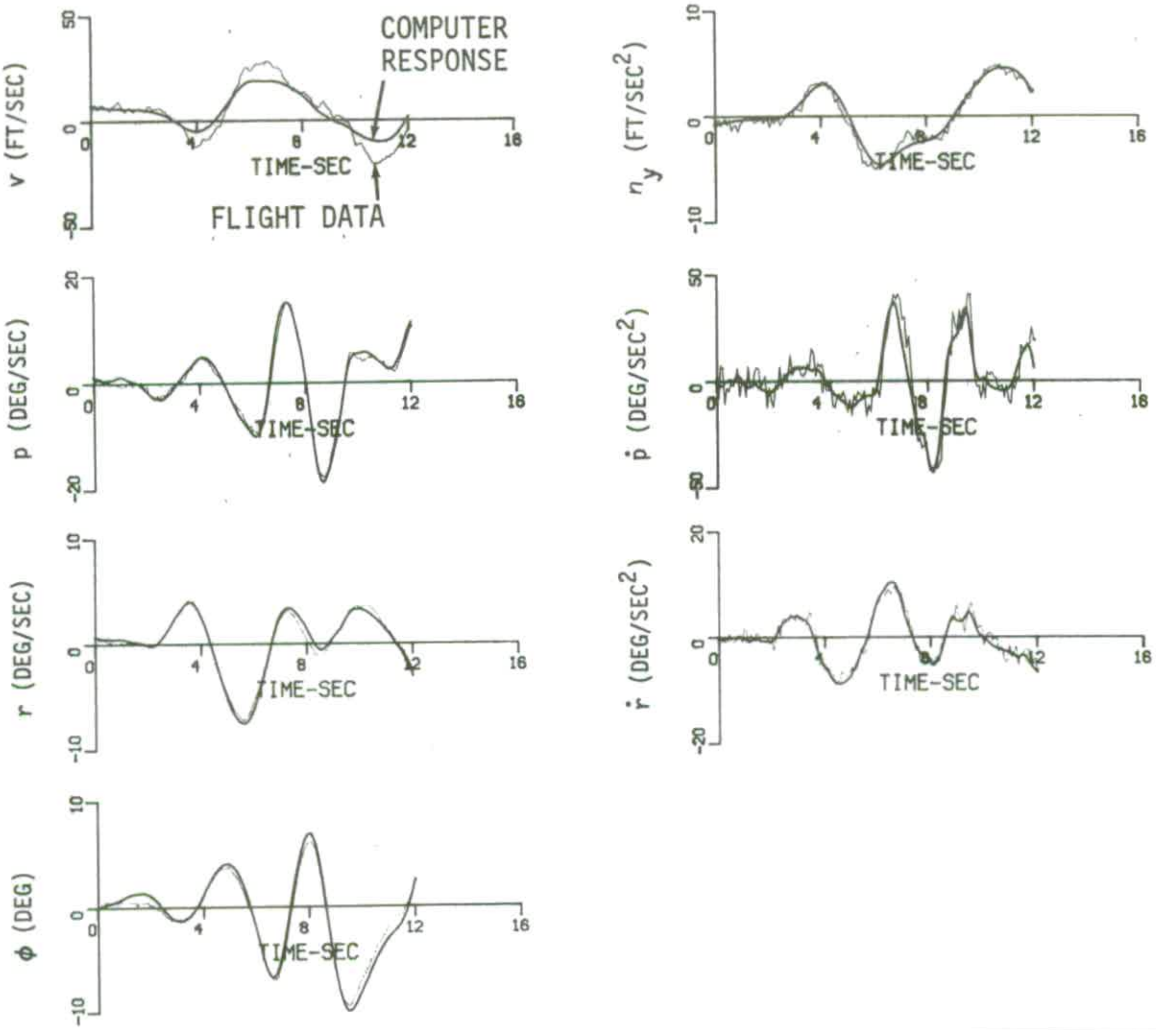


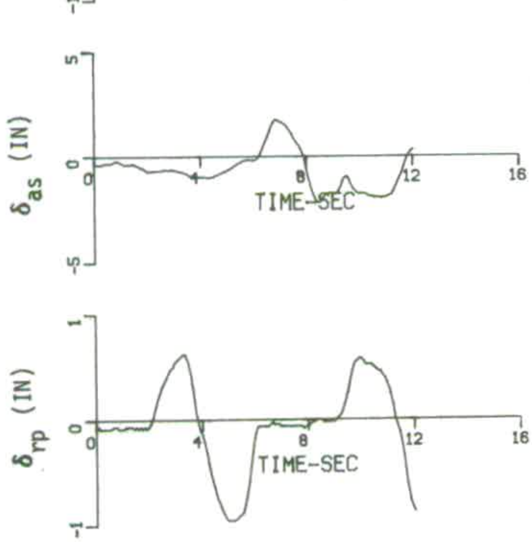


IDENTIFIED DERIVATIVES

M_u	= -0.0066	X_u	= -0.19
M_w	= -0.0049	X_w	= 0.087
M_q	= -3.16	X_θ	= ——
M_θ	= ——	$X_{\delta es}$	= 0.185
$M_{\delta es}$	= 0.378	Z_u	= -0.26
$M_{\delta cs}$	= 0.0462	Z_w	= -0.65
$X_{\delta cs}$	= 1.40	Z_θ	= ——
$Z_{\delta cs}$	= -0.45	$Z_{\delta es}$	= 0.768

Figure IV-6 IDENTIFICATION OF LONGITUDINAL CHARACTERISTICS, 15°/100 KT





IDENTIFIED DERIVATIVES

$Y_v = -0.30$

$Y_p = 0.347$

$Y_r = -1.49$

L_v	= -0.0386	N_v	= -0.00118
L_p	= -2.52	N_p	= -0.432
L_r	= 2.178	N_r	= -0.298
L_ϕ	= -2.87	N_ϕ	= -0.456
$L_{\delta_{as}}$	= 0.455	$N_{\delta_{as}}$	= 0.0775
$L_{\delta_{rp}}$	= -0.215	$N_{\delta_{rp}}$	= 0.122

Figure IV-7 IDENTIFICATION OF LATERAL-DIRECTIONAL CHARACTERISTICS, 15°/100 KT

It will be noted that the collective stick derivatives ($X_{\delta_{cs}}$, $Z_{\delta_{cs}}$, $M_{\delta_{cs}}$) are not identified from the records shown in this Appendix for $\lambda = 50^{\circ}$ and 90°; since no collective input was applied. These derivatives were obtained from separate records using sharp pulse inputs. In addition, attempts to identify duct angle effectiveness (X_{λ}, Z_{λ}, M_{λ}) derivatives were only marginally successful, and are not included; these derivatives are not particularly identifiable because the nature of the duct angle controller (constant rate of ± 5 deg/sec) does not permit well-tailored (e.g. sharp pulse) inputs. The values used in the design of the decoupled velocity control system (Section V) were therefore estimated by comparing the identification attempts with values from the ground simulator model (Reference 12), and weighting the latter more heavily; the values used are given in Section V.

As can be seen from the figures, the time history matches are quite good at all three flight conditions, which lends confidence to the derivative results. Further verification is possible for the $\lambda = 50^{\circ}$ cases by comparing these results to those obtained in the previous two STOL X-22A programs which were conducted at this flight condition (References 10, 11); for example, Configuration 14 of Reference 10 used rate feedback only, and the derivative results given here agree well with those for this configuration. This generally good correlation in derivative estimates over a span of several programs is indicative of the validity of the identification technique and procedures used in this experiment.

APPENDIX V

PILOT COMMENTARY

Summaries of all the pilot comments for the configurations evaluated in this experiment are presented in this appendix. These summaries were prepared from transcriptions of the tape-recorded comments made by the pilot at the conclusion of each evaluation as was discussed in Section VIII of this report. With respect to the Pilot Comment Card presented in Section 8.6, the summaries correspond directly to the major headings on the card; answers to some of the detailed questions (e.g. Aircraft Response particulars) are, however, grouped under the major heading only instead of being separated.

The comments as presented here are either direct quotations or minor paraphrasings of the actual transcriptions. In cases where it might not be clear from the recorded comments exactly what the pilot meant, explanatory editorial phrases are included in parentheses for clarity. In addition, any cases in which the system implementation or evaluation procedure differed from those discussed in Sections IV, V, VI, and VIII are noted in the summaries and summarized below:

- The sense of the altitude error diamond was "fly from" for flights F-108, F-120, and F-121 (five evaluations) and "fly to" for the remainder of the flights.
- The evaluations of the DVC control system on flight F-141 did not have the "Hover Mode" (increased velocity display sensitivity in the hover) available to the pilot.
- The second DVC:ED2 evaluation on flight F-141 was intended to be DVC:ED2+ and the pilot was so briefed; an incorrectly set potentiometer resulted in the ED2 display.
- The ATT/RATE:ED3 evaluation in flight F-133 was performed with a VBAR gain (δ_{as} control director) set too low by a factor of 1.75; this evaluation is not included in the data analyses.

The table at the top of each page of comments gives the control system and display presentation implemented for the evaluation. Note that the AUTO control system evaluations are designated here as attitude command with automatic duct rotation to correspond with the implementation of this system (i.e. AUTO is not called out separately). Also included are the measured estimates of winds and turbulence, which are discussed in Appendix VII.

CONTROL SYSTEM:	Rate Augmentation	PILOT RATING:	4B
DUCT ROTATION:	Manual	HEADWIND:	25.0
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	4.4(R)
ADI NEEDLES:	Off	TURBULENCE:	----
ITVIC:	On	FLIGHT NO:	F-108

GENERAL: Some aircraft system problems today. Airspeed tracking on horizontal needle not working up and away, but frankly it didn't bother me. Pitch attitude control doesn't feel precise without the bar, however. Very little wind. Pilot O.K.

APPROACH PERFORMANCE:

INTERCEPTION: Relatively easy for both localizer and glide slope.

TRACKING: Was able to track both localizer and glide slope very well. The localizer is a bit too sensitive. Deceleration profile quite reasonable. Approach was easy to perform.

HOVER: Problem with the heading and knowing which way to go. The director needles didn't seem to help. I look at the airplane symbol to drive up to the spot. I am getting a lot of good information from the velocity vector, however, and using it could get to the spot and stopped.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal and lateral forces good, no complaints. Don't like having to use the rudder so much to turn. Collective was good, I had good altitude control. No coupling between collective and other controls that I could see.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Needed the ITVIC light, don't think I would have stayed on the profile well without it. The display is coordinated with the control motions, although I didn't like the vertical bar too well.

ADI: Used in up and away, not on the last part.

FLIGHT DIRECTOR: Good except sensitivity of vertical bar.

SCAN: I use peripheral instruments up and away but not as I get to the hover.

SUMMARY: Adequate performance is attainable. I don't like the rudders, and I had some problems interpreting the display in the hover. Moderate pilot compensation required but it doesn't affect my mission accomplishment.

CONTROL SYSTEM:	Rate Augmentation	PILOT RATING:	4C
DUCT ROTATION:	Manual	HEADWIND:	17.6
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	10.1(L)
ADI NEEDLES:	Off	TURBULENCE:	2.8
ITVIC:	On	FLIGHT NO:	F-121

GENERAL: Like the control feel and forces. Lack of attitude stabilization is noticeable, but I did not have any troubles with the roll as I'd thought I might. Approaches were good. Display fine. Winds not a factor. Pilot O.K..

APPROACH PERFORMANCE:

INTERCEPTION: Very easy and natural for both localizer and glide slope, very airplane-like.

TRACKING: Glide slope and localizer tracking very easy tasks. The needles act like a flight director should, and it is very natural. Deceleration profile no problem.

HOVER: A bit of a problem. Tendency to overcontrol pitch because displayed motion reacts so slowly and I kept wanting to move aircraft. Don't get force feedback to help with the attitude, and attitude was more of a problem with this configuration.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal and lateral very good. Forces light and comfortable. Didn't have to hold airplane in turns with lateral stick or have longitudinal stick pushing at me when I make pitch changes during the approach. Had to use rudders to turn, didn't seem to need them much for localizer tracking. Collective technique very natural, no coupling that I could see.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Very good. I could follow the vertical and horizontal needles easily. Sensitivity was fine. I think I would prefer the opposite sense on the altitude error diamond, however.

ADI: Necessary up and away. Didn't use it on the approach because the vertical needle gave me satisfactory bank angle information.

FLIGHT DIRECTOR: Very good. Proper directions and very comfortable.

SCAN: Use the ADI as a bank angle reference and some for pitch attitude.

SUMMARY: Up and away it's very good. Good localizer tracking. I'm going to down rate it for the hover, however; I think there is a real tendency to overcontrol it in hover. I may even be a little easy on it. Fair amount of turbulence, not too much of a problem. No significant simulation deficiencies.

CONTROL SYSTEM:	Rate Augmentation	PILOT RATING:	7B
DUCT ROTATION:	Manual	HEADWIND:	-9.9
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	10.8(R)
ADI NEEDLES:	Off	TURBULENCE:	2.3
ITVIC:	On	FLIGHT NO:	F-130

GENERAL: Aircraft comfortable up and away. Display O.K.. Winds not much of a factor. Pilot depressed.

APPROACH PERFORMANCE:

INTERCEPTION: Quite easy for both localizer and glide slope, no problem knowing when to start down.

TRACKING: Glide slope easier than localizer. Lack of good bank attitude information on electronic display gives difficulty in keeping wings level, have to look at ADI and therefore get behind on localizer tracking. Very difficult to keep up with deceleration profile, particularly in getting the attitude-speed problem solved and keep heading right. Heading is biggest problem.

HOVER: Very depressing. Can't get heading rotation and bank angle problems solved and get airplane back over spot. Pitch control gets bad because of concentration on bank and heading, get $\pm 15^{\circ}$ pitch changes. Not possible to do the job.

LANDING POSSIBLE?: No.

AIRCRAFT RESPONSE: No complaints up and away. Airplane appears to have adverse yaw, keep tending to use rudder with lateral stick in hover; that transition in control technique is too much to ask of a pilot. Collective O.K., could keep up with commands, but get way behind when concentrating on rudder and lateral stick in hover. Rudder control a problem in hover; had to think about stopping rotation of RMI, then control of lateral position and height control last.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Electronic display does not give good enough roll information, and vertical needle seems too sensitive. Can not convert the information into aircraft control situation, particularly in hover. Heading information also minimal in hover (with earth-referenced format, did not switch to heading reference). Can't get heading rotation straightened out.

ADI: Needed for bank angle control.

FLIGHT DIRECTOR: O.K.. Sensitive in lateral – hard to tell if it is pilot problem or sensitivity of needle, but it moves a lot.

SCAN: Problem. Have to keep RMI in mind, use ADI for bank.

SUMMARY: Not acceptable for flight, hover ruins the whole thing. Turbulence not much of a factor, does rock wings a little.

CONTROL SYSTEM:	Rate Augmentation	PILOT RATING:	7C
DUCT ROTATION:	Manual	HEADWIND:	-4.5
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	6.9(R)
ADI NEEDLES:	Off	TURBULENCE:	3.2
ITVIC:	On	FLIGHT NO:	F-140

GENERAL: Not a bad airplane up and away except I don't like the amount you have to use your feet and the amount of rudder force. Airplane doesn't react as far as the ride qualities are concerned. Winds a problem in the hover, not so much up and away although I can't fly as tight as I want to. Pilot proud of himself for making it!

APPROACH PERFORMANCE:

INTERCEPTION: No problem in general. Have to watch attitude more carefully than with attitude command airplanes, can't just trim in an attitude.

TRACKING: Not as easy as desired, although could do it and make reasonably nice approach. Deceleration profile workload gets really high and you have to sacrifice some things. I cheat by staying high until I get the longitudinal and lateral problems solved, and then get down to the altitude I want.

HOVER: Biggest problem because of having to solve the heading problem. Had it solved on first approach, drifted off the spot on the second. Hover performance very, very poor, not acceptable.

LANDING POSSIBLE?: No.

AIRCRAFT RESPONSE: Light longitudinal and lateral stick forces, comfortable up and away but very complicated in hover when you are really having to provide the attitude stabilization: you have to spend a lot of time on the attitude indicator to provide that stabilization. Collective no problem — it does couple with pitch response and you have to make a correction at the beginning of the transition, but I am ahead of that most of the time. Rudders are a problem. Heavy up and away, requires a lot of rudder to get it around. Have to keep using feet in hover to stay pointed into wind so you can solve problem of getting over the pad.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Good, sensitivities no problem, coordinated with control motions.

ADI: Attitude indicator is a must. My technique is to use the ADI as a primary instrument and electronic display secondary. The problem is that you want to center horizontal bar (longitudinal stick control director) but it seems that you will then get large attitudes. I don't trust the horizontal bar to keep the attitude within its proper range is the problem, and have to go to attitude indicator to keep pitch attitude within limits and just let the horizontal bar drift off.

FLIGHT DIRECTOR: Good information except I lagged pitch bar as discussed.

SCAN: Used basic instruments as primary instruments, used electronic display to update the situation. Am very reluctant to get it down to altitude, and so solve that problem last.

SUMMARY: Couldn't land the airplane, it isn't acceptable for hover. Turbulence light, moderate effect.

CONTROL SYSTEM:	Rate Augmentation	PILOT RATING:	7A
DUCT ROTATION:	Manual	HEADWIND:	-5.6
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	11.8(R)
ADI NEEDLES:	Off	TURBULENCE:	2.6
ITVIC:	On	FLIGHT NO:	F-130

GENERAL: Aircraft easy to fly up and away. Display O.K.. No noticeable wind at altitude, problem in hover figuring out where it's coming from. Pilot O.K..

APPROACH PERFORMANCE:

INTERCEPTION: Very good for both localizer and glide slope, very much like flying a normal ILS. Do spend a fair bit of time flying basic instruments, however.

TRACKING: First part easy for both localizer and glide slope, but get saturated at lower part. Big problem keeping up with bank angle, get off on localizer. Glide slope with collective not difficult to fly. Keeping vector in diamond a bit difficult because wings get away. Felt the tracking was done pretty well.

HOVER: Really had troubles. Biggest problem is control of bank attitude and heading. Airplane turned faster than could control. Had two problems: would bank aircraft to get over spot but would find heading changing also, couldn't get the problem solved. When did get over spot, would have altitude off, get excessive rates of sink.

LANDING POSSIBLE?: No — couldn't solve heading well enough to control longitudinal and lateral attitudes.

AIRCRAFT RESPONSE: Longitudinal and lateral forces light and comfortable, easy to fly up and away. Collective was good — easy to follow commands. Attitude control got away in hover. Had to use rudder considerably up and away, although forces were comfortable. Problem is tendency to keep doing it in hover: when you put lateral input in, tend to push rudder, aircraft keeps turning.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Electronic display giving good information — no problem. ITVIC light is a must. Display is coordinated with motions.

ADI: Had to use quite a bit for bank angle control.

FLIGHT DIRECTOR: Velocity command is good unless I get way off in which case can't judge longitudinal corrections required if vector isn't in diamond.

SCAN: Bit of a problem, particularly in hover.

SUMMARY: Can not do precision hover portion of task. Don't think adequate performance attainable, don't think information is available to solve the problems. Even though the aircraft is good up and away, it is destroyed by inability to do precision hover. Turbulence influence is nil.

CONTROL SYSTEM:	Rate Augmentation	PILOT RATING:	8E
DUCT ROTATION:	Manual	HEADWIND:	19.0
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	6.0(R)
ADI NEEDLES:	Off	TURBULENCE:	3.4
ITVIC:	On	FLIGHT NO:	F-132

GENERAL: If you want me to cry wolf and say I couldn't do it, I'm afraid I'm going to have to say that! Airplane response good up and away, but I have to keep my eyes right on the ADI: I don't get any feedback from the feel of the inputs as to what the aircraft is doing. Electronic display a bit of a problem because using the stick alone to keep the velocity vector in the diamond leads to getting extreme attitudes: you have to do more than just move the stick.

APPROACH PERFORMANCE:

INTERCEPTION: Not good. It was obvious when to start down, and I would, but the next thing I'd know I'd be leveling off or starting back the other way.

TRACKING: Major problem. Glide slope required constant vigilance on ADI, tried to use ADI mostly up and away like flying an ILS, but that just didn't work when I got into the deceleration profile. Things happened too fast to keep up with, and both times I think I would have lost control of it at the end.

HOVER: Never got to precision hover — I wasn't good enough to get it there.

LANDING POSSIBLE?: No.

AIRCRAFT RESPONSE: Longitudinal and lateral good up and away through initial part of localizer and glide slope interception if I flew it like an airplane. Couldn't hack deceleration profile or hover. Needed lots of rudder pedals up and away, but inputs were in right direction and it wasn't a problem. Got way behind on collective because I couldn't scrutinize electronic display closely enough since I had to concentrate on the ADI. Got large corrections required and was always behind.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Electronic display became kind of secondary to flying the airplane. I couldn't use it for attitude control. Sensitivities seemed about right.

ADI: It was almost a primary instrument. Certainly necessary.

FLIGHT DIRECTOR: Good information except I needed attitude information.

SCAN: ADI primary, electronic display secondary. Lots of problems and needed lots of peripheral instruments.

SUMMARY: Didn't do a very good job. Adequate performance was certainly not attainable. Pilot control was a problem because I lost control both times. Pilot rating based on fact that you really have to pay attention to get control of aircraft. It was turbulent and windy, today was little bit unfair, and I haven't flown it for two weeks. Turbulence was noticeable and had a considerable effect on my performance.

CONTROL SYSTEM:	Rate Augmentation	PILOT RATING:	8½F
DUCT ROTATION:	Manual	HEADWIND:	21.3
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	1.8(L)
ADI NEEDLES:	Off	TURBULENCE:	3.6
ITVIC:	On	FLIGHT NO:	F-134

GENERAL: Airplane response for this configuration in this level of turbulence borders on the ridiculous. Can't get good enough pitch and bank attitude information off electronic display, had to use ADI as primary instrument, electronic display secondary. Wind strong and gusty, pilot saying "Why me?"

APPROACH PERFORMANCE:

INTERCEPTION: Not too bad. Flies like an airplane, got started down in good fashion.

TRACKING: Not too bad until deceleration. First approach I lost control of pitch attitude, got behind on duct rotation while trying to recover, never got to the hover. Kept up with second one by flying primarily the ADI and then using the electronic display secondary. By putting primary emphasis on attitude control I at least got to the spot.

HOVER: A bit ridiculous. The strong wind helped me stay turned into the wind to minimize yawing problem but I still couldn't really stop the vector from rotating around. Just played around the spot, performance was very poor.

LANDING POSSIBLE?: No.

AIRCRAFT RESPONSE: Longitudinal and lateral forces light, airplane reasonably responsive though not really fast, comfortable. Lack of attitude stabilization is a real problem in the hover for me. Keeping up with collective was one of the easier parts of the task even though you get behind so quickly I didn't do a good job. Rudder pedals used, were a bit of a problem, not very good in solving yawing problem in hover.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Electronic display was used secondarily – I emphasize that. ITVIC used for rotation. Sensitivity O.K., coordinated with motions.

ADI: Primary instrument.

FLIGHT DIRECTOR: Information good, but get behind quickly when devoting so much attention to attitude. Used only secondarily.

SCAN: Is a problem. Have to pick up information quickly which isn't easy to do.

SUMMARY: It is controllable if you are really compromising on the experiment (the task). Adequate performance is not attainable, deficiencies require improvement. Considerable pilot compensation required simply to maintain control of aircraft. I didn't like it at all. Turbulence compromised evaluation, had a major effect, intolerable.

CONTROL SYSTEM:	Rate Augmentation	PILOT RATING:	7A
DUCT ROTATION:	Manual	HEADWIND:	16.0
ED FORMAT:	Velocity Command (ED2)	CROSSWIND:	7.6(R)
ADI NEEDLES:	Off	TURBULENCE:	2.0
ITVIC:	On	FLIGHT NO:	F-124

GENERAL: Like airplane up and away, smooth and comfortable, nice light forces, reacts like an airplane, gives me feedback from the stick position and forces, very nice.

APPROACH PERFORMANCE:

INTERCEPTION: No problem for either localizer or glide slope.

TRACKING: Easy for both, although occasionally have to cross check ADI for bank angle. Deceleration profile no problem — can make nice smooth corrections and stop airplane where desired.

HOVER: Really a problem. Hard to get enough attitude information from electronic display. Performance very poor, got large attitudes trying to get to and stay over spot.

LANDING POSSIBLE?: No. Poor attitude control makes airplane move left and right too quickly.

AIRCRAFT RESPONSE: Really liked longitudinal and lateral response. Nice collective control — I understand this display well enough to know what to do. No serious coupling between collective and pitch, although several times I did make noticeable pitch trim changes. Rudders have to be used, particularly up and away but also on the localizer, and it's a noticeable problem.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Could keep up with display. Sensitivity satisfactory. Particularly like the directional and velocity profile presentation. Display is coordinated with motions. Some difficulty tracking localizer because tendency is to leave in a bank angle. Only real problem was attitude in hover.

ADI: Used during approach to check on bank attitude. Became more necessary in hover.

FLIGHT DIRECTOR: ------

SCAN: Scan to ADI for attitude information in hover created a problem in keeping over spot.

SUMMARY: Pilot rating is a dilemma because I really liked it up and away but the hover is unsatisfactory. I don't think I could get the airplane over the spot and landed. The display-airplane combination is not adequate to complete the precision hover and landing. Very little turbulence and no effect.

CONTROL SYSTEM:	Rate Augmentation	PILOT RATING:	7½B
DUCT ROTATION:	Manual	HEADWIND:	-9.4
ED FORMAT:	Position only (ED1)	CROSSWIND:	14.0(R)
ADI NEEDLES:	On	TURBULENCE:	2.7
ITVIC:	On	FLIGHT NO:	F-130

GENERAL: Aircraft easy to fly up and away, but overcontrol a problem in the hover. Don't have good information — display is minimal. Winds not a factor. Pilot shaken.

APPROACH PERFORMANCE:

INTERCEPTION: Quite good for both localizer and glide slope. Like aircraft up and away. Did good job because ADI is primary instrument since the flight director information is on its needles.

TRACKING: A problem for both, particularly localizer because it is very sensitive up and away, small bank angles move needle back and forth. Not too bad until start decelerating and then get behind quickly, although that part is still acceptable.

HOVER: A real problem. Don't have enough information to get over the spot and stay there. Lack of velocity information big problem. Can not kill lateral and longitudinal motions.

LANDING POSSIBLE?: No.

AIRCRAFT RESPONSE: Longitudinal and lateral easy to fly up and away. Require rudder with lateral stick, which causes problem when hovering since there is a tendency to continue "coordinating" with rudder. Airplane therefore continuously turning, make conscious effort to look at RMI to stop and then get off spot. Felt coupling between collective and airplane motions, required constant trimming adjustments.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Electronic display useless up and away, minimal usefulness in hover. Coordinated with motions.

ADI: Primary instrument. Used flight director information on it. Helps keep track of bank angle up and away but not much help in hover.

FLIGHT DIRECTOR: ------

SCAN: Problem because of need to go between ADI, RMI, and electronic display in hover.

SUMMARY: Concerned about longitudinal and lateral attitudes in hover, verged on having control problems. Could make approach safely but could not hover and got large pitch and roll motions. Turbulence negligible although some influence.

CONTROL SYSTEM:	Attitude/Rate Command	PILOT RATING:	3D
DUCT ROTATION:	Manual	HEADWIND:	22.4
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	13.2(L)
ADI NEEDLES:	Off	TURBULENCE:	3.3
ITVIC:	On	FLIGHT NO:	F-128

GENERAL: Like airplane up and away, particularly in roll. Turbulence seems to rock the wings a bit, requiring more concentration. Good information on display – got off track and was able to get back on. Fairly good wind at altitude, but not bad. Pilot O.K..

APPROACH PERFORMANCE:

INTERCEPTION: No problem with either glide slope or localizer. Easy to comprehend what you're doing.

TRACKING: Glide slope tracking good. Localizer a problem because turbulence oscillates aircraft in roll and vertical bar quite sensitive. Turbulence inputs move the bar too much. Tendency is to lag vertical bar to see if movement is caused by turbulence and therefore get behind on localizer. Deceleration profile O.K..

HOVER: Some tendency to lay off a wing, which requires checking the ADI. Not a big problem.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal good – fairly stiff, use trim quite a bit. Lateral very light; good control, but have to pay more attention to it because of turbulence. Collective good – easy to follow flight director, easy to tell when you're getting off. Tried to use rudders to help with localizer tracking, but that complicated things more than helping.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Vertical bar is too sensitive in turbulence. Display is well coordinated with motion, airplane can be put where desired.

ADI: Needed at altitude, used in hover to keep wings level.

FLIGHT DIRECTOR: Good information. Vertical bar is too sensitive.

SCAN: Have to keep track of bank attitude.

SUMMARY: Airplane is acceptable and satisfactory. Sensitivity of vertical bar in turbulence is mildly unpleasant deficiency, but requires only minimum pilot compensation. Moderate turbulence affects the airplane quite a bit – I have to compensate and it affects my performance.

CONTROL SYSTEM:	Attitude/Rate Command	PILOT RATING:	6B
DUCT ROTATION:	Manual	HEADWIND:	7.8
ED FORMAT:	Control Directors (ED3)*	CROSSWIND:	3.9(L)
ADI NEEDLES:	Off	TURBULENCE:	2.2
ITVIC:	On	FLIGHT NO:	F-133

*Different VBAR gains implemented.

GENERAL: Airplane response was a problem. Strong tendency to overbank, pitch wasn't as tight as desired. Continuous roll inputs either for small stability problem or just overcontrolling the airplane. Display good — I like the director display. Winds steady at 10, not a factor. Pilot not a factor.

APPROACH PERFORMANCE:

INTERCEPTION: Tendency to overbank for localizer acquisition because needle asks for large inputs. Once on localizer, however, bank angle seemed to be directly correlated with vertical needle, bank control wasn't much of a factor during tracking.

TRACKING: Glide slope not difficult to track — good information from collective command. Vertical needle helps localizer tracking. Deceleration profile reasonable — biggest problem was keeping everything coordinated together and get near spot for hover.

HOVER: A bit of a problem. Trying to use force input for lateral corrections leads to overbanking. On second approach, tried to correct heading with rudders while still in ATC, got rudders and stick working against each other and drifted quite a ways off the landing pad with a very large bank angle. I probably wouldn't have had this problem if I'd switched to HH as I did on the first approach. Anyway, hover was a problem because of overbank tendency. Didn't notice pitch problem I thought I'd seen up and away.

LANDING POSSIBLE?: It would be possible if you were very careful, because you get large lateral motions going with the light controls.

AIRCRAFT RESPONSE: Longitudinal response seemed a little slow, lightish forces up and away. Some overcontrolling up and away, not so much on approach and hover. Overcontrol on lateral — good chance to play fighter pilot in the X-22A! Collective good because of the director display — I can keep up with it very nicely and know exactly where to put control rather than guessing where something is going to drift. Rudder pedals not a factor except for trying to make heading corrections in hover while still in ATC instead of HH. I don't think you should be that dependent on changing modes.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Very good information. Duct rotation command from ITVIC no problem. Sensitivities seemed good, coordinated with motion. The vertical needle sure did keep bank angle under control on the approach, but less good in hover because I don't use the flight director much there — I tend to use horizontal situation information to get lined up and I did overcontrol it.

ADI: A "must". Airplane felt spirally unstable up and away, although that's purely engineering supposition on my part. I did overbank it.

FLIGHT DIRECTOR: Good — really helped with bank angle control on the approach.

SCAN: A problem in hover when you have to keep up with the ADI while trying to control altitude within a few feet.

SUMMARY: All the preceding comments sound totally negative, but I do think that you can perform the mission, you could get it into the hover, adequate performance is attainable. I do not feel it is satisfactory without improvement. I think it was very objectionable, I didn't like the tendency for airplane to get away from me after I'd convinced myself I was doing a good job. Very little turbulence, did affect evaluation, was noticeable but light, negligible.

CONTROL SYSTEM:	Attitude/Rate Command	PILOT RATING:	3C
DUCT ROTATION:	Manual	HEADWIND:	0.0
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	8.7(R)
ADI NEEDLES:	Off	TURBULENCE:	3.2
ITVIC:	On	FLIGHT NO:	F-142

GENERAL: Airplane response very solid in pitch, a little rolly in roll, very light roll stick forces which I enjoy. Display good. Interesting comment is that I have flown mostly automatic rotation recently and therefore forgot about the (ITVIC) light on first approach, got nose high and really into a bind. Kept up with it after that. Winds a little problem at bottom, not significant. Pilot in good shape.

APPROACH PERFORMANCE:

INTERCEPTION: Localizer no problem. Some tendency to roller coast with collective on glide slope. Notice the lack of height damping and different collective sensitivities from previous evaluation (DVC), the previous one much better situation for collective control.

TRACKING: No problem. Some problem overbanking the aircraft, but that dissipates when I'm tracking the vertical bar closely. Deceleration profile reasonable, no problem.

HOVER: Good, feel I have more precise control of aircraft and can make it go where I want more quickly (than with DVC). Performance satisfactory.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal heavy but good, lateral nice and light, very good for up and away, quite comfortable and not much of a problem. I don't understand, though, why I didn't have to make such large pitch changes with the DVC, looks as if the duct rotation schedule is different. Collective is just a matter of following the bouncing ball, no problem. Rudder pedals not a factor.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Good. A little sensitive in collective initially but otherwise O.K.. Coordinated with control motions.

ADI: Used up and away for bank angle because of slight tendency to overbank aircraft.

FLIGHT DIRECTOR: Good, no problem.

SCAN: Not a problem, down low need to get information from places other than electronic display.

SUMMARY: A bit more attention to bank angle control is required than I'd like, is the biggest problem, is a mildly unpleasant deficiency. Turbulence is noticeable, doesn't affect the configuration very much.

CONTROL SYSTEM:	Attitude/Rate Command	PILOT RATING:	4D
DUCT ROTATION:	Manual	HEADWIND:	15.5
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	9.2(L)
ADI NEEDLES:	Off	TURBULENCE:	3.3
ITVIC:	On	FLIGHT NO:	F-128

GENERAL: Like the airplane up and away, display fine. Fair amount of turbulence affects evaluation. Pilot O.K..

APPROACH PERFORMANCE:

INTERCEPTION: Great for both localizer and glide slope. Display really tells you when to start down if you're well set up. Glide slope interception easy and good on both approaches.

TRACKING: Some problem because turbulence seems to upset roll and so the diamond gets away from the end of the vector. Result is a bit more of a problem tracking both localizer and glide slope. Deceleration profile reasonable — no problem.

HOVER: No problem once settled down. Didn't get there quite as well as desired.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal heavy, used lots of trim. Lateral is light, had to keep checking ADI since turbulence upset wings. Collective very good. Rudders no problem — not used.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Having ITVIC light is a good thing. Electronic display good if you're on track, but the lateral moves a bit when turbulence bobbles the wings and it's not as easy to interpret. The problem seems to be more the upsets than the sensitivity. Display is coordinated with motions.

ADI: Necessary, particularly up and away to keep wings from rolling off.

FLIGHT DIRECTOR: Velocity commands good if you're doing a good job, but if lateral moves off you don't have the precise pitch and velocity control I want. No interpretation problem — just tend to concentrate too much on the lateral.

SCAN: Have to keep going to the ADI.

SUMMARY: Controllable, adequate performance attainable with tolerable pilot workload. It is not satisfactory. The deficiencies warrant improvement but are only minor and annoying. Turbulence seems to upset this configuration and it did affect my evaluation noticeably. A moderate influence.

CONTROL SYSTEM:	Attitude/Rate Command	PILOT RATING:	4D
DUCT ROTATION:	Manual	HEADWIND:	22.5
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	7.7(R)
ADI NEEDLES:	Off	TURBULENCE:	4.1
ITVIC:	On	FLIGHT NO:	F-132

GENERAL: Airplane response nice up and away, display working fine. Quite a bit of wind and fairly turbulent. Haven't flown for a couple of weeks, and had some vertigo on first approach.

APPROACH PERFORMANCE:

INTERCEPTION: Localizer and glide slope interception easy to perceive. I had good set ups on both of them.

TRACKING: Localizer tracking not as easy as desired because of tendency to overbank aircraft. Didn't like first approach — got uncomfortable at the end, but liked the second approach: even though I got behind, I caught up to it. Deceleration profile reasonable, although the necessity to pay attention to rotating ducts and maintaining pitch attitude meant I tended to get behind on the lateral problem.

HOVER: Didn't like on first approach, but did a good job on the second. Tendency to overbank and get large excursions is uncomfortable but it never got out of hand and I never felt that I was going to lose it or anything.

LANDING POSSIBLE?: Yes, although getting lateral problems sorted out would have been a little bit difficult.

AIRCRAFT RESPONSE: Longitudinal response good. Lateral good up and away, nice and light on the control. Some tendency to overbank. Collective no problem, even though I tended to get behind and end up high. Rudders no problem. Some coupling of duct rotation with collective at very beginning of transition.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Good, sensitivity just about right, coordinated with motions.

ADI: Mandatory. I really needed to know my bank attitude, and had to keep going to ADI to get it.

FLIGHT DIRECTOR: Good information, never got very far off. Might have had problems if I had gotten a ways off.

SCAN: Had to keep going to ADI to get bank attitude.

SUMMARY: It is controllable. It is certainly adequate — I could do the job. It is not totally satisfactory, I don't like the tendency to overbank. Pilot rating based on that and the fact that I had problems in the hover on the first approach. Fairly turbulent, does roll airplane and that's the biggest problem. It affected the evaluation noticeably and had a moderate effect on my performance.

CONTROL SYSTEM:	Attitude/Rate Command	PILOT RATING:	5D
DUCT ROTATION:	Manual	HEADWIND:	25.0
ED FORMAT:	Velocity Command (ED2)	CROSSWIND:	4.4(R)
ADI NEEDLES:	Off	TURBULENCE:	----
ITVIC:	On	FLIGHT NO:	F-127

GENERAL: Like the airplane up and away. Like the control forces, it's comfortable. Display fine. Pretty strong winds, not too much turbulence down low. Had problems with control tower today, so evaluation not really satisfactory. Pilot O.K..

APPROACH PERFORMANCE:

INTERCEPTION: Just great for both localizer and glide slope. Second approach had best yet. Easy to fly.

TRACKING: Early part easy, feels like normal ILS on a decent airplane. Once deceleration starts, however, I tend to get behind on localizer tracking because I can't keep up with bank angle. Have to pay a lot of attention to bank attitude, and that information on electronic display isn't good enough. Pitch is not a problem.

HOVER: Tower wouldn't let us hover enough to give any useful information.

LANDING POSSIBLE?: Can't answer.

AIRCRAFT RESPONSE: Liked both longitudinal and lateral, particularly light roll forces. Collective quite easy, although a bit more difficult than with collective director because diamond tends to move around when you get toward end. Easy to interpret. Rudders gave some problem – trim appeared to be important with this system, and had to be a bit more attentive to basic instruments up and away. No coupling problems.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: No real difficulties. Coordinated with motions, easy to understand.

ADI: Had to use frequently to check bank angle.

FLIGHT DIRECTOR: Velocity commands easy to understand. Only problem is inability to control roll precisely down low so display wavers directionally.

SCAN: Have to use peripheral instruments more frequently.

SUMMARY: Airplane is acceptable but not satisfactory. Deficiencies are moderately objectionable because I have to pay too much attention to roll when down low; this is only a moderate objection because it could be overcome with sufficient pilot compensation. Can't talk about the hover. Had to work at flying airplane more than desired and interpret that as considerable pilot compensation. Turbulence affected the evaluation and was in the noticeable category, moderate influence.

CONTROL SYSTEM:	Attitude/Rate Command	PILOT RATING:	4½B
DUCT ROTATION:	Manual	HEADWIND:	9.3
ED FORMAT:	Velocity Command (ED2)	CROSSWIND:	6.5(L)
ADI NEEDLES:	Off	TURBULENCE:	1.9
ITVIC:	On	FLIGHT NO:	F-133

GENERAL: No problem with aircraft pitch response, but roll response seems relatively slow, aircraft seems to come gently and slowly and continuously to roll up in bank and I invariably overbank. Forces were light and comfortable. I enjoyed it up and away but had problems on approach. Display good. Winds not a factor — no turbulence. Pilot in good shape.

APPROACH PERFORMANCE:

INTERCEPTION: Had some problems, because set up was poor and I tended to get slow as I was trying to turn in. Also kept putting in more bank and getting more turn than I wanted. When the vector is not very close to the diamond it's hard to interpret longitudinal velocity, and this kept happening because I kept overturning. Problems weren't all that gross and I kept up with it, but it complicated life.

TRACKING: Not as good as I've done before. On the deceleration, I kept trying to lead altitude but I kept overcontrolling it and the need to do the manual rotation made me less precise. Profile itself was reasonable.

HOVER: Aircraft fair in the hover. Tendency to roll too much when making lateral corrections. Performance was still satisfactory in hover.

LANDING POSSIBLE?: Yes, but would have been touchy and more difficult than desired.

AIRCRAFT RESPONSE: Longitudinal response fair. Lateral a problem — a real tendency to overbank, particularly when I initially got the airplane. Forces were nice and light, but response seemed slow. Some problem with collective because with this display the diamond and circle move on their own and when I see motion I make a correction even though it's already doing the right thing. Therefore have tendency to anticipate and overcontrol. No problem interpreting what to do, however. Rudder pedals not a factor.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Good, sensitivities and coordination good.

ADI: A "must" — had to use it to figure out bank angle. Workload gets high when you get low (toward end of approach) and you have to keep scanning.

FLIGHT DIRECTOR: Information not too good when you're not close. Can't interpret longitudinal until lateral problem is solved.

SCAN: More of a problem than desired because of need to keep ADI in view. Peripheral instruments O.K., good information.

SUMMARY: It is not satisfactory as it is. It has a lot of small problems. Bank angle didn't get away because it's a smooth day. Did feel fairly comfortable in the approaches. Half rating is because it's a little worse than a 4 but not bad enough to be considerable pilot compensation. Primary reason for rating is tendency to overcontrol in bank. Little or no turbulence except for burble off runway down close, which does give a noticeable effect. Light, negligible.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	3D
DUCT ROTATION:	Manual	HEADWIND:	25.4
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	9.2(R)
ADI NEEDLES:	Off	TURBULENCE:	3.7
ITVIC:	On	FLIGHT NO:	F-120

GENERAL: Mild conflict on the display in the hover between the vertical and horizontal needles and the situation information. Airplane felt pretty good. Approaches were good. It is quite turbulent today and noticeable in the cockpit.

APPROACH PERFORMANCE:

INTERCEPTION: Pretty good for both localizer and glide slope. Seemed to start off low today, which helped glide slope interception. Although the localizer comes across rapidly at first I can follow it naturally and it is not very difficult.

TRACKING: Took quite a lot of concentration for both localizer and glide slope – it's not hard to get behind. Deceleration profile is reasonable and it's natural to do what it tells me to.

HOVER: Some problems because of variance between directors and situation today, but I got it worked out. Tended to get in trouble using the rudders, and it worked better when I took my feet off. Performance O.K., although things develop slowly and you can pick up a drift.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal control good, requires large nose down change at glide slope interception. Lateral forces heavy. Collective good – just follow command. Didn't notice much coupling. Didn't use rudder pedals much.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: ITVIC is invaluable at this point in the program – could not have kept up with peripheral instruments. Display is coordinated with control motions. Vertical director seems a little jumpy but O.K..

ADI: Used for turns up and away but not on the glide slope because I have attitude command.

FLIGHT DIRECTOR: Used almost exclusively to get sufficient lead information to keep up with display.

SCAN: Use peripheral instruments somewhat during approach, but if I concentrate on them too much I get behind.

SUMMARY: This configuration is satisfactory. Unpleasant deficiencies are the slowness of the display in hover and the difficulty of catching up if you get behind. The airplane was quite responsive to turbulence. It did not make the evaluation impossible, it did not compromise the rating, but it did have a moderate influence. No simulation deficiencies.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	2A
DUCT ROTATION:	Manual	HEADWIND:	3.5
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	3.6(L)
ADI NEEDLES:	Off	TURBULENCE:	2.5
ITVIC:	On	FLIGHT NO:	F-131

GENERAL: Airplane response heavy at altitude, use trim quite a bit, which isn't a bad idea on approach. Display fine, little turbulence with slight left cross-wind is no problem. Pilot in good mood.

APPROACH PERFORMANCE:

INTERCEPTION: Easy, no problem determining when to start down.

TRACKING: Very easy task, good information. Deceleration profile no problem: reasonable and comfortable to perform.

HOVER: A "dream" — good information, good control. Just pull on stick to get aircraft headed or stopped where I want, trim it out and aircraft stays put.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: A little heavy up and away but very comfortable on the approach when making small corrections. Used trim extensively. Collective is easy because of good information. Do notice down collective required at beginning of transition from 15°, can anticipate that. Very little use of rudder pedals. Some use up and away to aid turn coordination — it is comfortable.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Very good, sensitivity not a factor, coordinated with control motions.

ADI: Very little use of ADI except occasional check.

FLIGHT DIRECTOR: Good information, no problems.

SCAN: No problem — can easily fly aircraft completely off the electronic display.

SUMMARY: Aircraft is controllable, acceptable, satisfactory. Pilot compensation is not a factor: it's amazing how you can relax with this one. Little or no turbulence, no influence on evaluation.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	3D
DUCT ROTATION:	Manual	HEADWIND:	-6.3
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	12.5(R)
ADI NEEDLES:	Off	TURBULENCE:	3.3
ITVIC:	On	FLIGHT NO:	F-139

GENERAL: Airplane response reasonable. Fairly turbulent, aircraft has sharp turbulence response which is uncomfortable. Display good. Winds a big problem — at altitude we seemed to have a tailwind component. Pilot performance noteworthy, I think — haven't flown for six weeks.

APPROACH PERFORMANCE:

INTERCEPTION: Had to really hack the collective command to get good glide slope interception. If I stayed up with it I did pretty good (sic). Could intercept glide slope acceptably.

TRACKING: Had high sink rates on approach but kept up with it well. Felt good about the tracking. Deceleration profile was reasonable — never noticed it.

HOVER: Display and aircraft control were not problems in hover, but inability to determine precisely what winds were doing was a problem. Winds were variable, and on second approach it seemed to be at my back, which was uncomfortable, got high trying to sort it out and display and radar altimeter seemed to give different indications. Performance was acceptable though uncomfortable.

LANDING POSSIBLE?: Probably yes.

AIRCRAFT RESPONSE: Longitudinal and lateral sticks heavy for making big turns but very comfortable on approach and in hover. Seemed to be more than normal coupling between collective and pitch attitude to maintain velocity. Collective is biggest problem on approach such as this with tailwind, because if you get behind you get large sink rates. Rudder pedals not a problem.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Sensitivity seems about right, coordinated with the maneuvers. I like the display, no problems.

ADI: Used to determine roll attitude, which was necessary because wind changes keep changing heading. You have to keep turning, and it feels like you're holding it in a protracted turn. Would like better attitude information on the electronic display.

FLIGHT DIRECTOR: Used flight director all the way. The harder I worked at it the closer I kept it and the better job I did, which kept sink rates lower and made it more comfortable. No problems.

SCAN: Not a bad problem considering I haven't flown the airplane for a long time. Had to keep up with peripheral instruments. Seemed to have incongruous information between the electronic display and radar altimeter.

SUMMARY: Only problem was not knowing where the winds were coming from in the hover. It's acceptable, I think it's satisfactory under the conditions we're flying today. I could do the job even though it's uncomfortable in the hover with the winds varying like they were. Fair amount of turbulence, sharp response to it did not compromise but did affect the evaluation, moderate influence on the airplane. No simulation deficiencies other than trying to fly in some **very** weird winds.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	3A
DUCT ROTATION:	Manual	HEADWIND:	11.0
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	4.7(L)
ADI NEEDLES:	Off	TURBULENCE:	2.0
ITVIC:	On	FLIGHT NO:	F-131

GENERAL: Aircraft response good, seemed to have a little problem with bank attitude control, but very minor. Display no problem, slight cross wind no problem, pilot in good shape.

APPROACH PERFORMANCE:

INTERCEPTION: Very easy to define with this configuration. The lengthening of the vector and movement of the diamond in the direction you want to go (due to onset of ground velocity information from radar) is good indication of when you should start down. Good glide slope interception on this one.

TRACKING: Both localizer and glide slope really very easy, good precision control and I don't get very far off. Deceleration profile comfortable, easy to keep up with.

HOVER: A "snap", feel very confident, even rushed the last approach to descend to 50 feet while still decelerating, stopped right at the spot.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal seems heavier than lateral, not as good on bank angle control. Collective control very good, simply follow the commands and very seldom overshoot or undershoot. Very comfortable. Very little use of rudder pedals except a little up and away.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Very good, sensitivity just about right, coordinated with motion.

ADI: Used occasionally to check bank angle.

FLIGHT DIRECTOR: Very easy to follow commands — keep in mind that I never get very far off because I have such good control.

SCAN: Not a problem — could pick up radar altimeter, bank attitude, and heading easily when needed.

SUMMARY: Controllable, acceptable, satisfactory. Slight problem with bank attitude control is a mildly unpleasant deficiency although minimum pilot compensation is required. Maybe I'm being a little harsh. Turbulence is nil, no effect.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	3E
DUCT ROTATION:	Manual	HEADWIND:	24.8
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	9.1(L)
ADI NEEDLES:	Off	TURBULENCE:	4.0
ITVIC:	On	FLIGHT NO:	F-134

GENERAL: Lots of turbulence, really sharp gusts. Airplane response not a factor — very stable, relatively high forces but comfortable. Display good. Winds are a factor, particularly in hover. Pilot not having much fun when it's as rough as it is today.

APPROACH PERFORMANCE:

INTERCEPTION: Localizer and glide slope quite good. Elongation of velocity vector good clue as to when to start down, good warning for glide slope interception, easy to do.

TRACKING: Quite a bit of work because of gusts, turbulence. Heading would wander around when I wasn't banking the aircraft and I tended to disbelieve it. I could keep it under control but it was confusing. Deceleration profile reasonable — did good job on second approach, better than first.

HOVER: Good information, could do it easily enough. On first approach, got caught by not knowing direction of wind, had heading of 270° and wind was strong from 250°, took a 10° bank to hold over spot which is uncomfortable and inducive to vertigo when under the hood. No problem, though, could fly airplane nicely in hover.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal and lateral forces heavy. Aircraft seems very well attitude stabilized — levels itself out if I take my hands off, which is quite comfortable when there is this much turbulence. Collective no problem because of good command display. Some coupling with initial duct rotation from 15°, requires down collective. Rudder pedals no problem.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: No problem. It seems more sensitive in turbulence because it does respond to turbulence and I try to keep up with that. Some problems created by flying high gain on things that move around for reasons other than my inputs. Display coordinated with control motions except for heading wandering which was some bother.

ADI: Did use to check that aircraft wasn't inadvertently in a bank. Couldn't resolve this point, and it was a little bit uncomfortable.

FLIGHT DIRECTOR: Good information, flew it reasonably tight so had good information about longitudinal and lateral control.

SCAN: Not a problem, even with increased use of ADI.

SUMMARY: Airplane is satisfactory without improvement. Mildly unpleasant deficiency is very sharp response to turbulence, which is confusing and causes you to work harder on task. Turbulence affected evaluation, effect on ability to fly airplane is considerable, moderate level.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	2½C
DUCT ROTATION:	Manual	HEADWIND:	4.2
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	13.6(R)
ADI NEEDLES:	Off	TURBULENCE:	3.2
ITVIC:	On	FLIGHT NO:	F-140

GENERAL: Airplane response satisfactory, display good. Wind a bit of a problem because it's a crosswind from the right. Pilot in pretty good shape.

APPROACH PERFORMANCE:

INTERCEPTION: Localizer and glide slope quite easy, easy to see particularly with advance notice of lengthening velocity vector. No problems — I even anticipate a little.

TRACKING: Initially really quite good. Deceleration profile no problem. Only problem is that crosswind requires more and more heading change as get closer to ground (and slower) to keep up with localizer, which can overload you. Ended up high on first approach, anticipated the problem better on the second approach. It causes you to have more work to do.

HOVER: Not a problem. Performance good, display good. Got smarter about trying to figure out what wind was doing. On second approach I kept the duct angle less than 90°, because on first I went to 90° and then got quite nose down getting up to the pad.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal and lateral responses good. Lateral stick forces a little lighter but enjoyable — no problem. No problem with speed or altitude. For collective, just followed the command, alghough it seemed a little slow as if I should put the circle in the diamond (ED 2) instead of on the bar, so it was a little confusing. Rudder pedals a problem down low because you need to figure out wind. Tried to use heading hold to work it around with the rudders, seemed reasonable, knew what I was trying to do.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Good. Sensitivity good. ITVIC light mandatory as far as I'm concerned. Display coordinated with control motions — no problem.

ADI: A "must" to keep checking bank attitude because approaches looked curving, even though only the heading was really curving.

FLIGHT DIRECTOR: Good information, easy to follow, never got very far off.

SCAN: No problem.

SUMMARY: Am impressed with ability to do the job after not having flown for a while. Airplane is acceptable and satisfactory without improvement. Main reason for half-rating is that the tendency to get overloaded at bottom where I have to worry about heading is a slightly more than negligible deficiency. A little turbulence. not very bad. It is noticeable, light, with moderate degradation of my performance.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	5D
DUCT ROTATION:	Manual	HEADWIND:	17.6
ED FORMAT:	Velocity Command (ED2)	CROSSWIND:	10.1(L)
ADI NEEDLES:	Off	TURBULENCE:	3.4
ITVIC:	On	FLIGHT NO:	F-121

GENERAL: Airplane takes a lot of muscle to fly, feel that I'm pushing it around.

APPROACH PERFORMANCE:

INTERCEPTION: Localizer O.K.. Had some problem with glide slope because of nose down trim change required, and tended to balloon or overfly the glide slope. This is partly due to the fact that I'd prefer the altitude error diamond to be of opposite sense.

TRACKING: Liked the localizer tracking: this display is very graphic and simple to interpret. Have trouble with the glide slope, because it takes me more time to figure out how to get to it. Speed tracking no problem, the deceleration profile certainly reasonable.

HOVER: Hover very comfortable, display fine, precision was very good.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Very heavy airplane, tiring to fly. Use the rudder in turns although I don't think it is necessary. Collective O.K. – I use the arm rest to make small collective inputs.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Liked the localizer and velocity presentation. Don't like the vertical, it takes too much thought.

ADI: Used little because airplane is attitude stabilized. Used only up and away. Didn't use in hover because I can tell by the stick forces when I change attitude, particularly roll.

FLIGHT DIRECTOR: ------

SCAN: No problems. Have less scan with attitude command because I get information from forces.

SUMMARY: It is acceptable but not satisfactory because of the concentration required on the glide slope. I can do the job but don't like the concentration required. Turbulence is sharp, demanding on the airplane. No simulation deficiencies.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	4B
DUCT ROTATION:	Manual	HEADWIND:	6.5
ED FORMAT:	Velocity Command (ED2)	CROSSWIND:	5.4(L)
ADI NEEDLES:	Off	TURBULENCE:	2.4
ITVIC:	On	FLIGHT NO:	F-123

GENERAL: Good approaches except that I undershot the final level off by 40 feet, which is too much. I like the sense of the altitude error diamond now. Airplane response good, although it feels a little squirrelly in roll today. No wind. Pilot O.K..

APPROACH PERFORMANCE:

INTERCEPTION: A little difficult for me to tell when to start following the diamond until the range at which velocity information comes in. Glide slope interception easy to interpret with this sense on the altitude diamond.

TRACKING: Relatively easy on glide slope although I lag the altitude. The deceleration causes a problem because I undershoot altitude, particularly at the end when I am trying to pick up the radar altimeter. It's more work at the end to control altitude than I like, and I tend to get behind on the approach path. Up and away tracking is good.

HOVER: Altitude control not as precise as desired. Get confused as to what to do with altitude rate error circle. It's a little confusing today.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal and lateral are heavy but quite comfortable. The roll seems more sensitive than it has been in past. Use small inputs on the collective, but wouldn't want less sensitivity. I seem to be able to control the display all right. Rudder pedals not a problem.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Liked the electronic display for the tracking and the velocity profile. It is coordinated with aircraft movement. Sensitivity good for localizer tracking, a bit less sensitive for glide slope than desired.

ADI: Used up and away, not much on the approach or in the pattern.

FLIGHT DIRECTOR: ------

SCAN: Use radar altimeter to help pick up lead on altitude. Today we have to watch the engines closely since it's warm.

SUMMARY: It is acceptable but not satisfactory. Altitude control should be better, I have to devote too much time to it. It's no more than a minor point. Turbulence just noticeable and it affected my evaluation a little bit.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	7D
DUCT ROTATION:	Manual	HEADWIND:	17.6
ED FORMAT:	Position Information (ED1)	CROSSWIND:	10.1(L)
ADI NEEDLES:	On	TURBULENCE:	4.0
ITVIC:	On	FLIGHT NO:	F-121

GENERAL: Airplane heavy to fly. Electronic display information deficient for getting airplane stopped at end and for hovering.

APPROACH PERFORMANCE:

INTERCEPTION: Totally dependent on ADI vertical needle for localizer interception. I am not sure you could do it with just the electronic display. Glide slope interception was similar, although altitude error diamond was some help. I think the sense of the altitude diamond should be reversed.

TRACKING: On first approach, I concentrated on the electronic display and had very poor glide slope tracking. There isn't enough information there for proper control. On second approach, I devoted attention to ADI flight director needles, did much better glide slope and localizer tracking until the bottom when I was dependent on the electronic display for altitude. Very large scan, very critical at bottom when I concentrated on altitude and let localizer tracking go to pot. The whole profile left something to be desired.

HOVER: Particularly bad. Could not be precise because you can't tell what the airplane is doing. You can not derive velocity information just from the relative motion of the airplane and pad symbols. About all you can do is get it stopped.

LANDING POSSIBLE?: Impossible. You need to know the small longitudinal and lateral velocities, which aren't on the display.

AIRCRAFT RESPONSE: Longitudinal and lateral very heavy. Collective is comfortable, but hard to know what to do with it using this display. Require a lot of nose down trim on glide slope interception. Use rudders up and away only during turns, and in the heading hold mode at hover. Don't use them on the approach.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: You must have the ITVIC light for this configuration — would have no chance without it. Electronic display is totally lacking, particularly in hover. We needed the flight director information on the ADI needles just to get there.

ADI: Used almost exclusively during the approach, mostly the needles. Attitude information only used up and away.

FLIGHT DIRECTOR: Had to have flight director information on the ADI needles. Used them exclusively.

SCAN: Quite large, very difficult and demanding.

SUMMARY: The airplane flies O.K. — I don't think we are going to crash. The display is unacceptable for approach and landing. It would be impossible I think to make a landing, or even a precision hover. Quite a bit of turbulence today. It is annoying although not too disturbing in control of the airplane.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	6D
DUCT ROTATION:	Manual	HEADWIND:	7.6
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	9.1(R)
ADI NEEDLES:	Off	TURBULENCE:	3.0
ITVIC:	Off	FLIGHT NO:	F-123

GENERAL: The roll seems sensitive. Turbulence a bit of a factor at altitude.

APPROACH PERFORMANCE:

INTERCEPTION: Localizer O.K., but had some "roller coaster" tendency on glide slope trying to follow commands.

TRACKING: Both localizer and glide slope tracking suffer because of concentration required in determining when to rotate ducts. Have to spend time looking at duct angle and velocity to keep a good profile, and there isn't enough information to do that easily.

HOVER: No problem — all the problems are sorted out by that point.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Heavy longitudinally and laterally. Collective gave good altitude control. Some collective — pitch coupling when I rotate the ducts. Rudder pedals not a factor, heading hold mode helps in hover.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Electronic display gives good information. Lack of the ITVIC director is a serious problem.

ADI: Used up and away but not on approach.

FLIGHT DIRECTOR: The needles give good information, but having to use the horizontal needle as both a stick director and a duct change director to slow down is a very difficult mental process.

SCAN: Really have to use peripheral instruments, particularly duct angle and velocity. Consequently approach performance suffers, and doing it is much more difficult.

SUMMARY: I think the job could be done. It's very objectionable, however, and your workload is very high. You need a fair amount of proficiency to keep up with it, but I think you can do it. You can hack the approach without the ITVIC but it is very difficult. Turbulence really bounced us around at altitude, not as much of a problem down low. It did influence the evaluation. Although not a simulation deficiency, there is a lot of radio chatter today which is making my job a lot harder than it should be.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	6C
DUCT ROTATION:	Manual	HEADWIND:	19.0
ED FORMAT:	Velocity Command (ED2)	CROSSWIND:	11.2(L)
ADI NEEDLES:	Off	TURBULENCE:	3.0
ITVIC:	Off	FLIGHT NO:	F-128

GENERAL: Airplane is stiff in both pitch and roll. Display O.K., wind not a factor. Pilot had some trouble on second approach.

APPROACH PERFORMANCE:

INTERCEPTION: Very easy for both localizer and glide slope, which is partially a result of being well set up initially on both approaches.

TRACKING: On first approach, both localizer and glide slope very good. On second approach, I got behind and it was difficult to figure out how to get back, particularly on localizer. It isn't difficult if you don't get very far off, but is hard if you do because everything gets bad at the same time. Deceleration profile no problem.

HOVER: No problem once everything is settled down. Precision hover satisfactory.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Heavy in roll — a little tiresome. Use lots of trim longitudinally. Collective not much of a problem, although I got behind when concentrating on the localizer. Rudders no problem.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Miss the ITVIC even though I thought on the simulator that I had the situation figured out and could do it. When I got off on the localizer, so the vector didn't pass through the diamond, then I get ahead or behind on the duct rotation. It's easy only if you're right on the localizer so vector passes through diamond. Display coordinated with motions, good sensitivity.

ADI: Didn't use much.

FLIGHT DIRECTOR: Velocity commands good.

SCAN: No problem.

SUMMARY: Rating is a dilemma because one approach was good, one bad. Adequate performance is attainable, but deficiencies are in major category, quite objectionable. You could learn to do it by keeping a tight loop on localizer, however. Turbulence is a factor, although not much.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	2B
DUCT ROTATION:	Automatic	HEADWIND:	22.0
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	12.7(R)
ADI NEEDLES:	Off	TURBULENCE:	----
ITVIC:	On	FLIGHT NO:	F-126

GENERAL: Airplane feels heavy, use trim almost exclusively for small corrections. Display good, winds fairly steady. Pilot O.K..

APPROACH PERFORMANCE:

INTERCEPTION: Both localizer and glide slope very good, very easy to see. Starting at correct altitude is a big help!

TRACKING: Very good for both localizer and glide slope. Easy to tell when deviating, and easy to get aircraft back on. Deceleration profile no problem – hardly feel any forces with automatic system.

HOVER: Quite satisfactory, display very good there. Don't like tendency for ducts to rotate to 93° if I go past the spot, so switch to manual.

LANDING POSSIBLE?: Yes. Some lack of confidence that airplane is pointed where display says it is, but could have landed.

AIRCRAFT RESPONSE: Heavy both longitudinally and laterally. Attitude command does, however, take away some worry, and only objection is the high forces for steady turns. Collective excellent – command very simple to follow, can put circle right on the cross line. Not much coupling between collective and attitude. Rudders no problem. Use ATC to let aircraft point into wind down low and then switch to heading hold.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: ITVIC useful even with automatic rotation as status information and it coordinates with the forces caused by duct rotation, which is good information.

ADI: Used to ensure airplane isn't trimmed in a bank. Essential up and away to get set up.

FLIGHT DIRECTOR: Used it all the way, takes me to the right spot, I have a lot of confidence in it and it's very easy to fly.

SCAN: No problem.

SUMMARY: Aircraft acceptable and certainly satisfactory. No deficiencies, pilot compensation not a factor. Not much turbulence, didn't have any influence on evaluation.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	2A
DUCT ROTATION:	Automatic	HEADWIND:	10.9
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	0.5(L)
ADI NEEDLES:	Off	TURBULENCE:	2.3
ITVIC:	On	FLIGHT NO:	F-131

GENERAL: Good aircraft response, good display information. Slight left cross wind. Pilot O.K..

APPROACH PERFORMANCE:

INTERCEPTION: Very good both localizer and glide slope.

TRACKING: Good on both localizer and glide slope: have such good control, don't get very far off. Glide slope much easier to control with automatic duct rotation because left hand has only one job to do. When I do the duct rotation collective control is not as precise. Deceleration profile no problem; automatic seems to speed it up, don't really have to concentrate, just do the job.

HOVER: No problem. Switch to manual at about 84 degree duct angle. Very good control, very confident. On both approaches, started down while still heading for spot, ended up at 50 feet right over spot as desired. Very easy task.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal response a little heavy, particularly when make 30° bank 180° turn. Lateral seemed lighter for some reason. Have to think more about bank angle. Collective no problem — good control since don't have to worry about duct rotation. Some coupling when ducts rotate from 15°, after that straightforward. Can anticipate what's going to happen. Seldom use rudder — only up and away.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Very good information, particularly for interception. Sensitivity O.K., coordinated with motions.

ADI: Used because felt bank angle needed checking and that information not easy to get off electronic display.

FLIGHT DIRECTOR: Easy to follow velocity commands.

SCAN: No problem — relieving necessity to do duct rotation a big help.

SUMMARY: Controllable, acceptable, satisfactory, pilot compensation not a factor for desired performance. No turbulence.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	3D
DUCT ROTATION:	Automatic	HEADWIND:	22.0
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	4.6(L)
ADI NEEDLES:	Off	TURBULENCE:	3.5
ITVIC:	On	FLIGHT NO:	F-134

GENERAL: Airplane heavy up and away, forces a little bit objectionable. Display O.K.. Fair amount of wind, gusty, a lot of turbulence. Pilot O.K..

APPROACH PERFORMANCE:

INTERCEPTION: Really quite easy, vector extension tells you you've got it made.

TRACKING: Localizer tracking difficult. Velocity vector rotating back and forth. Can't decide if it's a display sensitivity problem or something the airplane is doing that isn't my fault due to wind shears or turbulence. Will base evaluation on assuming it's a display sensitivity problem. Glide slope also sensitive, primarily because of shear and turbulence. No problem with deceleration profile.

HOVER: No problem. Would have been nice to have indication of where wind was coming from, because misalignment meant a lot of bank attitude. Not really a big factor.

LANDING POSSIBLE?: Yes, although wind would be a factor.

AIRCRAFT RESPONSE: Longitudinal and lateral forces heavy up and away but enjoyable in hover. No problem with collective, could control it satisfactorily. Command sensitive because of gusts. Some collective coupling when you come off the 15^{o} duct position, requires down collective. Rudder pedals not a factor.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Lateral sensitivity on the vector a little too great. Turbulence created some sensitivity problems on the collective command as well.

ADI: Not used much, not necessary. Feel the attitude of the airplane primarily through stick forces which relegates ADI to secondary position. Used only as crosscheck.

FLIGHT DIRECTOR: ------

SCAN: Not a problem — most necessary information right on the electronic display, quite interpretable.

SUMMARY: Could do the job without any improvement required. Problems were primarily the lateral display sensitivity, the high winds and turbulence, and the heavy forces up and away. Lots of turbulence, bangs aircraft around, is uncomfortable. It affected evaluation, was noticeable, was moderate.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	3C
DUCT ROTATION:	Automatic	HEADWIND:	13.3
ED FORMAT:	Velocity Command (ED2)	CROSSWIND:	2.3(R)
ADI NEEDLES:	Off	TURBULENCE:	3.0
ITVIC:	On	FLIGHT NO:	F-123

GENERAL: A lot of radio chatter today — you can't believe what it is like. Makes mental task much more demanding. Airplane is fine, although a little heavy. Display fine.

APPROACH PERFORMANCE:

INTERCEPTION: Localizer interception O.K.. Some "roller coaster" tendency on the glide slope interception.

TRACKING: Localizer tracking O.K., I liked the localizer guidance. Glide slope tracking is a lot easier with automatic duct rotation. The deceleration profile is easier to fly, and I didn't undershoot the final altitude as I have before with this display.

HOVER: No problem. Switched to manual to keep ducts from over-rotating if I went past pad. Very comfortable, very easy to fly in the hover.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal and lateral forces are heavy but no problem. Collective seems to give some pitch coupling, but I was making large corrections during the interception. Used the rudder pedals in the approach — didn't couple with the airplane very much.

DISPLAY CHARACTERISTICS:

ELECTRNOIC DISPLAY, ITVIC: Electronic display is easy to follow with the automatic duct rotation. I like having the ITVIC light as status information. The display is well coordinated with the control motions, and I had no tendency to undershoot altitude.

ADI: Used up and away only.

FLIGHT DIRECTOR: Velocity command is easy to do.

SCAN: Very little required with the automatic rotation. I use radar altimeter as lead information for the final level off.

SUMMARY: The airplane is satisfactory. It's difficult for me today because of all the radio chatter, and it would be easier to decide if we didn't have it. I like the airplane primarily because the load is reduced and that's a big help. Turbulence was rough up and away, reasonably smooth at the bottom. The influence was minor.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	2½A
DUCT ROTATION:	Automatic	HEADWIND:	9.4
ED FORMAT:	Velocity Command (ED2)	CROSSWIND:	5.0(L)
ADI NEEDLES:	Off	TURBULENCE:	2.0
ITVIC:	On	FLIGHT NO:	F-133

GENERAL: Very smooth airplane, smooth day. Pilot proud of himself for doing job easily after not flying for two weeks. Felt comfortable, had good control, could put aircraft where I wanted it. Display fine. Wind only about 10 kt, almost on the approach course.

APPROACH PERFORMANCE:

INTERCEPTION: Localizer and glide slope quite easy. Good set ups, obvious when to start down, only needed to make small corrections.

TRACKING: Both very easy. Deceleration profile quite reasonable, comfortable.

HOVER: Excellent hover capability. Could switch to manual ducts without getting off altitude or course. Performance was good.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Forces do not feel exorbitant longitudinally and laterally, even for turns. Like them both. Very little coupling with speed or altitude changes. Tend to lead the collective a little bit — get a bit behind if I just keep up with the diamond (keep the circle in the diamond). Some collective coupling with initial duct rotation — have to put in down collective as the ducts come off 15°. Used rudders mostly out of habit — it wasn't all that necessary.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Easy to interpret, sensitivities about right, coordinated with control motions. The automatic rotation makes it easier to keep up with the scenario, removes one thought process, and I like that.

ADI: Used only as crosscheck, didn't have to concentrate on it at all.

FLIGHT DIRECTOR: Good, no problem.

SCAN: Not a problem even after a two-week layoff. Used peripheral instruments more, and it was comfortable.

SUMMARY: Airplane is satisfactory without improvement. Pilot compensation not much of a factor — certainly minimal. Altitude control could have been a little better since I felt I had to lead it. Little or no turbulence, no effect whatsoever on evaluation.

CONTROL SYSTEM:	Attitude Command	PILOT RATING:	7B
DUCT ROTATION:	Automatic	HEADWIND:	16.0
ED FORMAT:	Position Information (ED1)	CROSSWIND:	11.8(R)
ADI NEEDLES:	Off	TURBULENCE:	2.8
ITVIC:	On	FLIGHT NO:	F-124

GENERAL: That one was a beauty! Airplane is heavy up and away. Winds are calm. Display information left a little bit to be desired.

APPROACH PERFORMANCE:

INTERCEPTION: Interception is a big guess for both localizer and glide slope. The glide slope is the better, and you could get it fairly well like a normal ILS. For localizer, you can just try to head the aircraft in the proper direction and hope it gets there. It requires paying a lot of attention to the tail of the symbol on the display to make sure direction is correct.

TRACKING: Tracking localizer very difficult because there isn't enough information. Tried instead just to keep airplane going in the general direction and then get it somewhere near pad at the end. Glide slope tracking was pretty good up and away, but the commanded level off at 100 feet is impossible. You can't get enough information quickly enough there: I overshot dramatically and think we would have hit the ground. Deceleration profile very difficult with no velocity display.

HOVER: Very difficult without velocity display. You can't tell how fast the airplane is going or to where. Performance was very poor.

LANDING POSSIBLE?: No way.

AIRCRAFT RESPONSE: Longitudinal and lateral response heavy. Collective technique very difficult because you have to try to lead the glide slope. Also, since glide slope command changes at the end, it's difficult to tell whether you're setting up the problem or the command is changing. I had real difficulty with altitude control at the end. Rudders no problem. Automatic duct rotation did take one thought process out of the problem, which helped since I was overloaded as it was.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Electronic display didn't have enough information on it to control the aircraft. The lack of velocity information is a real problem even with automatic ducts. I had no feel for whether I was fast or slow, and consequently tended to let the attitude of the airplane get away from me. Just trying to fly along the approach keeping some undetermined attitude is unsatisfactory.

ADI: Used up and away but not on approach.

FLIGHT DIRECTOR: ------

SCAN: Not a problem. The thought process of trying to figure out what to do with the limited information was the big problem.

SUMMARY: The airplane is not at all satisfactory. I think we would have run into the ground even though it would have been a controlled crash. The airplane was controllable, certainly not adequate. I think considerable pilot compensation was required, not so much for control of the airplane but just to do the job. I did not feel the airplane was going to do something weird and that I would lose control. A fantastic amount of thought process was required to interpret the display, but I don't think there was a controllability problem. The description (of PR = 7 on the Cooper-Harper Scale) is the best one. Little or no turbulence, negligible influence.

CONTROL SYSTEM:	Decoupled Velocity Control	PILOT RATING:	2C
DUCT ROTATION:	Automatic	HEADWIND:	0.0
ED FORMAT:	Control Directors (ED3)	CROSSWIND:	12.5(R)
ADI NEEDLES:	Off	TURBULENCE:	3.0
ITVIC:	On	FLIGHT NO:	F-142

GENERAL: Airplane response good, lack of good pitch attitude control is minor objection. Display good, winds not a factor, pilot not a factor.

APPROACH PERFORMANCE:

INTERCEPTION: Localizer and glide slope quite easy, good evidence of when you are going (down), collective sensitivity is good so that it is easy to do.

TRACKING: Localizer and glide slope easy enough. Deceleration profile quite reasonable, don't have to work very hard at it particularly with automatic rotation.

HOVER: Some problem with attitude and displacement command changes when we go to hover mode, they change and it takes a while to settle down. I got high on the last approach waiting for it to settle down. I think you can get a precise hover, however.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Lateral O.K., need more pitch response to longitudinal. I don't understand why I don't have to make pitch attitude change for the approach with this control system. Collective easy, simply follow the bouncing ball, some coupling with initial duct rotation requires down collective. Collective sensitivity for this control system is far better than for others, requires smaller inputs, I don't know if that's a function of height damping or what but it's an improvement. Rudder pedals no problem.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Good, sensitivity good, coordinated with motions.

ADI: Minimal use.

FLIGHT DIRECTOR: Good information all the way down, very easy to follow, no problems.

SCAN: Not a factor.

SUMMARY: It is satisfactory for this mission, good enough as it is. Am not sure everybody would accept flying a control system like this, but certainly for this task little or no pilot compensation is required. Turbulence picking up near the end, quite noticeable, turbulence itself seemed moderate but effect on what I was doing was minor. Quite high turbulence, not affecting airplane very much.

CONTROL SYSTEM:	Decoupled Velocity Control	PILOT RATING:	2C
DUCT ROTATION:	Automatic	HEADWIND:	0.0
ED FORMAT:	Velocity Command/Collective Director (ED2+)	CROSSWIND:	10.9(R)
ADI NEEDLES:	Off	TURBULENCE:	3.6
ITVIC:	On	FLIGHT NO:	F-142

GENERAL: Airplane is comfortable, display is very easy to follow. Winds a bit of problem down low but not a real factor.

APPROACH PERFORMANCE:

INTERCEPTION: Localizer and glide slope absolutely no problem. Made one initial approach where we'd engaged (the VSS) at too low airspeed, didn't get caught up before starting down. Other two good.

TRACKING: No sweat, real easy, no problem staying right where you need to be. Deceleration profile not noticeable, not a factor.

HOVER: Reasonably impressed with the hover. It's not at all difficult to use ducts to control fore and aft motion when you have good information, which I had particularly in hover mode. Performance was satisfactory.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal and lateral good, no problem. Pitch response a little strange, would like to have aircraft more responsive in pitch, sensitivity seems very low and it takes a lot of input to move aircraft. Collective no problem, just controlled right to where I wanted to be, very little coupling except at initial duct rotation when you require some down collective. Rudder pedals no problem, no coupling.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Had automatic rotation so ITVIC wasn't a factor, but it's nice to have on as an indication of what's happening. Electronic display was used, was coordinated with control motions, no problem there.

ADI: Used only marginally.

FLIGHT DIRECTOR: Good information on the electronic display, didn't get very far off most of the way down.

SCAN: Had plenty of time to look at peripheral instruments, scan wasn't a problem.

SUMMARY: Configuration is satisfactory without improvement. Object a little to sensitivity of pitch stick, don't have real solid pitch control. No problem controlling fore and aft motions with ducts now with the hover mode on the display. Turbulence light but noticeable, had minor effect on my performance.

CONTROL SYSTEM:	Decoupled Velocity Control	PILOT RATING:	2B
DUCT ROTATION:	Automatic	HEADWIND:	12.7
ED FORMAT:	Velocity Command (ED2)*	CROSSWIND:	7.6(R)
ADI NEEDLES:	Off	TURBULENCE:	2.6
ITVIC:	On	FLIGHT NO:	F-141

*Hover mode not available on this flight.

GENERAL: Airplane response good, no problems. It's a little bit weird up and away because you don't get a good pitch attitude response. Display good, good informations. A little crosswind down low, not much of a problem. Pilot in good shape.

APPROACH PERFORMANCE:

INTERCEPTION: Some problems getting airplane to go fast enough to put vector in diamond, kept trying to push nose down but it didn't get there, had to lag behind until pretty close to interception when it caught up. Interception is no problem.

TRACKING: Quite easy for localizer and glide slope, very comfortable and very simple to do. Deceleration profile is reasonable.

HOVER: First hover good, no problem except airplane is a little slow responding to ducts (for longitudinal velocity): you don't feel you have as good a control as you would like. Had good information and enough control with attitude to do the job. Had problems on second approach because of traffic.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal and lateral no problem, airplane responds to them to make display change as desired, can fly a very smooth approach. Collective response no difference – simply move airplane where you want to go in vertical plane and it did exactly what I had hoped it would do. Rudder pedals no problem, no coupling.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Good. Sensitivity and coordination with motions good.

ADI: No tendency to use ADI, airplane seemed very stable and I was never in doubt as to what attitude was.

FLIGHT DIRECTOR: Good information. Some tendency to lag behind up and away, a little slow at the bottom for getting over the spot. Otherwise very comfortable.

SCAN: No problem. Things happen slowly, I'm relieved of enough duties that I had good time to watch radar altimeter.

SUMMARY: Airplane is certainly acceptable, it's satisfactory without improvement. I'm reasonably impressed. One problem is tendency to lag the airplane initially, second is slow velocity response in hover. I consider them negligible. Turbulence didn't move airplane around much, was light, influence was negligible.

CONTROL SYSTEM:	Decoupled Velocity Control	PILOT RATING:	2B
DUCT ROTATION:	Automatic	HEADWIND:	11.4
ED FORMAT:	Velocity Command (ED2)*	CROSSWIND:	9.7(R)
ADI NEEDLES:	Off	TURBULENCE:	2.7
ITVIC:	On	FLIGHT NO:	F-141

*Intended to be ED2+ and pilot so briefed, potentiometer mis-set.
Hover mode not available on this flight.

GENERAL: Airplane response and display O.K., winds a bit of a problem in the hover, pilot in good spirits.

APPROACH PERFORMANCE:

INTERCEPTION: Easy to tell when you're getting there and when you should start down. It wasn't as easy as it should have been because a pot was mis-set,didn't get collective director information. Still was able to fly the thing O.K..

TRACKING: O.K., didn't get far off. Deceleration profile reasonable.

HOVER: I rushed things at the bottom and never really got the heading problem solved, really had to work hard to get over spot, but felt I had good control and could do the job.

LANDING POSSIBLE?: Yes.

AIRCRAFT RESPONSE: Longitudinal and lateral stick O.K., I really miss getting a good pitch response to longitudinal stick, other than that no problem. Lateral control good. Collective didn't seem to be following well but that's because mis-set pot gave me velocity error instead of director information. Still had a good, I thought reasonable, profile. Rudder pedals not much of a factor although I didn't get heading solved in hover as well as desired because of winds. If you don't get headed into wind it is very difficult to get airplane over spot.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Electronic display good. Sensitivities good, only coordination problem was due to mis-set pot and resulting confusion.

ADI: Used purely as cross reference, really not needed very much for this system.

FLIGHT DIRECTOR: ------

SCAN: Not a problem, peripheral instruments used only for catching up on information, didn't feel they were really necessary.

SUMMARY: Airplane is acceptable, it is satisfactory without improvement. I probably would have done better if I had had some idea of what to do with the collective, but that part didn't bother me at all surprisingly enough. Object a little to slowness of (longitudinal velocity) response in hover, still need a better way to tell where wind is coming from to head airplane into it. Even with that I thought it was a good machine. Turbulence noticeable, light, negligible.

CONTROL SYSTEM:	Decoupled Velocity Control	PILOT RATING:	7B
DUCT ROTATION:	Automatic	HEADWIND:	15.2
ED FORMAT:	Position Information (ED1)*	CROSSWIND:	12.7(R)
ADI NEEDLES:	Off	TURBULENCE:	2.3
ITVIC:	On	FLIGHT NO:	F-141

*Hover mode not available on this flight.

GENERAL: Airplane response O.K. up and away. A little bit touch and go at bottom because you don't have enough information. Display is very poor, unacceptable. Winds not creating much of a problem, pilot feels pretty good.

APPROACH PERFORMANCE:

INTERCEPTION: Both localizer and glide slope very, very difficult, you really have to try to anticipate, I got several false starts. Localizer is worse than glide slope because you don't have enough information, you just drive airplane over and try to turn to fly up the approach path, would be impossible in a crosswind.

TRACKING: Both localizer and glide slope very poor, always behind. Not a problem up and away, but both approaches I flew through the 100 ft. level off altitude. Localizer is a question of trying to keep headed in right direction and waiting to solve problem when you get to bottom.

HOVER: Display very poor because of no velocity information. Just try to get over spot, slow (velocity) response to ducts isn't very good. You would never know when you got the drift killed in either direction.

LANDING POSSIBLE?: No. I think you would probably tip the airplane over or land backwards.

AIRCRAFT RESPONSE: Longitudinal and lateral O.K.. Collective is a matter of trying to guess how you're doing, use rate of sink to get some lead, job is very, very difficult to do with this information. Nothing "magic" – you just try to lead it when you can. Rudder pedals not a factor.

DISPLAY CHARACTERISTICS:

ELECTRONIC DISPLAY, ITVIC: Biggest problem is lack of information. Without velocity profile information I tried to use airspeed and duct angle readouts to see if I was progressing O.K.. Would not want to do it on a dark stormy night. What information I had was coordinated with the movements.

ADI: Used only as a very peripheral instrument, really isn't necessary with this type of augmentation system.

FLIGHT DIRECTOR: Not applicable.

SCAN: Spent a lot of time looking at airspeed and rate of sink trying to correlate them with radar altimeter so that I could get some lead on the display. Really had to use peripheral instruments, it was difficult.

SUMMARY: Don't think I could land it. Wouldn't want to have to try to do this as a matter of course although I really didn't feel anything unsafe. Pilot rating is because information was insufficient. Turbulence very light, barely noticeable, didn't give me any problem.

APPENDIX VI

SYSTEM PERFORMANCE AND PILOT WORKLOAD ANALYSIS

Summary

The purpose of this appendix is to present in detail the results of the analyses conducted on the selected pilot-vehicle performance and pilot workload measures in order to determine the existence, and cause of, significant differences among these measures for the configurations evaluated (described in Section VII). The first portion of this appendix describes the chosen performance/workload measures and a rationale for their selection; included is a listing of these measures for each evaluation approach and of the processed flight data which determined their values. The results of the statistical analysis of variance (ANOVA) technique outlined in Section X are then presented. Finally, selected time histories and probability density functions of the flight data are presented and interpreted in the light of the results of the ANOVA and of the flying qualities results of Section IX.

System Performance and Pilot Workload Measures

The flight data which yielded the performance and workload measures are:

Performance:

- $\epsilon_{\dot{x}_h} \; (= \dot{x}_{h_c} - \hat{\dot{x}}_h)$ - heading-referenced longitudinal velocity error (ft/sec)
- θ - pitch attitude (deg)
- $\epsilon_z \; (= z_{e_c} - \hat{z}_e)$ - altitude error (ft)
- $\epsilon_{\dot{Y}_h} \; (= \dot{Y}_{h_c} - \hat{\dot{Y}}_h)$ - heading-referenced lateral velocity error (ft/sec)
- ϕ - bank attitude (deg)

Workload:

- δ_{es}, δ_{cs}, δ_{as} - evaluation pilot longitudinal, collective, and lateral stick position inputs (inches for δ_{es}, δ_{as}; degrees for δ_{cs})
- ITVIC - the signal which drives the duct rotation director light (sec)

Based upon the pilot commentary presented in Appendix V, the elements of the evaluation task prior to the commencement of the deceleration, i.e., the localizer acquisition and glide slope intercept, were judged not to have influenced any of the pilot ratings significantly. Therefore, the performance and workload data were only gathered from the deceleration and hover elements of the task. This final portion of the evaluation task was further broken down into two separate regions: the deceleration on the glide slope and the level deceleration to the hover; this particular distinction was made in response to pilot commentary which indicated that the ratings assigned to several of the less complex control/display systems came as a result of their degraded characteristics at or near the hover.

The processing of the performance and workload data involved the calculations of the means $(\bar{X})$ and standard deviations (s) of each parameter for each of the two task elements of interest: the deceleration on the glide slope (from deceleration commencement to level off), requiring approximately 60 seconds, and the level deceleration to the hover which required approximately 30 seconds. The actual performance measures used are in general the maximum values of the quantity $|\bar{X} \pm 2s|$; the only exception is the pitch attitude performance measure during the glide slope deceleration which is simply the standard deviation of that quantity. The maximum value of $|\bar{X} \pm 2s|$, denoted as $|(\ )|_{max}$, was selected as a statistically sound method of indicating the maximum values of the error terms and attitudes; assuming a normal distribution of each performance parameter in the universe, there exists only a 2.5% probability that the universe mean exceeds the value of the selected performance measure. The one exception arose because of the fact that the deceleration on the glide slope was not necessarily a constant pitch attitude task; in this case, the simple standard deviation provides a more meaningful measure for the comparison of the magnitude of the pitch attitude excursions required for vernier velocity control.

In an attempt to further quantify the pilot's evaluation of his mental workload, an independent measure of pilot workload margin was derived based upon the pilot's performance of the non-continuous manual duct rotation task in response to the ITVIC light. Reference 51 suggests that workload margin be defined as the ability (or capacity) to accomplish additional (expected or unexpected) tasks; hence the individual time intervals between the appearance of the duct rotation light and actual duct rotation by the pilot were calculated and processed to yield a mean and standard deviation for each deceleration on the glide slope. The mental workload performance measure is again the maximum value of $(\bar{X} \pm 2s)$ for the ITVIC time delay.

The pilot's physical workload is indicated by the characteristics of his outputs, i.e., his control activity. Control usage data for the three primary controlled axes: longitudinal (δ_{es}), lateral (δ_{as}), and thrust magnitude (δ_{cs}) controller positions, were collected for the deceleration on the glide slope only. The data from the level deceleration to the hover were not analyzed because of the relatively unconstrained nature of the final portion of this element of the task; that is, the several options available to the pilot for the hover would have made inter-configuration comparisons of dubious value because of the lack of a well-defined boundary between the deceleration and hover elements of the task. In contrast, the deceleration on the glide slope represents a tightly-constrained element of the task and is therefore more suitable for valid workload comparisons.

The processing of the control usage data yielded sample means and standard deviations for each of the three controller positions during the deceleration on the glide slope. Only the RMS values of the data are used as measures of pilot physical workload; the mean values of δ_{es} and δ_{cs} are not directly comparable for different evaluations because of the nature of the task and the characteristics of the variable stability system. Since the deceleration on the glide-slope was not a constant-attitude task, the "trim" positions of δ_{es} and δ_{cs} were not identical functions of time for the same controlled vehicle characteristics during the transition. In addition, the null value of δ_{cs} is determined by the evaluation pilot's collective stick position at the time of system engagement and therefore must be considered as a variable. Finally, variations in controlled vehicle characteristics cause variations in the "trim" positions of δ_{es} and δ_{cs} through identical transitions. Since the wings-level trim position of the lateral stick is zero the RMS value of δ_{as} is also a suitable workload measure.

Special care must be taken in the interpretation of workload measures based upon RMS values of control positions taken from vehicles with widely-varying stability/control characteristics because of the variations in the characteristics of the aircraft response to identical control inputs. However, with the exception of the decoupled velocity control (DVC) system pitch stick, the longitudinal and lateral stick force gradients remained the same for all levels of control system complexity investigated in this experiment. As a result, similar RMS values for δ_{es} and δ_{as} represent similar RMS stick force inputs by the pilot. The RMS levels of collective stick activity are directly comparable for all the stability/control augmentation schemes investigated with the exception of the DVC system. With the one exception, no stability augmentation was implemented in the vertical axis; the collective stick gearing remained the same for these unaugmented configurations.

Tables VI-1 through VI-4 present the processed flight data and performance/workload measures for both the descending and level elements of the deceleration for each evaluation approach. The data are ordered by display format and, within each display format, by control system.

Performance/Workload Analysis of Variance (ANOVA)

The performance/workload measures developed in the preceding sub-section were arranged in a control/display matrix format for the analysis of variance described in Section 10.1. In an attempt to eliminate the effects of turbulence from the results of the analysis, those configurations with turbulence effect ratings (TER) of A through C (minor effect of turbulence on evaluation) were analyzed separately from those with an assigned TER of D or E (moderate effect of turbulence on evaluation); this technique also allowed an evaluation of the relative effects of turbulence on several of the control/display combinations.

For the deceleration on the glide slope, both the performance and workload

Table VI-1(a)
PROCESSED FLIGHT DATA
(ED-3; DESCENDING DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\epsilon_{\dot{X}_h}$ (ft/sec)	$\epsilon_{\dot{Y}_h}$ (ft/sec)	ϵ_Z (ft)	θ (deg)	ϕ (deg)	ITVIC Δt (sec)
RATE:ED-3	121	1	-3.9(5.2)	-0.1(7.4)	14.9(16.6)	-2.6(2.5)	-0.3(2.4)	.67(0.2)
		2	-1.3(5.7)	-2.5(5.9)	20.4(9.6)	-6.4(2.6)	0.6(2.0)	.80(0.67)
	130	5	-3.0(6.1)	-5.5(10.0)	-10.4(14.1)	-7.2(3.)	0.3(3.5)	.69(0.22)
		6	-5.4(8.8)	3.7(12.1)	-15.9(25.0)	-3.3(3.5)	2.1(4.1)	1.17(0.88)
	140	3	7.3(7.8)	-8.1(6.0)	-42.7(18.0)	-11.4(3.2)	-0.6(2.5)	.66(0.30)
		4	5.6(7.3)	-10.2(3.6)	-19.1(6.6)	-10.7(2.6)	-1.0(2.2)	.46(0.14)
ATT-RT:ED-3	128	1	-4.7(3.1)	-6.1(9.2)	2.9(4.0)	0.6(0.7)	-0.2(2.3)	.66(0.11)
		2	-11.3(3.3)	-1.2(4.3)	-0.6(4.6)	1.5(1.6)	1.6(1.8)	.85(0.32)
	133	5	-0.1(3.3)	-0.8(3.3)	-7.8(8.3)	-5.7(1.5)	0.8(2.1)	.38(0.14)
		6	-0.4(3.1)	-1.8(5.0)	-12.4(9.4)	-6.0(1.9)	0.4(2.0)	.54(0.16)
	142	2	-6.0(5.0)	1.8(4.2)	-4.6(7.7)	-3.2(1.1)	0.8(1.9)	.78(0.50)
		3	-0.4(3.6)	-2.3(3.5)	-8.4(4.5)	-8.1(1.5)	-0.1(1.5)	.52(0.41)
ATT:ED-3	120	1	-1.6(6.1)	1.8(5.4)	11.0(23.0)	-3.0(2.3)	1.9(2.2)	.64(0.24)
		2	-2.8(4.4)	-2.3(4.0)	23.2(19.0)	-5.7(1.6)	1.6(2.5)	.61(0.30)
NO ITVIC	123	3	-4.1(7.4)	2.8(3.7)	4.0(17.4)	-7.0(1.5)	1.7(2.3)	N/A
		4	-0.7(8.1)	-1.6(3.8)	11.8(15.2)	-6.7(2.2)	0.4(1.8)	N/A
	131	1	-1.4(3.9)	-2.5(4.5)	-4.9(6.6)	-6.5(1.9)	1.1(2.8)	.66(0.25)
		2	-2.8(3.4)	-1.5(4.2)	-2.8(6.1)	-9.2(2.8)	1.4(2.1)	.72(0.25)
	139	1	0.4(4.3)	-3.2(5.8)	-12.6(11.7)	-5.5(2.4)	1.0(2.4)	.64(0.24)
		2	-3.7(4.8)	0.0(4.3)	-10.7(12.5)	-2.2(1.8)	0.9(2.2)	.49(0.12)
AUTO:ED-3	126	1	-5.7(6.6)	2.0(5.1)	7.5(11.6)	-3.1(2.5)	0.03(1.7)	N/A
		2	3.7(6.3)	-0.2(4.6)	-7.0(16.7)	-8.1(2.9)	0.5(2.2)	N/A
DVC:ED-3	142	4	-3.5(2.1)	1.3(4.2)	-2.0(8.4)	-1.3(1.6)	0.0(2.1)	N/A
		5	-1.6(3.2)	0.8(4.1)	-6.2(7.4)	-1.4(2.8)	0.4(2.9)	N/A

(Numbers Without Parentheses Are Means, Numbers In Parentheses Are Standard Deviations)

Table VI-1(b)
PERFORMANCE/WORKLOAD MEASURES
(ED-3; DESCENDING DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\lvert\epsilon_{\dot{x}_h}\rvert_{max}$	$\lvert\epsilon_{\dot{y}_h}\rvert_{max}$	$\lvert\epsilon_z\rvert_{max}$	σ_θ	$\lvert\phi\rvert_{max}$	$\left(\frac{ITVIC}{\Delta t}\right)_{max}$	$\sigma_{\delta_{es}}$	$\sigma_{\delta_{as}}$	$\sigma_{\delta_{cs}}$	PR/TER
RATE:ED-3	121	1	14.3	14.9	48.1	2.5	5.1	1.07	0.84	0.38	2.44	
		2	12.7	14.3	39.6	2.6	4.6	2.14	0.92	0.27	2.41	4C
	130	5	15.2	25.5	38.6	3.0	7.3	1.13	0.90	0.27	2.03	
		6	23.0	27.9	65.9	3.5	10.3	2.93	0.87	0.21	2.27	7B
	140	3	22.9	20.1	78.7	3.2	5.6	0.96	0.97	0.23	1.86	
		4	20.2	17.4	32.3	2.6	5.4	0.74	0.96	0.22	1.90	7C
ATT-RT:ED-3	128	1	10.9	24.5	10.9	0.7	4.8	0.88	0.27	0.18	0.99	
		2	17.9	9.8	9.8	1.6	5.2	1.49	0.22	0.16	2.11	3D
	133	5	6.7	7.4	24.4	1.5	5.0	0.66	0.44	0.15	1.76	
		6	6.6	11.8	31.2	1.9	4.4	0.86	0.50	0.18	2.21	6B
	142	2	16.0	10.2	20.0	1.1	4.6	1.78	0.36	0.14	2.04	
		3	7.6	9.3	17.4	1.5	3.1	1.34	0.45	0.11	2.19	3C
ATT:ED-3	120	1	13.8	12.6	57.0	2.3	6.3	1.12	0.63	0.25	2.13	
		2	11.6	10.3	61.2	1.6	6.6	1.21	0.45	0.23	1.85	3D
NO ITVIC	123	3	18.9	10.2	38.8	1.5	6.3	N/A	0.65	0.17	2.28	
		4	16.9	9.2	42.2	2.2	4.0	N/A	0.19	0.29	1.73	6D
	131	1	9.2	11.5	18.1	1.9	6.7	1.16	0.47	0.26	2.06	
		2	9.6	9.9	15.0	2.8	5.6	1.22	0.62	0.24	1.86	2A
	139	1	9.0	14.8	36.0	2.4	5.8	1.12	0.62	0.20	2.67	
		2	13.3	8.6	35.7	1.8	5.3	0.73	0.46	0.22	2.20	3D
AUTO:ED-3	126	1	18.9	12.2	30.7	2.5	3.4	N/A	0.55	0.19	2.10	
		2	16.3	9.4	40.4	2.9	4.9	N/A	0.64	0.21	2.16	2B
DVC:ED-3	142	4	7.7	9.7	18.8	1.6	4.2	N/A	0.29	0.21	1.27	
		5	8.0	9.0	21.0	2.8	6.2	N/A	0.31	0.28	1.62	2C

Table VI-1(c)

PROCESSED FLIGHT DATA (ED-3; LEVEL DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\epsilon_{\dot{X}_h}$ (ft/sec)	$\epsilon_{\dot{Y}_h}$ (ft/sec)	ϵ_Z (ft)	θ (deg)	ϕ (deg)
RATE:ED-3	121	1	-11.1 (6.1)	11.0(7.5)	-3.4(17.2)	-6.5 (2.7)	5.9 (2.5)
		2	-14.4 (7.7)	14.1(8.8)	-8.9(15.5)	-5.3 (5.2)	6.3 (2.2)
	130	5*					
		6	-16.0(11.1)	0.0(5.3)	-33.3(14.1)	-6.6 (9.6)	5.1 (4.2)
	140	3	-5.9 (2.4)	-5.8(9.2)	-43.1(14.4)	-13.4 (1.3)	-3.1 (3.4)
		4	-6.8 (6.2)	-5.6(3.4)	-43.2 (7.6)	-15.4 (2.6)	-3.3 (1.8)
ATT-RT:ED-3	128	1	-8.1 (5.6)	-2.9(6.5)	-3.7 (8.1)	-0.03(2.4)	-2.5 (3.0)
		2	-1.7(13.5)	-6.2(5.6)	-10.2 (7.2)	0.25(3.6)	-1.2 (3.3)
	133	5	-2.0 (6.6)	-4.2(2.6)	-23.0 (5.4)	-7.6 (1.6)	1.1 (2.0)
		6	4.8 (6.5)	0.1(2.0)	-36.4 (9.0)	-8.5 (0.9)	1.2 (2.0)
	142	2	-15.5(16.4)	5.5(2.6)	-22.6 (7.6)	-1.0 (1.9)	1.1 (1.4)
		3	2.1 (1.9)	1.1(5.9)	-26.7 (7.0)	-9.1 (0.9)	-2.3 (3.0)
ATT:ED-3	120	1	4.7(10.0)	7.6(3.1)	0.2 (8.9)	-9.8 (2.8)	3.6 (2.0)
		2	1.9 (3.5)	3.7(3.1)	-4.1 (7.9)	-10.1 (1.2)	0.6 (2.0)
NO ITVIC	123	3	-14.4 (4.6)	1.8(2.7)	6.9(16.7)	-7.4 (3.0)	2.3 (2.1)
		4	-10.9 (4.3)	1.5(1.7)	21.8(19.0)	-6.1 (2.5)	0.4 (1.3)
	131	1	3.5 (1.5)	-5.7(2.1)	-3.9 (4.5)	-7.3 (0.9)	-2.7 (3.0)
		2	-10.6 (3.7)	-4.8(1.5)	-9.1 (3.6)	-9.1 (2.0)	1.6 (1.4)
	139	1	-13.6 (4.6)	3.0(2.8)	-33.4 (5.5)	-7.8 (3.1)	3.1 (1.7)
		2	-11.3(12.3)	13.7(6.4)	-15.9(18.0)	0.1 (1.6)	3.2 (4.7)
AUTO:ED-3	126	1	-1.8 (4.2)	2.6(2.4)	-12.1(16.6)	-5.5 (2.5)	0.75(2.0)
		2	-8.5 (3.0)	1.0(2.4)	-13.7 (4.5)	-13.3 (2.2)	1.9 (1.9)
DVC:ED-3	142	4	-1.9 (2.9)	7.8(2.8)	4.6(11.5)	-1.3 (1.2)	0.6 (2.0)
		5	-5.1 (3.6)	-7.3(4.1)	-9.5 (4.5)	0.9 (0.9)	-2.3 (2.3)

*Data Not Available for this Record.

(Numbers Without Parentheses Are Means, Numbers In Parentheses Are Standard Deviations)

Table VI-1(d)

PERFORMANCE MEASURES (ED-3; LEVEL DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\lvert\epsilon_{\dot{X}_h}\rvert_{max}$	$\lvert\epsilon_{\dot{Y}_h}\rvert_{max}$	$\lvert\epsilon_Z\rvert_{max}$	$\lvert\theta\rvert_{max}$	$\lvert\phi\rvert_{max}$	PR/TER
RATE:ED-3	121	1	23.2	26.0	37.8	11.9	10.9	
		2	29.8	31.7	39.9	15.7	10.7	4C
	130	5*						
		6	38.2	10.6	61.5	25.8	13.5	7B
	140	3	10.7	24.2	71.9	16.0	9.9	
		4	19.2	12.4	58.4	15.9	6.9	7C
ATT-RT:ED-3	128	1	19.3	15.9	19.9	4.8	8.5	
		2	28.7	17.4	24.6	7.5	7.8	3D
	133	5	15.2	9.4	33.8	10.8	5.1	
		6	17.8	4.1	54.4	10.3	5.2	6B
	142	2	48.3	10.7	37.8	4.8	3.9	
		3	5.9	12.9	40.7	10.9	8.3	3C
ATT:ED-3	120	1	24.7	13.8	18.0	15.4	7.6	
		2	8.9	9.9	19.9	12.5	4.6	3D
NO ITVIC	123	3	23.6	7.2	30.3	13.4	6.5	
		4	19.5	4.9	59.8	11.1	3.0	6D
	131	1	6.5	9.9	12.9	9.1	8.7	
		2	18.0	7.8	16.3	13.1	4.4	2A
	139	1	22.8	8.6	44.4	14.0	6.5	
		2	35.9	26.5	51.9	3.3	12.6	3D
AUTO:ED-3	126	1	10.2	7.4	45.3	10.5	4.8	
		2	14.5	5.8	22.7	17.7	5.7	2B
DVC:ED-3	142	4	7.7	13.4	27.6	3.7	4.6	
		5	12.3	15.5	18.5	2.7	6.9	2C

*Data Not Available for this Record.

Table VI-2(a)

PROCESSED FLIGHT DATA (ED-2+; DESCENDING DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\epsilon_{\dot{X}_h}$ (ft/sec)	$\epsilon_{\dot{Y}_h}$ (ft/sec)	ϵ_z (ft)	θ (deg)	ϕ (deg)	ITVIC Δt (sec)
RATE:ED-2+	130	1	-3.1 (9.0)	0.6 (2.8)	-5.6 (4.8)	-5.5(2.4)	0.6(1.8)	.72(0.26)
		2	-2.0(12.3)	1.0 (7.1)	-1.7 (9.7)	-0.9(5.6)	0.3(3.2)	.67(0.37)
	132	3	-8.8 (4.2)	-2.7 (3.8)	-30.0(12.5)	-2.8(2.2)	0.2(2.9)	.73(0.21)
		4	-5.7(12.4)	-6.8(16.9)	-2.9 (5.3)	-4.6(5.1)	0.2(5.8)	.55(0.11)
	134	3	3.5(13.8)	-3.8(13.8)	-62.8(20.4)	-3.9(3.7)	1.4(4.3)	1.61(2.4)
		4	-13.2 (7.4)	-5.4(11.1)	-49.1(26.1)	-5.0(2.8)	0.5(2.9)	.71(0.17)
ATT-RT:ED-2+	128	5	-9.5 (3.0)	-9.7(10.9)	-6.0 (6.0)	-4.3(1.0)	0.2(2.8)	.57(0.15)
		6	-8.5 (3.4)	-7.8(12.6)	-8.9 (8.8)	-4.4(0.9)	1.0(3.6)	.69(0.27)
	132	1	-10.1 (2.6)	-4.6 (2.3)	-0.8 (3.9)	0.0(0.6)	0.7(2.0)	.77(0.35)
		2	-9.2 (4.3)	-3.6 (4.2)	-0.8 (4.1)	-1.3(0.6)	0.3(2.6)	.58(0.12)
ATT:ED-2+	131	3	-9.5 (5.1)	-5.3 (1.8)	0.5 (4.0)	-3.0(1.5)	0.0(2.0)	.66(0.32)
		4	-8.8 (3.7)	-3.0 (2.8)	-0.8 (2.8)	-5.3(1.4)	1.2(2.2)	.79(0.33)
	134	1	-4.7 (1.9)	-4.5 (9.0)	-30.0(23.1)	-0.3(0.8)	-0.5(2.5)	.70(0.18)
		2	-5.9 (4.3)	-7.9(13.7)	-9.3 (9.3)	-2.1(0.7)	-0.2(2.6)	.67(0.19)
	140	1	-7.7 (4.3)	0.7 (5.4)	-14.6(12.6)	-8.8(2.7)	0.8(2.9)	.52(0.23)
		2	-2.9 (6.2)	0.3 (5.8)	-35.1(12.4)	-11.6(3.6)	-0.1(2.9)	.52(0.12)
AUTO:ED-2+	131	5	-7.0 (2.6)	-1.6 (3.1)	-3.7 (5.5)	-3.0(1.1)	0.3(2.8)	N/A
		6	-13.1 (5.4)	-2.0 (4.2)	0.5 (5.8)	-5.5(1.8)	1.5(2.9)	
	134	5	-11.8 (3.2)	-5.0 (6.4)	-10.3(17.5)	-2.4(0.5)	-0.3(1.8)	
		6	-9.7 (4.1)	-4.7(16.0)	-6.7 (9.1)	-3.4(0.5)	0.8(4.8)	
DVC:ED-2+	142	1	-5.2 (2.1)	-1.0 (4.4)	-6.0 (9.3)	0.0(1.9)	-0.1(1.7)	

(Numbers Without Parentheses Are Means, Numbers In Parentheses Are Standard Deviations)

Table VI-2(b)

PERFORMANCE/WORKLOAD MEASURES (ED-2+; DESCENDING DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\lvert\epsilon_{\dot{X}_h}\rvert_{max}$	$\lvert\epsilon_{\dot{Y}_h}\rvert_{max}$	$\lvert\epsilon_z\rvert_{max}$	σ_θ	$\lvert\phi\rvert_{max}$	$\left(\frac{ITVIC}{\Delta t}\right)_{max}$	$\sigma_{\delta_{es}}$	$\sigma_{\delta_{as}}$	$\sigma_{\delta_{cs}}$	PR/TER
RATE:ED-2+	130	1	21.1	6.2	15.2	2.4	4.2	1.24	0.89	0.17	2.87	
		2	26.6	15.2	21.1	5.6	6.7	1.41	0.93	0.27	2.69	7A
	132	3	17.2	10.3	55.0	2.2	6.0	1.15	0.60	0.25	0.79	
		4	30.5	40.6	13.5	5.1	11.8	0.77	0.80	0.35	2.67	8D
	134	3	31.1	31.4	103.6	3.7	10.0	6.41	0.80	0.36	1.78	
		4	28.0	27.6	101.3	2.8	6.3	1.05	0.60	0.32	1.12	8-1/2F
ATT-RT:ED-2+	128	5	15.5	31.5	18.0	1.0	5.8	0.87	0.27	0.20	1.87	
		6	15.3	33.0	26.5	0.9	8.2	1.23	0.27	0.24	1.68	4D
	132	1	15.3	9.2	8.6	0.6	4.7	1.47	0.22	0.19	1.17	
		2	17.8	12.0	9.0	0.6	5.5	0.82	0.23	0.20	2.79	4D
ATT:ED-2+	131	3	19.7	8.9	8.5	1.5	4.0	1.30	0.39	0.18	1.70	
		4	16.2	8.6	6.4	1.4	5.6	1.45	0.33	0.21	1.57	3A
	134	1	8.5	22.5	76.2	0.8	5.5	1.06	0.12	0.21	1.31	
		2	14.5	35.3	27.9	0.7	5.4	1.05	0.09	0.24	1.86	3E
	140	1	16.3	11.5	39.8	2.7	6.6	0.98	0.67	0.28	2.53	
		2	15.3	11.9	59.9	3.6	5.9	0.76	0.67	0.28	1.97	2-1/2C
AUTO:ED-2+	131	5	12.2	7.8	14.7	1.1	5.9	N/A	0.18	0.26	1.50	
		6	23.9	10.4	12.1	1.8	7.3		0.42	0.26	1.87	2A
	134	5	17.2	17.8	45.3	0.5	3.9		0.14	0.18	1.79	
		6	17.9	36.7	24.9	0.5	10.4		0.10	0.42	1.65	3D
DVC:ED-2+	142	1	9.4	9.8	24.6	1.9	3.5		0.35	0.16	1.23	2C

Table VI-2(c)

PROCESSED FLIGHT DATA (ED-2+; LEVEL DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\epsilon_{\dot{X}_h}$ (ft/sec)	$\epsilon_{\dot{Y}_h}$ (ft/sec)	ϵ_z (ft)	θ (deg)	ϕ (deg)
RATE:ED-2+	130	1	-12.2(2.5)	10.5(4.3)	-14.9(2.1)	-9.8(2.3)	1.9(2.6)
		2	-13.9(8.7)	5.2(2.1)	-12.0(5.4)	-1.3(6.3)	3.5(4.8)
	132	3*					
		4*					
	134	3**					
		4	-8.8(5.5)	-5.1(2.6)	-1.4(6.5)	-0.1(2.1)	1.4(2.7)
ATT-RT:ED-2+	128	5	-8.6(2.9)	-0.9(2.5)	0.6(3.5)	-3.7(2.0)	-0.7(3.1)
		6	-13.1(5.2)	-4.7(5.2)	3.9(4.8)	-0.8(2.2)	-2.0(3.5)
	132	1*					
		2*					
ATT:ED-2+	131	3	-7.6(1.7)	-4.8(1.9)	-17.6(3.9)	-2.9(0.7)	2.6(1.7)
		4	-2.2(1.3)	-3.4(1.5)	-11.8(2.2)	-6.8(0.9)	0.6(1.2)
	134	1	-10.8(3.4)	-8.0(1.5)	-29.4(6.2)	-0.4(0.8)	0.5(2.4)
		2	-5.5(2.0)	-5.6(2.4)	-11.6(3.2)	-2.0(1.0)	-3.5(2.4)
	140	1*					
		2	-15.8(5.9)	7.2(3.2)	-52.7(8.7)	-12.4(4.3)	-0.3(2.1)
AUTO:ED-2+	131	5	-4.6(3.1)	-2.1(3.5)	-2.9(1.4)	-2.7(0.5)	-1.6(3.0)
		6	-13.8(1.5)	-1.2(2.1)	-2.1(9.4)	-6.1(1.2)	2.8(2.2)
	134	5	-10.0(6.8)	-1.4(4.2)	-0.2(11.6)	-0.9(1.0)	-1.1(3.5)
		6	-4.0(3.8)	-1.1(1.8)	-13.1(11.0)	-4.1(1.0)	0.7(2.2)
DVC:ED-2+	142	1	-5.3(3.5)	0.7(5.2)	-7.0(8.2)	-1.3(1.1)	-0.3(3.5)

* HOVER DATA NOT AVAILABLE

** WAVE-OFF PRIOR TO LEVEL DECELERATION

(Numbers Without Parentheses Are Means, Numbers In Parentheses Are Standard Deviations)

Table VI-2(d)

PERFORMANCE MEASURES (ED-2+; LEVEL DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\lvert\epsilon_{\dot{x}_h}\rvert_{max}$	$\lvert\epsilon_{\dot{y}_h}\rvert_{max}$	$\lvert\epsilon_z\rvert_{max}$	$\lvert\theta\rvert_{max}$	$\lvert\phi\rvert_{max}$	PR/TER
RATE:ED-2+	130	1	17.2	19.1	19.1	14.4	7.1	
		2	31.3	9.3	22.8	13.9	13.1	7A
	132	3*						
		4*						8D
	134	3**						
		4	19.8	10.3	14.4	4.3	6.8	8 1/2F
ATT-RT:ED-2+	128	5	14.4	5.9	7.6	7.7	6.9	
		6	23.5	15.1	13.5	5.2	9.0	4D
	132	1						
		2						4D
ATT:ED-2+	131	3	11.0	8.6	22.4	4.3	6.0	
		4	4.8	6.4	16.2	8.6	3.0	3A
	134	1	17.6	11.0	41.8	2.0	5.3	
		2	9.5	10.4	18.0	4.0	8.3	3E
	140	1*						
		2	27.6	13.6	60.1	21.0	4.5	2 1/2C
AUTO:ED-2+	131	5	10.8	9.1	5.7	3.7	7.6	
		6	16.8	5.4	20.9	8.5	7.2	2A
	134	5	23.6	9.8	23.4	2.9	8.1	
		6	11.6	4.7	35.1	6.1	5.1	3D
DVC:ED-2+	142	1	12.3	11.1	23.4	3.5	7.3	2C

*Hover Data Not Available.
**Wave-off Prior to Level Deceleration.

Table VI-3(a)

PROCESSED FLIGHT DATA (ED-2, DESCENDING DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\epsilon_{\dot{x}_h}$ (ft/sec)	$\epsilon_{\dot{Y}_h}$ (ft/sec)	ϵ_z (ft)	θ (deg)	ϕ (deg)	ITVIC Δt (sec)
RATE:ED-2	124	1	-2.9 (6.7)	-1.3 (3.5)	22.0 (9.1)	-2.8(1.8)	0.2(2.3)	.98(0.71)
		2	-4.7(12.4)	-0.4 (4.7)	8.7(16.9)	-4.1(4.3)	-0.4(2.8)	.95(0.12)
ATT-RT:ED-2	133	3	-1.5 (2.0)	-2.2 (4.4)	-5.2 (8.0)	-3.0(1.2)	-0.2(2.7)	.47(0.14)
		4	-3.1 (3.0)	-1.6 (5.4)	-16.0(13.8)	-4.0(1.2)	0.6(3.2)	.49(0.18)
ATT:ED-2	121	3	-10.2 (6.4)	6.5 (9.7)	0.1(41.5)	-3.7(2.0)	0.5(2.6)	.66(0.24)
		4	-17.4 (4.6)	4.5 (7.4)	44.0(28.8)	-4.8(2.2)	1.3(3.3)	1.30(1.06)
	123	1	-12.9 (7.8)	1.5 (6.4)	-8.6(53.0)	-3.4(1.1)	0.2(3.2)	.41(0.19)
		2	-13.9 (5.9)	1.5 (4.3)	20.2(14.0)	-5.2(1.3)	1.4(2.9)	.41(0.18)
NO ITVIC	128	3	-16.3 (4.0)	-4.3 (8.4)	-4.3 (8.5)	-2.5(1.4)	0.6(2.5)	N/A ↓
		4	-16.8 (7.0)	-6.3(10.5)	-6.1 (9.7)	-0.4(0.6)	0.8(3.6)	
AUTO:ED-2	123	5	-9.4 (6.2)	2.4 (4.8)	41.6(14.8)	-3.3(0.7)	1.0(2.5)	
	133	1	-11.5 (3.7)	-1.8 (2.7)	8.7 (9.3)	1.8(0.9)	0.9(2.3)	
		2	-0.6 (2.6)	-0.6 (2.6)	-6.7(16.2)	-2.1(1.2)	1.1(2.1)	
DVC:ED-2	141	1	-3.5 (3.4)	2.1 (3.0)	-3.7(11.1)	-1.3(1.7)	0.8(2.2)	
		2	-4.0 (3.6)	0.7 (3.5)	-6.3(10.7)	-4.2(2.6)	0.2(2.3)	
		5	-3.9 (2.1)	0.9 (2.9)	-67.5(23.5)	-6.3(1.9)	1.1(1.7)	
		6	-1.2 (3.5)	1.5 (3.1)	-12.2 (9.9)	-6.1(1.5)	0.1(2.5)	

(Numbers Without Parentheses Are Means, Numbers In Parentheses Are Standard Deviations)

Table VI-3(b)

PERFORMANCE/WORKLOAD MEASURES (ED-2; DESCENDING DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\lvert \epsilon_{\dot{x}_h} \rvert_{max}$	$\lvert \epsilon_{\dot{y}_h} \rvert_{max}$	$\lvert \epsilon_{z} \rvert_{max}$	σ_{θ}	$\lvert \phi \rvert_{max}$	$\left(\frac{ITVIC}{\Delta t}\right)_{max}$	$\sigma_{\delta_{es}}$	$\sigma_{\delta_{as}}$	$\sigma_{\delta_{cs}}$	PR/TER
RATE:ED-2	124	1	16.3	8.3	40.2	1.8	4.8	2.40	0.97	0.28	2.62	
		2	29.5	9.8	32.5	4.3	6.0	1.19	0.88	0.17	2.12	7A
ATT-RT:ED-2	133	3	5.5	11.0	21.2	1.2	5.6	0.75	0.34	0.22	1.71	
		4	9.1	12.4	43.6	1.2	7.0	0.85	0.32	0.24	1.60	4 1/2B
ATT:ED-2	121	3	23.0	25.9	83.1	2.0	5.7	1.14	0.38	0.27	2.82	
		4	26.6	19.3	101.6	2.2	7.9	3.42	0.44	0.30	1.96	5D
	123	1	28.5	14.3	114.6	1.1	6.6	0.79	0.21	0.34	2.18	
		2	25.7	10.1	48.2	1.3	7.2	0.77	0.37	0.26	2.33	4B
NO ITVIC	128	3	24.3	21.1	21.3	1.4	5.6	N/A	0.15	0.22	1.89	
		4	30.8	27.3	25.5	0.6	8.0		0.07	0.30	1.46	6C
AUTO:ED-2	123	5	21.8	12.0	71.2	0.7	6.0		0.48	0.24	2.06	3C
	133	1	18.9	7.2	27.3	0.9	5.5		0.14	0.23	1.54	
		2	5.8	5.8	39.1	1.2	5.3		0.21	0.25	1.86	2 1/2A
DVC:ED-2	141	1	10.3	8.1	25.9	1.7	5.2		0.26	0.21	1.32	
		2	11.2	7.7	27.7	2.6	4.8		0.45	0.24	1.29	2B
		5	8.1	6.7	114.5	1.9	4.5		0.47	0.17	0.51	
		6	8.2	7.7	32.0	1.5	5.1		0.35	0.24	1.20	2B

Table VI-3(c)

PROCESSED FLIGHT DATA (ED-2; LEVEL DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\epsilon_{\dot{X}_h}$ (ft/sec)	$\epsilon_{\dot{Y}_h}$ (ft/sec)	ϵ_Z (ft)	θ (deg)	ϕ (deg)
RATE:ED-2	124	1	-26.7 (7.3)	4.8(2.5)	-1.4(12.5)	-3.4(1.0)	2.0(0.8)
		2	-11.0(10.7)	6.4(2.3)	-25.1(21.0)	-4.5(2.0)	3.0(2.3)
ATT-RT:ED-2	133	3	-13.0 (2.5)	1.0(2.8)	-18.9 (6.5)	-4.3(1.1)	-1.5(2.7)
		4	-5.5 (1.8)	-1.1(1.6)	-18.5 (7.9)	-5.9(0.5)	0.4(1.2)
ATT:ED-2	121	3	-1.8 (8.8)	2.7(4.4)	6.6 (6.5)	-6.9(1.1)	4.5(2.4)
		4	-0.5 (1.8)	0.2(4.9)	-4.3(10.0)	-1.7(0.6)	4.1(3.1)
	123	1	3.2 (3.9)	6.4(3.2)	-50.3(24.3)	-5.3(2.1)	1.6(1.5)
		2	-19.2 (4.7)	5.2(3.5)	11.6(11.3)	-7.3(3.3)	3.0(2.8)
NO ITVIC	128	3	-8.1(11.2)	-0.3(4.0)	-14.6(13.4)	-1.1(3.3)	-2.0(2.7)
		4	-15.7 (9.8)	-5.4(3.6)	-17.9 (8.3)	-0.7(2.3)	-0.9(3.0)
AUTO:ED-2	123	5	-7.5 (2.5)	3.3(1.8)	19.5 (7.6)	-7.4(0.9)	1.0(1.5)
	133	1	-7.9 (7.2)	-2.5(2.8)	-20.6(10.3)	2.6(1.4)	1.7(2.4)
		2	-6.5 (3.3)	1.9(4.5)	-11.1 (3.7)	-2.6(0.9)	5.1(3.7)
DVC:ED-2	141	1	-4.8 (4.5)	5.4(3.7)	-3.2(11.0)	-2.2(1.3)	1.1(2.1)
		2	-7.9 (9.3)	-5.1(3.3)	-22.9(14.4)	-3.0(1.2)	-3.4(2.1)
		5	-13.1 (3.7)	1.7(3.3)	-12.4 (5.0)	-3.3(2.5)	0.9(1.3)
		6	-15.6 (6.9)	3.8(2.8)	-9.1(13.0)	-4.6(2.5)	2.7(3.1)

(Numbers Without Parentheses Are Means, Numbers In Parentheses Are Standard Deviations)

Table VI-3(d)

PERFORMANCE MEASURES (ED-2; LEVEL DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\lvert\epsilon_{\dot{x}_h}\rvert_{max}$	$\lvert\epsilon_{\dot{y}_h}\rvert_{max}$	$\lvert\epsilon_z\rvert_{max}$	$\lvert\theta\rvert_{max}$	$\lvert\phi\rvert_{max}$	PR/TER
RATE:ED-2	124	1	41.3	9.8	26.4	5.4	3.6	
		2	32.4	11.0	67.1	8.5	7.6	7A
ATT-RT:ED-2	133	3	18.0	6.6	31.9	6.5	6.9	
		4	9.1	4.3	34.3	6.9	2.8	4 1/2B
ATT:ED-2	121	3	19.4	11.5	19.6	9.1	9.3	
		4	4.1	10.0	24.3	2.9	10.3	5D
	123	1	11.0	12.8	98.9	9.5	4.6	
		2	28.6	12.2	34.2	13.9	8.6	4B
NO ITVIC	128	3	30.5	8.6	41.4	7.7	1.4	
		4	35.3	12.6	34.5	5.3	6.9	6C
AUTO:ED-2	123	5	12.5	6.9	34.7	9.2	4.0	3C
	133	1	22.3	8.1	41.2	5.4	6.5	
		2	13.1	10.9	18.5	4.4	12.5	2 1/2A
DVC:ED-2	141	1	13.8	12.8	25.2	4.8	5.3	
		2	26.5	11.7	51.7	5.4	7.6	2B
		5	20.5	8.3	22.4	8.3	3.5	
		6	29.4	9.4	35.1	9.6	8.9	2B

Table VI-4(a)

PROCESSED FLIGHT DATA (ED-1; DESCENDING DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\epsilon_{\dot{x}_h}$ (ft/sec)	$\epsilon_{\dot{Y}_h}$ (ft/sec)	ϵ_z (ft)	θ (deg)	ϕ (deg)	ITVIC Δt (sec)
RATE:ED-1/FD	130	3	2.9(5.9)	1.3 (9.9)	-0.4 (9.4)	-2.5(2.5)	2.5(3.9)	.89(0.93)
		4	1.8(4.8)	0.2(12.8)	-1.1 (7.5)	-2.0(2.4)	1.2(3.7)	.56(0.15)
ATT:ED-1/FD	121	5	-1.2(6.8)	2.3 (5.2)	8.5(25.8)	-1.0(1.2)	2.0(2.9)	1.30(1.8)
		6	-0.4(4.2)	-3.3 (4.1)	40.5(31.0)	-4.8(1.9)	0.1(1.9)	.67(0.23)
AUTO:ED-1	124	3	-12.0(4.0)	5.5(19.4)	25.0(54.9)	-2.2(1.4)	-0.1(4.5)	N/A
		4	-14.0(5.5)	23.8(12.4)	47.1(31.5)	-5.5(2.4)	0.6(2.7)	↓
DVC:ED-1	141	3	-2.4(5.9)	-3.4(11.1)	-11.3(21.7)	-4.6(1.9)	-0.7(2.6)	↓
		4	-4.7(3.4)	17.8 (8.0)	-2.2(12.9)	-3.9(2.2)	0.6(2.8)	↓

(Numbers Without Parentheses Are Means, Numbers In Parentheses Are Standard Deviations)

Table VI-4(b)

PERFORMANCE/WORKLOAD MEASURES (ED-1; DESCENDING DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\|\epsilon_{\dot{x}_h}\|_{max}$	$\|\epsilon_{\dot{Y}_h}\|_{max}$	$\|\epsilon_z\|_{max}$	σ_θ	$\|\phi\|_{max}$	$\left(\begin{matrix}ITVIC\\ \Delta t\end{matrix}\right)_{max}$	$\sigma_{\delta_{es}}$	$\sigma_{\delta_{as}}$	$\sigma_{\delta_{cs}}$	PR/TER
RATE:ED-1/FD	130	3	14.7	21.1	19.2	2.5	10.3	2.75	0.91	0.37	2.49	
		4	11.4	25.8	16.1	2.4	8.6	0.86	0.90	0.34	2.09	7 1/2B
ATT:ED-1/FD	121	5	14.8	12.7	60.1	1.2	7.8	4.90	0.38	0.32	2.21	
		6	8.8	11.5	102.5	1.9	3.9	1.13	0.49	0.20	1.53	7D
AUTO:ED-1	124	3	20.0	44.3	134.8	1.4	9.1	N/A	0.30	0.37	2.03	
		4	25.0	48.6	110.1	2.4	6.0	↓	0.50	0.23	1.34	7B
DVC:ED-1	141	3	14.2	25.6	54.7	1.9	5.9	↓	0.11	0.22	1.17	
		4	11.5	33.8	28.0	2.2	6.2	↓	0.17	0.25	2.06	7B

Table VI-4(c)

PROCESSED FLIGHT DATA (ED-1; LEVEL DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\epsilon_{\dot{x}_h}$ (ft/sec)	$\epsilon_{\dot{y}_h}$ (ft/sec)	ϵ_z (ft)	θ (deg)	ϕ (deg)
RATE:ED-1/FD	130	3 4 *	-5.1(6.7)	2.4(3.2)	-4.3 (0.7)	-5.3(3.9)	5.6(1.8)
ATT:ED-1/FD	121	5 6 *	-6.1(3.2)	8.0(2.1)	-13.4(14.6)	-1.8(0.7)	5.9(1.9)
AUTO:ED-1	124	3 4	-28.2(6.0) -28.4(8.3)	3.1(1.1) 3.1(3.2)	30.5(11.8) 41.9(47.2)	-7.9(1.5) -6.0(3.7)	0.4(1.0) 0.5(2.5)
DVC:ED-1	141	3 4	5.3(2.6) -10.6(6.4)	20.0(6.9) 6.9(7.6)	-27.9(14.2) -28.8(15.8)	-3.8(1.4) -4.5(2.3)	1.5(2.1) 2.3(3.5)

*DATA NOT AVAILABLE FOR THIS RECORD.

(Numbers Without Parentheses Are Means, Numbers In Parentheses Are Standard Deviations)

Table VI-4(d)

PERFORMANCE MEASURES (ED-1; LEVEL DECELERATION)

CONFIG.	FLIGHT NO.	APPROACH	$\lvert\epsilon_{\dot{x}_h}\rvert_{max}$	$\lvert\epsilon_{\dot{y}_h}\rvert_{max}$	$\lvert\epsilon_z\rvert_{max}$	$\lvert\theta\rvert_{max}$	$\lvert\phi\rvert_{max}$	PR/TER
RATE:ED-1/FD	130	3 4*	18.5	8.8	5.7	13.1	9.2	7 1/2B
ATT:ED-1/FD	121	5 6*	12.5	12.2	42.6	3.2	9.7	7D
AUTO:ED-1	124	3 4	40.2 45.0	5.3 9.5	54.1 136.3	10.9 13.4	2.4 5.5	7B
DVC:ED-1	141	3 4	10.5 23.4	43.8 22.1	56.3 60.1	6.6 9.1	5.7 9.3	7B

*DATA NOT AVAILABLE FOR THIS RECORD

measures were analyzed for the light and moderate turbulence cases. The light turbulence matrixes are 3 x 5 arrays of the performance and workload measures for all possible combinations of the ED-3, ED-2+, and ED-2 display formats and the five levels of stability/control augmentation; the moderate turbulence matrices are 2 x 3 arrays: all possible combinations of the ED-3 and ED-2+ display formats and the rate, attitude/rate, and attitude augmentation control systems. In addition, separate 2 x 2 arrays were constructed to analyze the effects on performance and workload of:

- the absence of the configuration change director light - the ATT: ED-3 and ATT: ED-2 configuration were evaluated both with and without the ITVIC light

- the lack of displayed velocity information - the AUTO and DVC control system were evaluated both with the ED-2 and with the ED-1 format

- a separated control director - the RATE and ATT control systems were evaluated both with the ED-3 and with the ED-1/FD format.

For the level deceleration to the hover, only the performance measures were analyzed for the light turbulence case, producing the same 3 x 5 arrays of performance and workload measures as were obtained for the descending deceleration element of the task. This procedure allows not only an analysis of the effects of control, display, and control/display interaction but also the direct comparison of the data from the two final elements of the task in order to determine the existence of any effects due to the interaction of task element and control/display combination.

The results of the ANOVA are presented in Tables VI-5 through VI-10 as follows:

TABLE	ANOVA
VI-5	Performance/workload: descending deceleration, light turbulence effect
VI-6	Performance/workload: descending deceleration, moderate turbulence effect
VI-7	Performance/workload: effect of configuration change director, descending deceleration
VI-8	Performance/workload: effect of velocity information, descending deceleration
VI-9	Performance/workload: effect of control director presentation, descending deceleration

VI-10 Performance: level deceleration, light turbulence effect

The evaluation flights from which the individual performance/workload measures were derived are identified in each table. The format for the individual ANOVA consists of: 1) a table of cell (i.e., configuration) means for the particular performance or workload measure analyzed which includes the row and column means and the grand mean of the measure and 2) an analysis of variance table which demonstrates the results of the analysis.

For each r x c table of cell means, the corresponding ANOVA table is presented as follows, assuming 2 replications per test cell:

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
Between Rows	r-1	SSR (between row means and grand mean)	$MSR=\frac{SSR}{r-1}$	$\frac{MSR}{MSE}$ (.01, .05, or -)
Between Columns	c-1	SSC (between columns means and grand mean)	$MSC=\frac{SSC}{c-1}$	$\frac{MSC}{MSE}$ (.01, .05, 05 -)
Interaction	(r-1)(c-1)	SSI=SSM-SSR -SSC SSM(between cell means and grand mean)	$MSI = \frac{SSI}{(r-1)(c-1)}$	$\frac{MSI}{MSE}$ (.01, .05, or -)
Random Error	rc	SSE=SST-SSM SST (between cell elements and grand mean)	$MSE=\frac{SSE}{rc}$	———

In the case where the interaction effect is found to be insignificant, MSE is replaced by $MSE'\left(= \frac{SSE+SSI}{rc+(r-1)(c-1)}\right)$ and the error degrees of freedom are increased accordingly. In addition, in many of the analyses, an unequal number of replications were performed for each test cell; the method of unweighted means described in Reference 50 is used in this situation to determine the appropriate value of MSE. In this case the error degrees of freedom are (N-rc) where N is the total number of observations for the matrix.

Table VI-5

PERFORMANCE/WORKLOAD ANOVA: DESCENDING DECELERATION WITH LIGHT TURBULENCE EFFECT

SOURCE OF DATA

	RATE	ATT/ RATE	ATT	AUTO	DVC
ED-3	F-121	F-133 F-142	F-131	F-126	F-142
ED-2+	F-130	F-132	F-131	F-131	F-142
ED-2	F-124	F-133	F-133	F-123 F-133	F-141

Table VI-5 (a)

$|\epsilon_{\dot{x}_h}|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS	
ED-3	13.5	9.23	9.4	17.6	7.85	11.52	
ED-2+	23.85	16.55	17.95	18.05	9.4	17.16	
ED-2	22.9	7.3	27.1	15.5	9.45	16.45	
CONTROL MEANS	20.08	11.03	18.15	17.05	8.9	15.04	(GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	640.95	160.24	34.53(.01)
DISPLAY	2	255.89	127.95	27.58(.01)
CONTROL/DISPLAY	8	301.68	37.71	8.13(.01)
RANDOM ERROR	19	180.63	4.64	———

Table VI-5 (b)

σ_θ

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	2.55	1.5	2.35	2.7	2.2	2.26
ED-2+	4.0	0.6	1.45	1.45	1.9	1.88
ED-2	3.05	1.2	1.2	1.4	1.93	1.76
CONTROL MEANS	3.2	1.1	1.67	1.85	2.01	1.97 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	15.14	3.79	54.14(.01)
DISPLAY	2	1.48	0.74	10.57(.01)
CONTROL/DISPLAY	8	7.16	0.9	12.79(.01)
RANDOM ERROR	19	2.67	0.07	———

Table VI-5 (c)

$\sigma_{\delta_{es}}$

TABLE OF CELL MEANS

	RATE	ATT/RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	.895	.438	.545	.595	.300	.555
ED-2+	.910	.225	.360	.300	.350	.429
ED-2	.925	.330	.290	.277	.383	.441
CONTROL MEANS	.910	.331	.398	.391	.344	.475 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	1.7996	.4499	264.64(.01)
DISPLAY	2	.2198	.1099	64.6 (.01)
CONTROL/DISPLAY	8	.0594	.0074	4.37(.01)
RANDOM ERROR	19	.076	.0017	———

Table VI-5 (d)

$\left| \epsilon_z \right|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	43.85	23.25	16.55	35.55	19.9	27.82
ED-2+	18.15	8.8	7.45	13.4	24.6	14.48
ED-2	36.35	32.4	81.4	45.87	28.53	44.91
CONTROL MEANS	32.78	21.48	35.13	31.61	24.34	29.07 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	954.99	238.75	4.05(.05)
DISPLAY	2	4810.73	2405.37	40.76(.01)
CONTROL/DISPLAY	8	4328.29	541.04	9.17(.01)
RANDOM ERROR	19	2145.92	59.02	———

Table VI-5 (e)

$\sigma_{\delta_{cs}}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	2.29	2.12	1.96	2.13	1.45	1.99
ED-2+	2.78	1.98	1.94	1.67	1.23	1.92
ED-2	2.37	1.66	2.26	1.82	1.27	1.88
CONTROL MEANS	2.48	1.92	2.05	1.87	1.32	1.93 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	4.318	1.080	107.95(.01)
DISPLAY	2	.314	.157	15.7 (.01)
CONTROL/DISPLAY	8	.642	.080	8.03(.01)
RANDOM ERROR	19	.418	.010	———

Table VI-5 (f)

$\left|\epsilon_{\dot{Y}_h}\right|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	14.6	9.68	10.7	10.8	9.35	11.03
ED-2+	10.7	10.6	8.75	9.85	9.8	9.94
ED-2	9.05	11.7	12.2	8.33	7.55	9.77
CONTROL MEANS	11.45	10.66	10.55	9.66	8.9	10.24 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	36.0	9.0	13.64(.01)
DISPLAY	2	13.79	6.90	10.45(.01)
CONTROL/DISPLAY	8	50.59	6.32	9.58(.01)
RANDOM ERROR	19	25.53	0.66	———

Table VI-5 (g)

$|\phi|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	4.85	4.28	6.15	4.15	5.2	4.93
ED-2+	5.45	5.1	4.8	6.6	3.5	5.09
ED-2	5.4	6.3	6.9	5.6	4.9	5.82
CONTROL MEANS	5.23	5.23	5.95	5.45	4.53	5.28 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	5.35	1.34	7.43(.01)
DISPLAY	2	4.45	2.23	12.39(.01)
CONTROL/DISPLAY	8	14.17	1.77	9.84(.01)
RANDOM ERROR	19	6.96	0.18	———

Table VI-5 (h)

$\sigma_{\delta_{as}}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	.283	.125	.250	.200	.245	.221
ED-2+	.220	.195	.200	.260	.160	.207
ED-2	.225	.230	.300	.240	.215	.242
CONTROL MEANS	.243	.183	.250	.233	.207	.223 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	.0206	.0052	12.88(.01)
DISPLAY	2	.0039	.0020	4.88(.05)
CONTROL/DISPLAY	8	.0346	.0043	10.81(.01)
RANDOM ERROR	19	.0157	.0004	———

Table VI-5 (i)

$(\text{ITVIC}\,\Delta t)_{max}$

TABLE OF CELL MEANS -

						DISPLAY MEANS
ED-3	1.82	1.56	1.19	——	——	1.52
ED-2+	1.33	1.15	1.12	——	——	1.20
ED-2	1.80	0.80	0.78	——	——	1.13
	RATE	ATT/ RATE	ATT	AUTO	DVC	
CONTROL MEANS	1.65	1.17	1.03			1.28 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	2	1.79	0.895	100.67(.01)
DISPLAY	2	0.99	0.495	55.68(.01)
CONTROL/DISPLAY	4	0.14	0.035	3.94(.05)
RANDOM ERROR	13	0.26	0.008	————

Table VI-6

PERFORMANCE/WORKLOAD ANOVA: DESCENDING DECELERATION WITH MODERATE TURBULENCE EFFECT

	SOURCE OF DATA		
ED-3	F-140	F-128	F-120
ED-2+	F-132	F-128	F-134
	RATE	ATT/ RATE	ATT

Table VI-6 (a)

$|\epsilon_{\dot{x}_h}|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	21.55	14.4	12.7	—	—	16.22
ED-2+	23.85	15.4	11.5	—	—	16.92
ED-2	—	—	—	—	—	
CONTROL MEANS	22.7	14.9	12.1			16.57 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	2	241.39	120.7	6.74(.05)
DISPLAY	1	1.47	1.47	0.08(-)
CONTROL/DISPLAY	2	6.26	3.13	0.14(-)
RANDOM ERROR	8	137.03	17.91	—

Table VI-6 (b)

σ_{θ}

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	2.9	1.15	1.95	—	—	2.0
ED-2+	3.65	0.95	0.75	—	—	1.78
ED-2	—	—	—	—	—	
CONTROL MEANS	3.28	1.05	1.35			1.89 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	2	11.66	5.83	6.7 (.05)
DISPLAY	1	0.14	0.14	0.16(-)
CONTROL/DISPLAY	2	1.91	0.96	1.14(-)
RANDOM ERROR	8	5.04	0.87	———

Table VI-6 (c)

$\sigma_{\delta_{es}}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	.965	.245	.54	—	—	.583
ED-2+	.700	.270	.105	—	—	.358
ED-2	—	—	—	—	—	
CONTROL MEANS	.833	.258	.323			.471 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	2	.7932	.3966	21.7 (.01)
DISPLAY	1	.1519	.1519	18.6 (.05)
CONTROL/DISPLAY	2	.0973	.0487	5.97(.05)
RANDOM ERROR	6	.0489	.0082	—

Table VI-6 (d)

$|\epsilon_z|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	55.5	10.35	59.1	——	——	41.65
ED-2+	34.25	22.25	52.05	——	——	36.18
ED-2	——	——	——	——	——	
CONTROL MEANS	44.88	16.3	55.58			38.92 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	2	3298.07	1649.04	3.56(-)
DISPLAY	1	89.66	89.66	0.19(-)
CONTROL/DISPLAY	2	553.21	276.61	0.53(-)
RANDOM ERROR	8	3149.6	462.85	————

Table VI-6 (e)

$\sigma_{\delta_{cs}}$

TABLE OF CELL MEANS

	RATE	ATT/RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	1.88	1.55	1.99	——	——	1.81
ED-2+	1.73	1.78	1.59	——	——	1.70
ED-2	——	——	——	——	——	
CONTROL MEANS	1.81	1.66	1.79			1.75 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	2	0.05	0.025	0.07 (-)
DISPLAY	1	0.03	0.03	0.09 (-)
CONTROL/DISPLAY	2	0.21	0.105	0.24 (-)
RANDOM ERROR	6	2.6	0.433	————

Table VI-6 (f)

$\left|\epsilon_{\dot{Y}_h}\right|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	18.75	17.15	11.45	——	——	15.78
ED-2+	25.45	32.25	28.9	——	——	28.87
ED-2	——	——	——	——	——	
CONTROL MEANS	22.1	24.7	20.18			22.33 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	2	41.25	20.63	0.23(-)
DISPLAY	1	513.52	513.52	5.7 (.05)
CONTROL/DISPLAY	2	63.89	31.95	0.29(-)
RANDOM ERROR	8	656.42	90.04	——

Table VI-6 (g)

$|\phi|_{max}$

TABLE OF CELL MEANS

						DISPLAY MEANS
ED-3	5.5	5.0	6.45	—	—	5.65
ED-2+	8.9	7.0	5.45	—	—	7.12
ED-2	—	—	—	—	—	
	RATE	ATT/ RATE	ATT	AUTO	DVC	
CONTROL MEANS	7.2	6.0	5.95			6.38 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	2	4.01	2.01	0.55 (-)
DISPLAY	1	6.46	6.46	1.73 (-)
CONTROL/DISPLAY	2	10.1	5.05	1.53 (-)
RANDOM ERROR	8	19.85	3.74	———

Table VI-6 (h)

$\sigma_{\delta_{as}}$

TABLE OF CELL MEANS

	RATE	ATT/RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	.225	.170	.240	——	——	.212
ED-2+	.300	.220	.225	——	——	.248
ED-2	——	——	——	——	——	
CONTROL MEANS	.263	.195	.233			.230 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	2	.0091	.0046	3.27 (-)
DISPLAY	1	.0040	.0040	2.88 (-)
CONTROL/DISPLAY	2	.0045	.0023	2.05 (-)
RANDOM ERROR	8	.0066	.0014	————

Table VI-6 (i)

$(\text{ITVIC } \Delta t)_{max}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	0.85	1.19	1.05	——	——	1.03
ED-2+	0.96	1.05	1.06	——	——	1.02
ED-2	——	——	——	——	——	
CONTROL MEANS	0.91	1.12	1.06			1.03 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	2	.095	.048	48.78(.01)
DISPLAY	1	.001	.001	1.03(-)
CONTROL/DISPLAY	2	.029	.015	14.89(.01)
RANDOM ERROR	8	.017	.001	——

Table VI-7

PERFORMANCE/WORKLOAD ANOVA: EFFECT OF CONFIGURATION CHANGE DIRECTOR, DESCENDING DECELERATION

SOURCE OF DATA

ATT:ED-3	F-123	F-120
ATT:ED-2	F-128	F-123
ITVIC:	NO	YES

Table VI-7 (a)

$$\left|\epsilon_{\dot{x}_h}\right|_{max}$$

TABLE OF CELL MEANS

			MEANS	
ATT:ED-3	17.9	12.7	15.3	
ATT:ED-2	27.55	27.1	27.33	
ITVIC	NO	YES		
MEANS	22.73	19.9	21.31	(GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL/DISPLAY	1	289.2	289.2	35.48(.05)
ITVIC	1	15.96	15.96	1.96(-)
CONTROL/DISPLAY/ITVIC	1	11.29	11.29	1.53(-)
RANDOM ERROR	5	29.46	8.15	————

Table VI-7 (b)

$\sigma_{\delta_{es}}$

TABLE OF CELL MEANS

			MEANS
ATT:ED-3	.42	.54	.48
ATT:ED-2	.11	.29	.20
ITVIC	NO	YES	
MEANS	.27	.42	.34 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL/DISPLAY	1	.157	.157	5.57 (-)
ITVIC	1	.045	.045	1.6 (-)
CONTROL/DISPLAY/ITVIC	1	.001	.001	0.03 (-)
RANDOM ERROR	5	.14	.028	———

Table VI-7 (c)

$|\epsilon_z|_{max}$

TABLE OF CELL MEANS

			MEANS
ATT:ED-3	40.5	59.1	49.8
ATT:ED-2	23.4	81.4	52.4
ITVIC	NO	YES	
MEANS	31.95	70.25	51.1 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL/DISPLAY	1	13.52	13.52	0.02 (-)
ITVIC	1	2933.78	2933.78	4.9 (-)
CONTROL/DISPLAY/ITVIC	1	776.18	776.18	1.29 (-)
RANDOM ERROR	5	2227.9	600	———

Table VI-7 (d)

$\sigma_{\delta_{cs}}$

TABLE OF CELL MEANS

			MEANS
ATT:ED-3	2.0	1.99	2.00
ATT:ED-2	1.68	2.26	1.97
ITVIC	NO	YES	
MEANS	1.84	2.12	1.98 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL/DISPLAY	1	0.0	0.0	0.0 (-)
ITVIC	1	0.16	0.16	1.7 (-)
CONTROL/DISPLAY/ITVIC	1	0.18	0.18	2.48(-)
RANDOM ERROR	5	0.29	0.094	———

Table VI-7 (e)

$|\epsilon_{\dot{Y}_h}|_{max}$

TABLE OF CELL MEANS

			MEANS
ATT:ED-3	9.7	11.5	10.58
ATT:ED-2	24.2	12.2	18.2
ITVIC	NO	YES	
MEANS	16.95	11.83	14.39 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL/DISPLAY	1	116.28	116.28	14.91 (.05)
ITVIC	1	52.53	52.53	6.73 (-)
CONTROL/DISPLAY/ITVIC	1	94.54	94.54	12.12 (.05)
RANDOM ERROR	4	31.18	7.8	———

Table VI-7 (f)

$\sigma_{\delta_{as}}$

TABLE OF CELL MEANS

	NO	YES	MEANS
ATT:ED-3	.23	.24	.235
ATT:ED-2	.26	.30	.280
ITVIC	NO	YES	
MEANS	.245	.270	.26 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL/DISPLAY	1	.004	.004	1.39 (-)
ITVIC	1	.0012	.0012	0.42 (-)
CONTROL/DISPLAY/ITVIC	1	.0005	.0005	0.14 (-)
RANDOM ERROR	5	.0138	.0029	———

Table VI-8

PERFORMANCE/WORKLOAD ANOVA: EFFECT OF DISPLAYED VELOCITY INFORMATION, DESCENDING DECELERATION

SOURCE OF DATA

	AUTO	DVC
ED-2	F-123 F-133	F-141
ED-1	F-124	F-141

Table VI-8 (a)

$$\left| \epsilon_{\dot{x}_h} \right|_{max}$$

TABLE OF CELL MEANS

			MEANS
ED-2	15.5	9.45	12.48
ED-1	22.5	12.85	17.68
	AUTO	DVC	15.08 (GRAND MEAN)
MEANS	19.0	11.15	

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	162.4	162.4	810(.01)
DISPLAY	1	80.74	80.74	400(.01)
CONTROL/DISPLAY	1	0.0	0.0	0(—)
RANDOM ERROR	7	3.23	0.18	———

Table VI-8 (b)

$\sigma_{\delta_{es}}$

TABLE OF CELL MEANS

	AUTO	DVC	MEANS
ED-2	.277	.383	.33
ED-1	.400	.140	.27
MEANS	.339	.262	0.30 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	.0016	.0016	0.85(-)
DISPLAY	1	.0115	.0115	6.08(.05)
CONTROL/DISPLAY	1	.0851	.0851	45.83(.01)
RANDOM ERROR	7	.0334	.0019	———

Table VI-8 (c)

$|\epsilon_z|_{max}$

TABLE OF CELL MEANS

			MEANS
ED-2	45.87	28.53	37.20
ED-1	122.45	41.35	81.9
	AUTO	DVC	59.55 (GRAND MEAN)
MEANS	84.16	34.94	

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	4588.17	4588.17	65 (.01)
DISPLAY	1	4795.42	4795.42	68 (.01)
CONTROL/DISPLAY	1	2439.71	2439.71	34.5(.01)
RANDOM ERROR	7	1016.33	70.58	———

Table VI-8 (d)

$\sigma_{\bar{\delta}_{cs}}$

TABLE OF CELL MEANS

	AUTO	DVC	MEANS
ED-2	1.82	1.27	1.55
ED-1	1.69	1.62	1.65
MEANS	1.75	1.44	1.60 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	0.32	0.32	82.86(.01)
DISPLAY	1	0.026	0.026	6.68(.05)
CONTROL/DISPLAY	1	0.138	0.138	35.48(.01)
RANDOM ERROR	7	0.056	0.0039	———

Table VI-8 (e)

$\left|\epsilon_{\dot{Y}_h}\right|_{max}$

TABLE OF CELL MEANS

			MEANS
ED-2	8.33	7.55	7.94
ED-1	46.45	29.7	38.08
	AUTO	DVC	23.01 (GRAND MEAN)
MEANS	27.39	18.63	

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	203.91	203.91	49 (.01)
DISPLAY	1	2319.91	2319.91	558 (.01)
CONTROL/DISPLAY	1	77.71	77.71	18.68(.01)
RANDOM ERROR	7	73.76	4.16	———

Table VI-8 (f)

$\sigma_{\delta_{as}}$

TABLE OF CELL MEANS

			MEANS
ED-2	0.24	0.215	.228
ED-1	0.30	0.235	.268
	AUTO	DVC	.248 (GRAND MEAN)
MEANS	.27	.225	

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	.0049	.0049	288.24(.01)
DISPLAY	1	.0044	.0044	258.82(.01)
CONTROL/DISPLAY	1	.0005	.0005	29.41(.01)
RANDOM ERROR	7	.0003	.00002	———

Table VI-9

PERFORMANCE/WORKLOAD ANOVA: EFFECT OF CONTROL DIRECTOR PRESENTATION, DESCENDING DECELERATION

	SOURCE OF DATA	
ED-3	F-130	F-120
ED-1/FD	F-130	F-121
	RATE	ATT

Table VI-9 (a)

$|\epsilon_{\dot{x}_h}|_{max}$

TABLE OF CELL MEANS

	RATE	ATT	MEANS
ED-3	19.1	12.7	15.9
ED-1/FD	13.05	11.8	12.43
MEANS	16.08	12.25	14.16 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	29.26	29.26	2.1 (-)
DISPLAY	1	24.15	24.15	1.74(-)
CONTROL/DISPLAY	1	13.27	13.27	0.94(-)
RANDOM ERROR	5	56.28	13.91	———

Table VI-9 (b)

$\sigma_{\delta_{es}}$

TABLE OF CELL MEANS

	RATE	ATT	MEANS
ED-3	.885	.540	.713
ED-1/FD	.905	.435	.670
MEANS	.895	.488	.691 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	.3321	.3321	54.3 (.01)
DISPLAY	1	.0036	.0036	0.59(-)
CONTROL/DISPLAY	1	.008	.008	1.42(-)
RANDOM ERROR	5	.0226	.0061	———

Table VI-9 (c)

$|\epsilon_{\mathcal{Z}}|_{max}$

TABLE OF CELL MEANS

	RATE	ATT	MEANS
ED-3	52.25	59.1	55.68
ED-1/FD	17.65	81.3	49.48
MEANS	34.95	70.2	52.58 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	2485.12	2485.12	4.29 (-)
DISPLAY	1	76.87	76.87	0.13 (-)
CONTROL/DISPLAY	1	1613.14	1613.14	5.02 (-)
RANDOM ERROR	5	1285.14	579.66	———

Table VI-9 (d)

$\sigma_{\bar{\delta}_{cs}}$

TABLE OF CELL MEANS

			MEANS
ED-3	2.15	1.99	2.07
ED-1/FD	2.29	1.87	2.08
	RATE	ATT	
MEANS	2.22	1.93	2.08 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	.169	.169	2.05 (-)
DISPLAY	1	.001	.001	.01 (-)
CONTROL/DISPLAY	1	.032	.032	.34 (-)
RANDOM ERROR	5	.38	.082	———

Table VI-9 (e)

$|\epsilon_{\dot{Y}_h}|_{max}$

TABLE OF CELL MEANS

	RATE	ATT	MEANS
ED-3	26.7	11.45	19.08
ED-1/FD	23.45	12.1	17.78
MEANS	25.08	11.78	18.43 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	353.77	353.77	71.04(.01)
DISPLAY	1	3.37	3.37	0.68 (-)
CONTROL/DISPLAY	1	7.63	7.63	1.77 (-)
RANDOM ERROR	5	17.28	4.98	———

Table VI-9 (f)

$\sigma_{\delta_{as}}$

TABLE OF CELL MEANS

			MEANS
ED-3	.24	.24	.24
ED-1/FD	.355	.26	.308
	RATE	ATT	
MEANS	.298	.25	.274 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	.0045	.0045	1.58 (-)
DISPLAY	1	.0091	.0091	3.20 (-)
CONTROL/DISPLAY	1	.0046	.0046	1.92 (-)
RANDOM ERROR	5	.0096	.0028	———

Table VI-9 (g)

$\left(\frac{ITVIC}{\Delta t}\right)_{max}$

TABLE OF CELL MEANS

	RATE	ATT	MEANS
ED-3	2.03	1.17	1.60
ED-1/FD	1.81	3.02	2.41
MEANS	1.92	2.09	2.00 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	1	0.06	0.06	0.02 (-)
DISPLAY	1	1.32	1.32	0.52 (-)
CONTROL/DISPLAY	1	2.15	2.15	0.82 (-)
RANDOM ERROR	5	10.52	2.53	———

Table VI-10

PERFORMANCE ANOVA: LEVEL DECELERATION WITH LIGHT TURBULENCE EFFECT

SOURCE OF DATA

ED-3	F-121	F-133 F-142	F-131	F-126	F-142
ED-2+	F-130	F-132	F-131	F-131	F-142
ED-2	F-124	F-133	F-133	F-123 F-133	F-141
	RATE	ATT/ RATE	ATT	AUTO	DVC

Table VI-10 (a)

$|\epsilon_{\dot{x}_h}|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	26.5	21.8	12.25	12.35	10.0	16.58
ED-2+	24.35	18.95	7.9	13.8	12.3	15.46
ED-2	36.85	13.55	19.8	15.97	22.55	21.74
CONTROL MEANS	29.23	18.1	13.32	14.04	14.95	17.93 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	984.24	246.06	53.14(.01)
DISPLAY	2	189.34	94.67	20.45(.01)
CONTROL/DISPLAY	8	483.12	60.39	13.04(.01)
RANDOM ERROR	19	180.52	4.63	————

Table VI-10 (b)

$|\theta|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	13.8	9.2	11.1	14.1	3.2	10.28
ED-2+	14.15	6.45	6.45	6.1	3.5	7.33
ED-2	6.95	6.7	11.7	6.33	7.03	7.74
CONTROL MEANS	11.63	7.45	9.75	8.84	4.58	8.45 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	137.33	34.33	16.91(.01)
DISPLAY	2	48.12	24.06	11.85(.01)
CONTROL/DISPLAY	8	176.85	22.11	10.89(.01)
RANDOM ERROR	19	79.13	2.03	———

Table VI-10 (c)

$|\epsilon_z|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	38.85	41.68	14.6	34.0	23.05	30.44
ED-2+	20.95	10.55	19.3	13.3	23.4	17.5
ED-2	46.75	33.1	66.55	31.47	33.6	42.29
CONTROL MEANS	35.52	28.44	33.48	26.26	26.68	30.08 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	299.02	74.76	2.23(-)
DISPLAY	2	2904.56	1452.28	43.29(.01)
CONTROL/DISPLAY	8	3108.6	388.58	11.58(.01)
RANDOM ERROR	19	1306.7	33.55	———

Table VI-10 (d)

$|\epsilon_{\dot{Y}_h}|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	28.85	9.28	8.85	6.6	14.45	13.61
ED-2+	14.2	10.5	7.5	11.35	11.1	10.93
ED-2	10.4	5.45	12.5	8.63	10.55	9.51
CONTROL MEANS	17.82	8.41	9.62	8.86	12.0	11.35 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	371.9	92.98	18.67(.01)
DISPLAY	2	67.73	33.87	6.8 (.01)
CONTROL/DISPLAY	8	411.1	51.39	10.32(.01)
RANDOM ERROR	19	194.03	4.98	————

Table VI-10 (e)

$|\phi|_{max}$

TABLE OF CELL MEANS

	RATE	ATT/ RATE	ATT	AUTO	DVC	DISPLAY MEANS
ED-3	10.8	5.63	6.55	5.25	5.75	6.80
ED-2+	10.1	7.95	4.5	7.4	7.3	7.45
ED-2	5.6	4.85	6.6	7.67	6.33	6.21
CONTROL MEANS	8.83	6.14	5.88	6.77	6.46	6.82 (GRAND MEAN)

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	VARIANCE RATIO (SIGNIFICANCE LEVEL)
CONTROL	4	36.46	9.12	14.24(.01)
DISPLAY	2	7.08	3.54	5.53(.01)
CONTROL/DISPLAY	8	50.66	6.33	9.89(.01)
RANDOM ERROR	19	24.9	0.64	———

Evaluation Flight Time Histories

In order to provide a more complete understanding of the benefits and/or deficiencies inherent in each control/display combination investigated, representative time histories and the corresponding probability density functions from the evaluations of seven different configurations, with assigned pilot ratings ranging from 2 to 7 are presented in this portion of the appendix. The variables of interest are:

- $\epsilon_{\dot{x}_h}$ - heading referenced longitudinal velocity error (ft/sec)
- θ - pitch attitude (deg)
- δ_{es} - longitudinal stick position (in)
- ϵ_z - altitude error (ft)
- δ_{cs} - collective stick position (deg)
- $\epsilon_{\dot{y}_h}$ - heading referenced lateral velocity error (ft/sec)
- ϕ - bank attitude (deg)
- δ_{as} - lateral stick position (in)

Data from both the descending and level deceleration elements of the task are presented. The selected configurations, evaluation flight number, and assigned pilot rating/turbulence effect rating are summarized below:

FIGURE	CONFIGURATION	FLIGHT NO.	PR/TER
VI-1	RATE:ED-2+	F-130	7A
VI-2	RATE:ED-3	F-130	7B
VI-3	ATT/RATE:ED-2	F-133	4 1/2B
VI-4	ATT:ED-2+	F-131	3A
VI-5	ATT:ED-3	F-131	2A
VI-6	AUTO:ED-2+	F-131	2A
VI-7	DVC:ED-2+	F-142	2C

RATE:ED-2+ and RATE:ED-3 (Figures VI-1 and VI-2)

The time histories for the RATE configurations are taken from a crosswind flight (F-130) to demonstrate the difficulties encountered in the hover under these environmental conditions when the effect of the wind is not accounted for in either the control system or the display design. On the descending deceleration the collective director in both display formats yielded stable flight path control with errors rarely exceeding 25 ft; ED-3 yielded slightly smaller errors probably because of the artificial pitch attitude stabilization produced by the director. Large attitude excursions in pitch occured with both systems; however, the ED-2+ format yielded the larger excursions and appears to have induced a closed-loop instability with decreasing airspeed. A similar instability is evident in the roll angle and lateral velocity error time histories for the RATE:ED-2+ configuration.

Once in the level portion of the deceleration, each system exhibited different height-keeping characteristics: ED-2+ yielded a small and decreasing altitude error while, with the ED-3 format, the pilot allowed the aircraft to remain high while he concentrated on control in the horizontal plane. Large, low frequency attitude oscillations characterize the motions in pitch and roll, with ED-3 yielding the larger velocity errors because of the pilot's neglect of the control directors in favor of his status information near the hover.

ATT/RATE:ED-2 (Figure VI-3)

The addition of attitude stabilization in pitch yielded a more precise control of altitude and speed throughout the task. However the absence of the collective director and the difficulty of the lateral task resulted in degraded glide slope tracking performance. Localizer tracking performance was comparable to that of the RATE:ED-2+ configuration but was achieved through smaller, higher frequency lateral stick inputs.

Performance on the level deceleration was obviously superior to either of the RATE systems with no attitude stability problems evident. In this portion of the approach, the pilot devoted his efforts to the lateral and vertical task and allowed a "fast" speed error to build up.

ATT:ED-2+ (Figure VI-4)

With roll attitude stabilization provided, lateral performance improved, and the magnitude of the roll angle excursions decreased. The collective director yielded excellent glide slope tracking performance with altitude error never exceeding 10 ft during the descent. However the pilot remained "behind" on the deceleration by $\sim$5 kts throughout the descent. Once into the level deceleration, the pilot corrected his "fast" speed error while allowing a slightly larger vertical error to build up.

ATT:ED-3 (Figure VI-5)

The addition of the pitch and roll control directors improved the speed tracking performance during the descent but did not enhance the performance in the remaining controlled axes significantly. The initial "roller coaster" effect on speed and flight path control induced by the pitch stick director logic can be identified from this time history. In the level deceleration, the pilot apparently devoted more attention to his status display and collective director than to the pitch and roll stick directors as is suggested by the small but relatively constant horizontal velocity error.

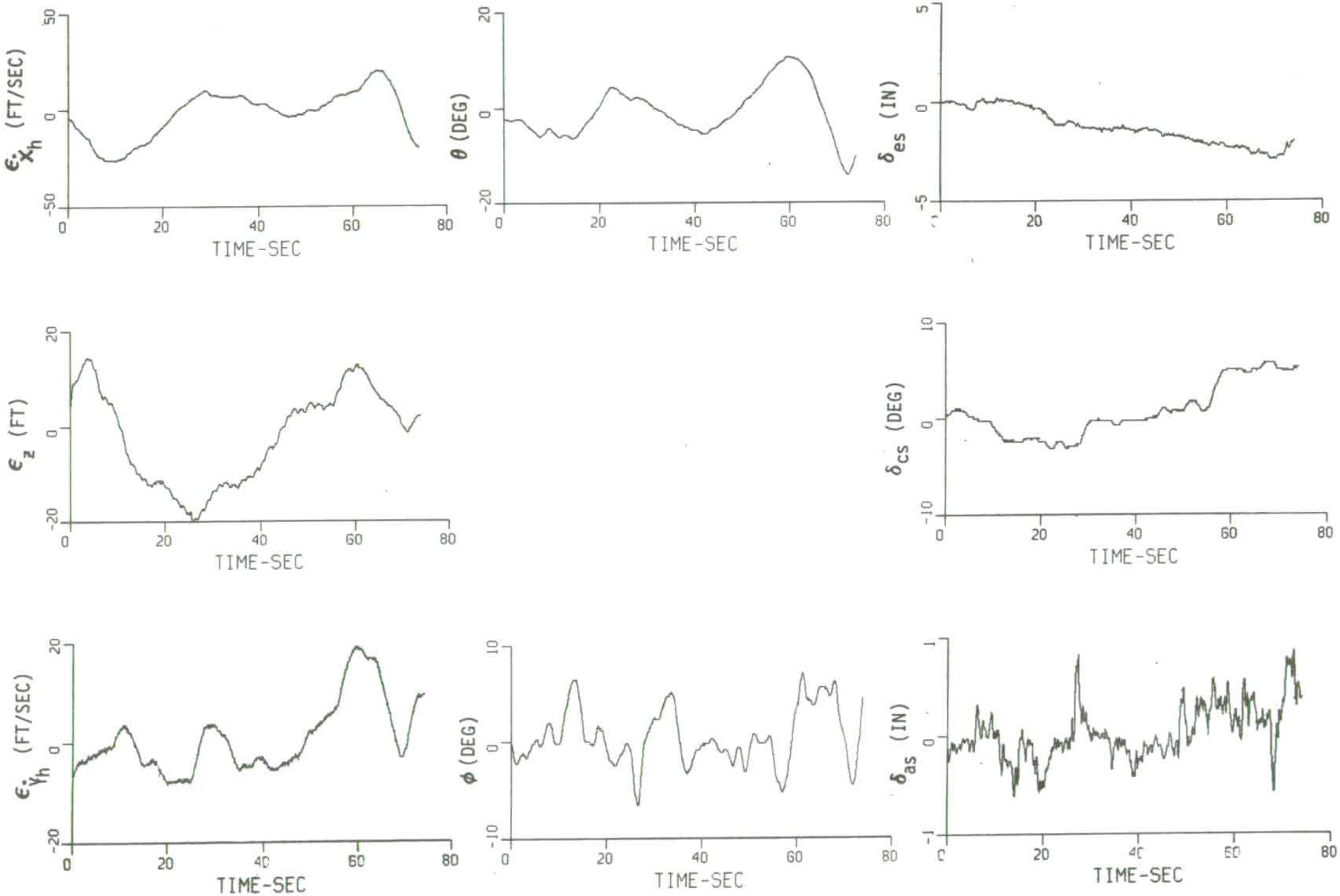


Figure VI-1 RATE: ED-2+, DESCENDING DECELERATION
(a) TIME HISTORIES

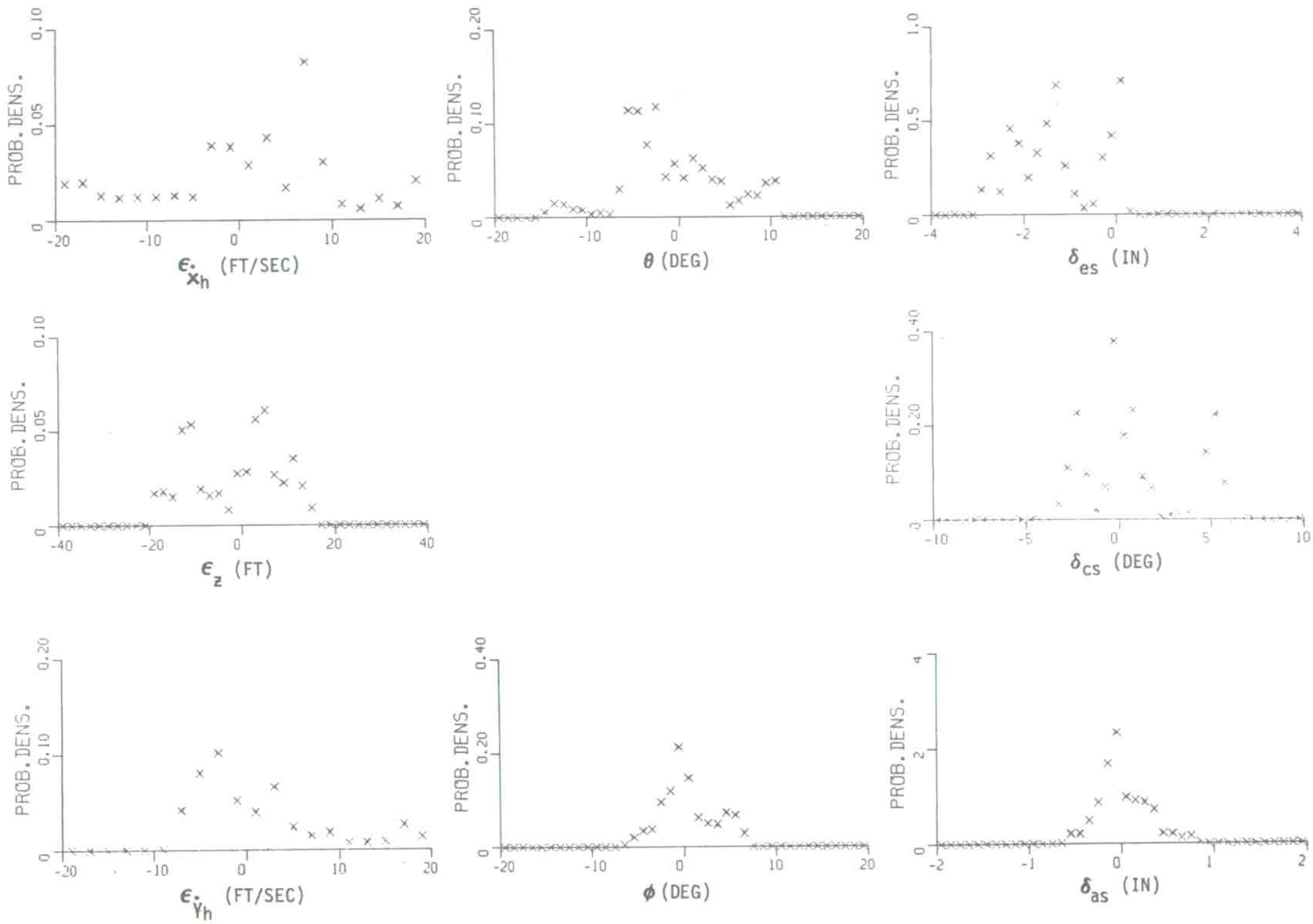


Figure VI-1 RATE: ED-2+, DESCENDING DECELERATION
(b) PROBABILITY DENSITY FUNCTIONS

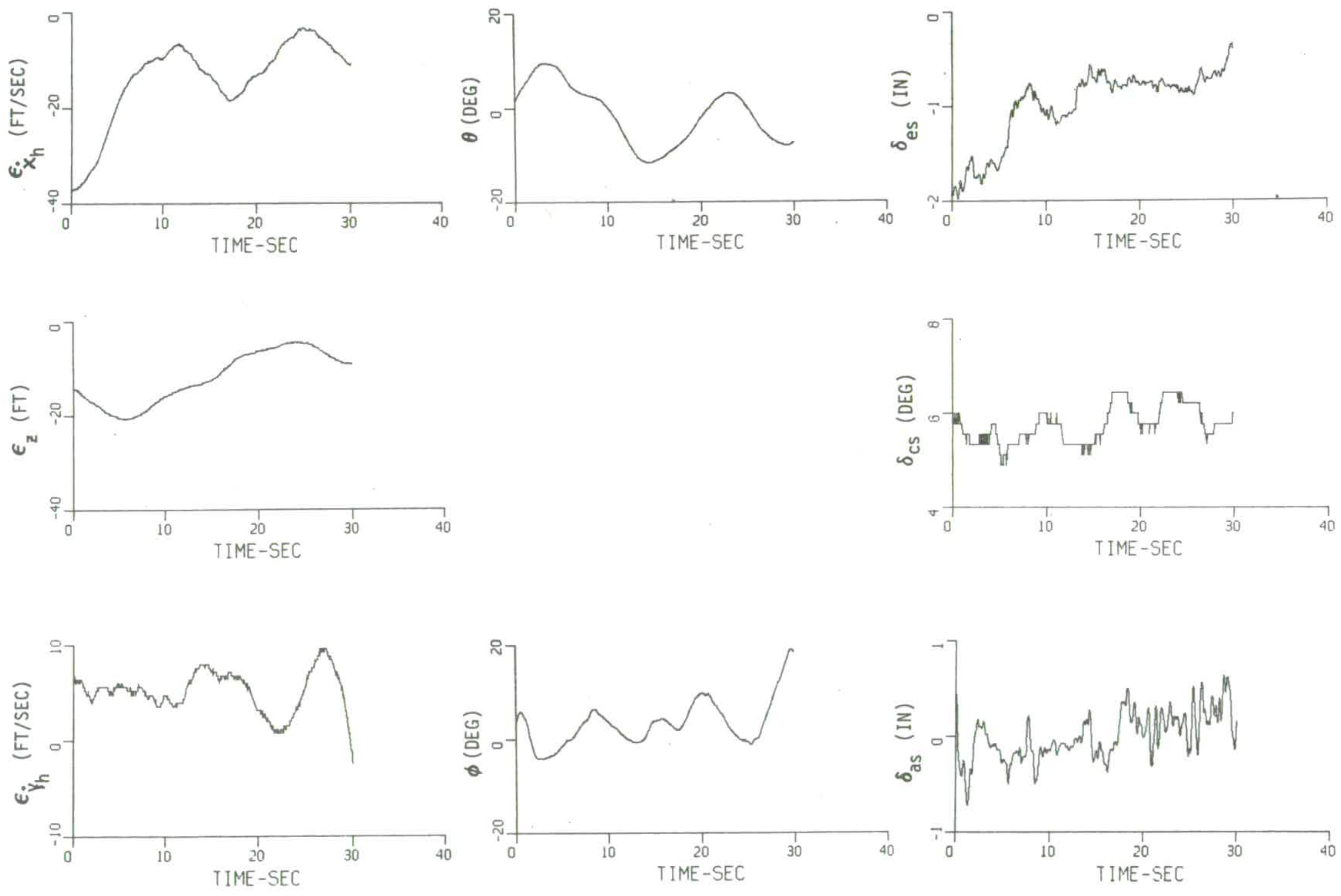


Figure VI-1 RATE: ED-2+, LEVEL DECELERATION
(c) TIME HISTORIES

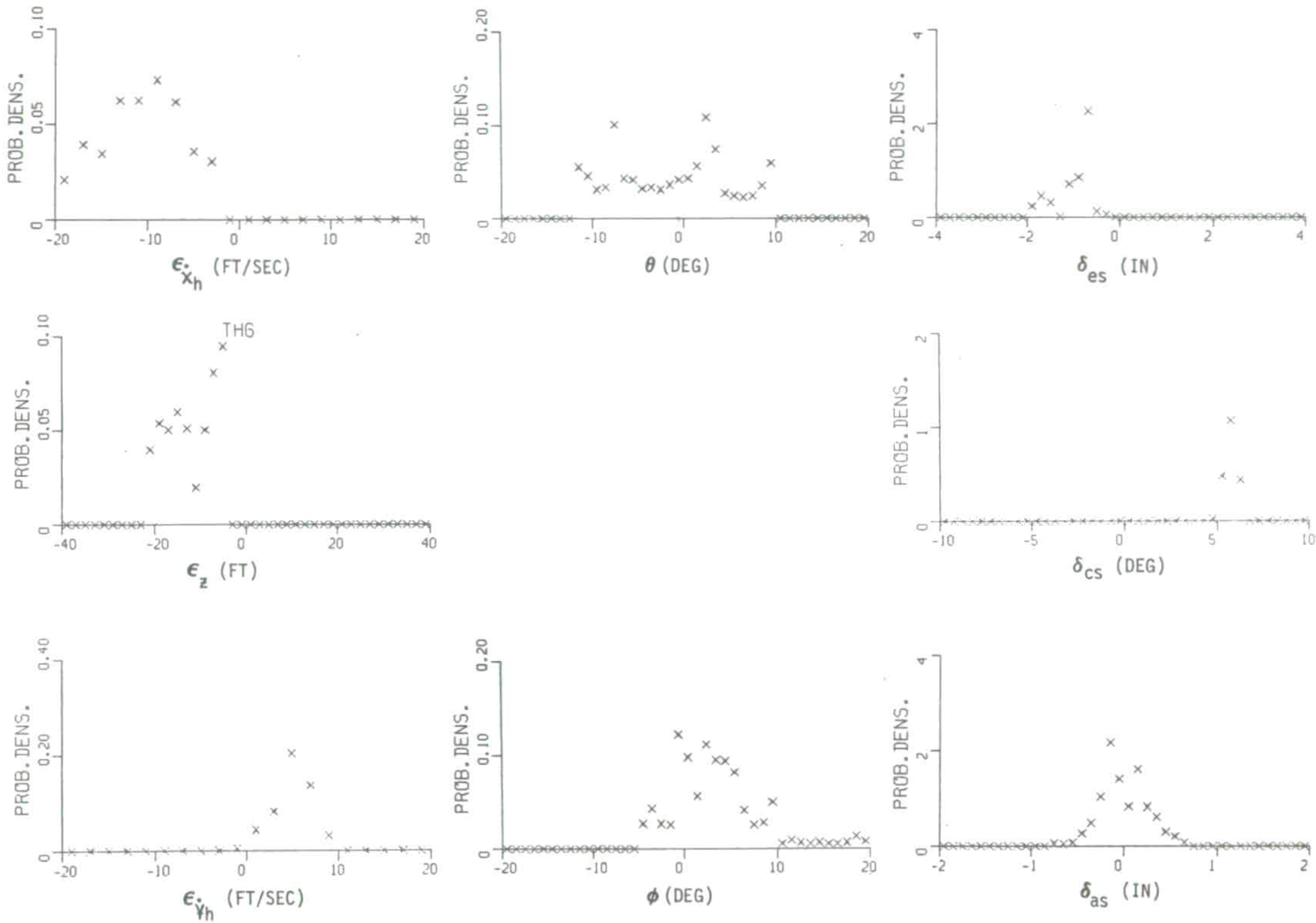


Figure VI-1 RATE: ED-2+, LEVEL DECELERATION
(d) PROBABILITY DENSITY FUNCTIONS

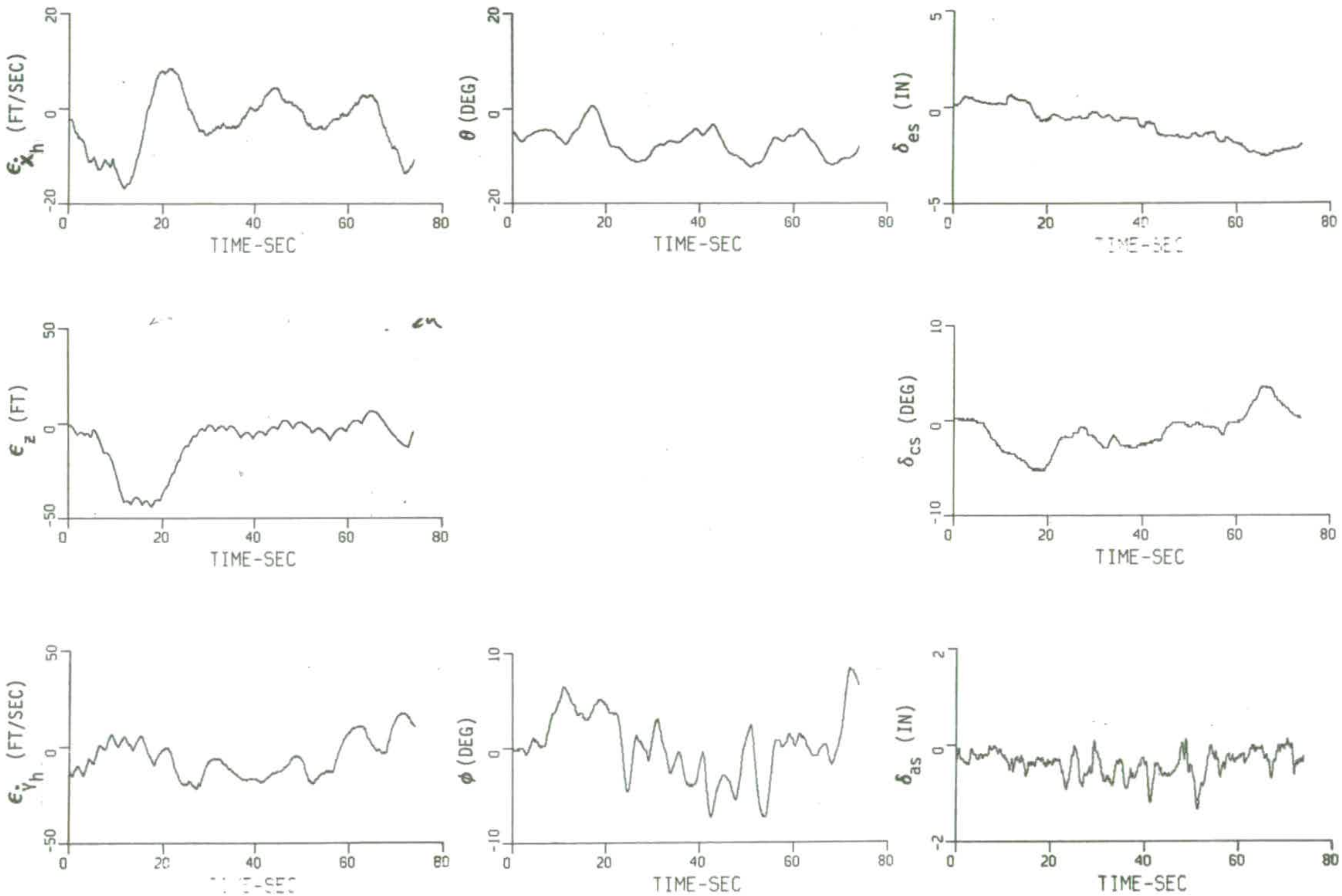


Figure VI-2 RATE: ED-3, DESCENDING DECELERATION
(a) TIME HISTORIES

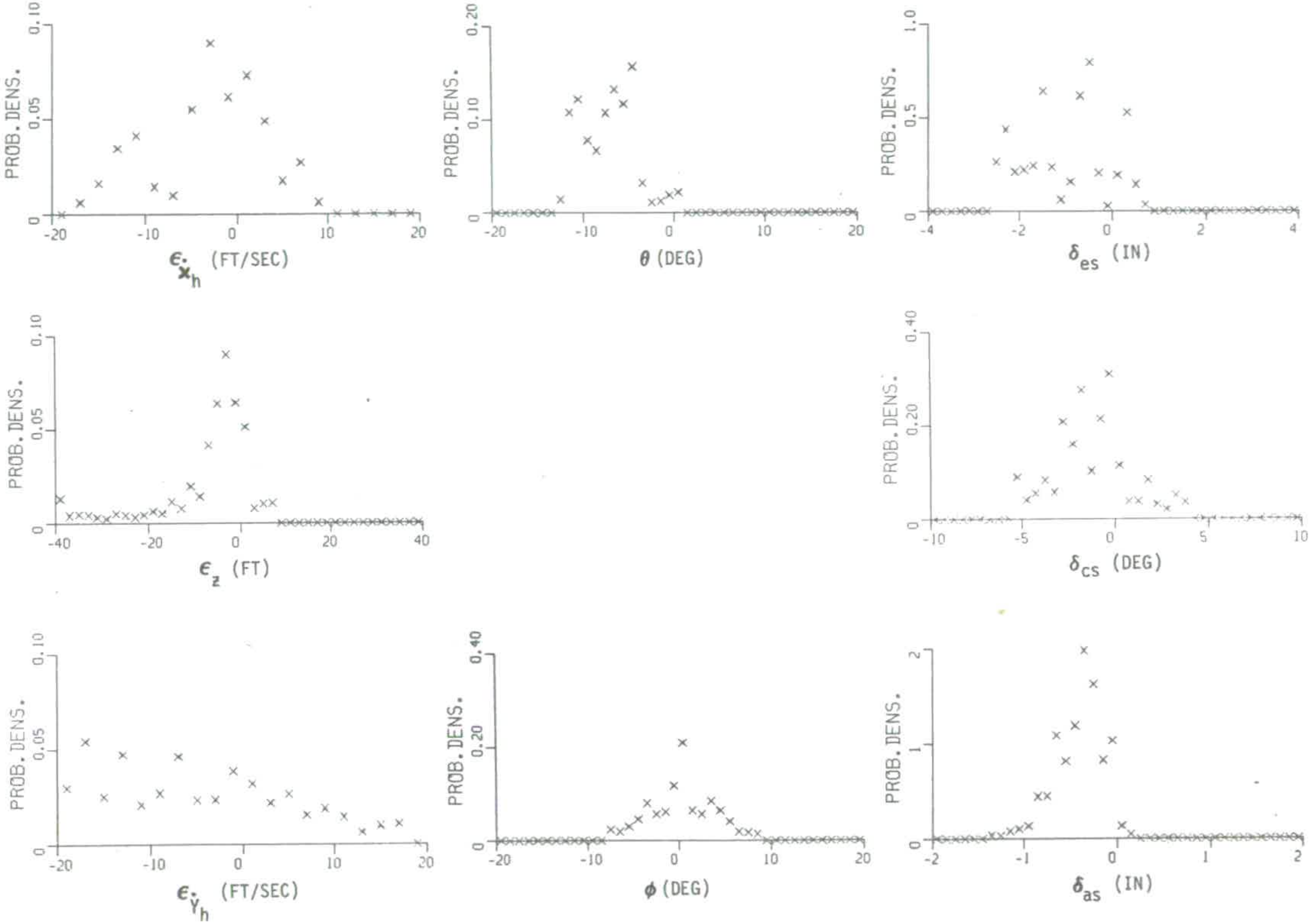


Figure VI-2 RATE: ED-3, DESCENDING DECELERATION
(b) PROBABILITY DENSITY FUNCTIONS

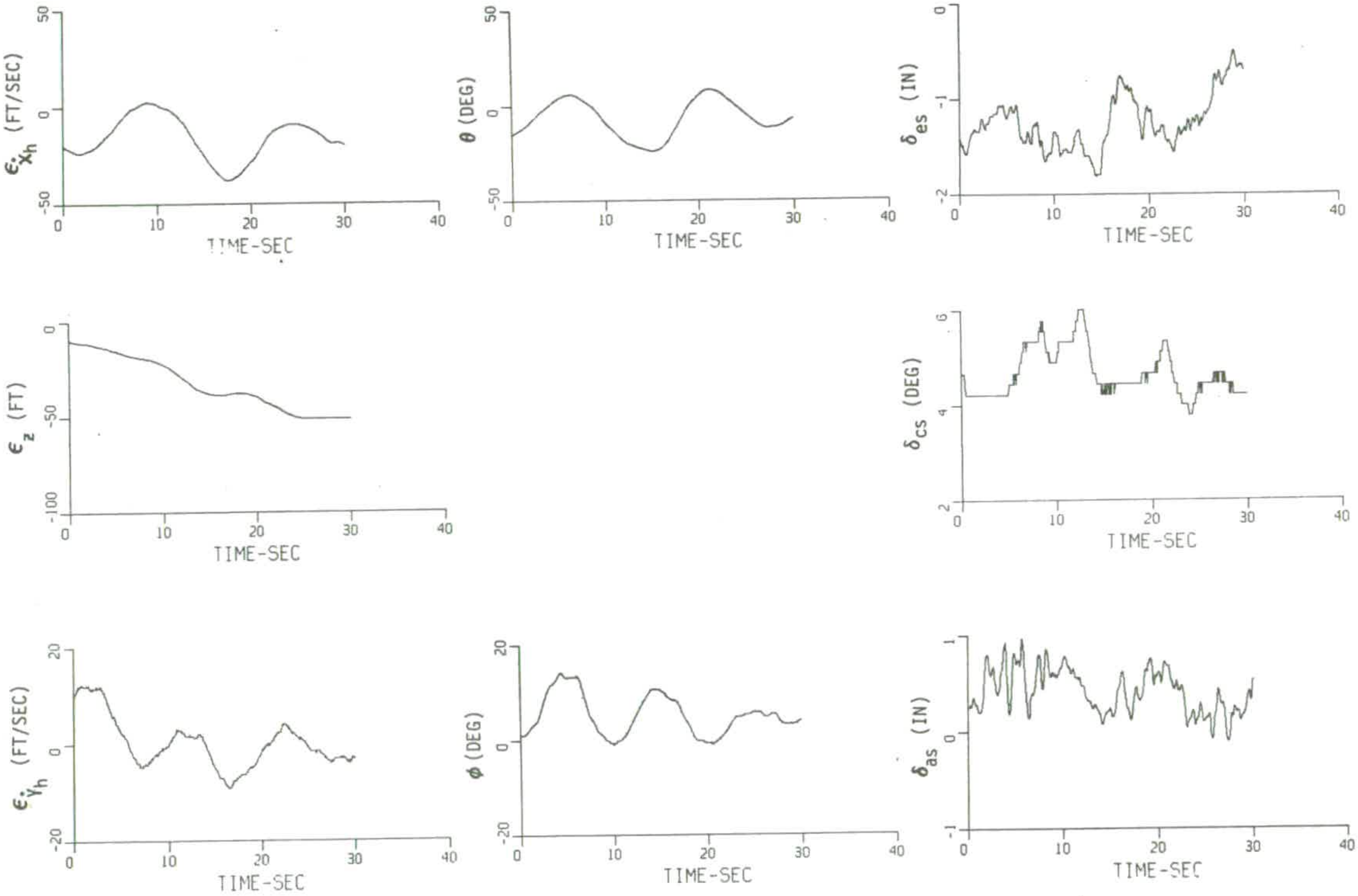


Figure VI-2 RATE: ED-3, LEVEL DECELERATION
(c) TIME HISTORIES

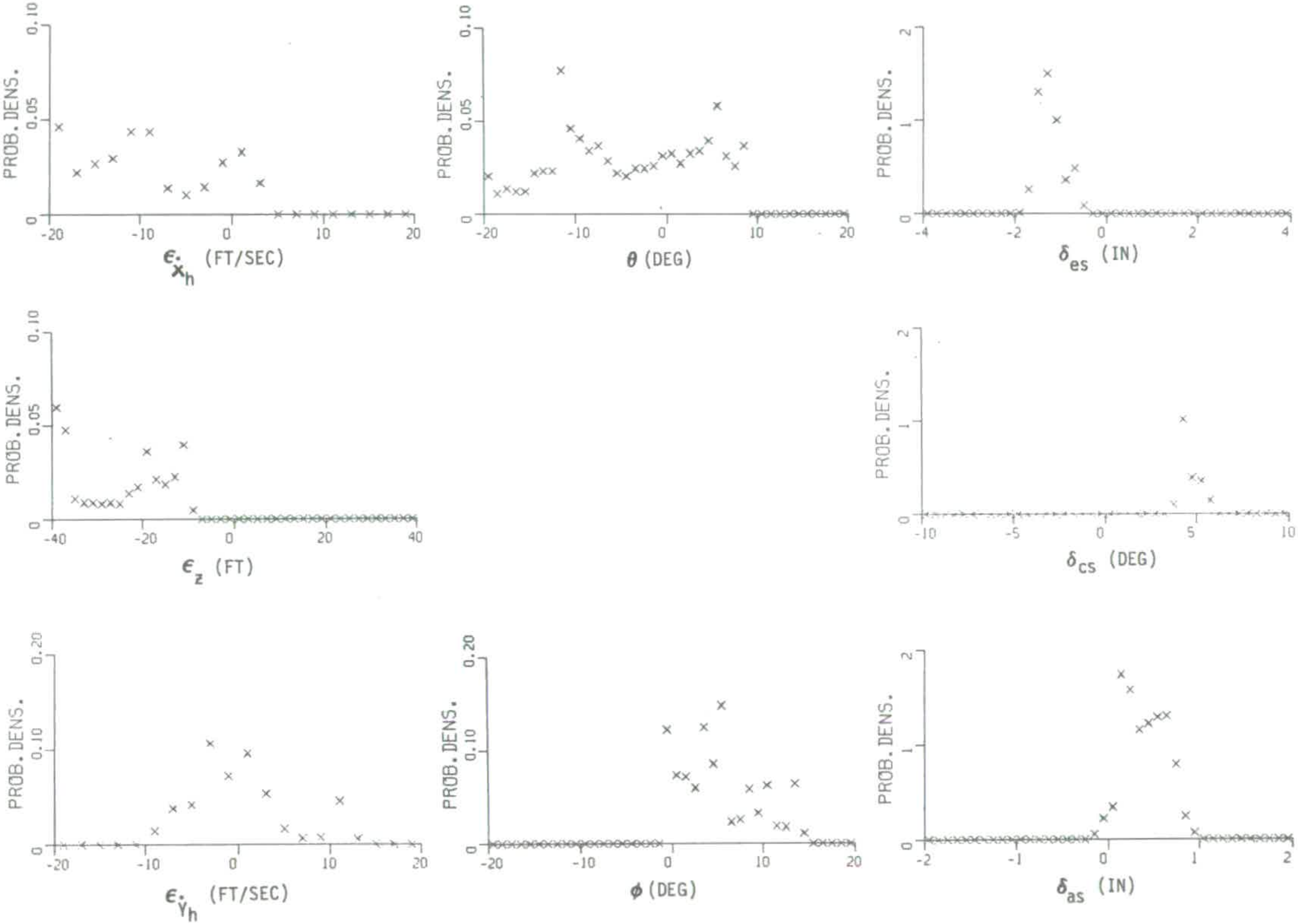


Figure VI-2 RATE: ED-3, LEVEL DECELERATION
(d) PROBABILITY DENSITY FUNCTIONS

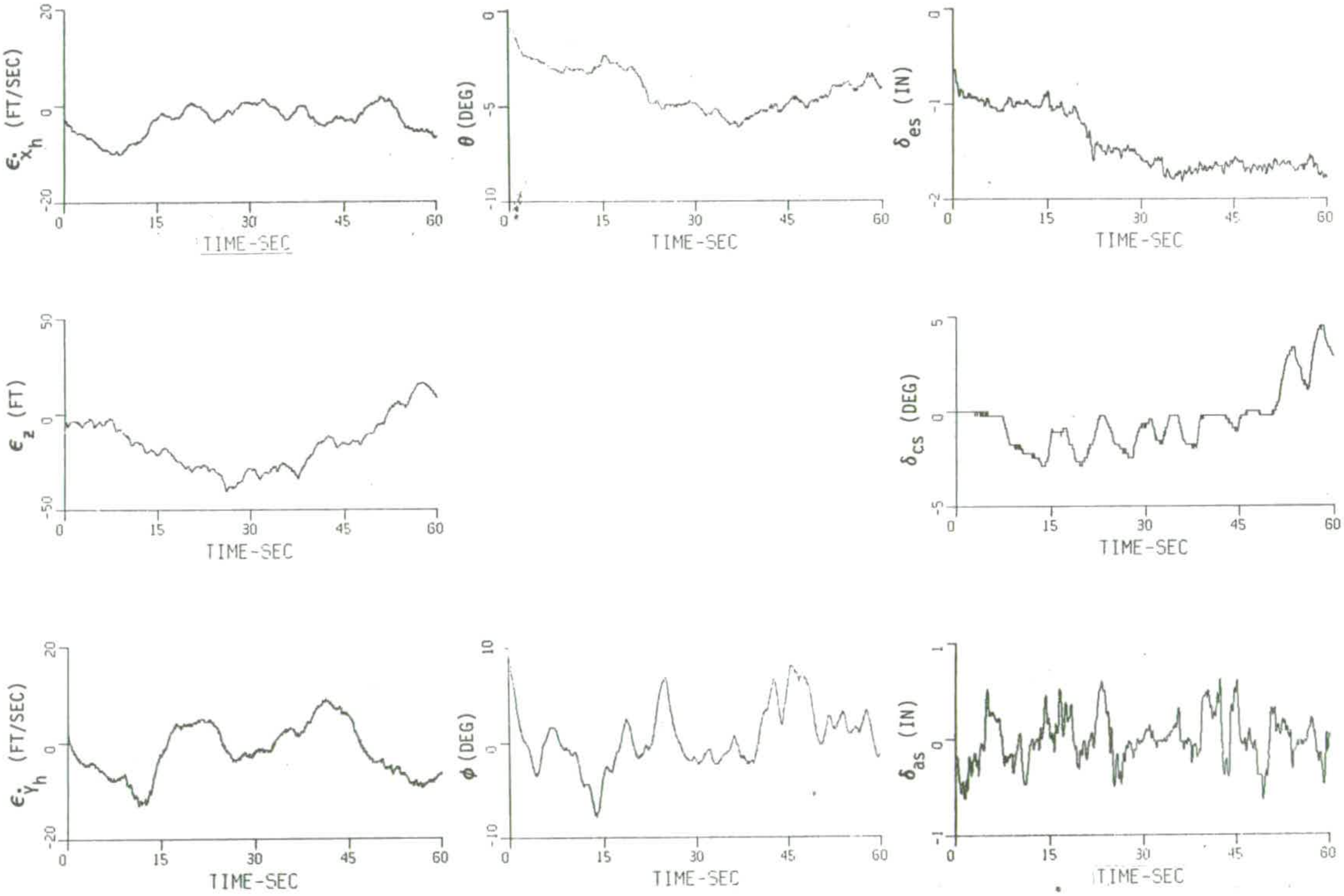


Figure VI-3 ATT/RATE: ED-2, DESCENDING DECELERATION
(a) TIME HISTORIES

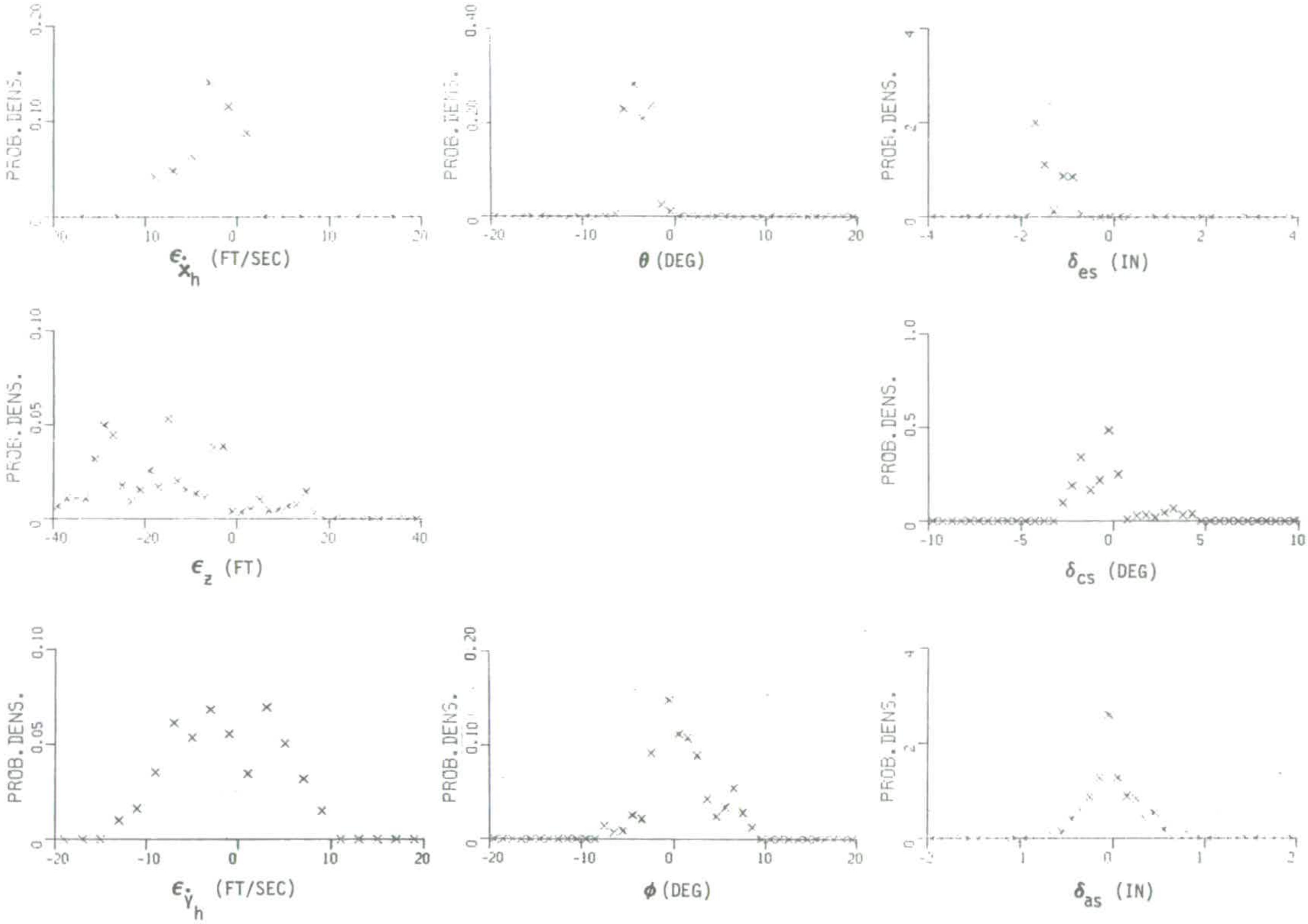


Figure VI-3 ATT/RATE: ED-2, DESCENDING DECELERATION
(b) PROBABILITY DENSITY FUNCTIONS

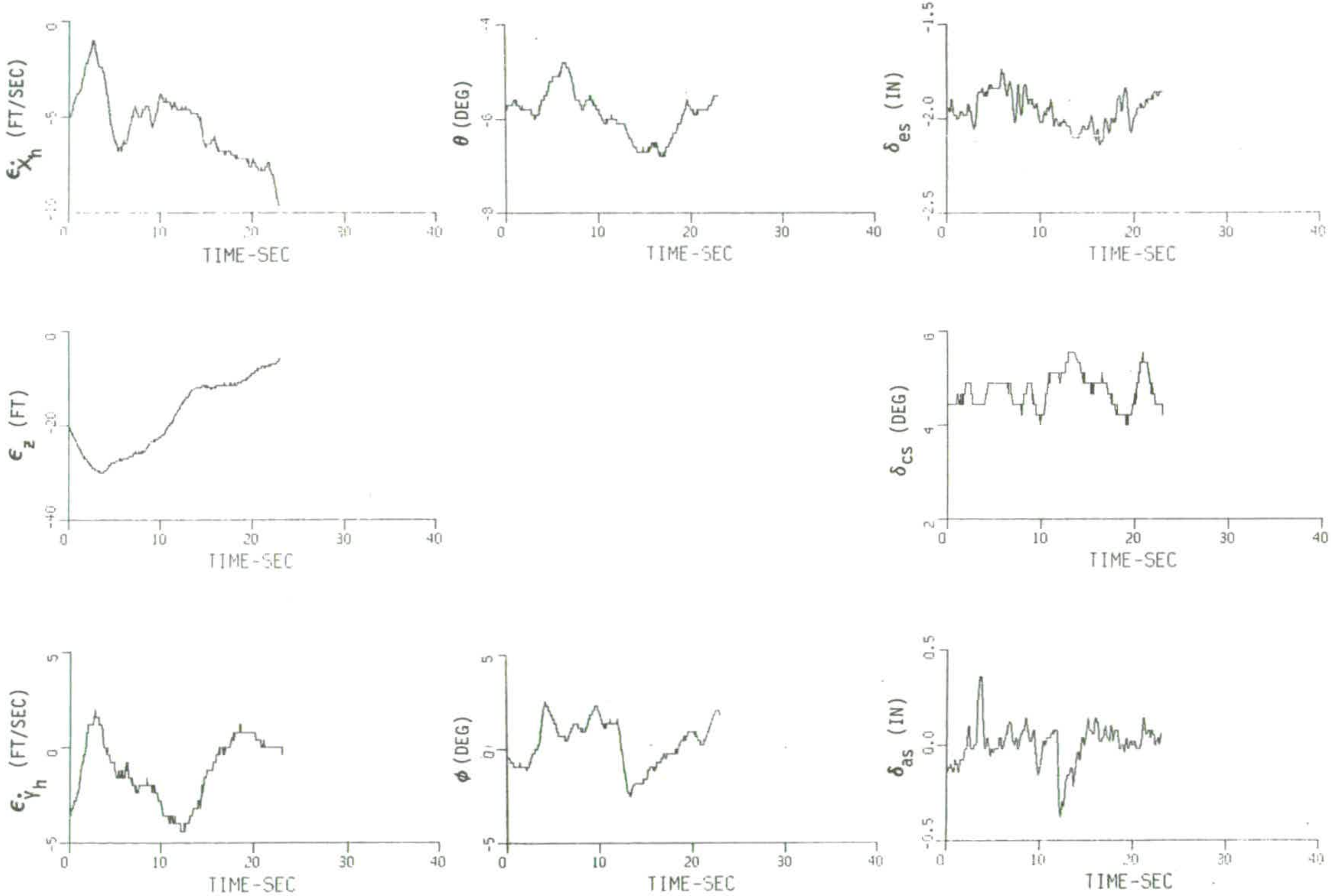


Figure VI-3   ATT/RATE: ED-2, LEVEL DECELERATION
(c) TIME HISTORIES

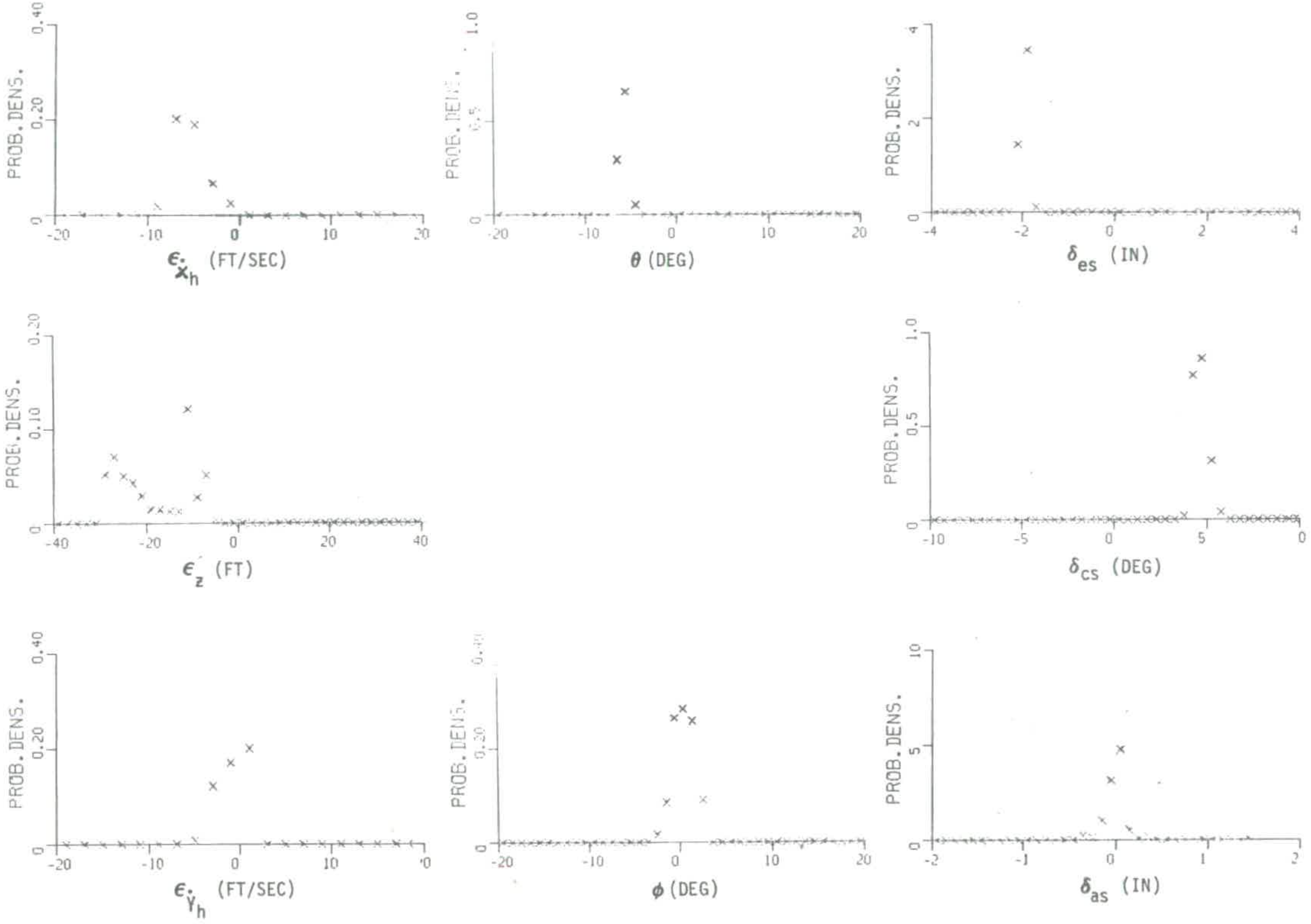


Figure VI-3 ATT/RATE: ED-2, LEVEL DECELERATION
(d) PROBABILITY DENSITY FUNCTIONS

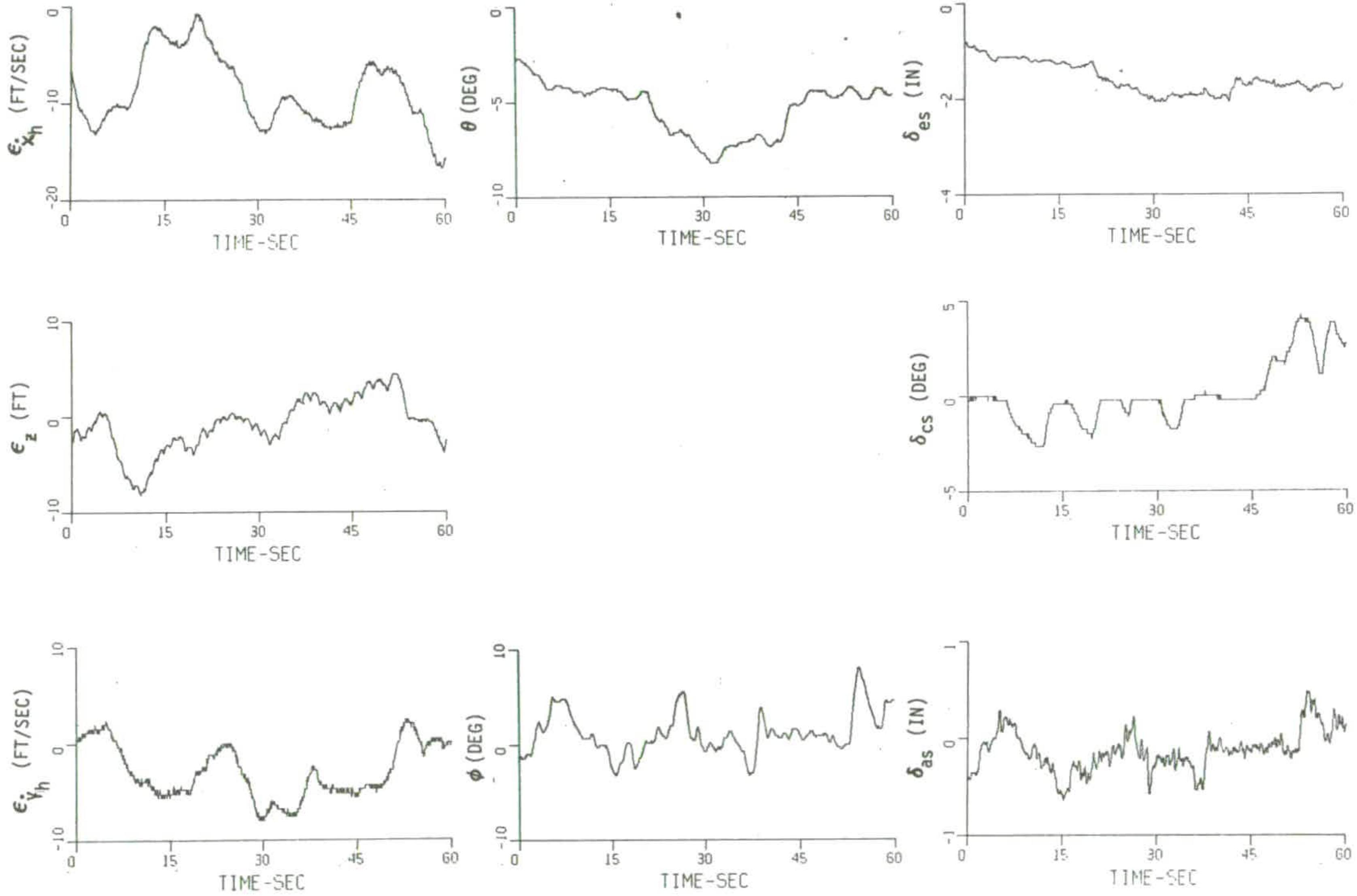


Figure VI-4 ATT:ED-2+, DESCENDING DECELERATION
(a) TIME HISTORIES

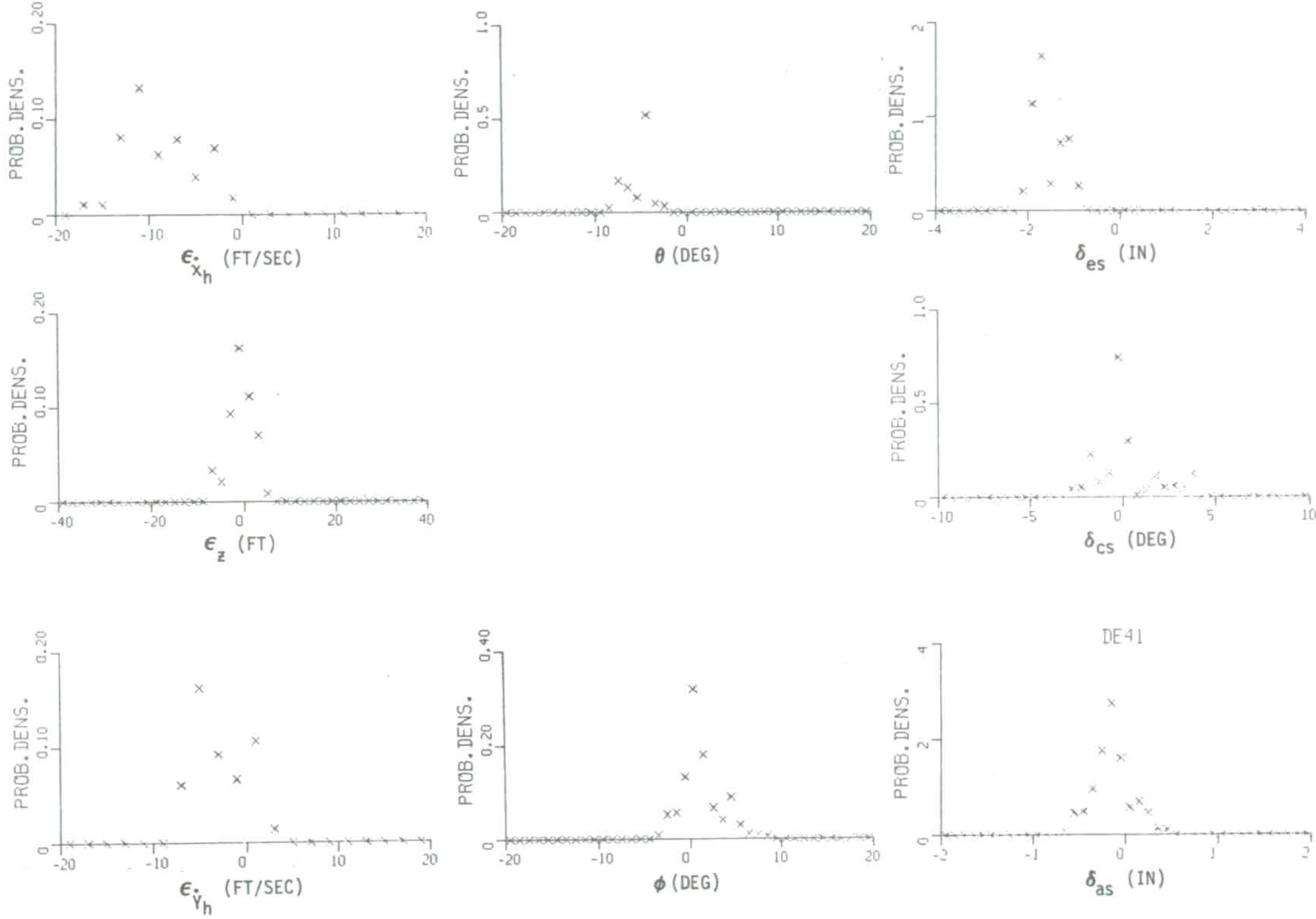


Figure VI-4 ATT:ED-2+, DESCENDING DECELERATION
(b) PROBABILITY DENSITY FUNCTIONS

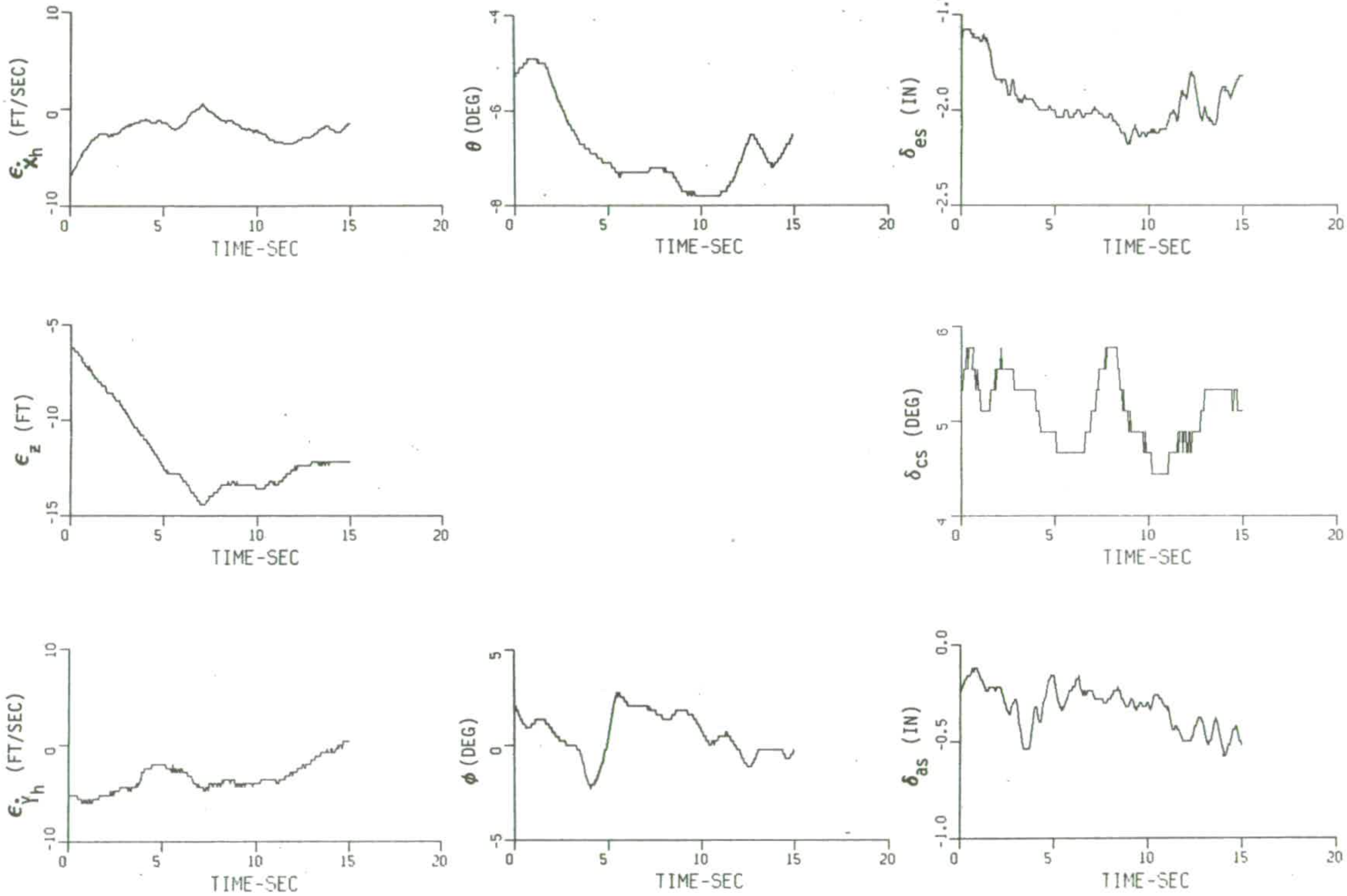


Figure VI-4 ATT:ED-2+, LEVEL DECELERATION
(c) TIME HISTORIES

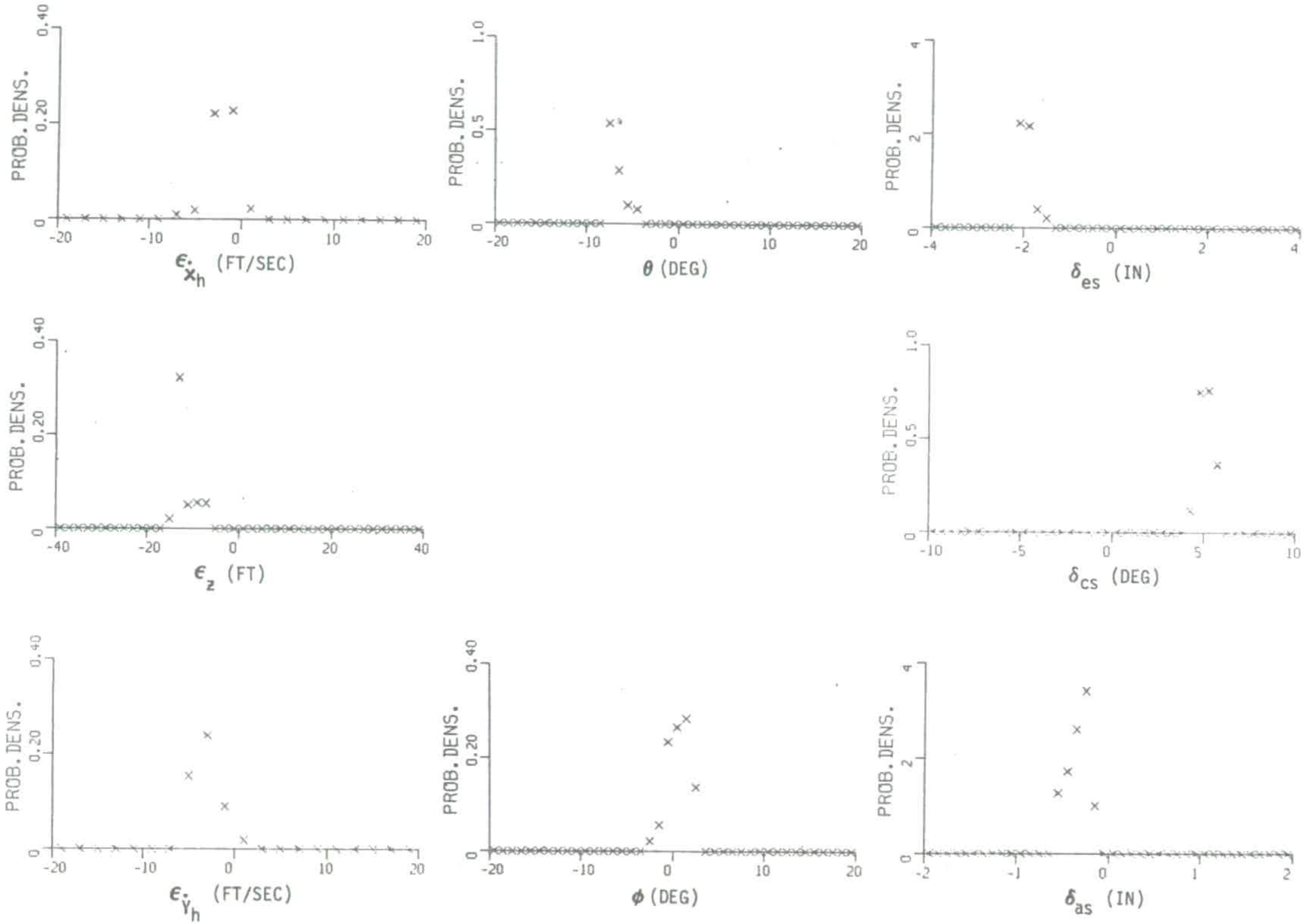


Figure VI-4 ATT:ED-2+, LEVEL DECELERATION
(d) PROBABILITY DENSITY FUNCTIONS

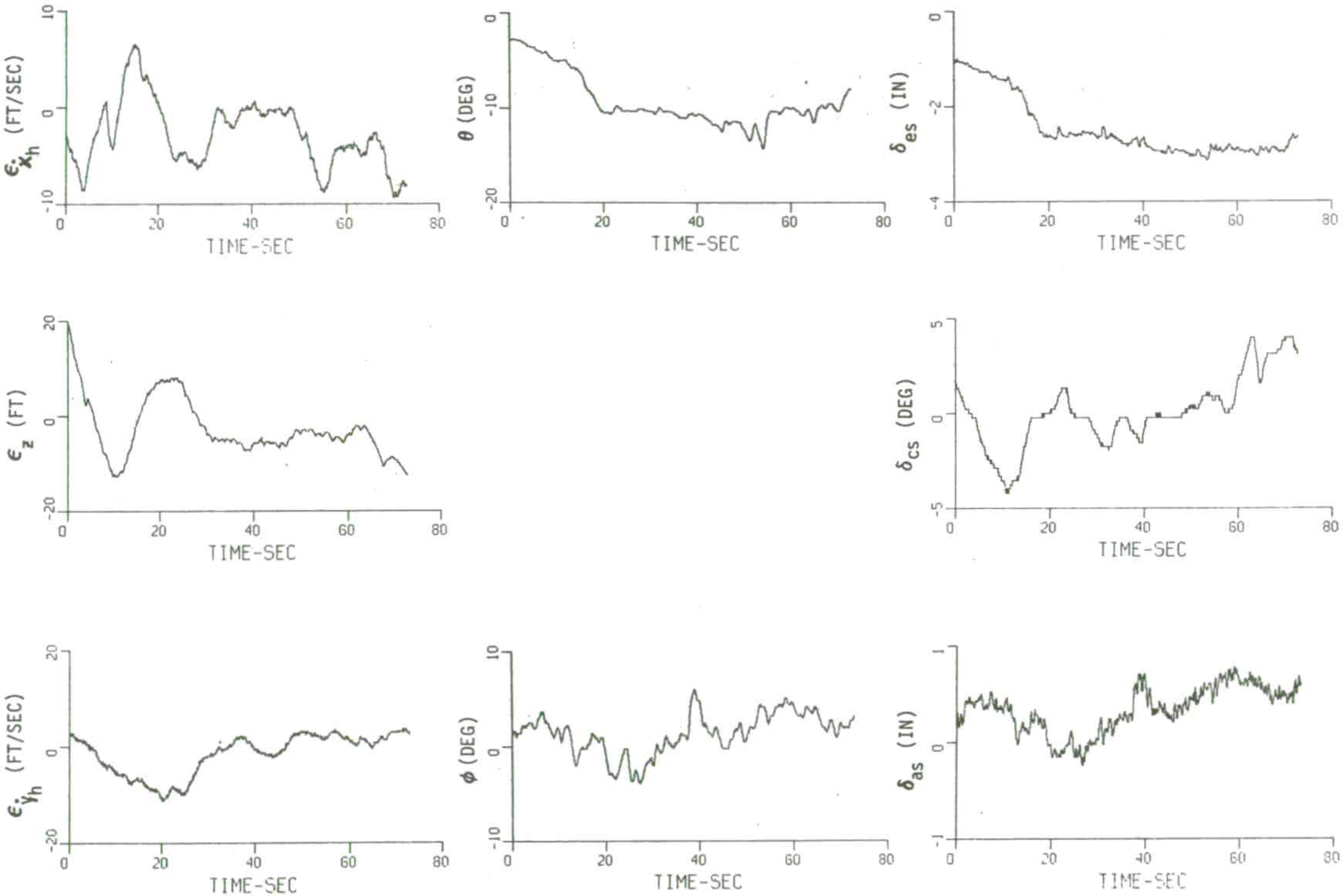


Figure VI-5 ATT:ED-3, DESCENDING DECELERATION
(a) TIME HISTORIES

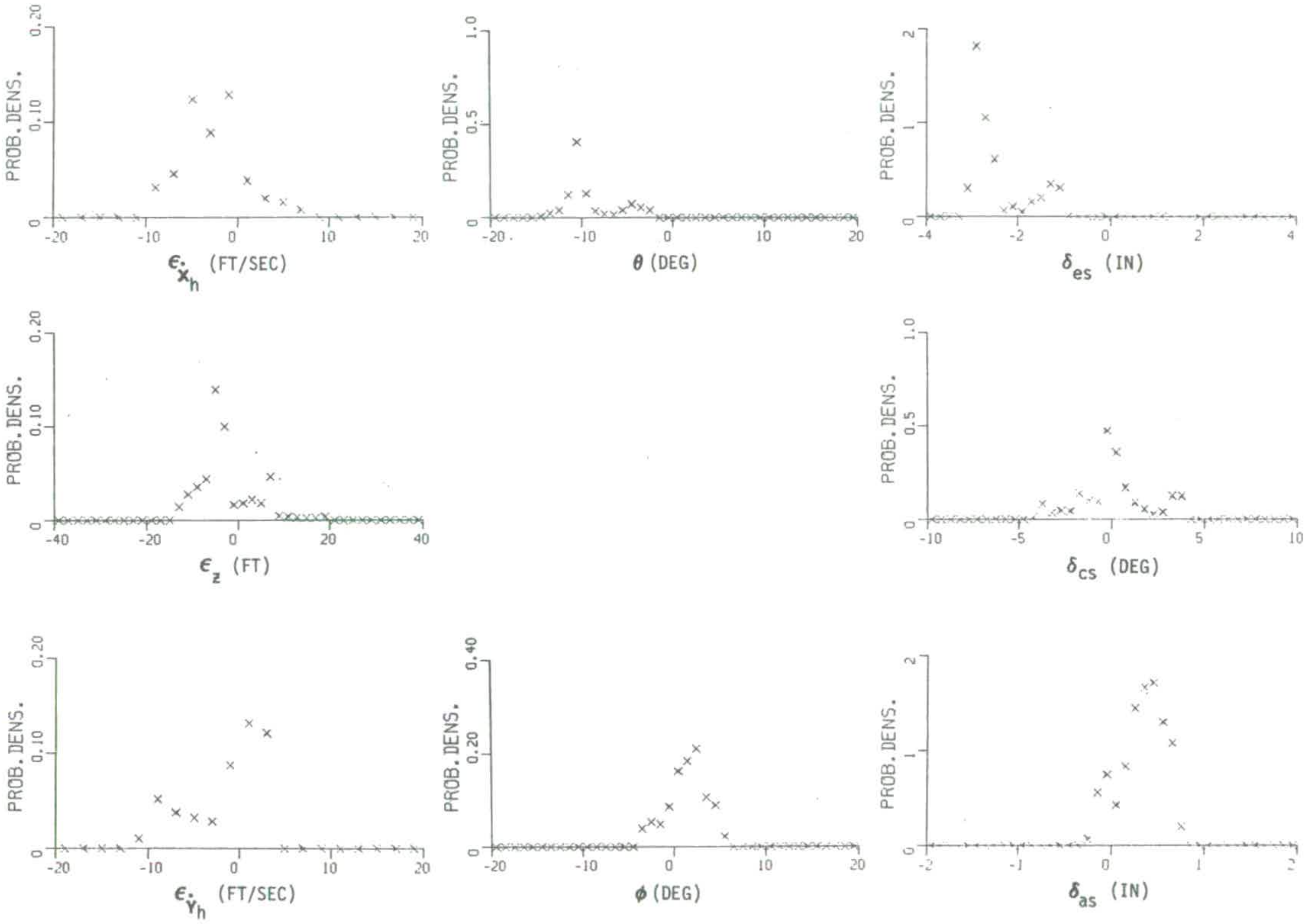


Figure VI-5 ATT:ED-3, DESCENDING DECELERATION
(b) PROBABILITY DENSITY FUNCTIONS

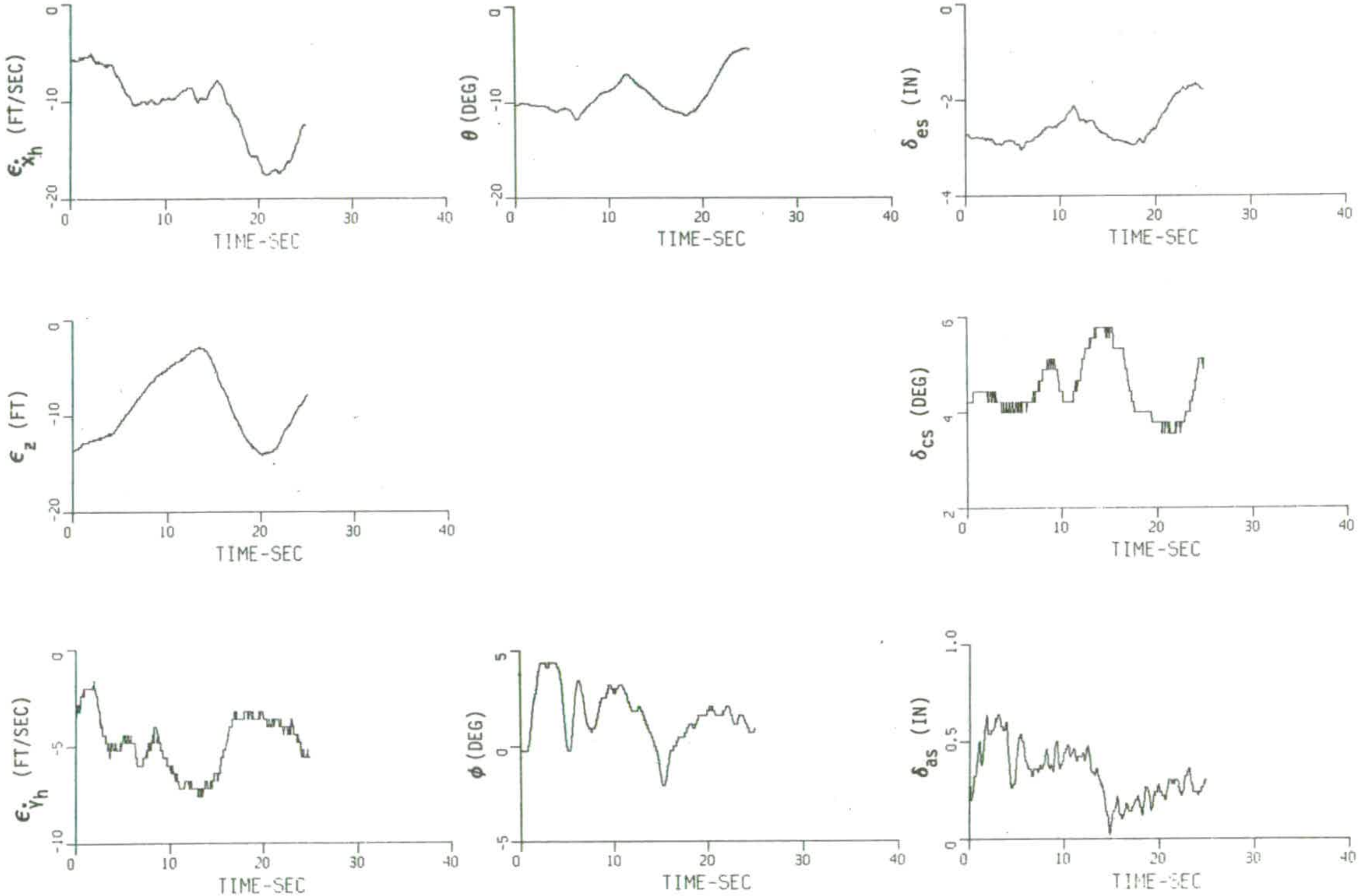


Figure VI-5 ATT:ED-3, LEVEL DECELERATION
(c) TIME HISTORIES

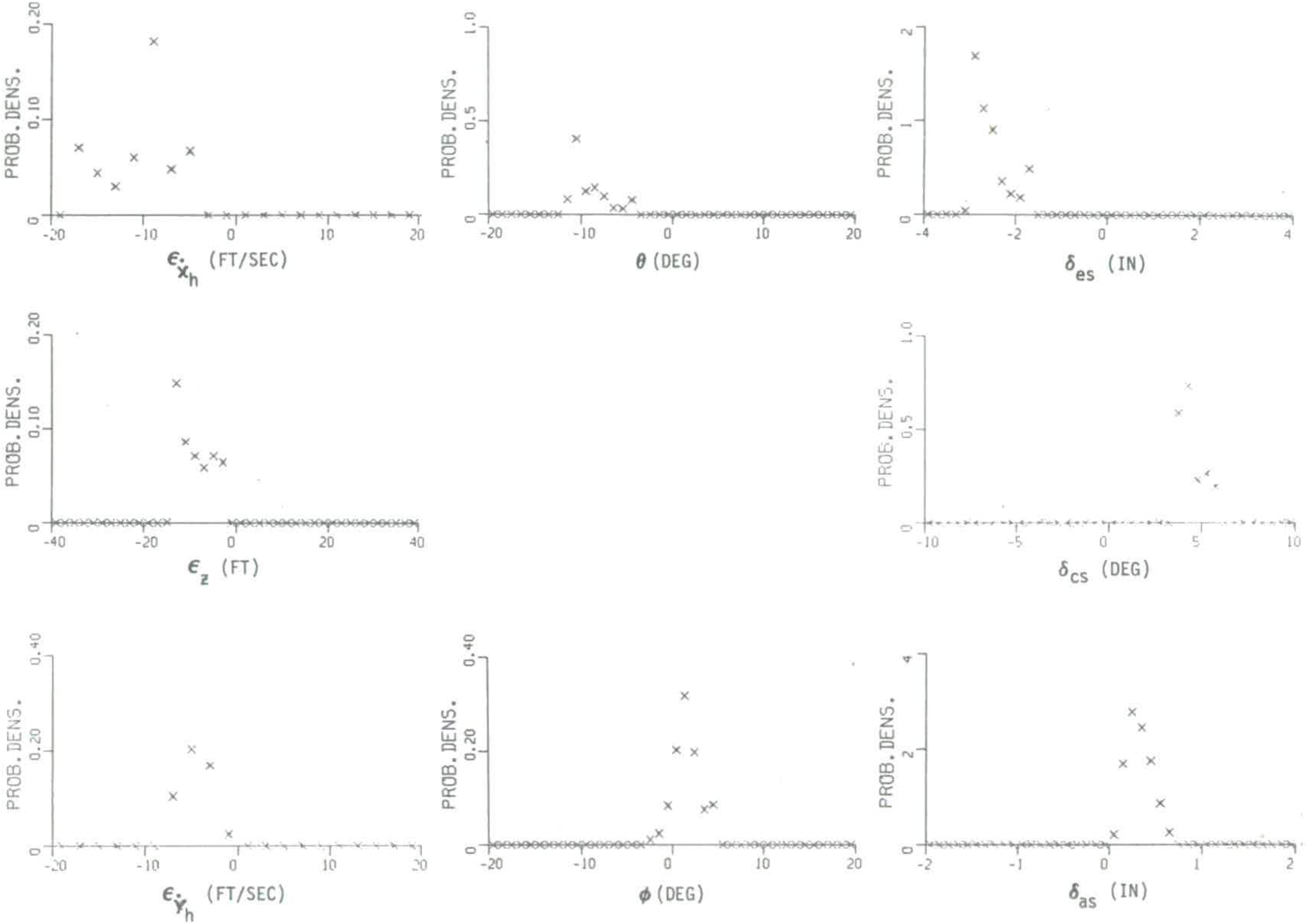


Figure VI-5 ATT:ED-3, LEVEL DECELERATION
(d) PROBABILITY DENSITY FUNCTIONS

AUTO: ED-2+ (Figure VI-6)

With the provision of automatic configuration change, the pilot was able to devote more of his efforts to the lateral problem during the descent as indicated by the larger roll excursions and smaller lateral velocity errors. A comparable glide slope tracking performance was achieved because of the collective director; however the pilot was content to remain slightly behind on the deceleration profile, a technique similar to that used for the ATT: ED-2+ configuration. Excellent performance was achieved in the level deceleration to the hover with altitude never straying more than five feet from the commanded height of 100 ft AGL; horizontal velocity errors were minimized in a rapid but controlled fashion.

DVC: ED-2+ (Figure VI-7)

Although the performance achieved in the longitudinal and vertical degrees of freedom through the use of the decoupled velocity control system was not significantly better than with the AUTO system, the precision of the control of lateral errors (small δ_{as} inputs, small roll angle excursions, and small lateral velocity error) is indicative of the reduction in overall workload caused by the DVC system. The apparent degradation of system performance in the level deceleration is caused by the pilot's "experiments" with this novel control system and provides an example of why only the descending deceleration was chosen for the detailed performance and workload analysis described earlier.

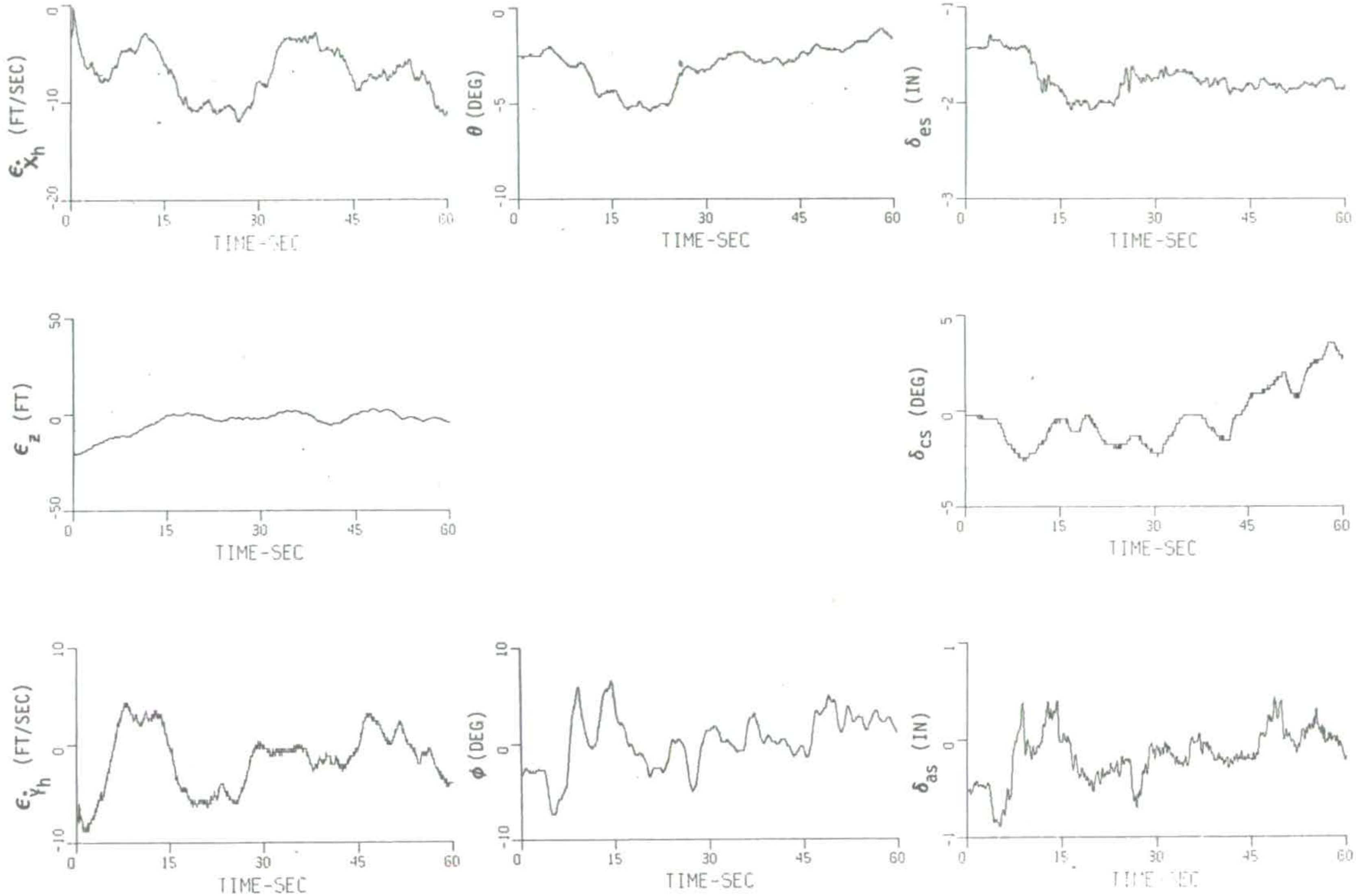


Figure VI-6 AUTO:ED-2+, DESCENDING DECELERATION
(a) TIME HISTORIES

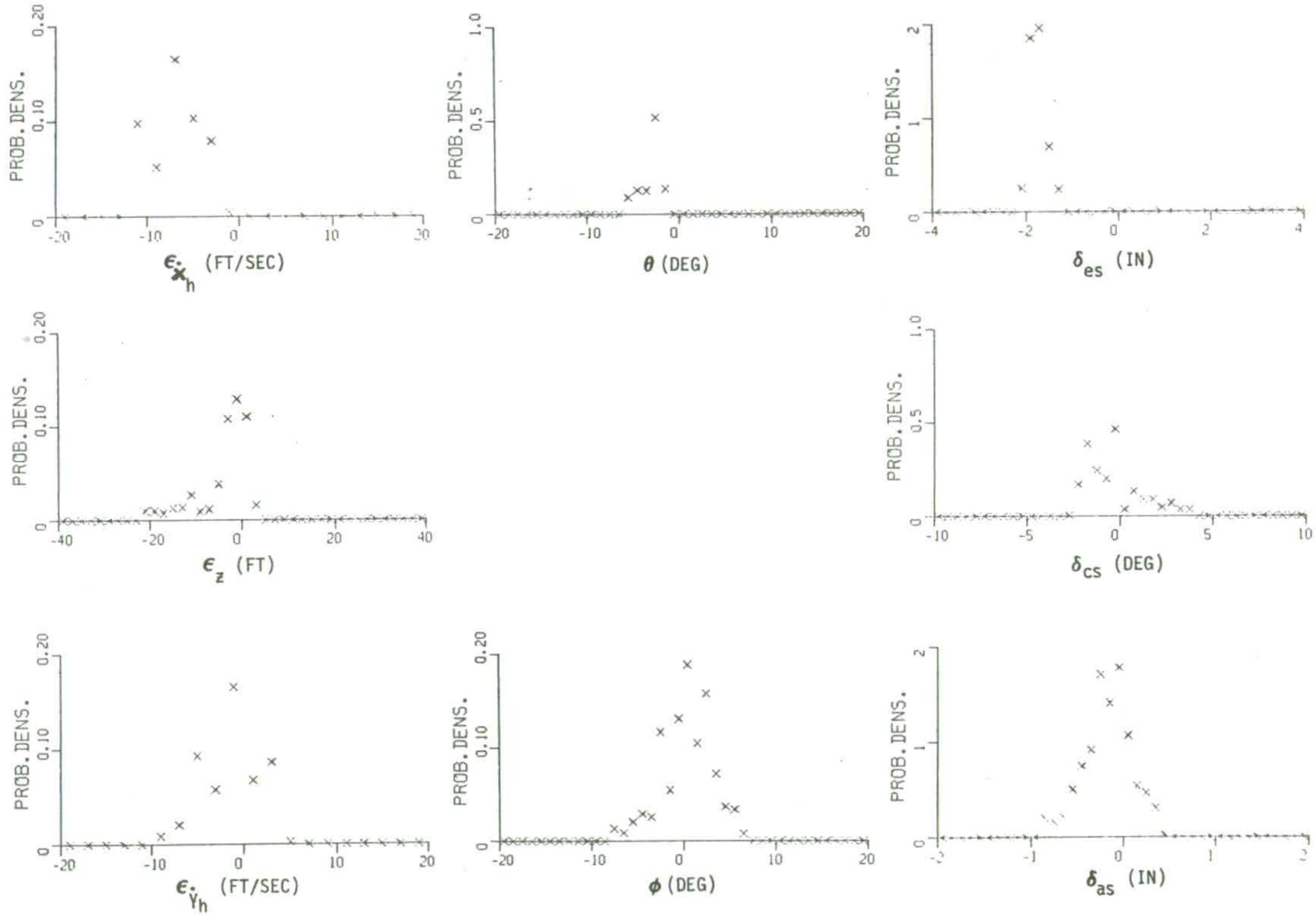


Figure VI-6 AUTO:ED-2+, DESCENDING DECELERATION
(b) PROBABILITY DENSITY FUNCTIONS

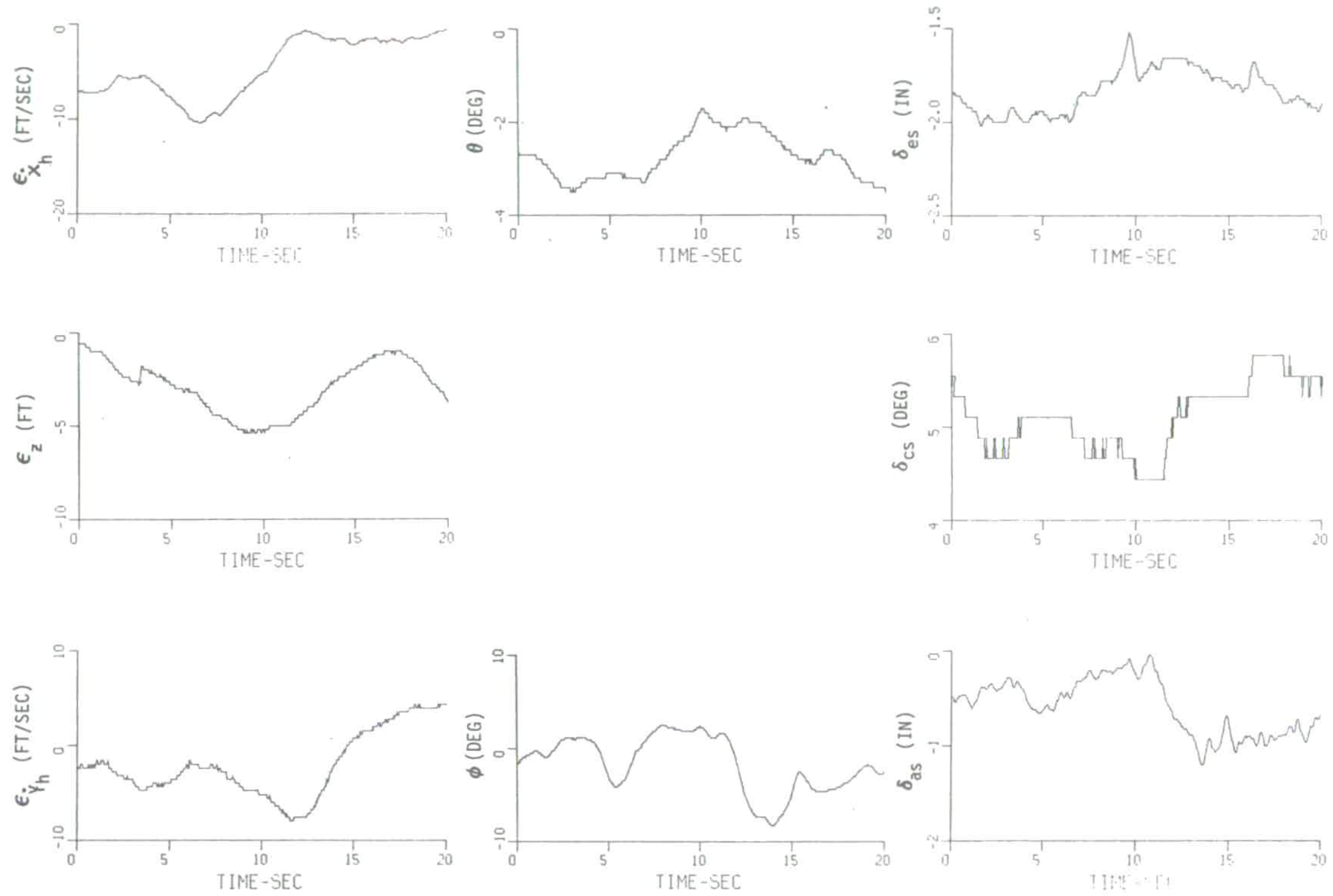


Figure VI-6   AUTO:ED-2+, LEVEL DECELERATION
(c) TIME HISTORIES

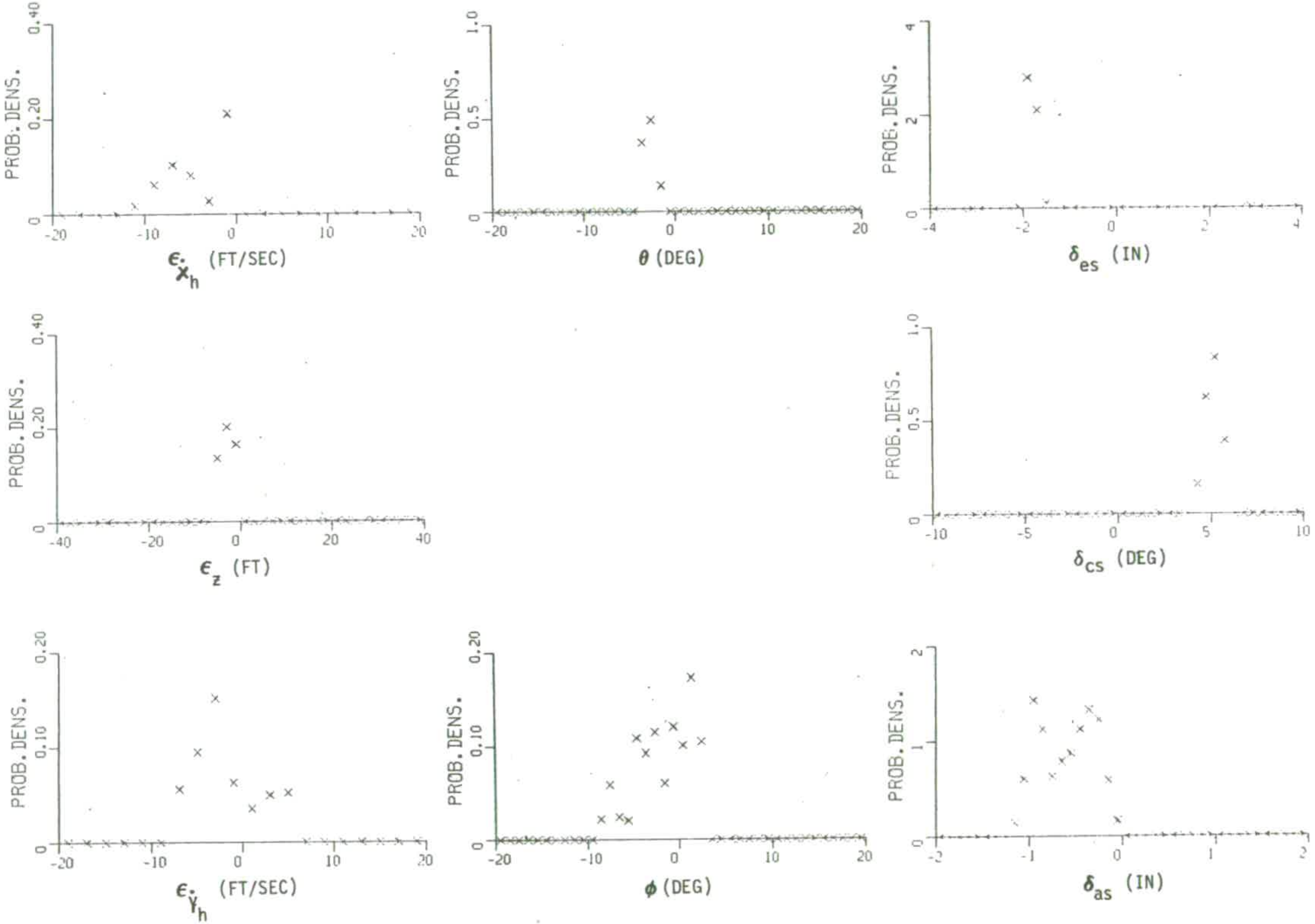


Figure VI-6 AUTO:ED-2+, LEVEL DECELERATION
(d) PROBABILITY DENSITY FUNCTIONS

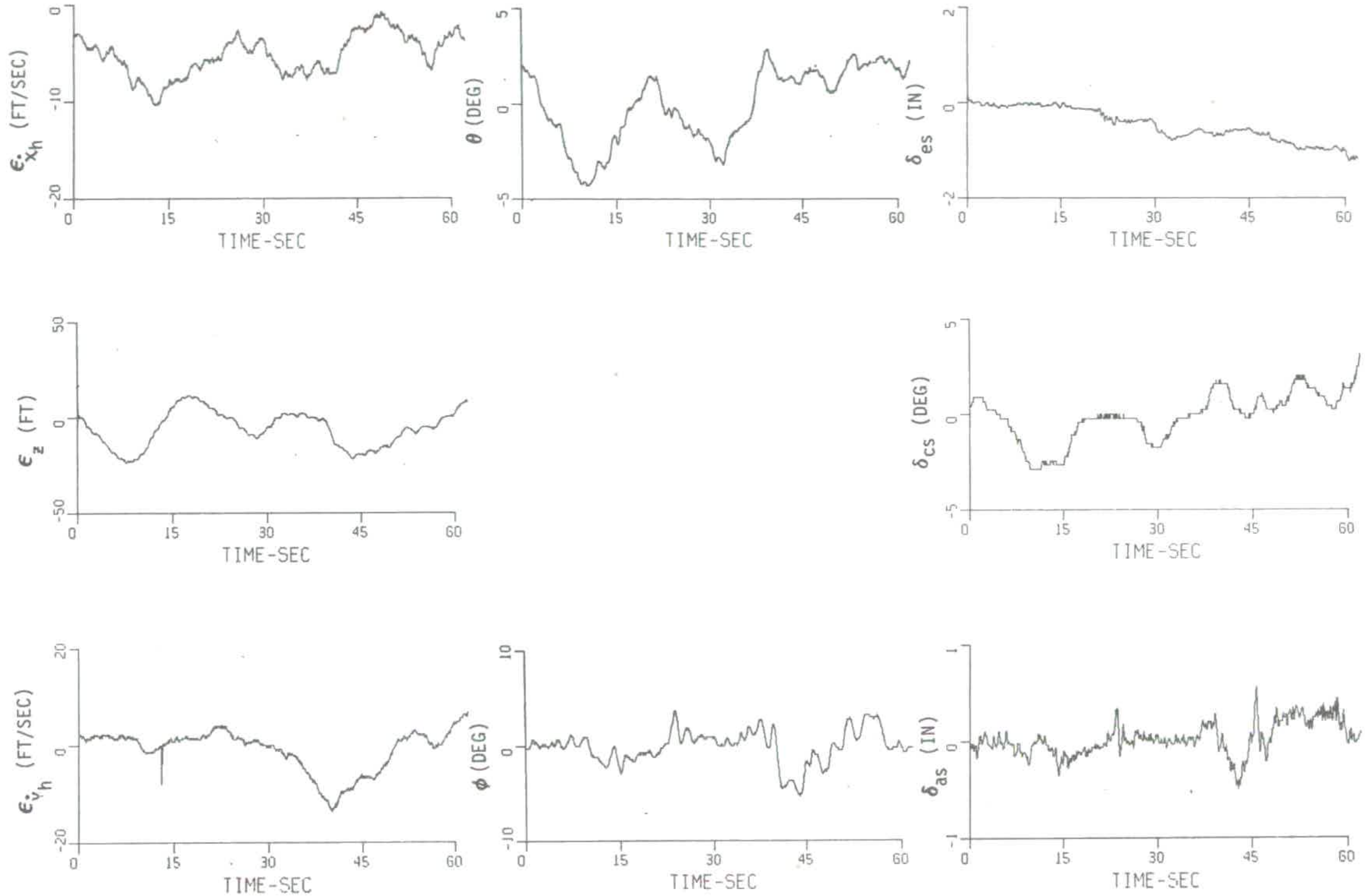


Figure VI-7 DVC:ED-2+, DESCENDING DECELERATION
(a) TIME HISTORIES

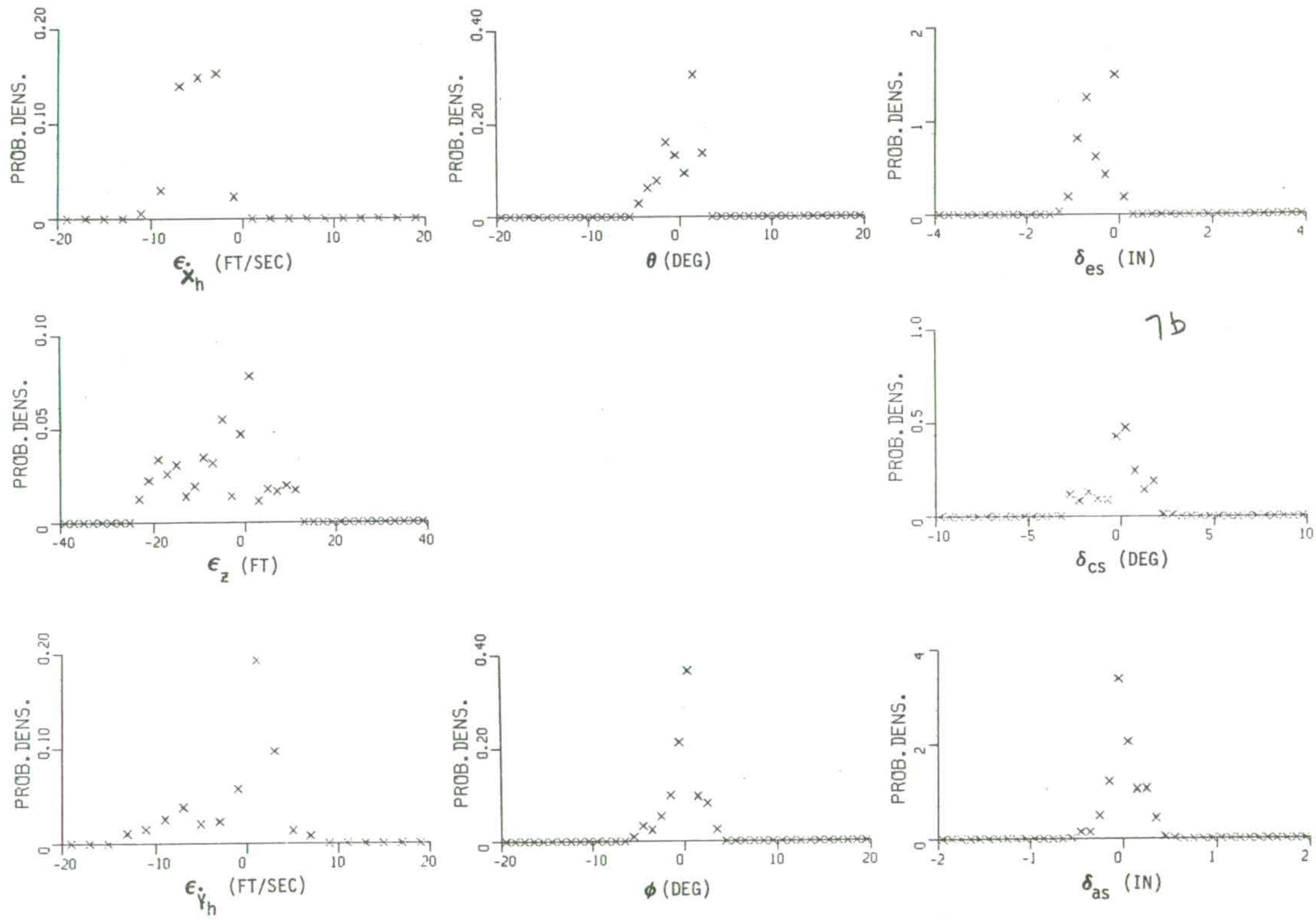


Figure VI-7 DVC:ED-2+, DESCENDING DECELERATION
(b) PROBABILITY DENSITY FUNCTIONS

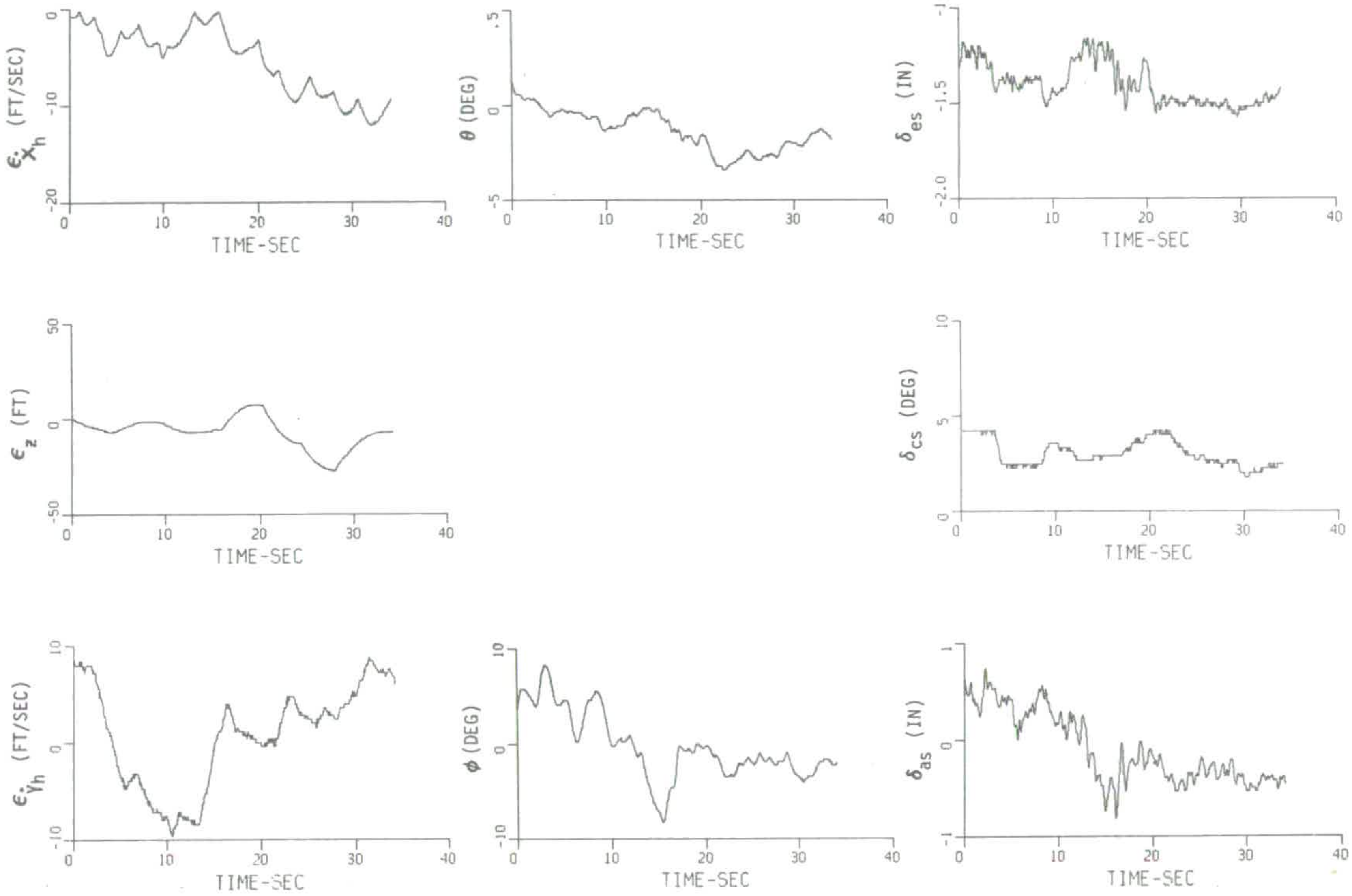


Figure VI-7 DVC:ED-2+, LEVEL DECELERATION
(c) TIME HISTORIES

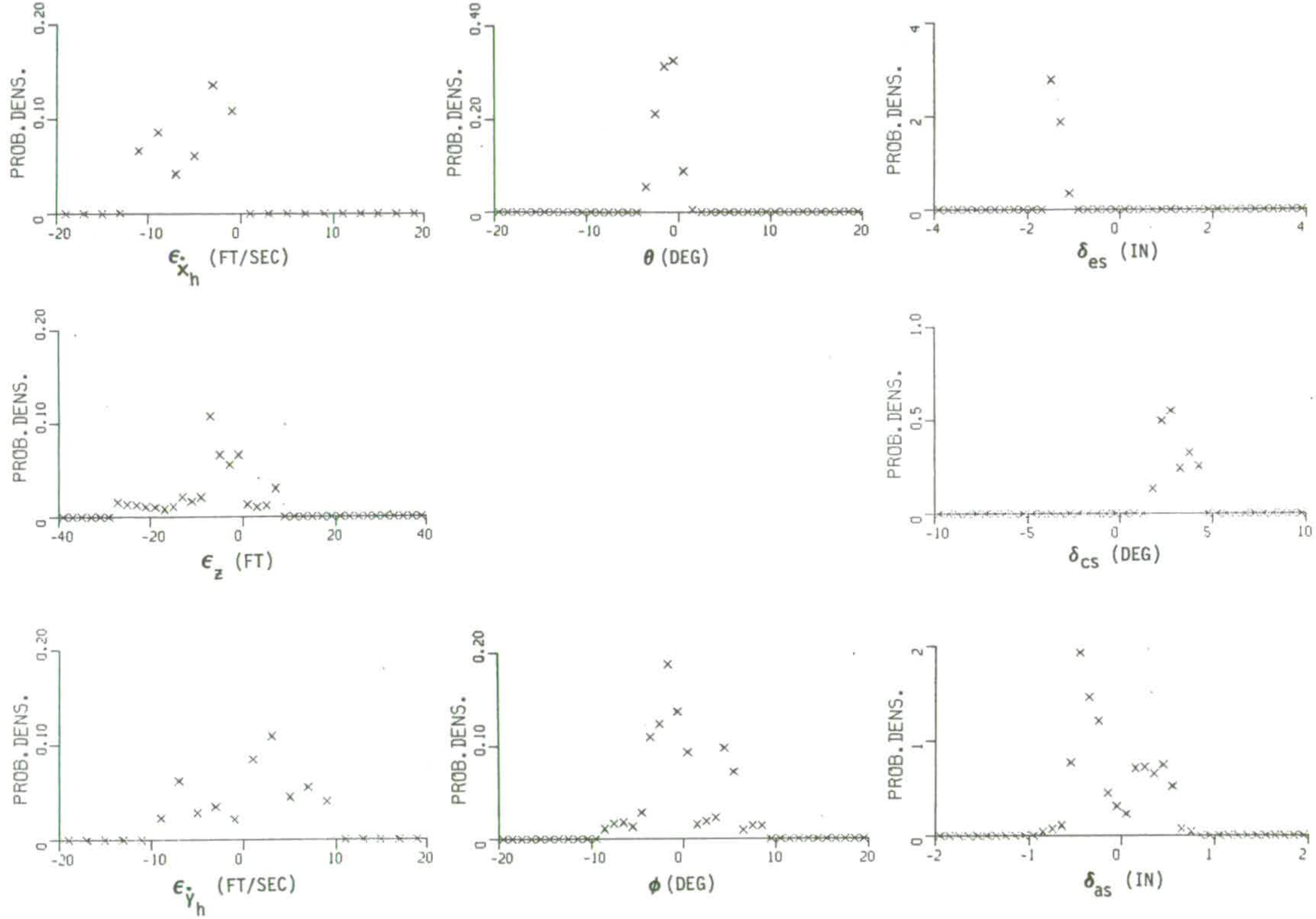


Figure VI-7 DVC:ED-2+, LEVEL DECELERATION
(d) PROBABILITY DENSITY FUNCTIONS

APPENDIX VII

MEASUREMENT OF WINDS AND TURBULENCE

Introduction and Summary

A continuous on-board measurement of wind conditions may be a requirement for the VTOL instrument landing problem: for example, in the generation of the guidance commands (Section IV), the automatic limitation of sideslip excursions, or the display of continuous relative wind information to the pilot. For this experiment, measurements of wind and turbulence were performed both to generate the proper guidance commands and to provide a quantitative comparison of the environmental conditions under which each evaluation was performed. In general the measurement technique was to compare the smoothed estimates of inertial velocity, obtained from the complementary filtering of radar position data and on-board accelerometer data (Section IV), with the measured velocity with respect to the air mass obtained from the LORAS (Linear Omnidirectional Resolving Airspeed System). This comparison yielded time histories of the estimated wind velocity components which were then processed to obtain means (the steady wind component) and standard deviations (the turbulence component).

This appendix presents the method used to derive the time histories of the wind velocity components, the estimated steady winds and turbulence obtained from these time histories for each evaluation approach, and a sample of the raw and processed data used to obtain these results.

Wind Velocity Measurement

The aircraft longitudinal and lateral velocity components with respect to the air mass as measured by the LORAS (u_L and v_L, respectively) must initially be corrected for the location of the sensor on the vertical tail of the aircraft; that is,

$$u = u_L + .271\, q \qquad \text{(ft/sec)}$$

and

$$v = v_L + .292\, r - .271\, p \qquad \text{(ft/sec)}$$

where p and q are measured in deg/sec.

Since these measurements are made in the aircraft body axis system, a transformation to the earth-referenced frame must be performed for a comparison of the air mass-referenced velocities with the inertial velocity estimates of the complementary filters. The three air mass-referenced velocity components in the earth axis system defined in Section IV are:

$$V_{x_a} = -u \cos\theta \cos\psi - v(\sin\phi \sin\theta \cos\psi - \cos\phi \sin\psi) - w(\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi) \qquad \text{(VII-1)}$$

$$V_{Y_a} = u \cos\theta \sin\psi + v(\sin\phi \sin\theta \sin\psi + \cos\phi \cos\psi)$$
$$+ w(\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi) \qquad \text{(VII-2)}$$

$$V_{Z_a} = u \sin\theta - v(\sin\phi \cos\theta) - w(\cos\phi \cos\theta) \qquad \text{(VII-3)}$$

For the purposes of the analysis it was assumed that no vertical wind component existed; that is

$$V_{Z_a} \doteq \hat{\dot{z}}_e$$

Therefore, from equation VII-3:

$$w \cong \frac{-\hat{\dot{z}}_e + u \sin\theta - v(\sin\phi \cos\theta)}{\cos\phi \cos\theta}$$

Substituting the above expression into Equations VII-1 and VII-2:

$$V_{Z_a} \doteq -u\left(\frac{\cos\psi}{\cos\theta} + \frac{\sin\theta \sin\phi \sin\psi}{\cos\phi \cos\theta}\right) + v\left(\frac{\sin\psi}{\cos\phi}\right)$$
$$+ \hat{\dot{z}}_e\left(\frac{\sin\theta \cos\psi}{\cos\theta} + \frac{\sin\phi \sin\psi}{\cos\phi \cos\theta}\right)$$

$$V_{Y_a} \doteq u\left(\frac{\sin\psi}{\cos\theta} - \frac{\sin\theta \sin\phi \cos\psi}{\cos\phi \cos\theta}\right) + v\left(\frac{\cos\psi}{\cos\phi}\right)$$
$$- \hat{\dot{z}}_e\left(\frac{\sin\theta \sin\psi}{\cos\theta} - \frac{\sin\phi \cos\psi}{\cos\phi \cos\theta}\right)$$

Assuming small values for angles θ and ϕ :

$$V_{X_a} \doteq -u(\cos\psi + \sin\theta \sin\phi \sin\psi) + v \sin\psi$$
$$+ \hat{\dot{z}}_e (\sin\theta \cos\psi + \sin\phi \sin\psi) \qquad \text{(VII-1a)}$$

$$V_{Y_a} \doteq u(\sin\psi - \sin\theta \sin\phi \cos\psi) + v \cos\psi$$
$$- \hat{\dot{z}}_e (\sin\theta \sin\psi - \sin\phi \cos\psi) \qquad \text{(VII-2a)}$$

The inertial velocity estimates in the earth axis system are simply the complementary filter outputs $\hat{\dot{X}}_e$ and $\hat{\dot{Y}}_e$. Therefore the horizontal wind velocity components in the earth axis system are:

$$V_{\omega_{X_e}} = \hat{\dot{X}}_e - V_{X_a}$$

and

$$V_{\omega_{Y_e}} = \hat{\dot{Y}}_e - V_{Y_a}$$

where V_{X_a} and V_{Y_a} are obtained from equations VIII-1a and VII-2a, respectively.

Because of the definition of the earth axis system, a positive value of $V_{\omega_{X_e}}$ represents a headwind component and a positive value of $V_{\omega_{Y_e}}$ represents a crosswind component from the pilot's left during an approach. Time histories of $V_{\omega_{X_e}}$ and $V_{\omega_{Y_e}}$ were obtained for two 30-second segments of each evaluation approach: one at glide slope intercept (~1700 ft AGL), the other at the final flare to level flight (~100 ft AGL). The means (steady winds) and standard deviations (RMS turbulence level) of $V_{\omega_{X_e}}$ and $V_{\omega_{Y_e}}$ are presented in Table VII-1 for both segments of each evaluation approach.

Although the assigned turbulence effect rating (TER) is influenced not only by the turbulence level but also by the control/display configuration being evaluated, it was apparent from the data presented in Table VII-1 that, in general, TER of A through C were assigned when the RMS turbulence level was less than or equal to 3.2 ft/sec. Similarly, turbulence levels of greater than 3.2 ft/sec RMS were in general assigned a TER of D through F. Therefore, for the purpose of analysis, configurations which received TER of A through C were considered to have been evaluated in "light to moderate" turbulence while those receiving TER of D through F were assumed to have been evaluated in "moderate to high" turbulence levels.

A comparison of the on-board measurements of the steady wind components presented in Table VII-1 and the winds measured by the control tower transformed to the SPN-42 approach course reference system revealed good agreement in the value of the crosswind component ($V_{\omega_{Y_e}}$) at 100 ft AGL but large disparities in the values of the headwind component ($V_{\omega_{X_e}}$). However the mean values of $V_{\omega_{X_e}}$ measured on-board at ~1700 ft AGL in general agreed with the headwinds measured by the tower.

It is apparent, from the results of the analyses described in this appendix, that the in-flight measurement of winds and turbulence requires extremely accurate measurements of air mass-referenced velocities and inertial velocities in order to obtain valid wind data from the differences of these two quantities. Since the measurement of turbulence was not a primary objective of this program, the airspeed sensors were not calibrated precisely for every flight condition in the evaluation task; it is hypothesized that the apparent errors in the mean wind measurements were to a large degree a result of airspeed measurement errors caused by calibration errors and local flow effects, for example.

TABLE VII-1

WINDS/TURBULENCE MEASUREMENTS

FLIGHT NO.	APPROACH	CONFIGURATION	GLIDE SLOPE INTERCEPT		FLARE		TER
			$V_{w_{X_e}}$ ft/sec $\mu(\sigma)$	$V_{w_{Y_e}}$ ft/sec $\mu(\sigma)$	$V_{w_{X_e}}$ ft/sec $\mu(\sigma)$	$V_{w_{Y_e}}$ ft/sec $\mu(\sigma)$	
F-120	1	ATT:ED-3	1.4(3.9)	-25.1(3.3)	5.7(2.8)	-18.4(2.6)	D
	2		-0.2(3.7)	-20.1(3.7)	-2.6(2.7)	-13.6(2.1)	
F-121	1	RATE:ED-3	6.9(4.2)	-8.7(4.6)	-3.4(2.8)	10.1(4.3)	C
	2		-3.3(5.5)	-6.3(4.1)	-1.0(2.0)	7.6(2.4)	
	3	ATT:ED-2	3.2(3.2)	-2.4(4.4)	-1.6(3.2)	2.3(7.9)	D
	4		4.5(3.0)	1.7(2.9)	-3.7(3.6)	3.1(3.4)	
	5	ATT:ED1/FD	1.9(2.1)	0.2(3.3)	4.3(4.1)	8.1(5.3)	D
	6		4.2(2.8)	3.9(2.6)	-4.7(3.2)	7.4(3.2)	
F-123	1	ATT:ED-2	-11.6(7.3)	-20.1(3.1)	-8.7(2.5)	-13.0(2.4)	B
	2		-10.5(2.2)	-19.7(2.2)	-12.3(2.0)	-10.9(2.5)	
	3	ATT:ED-3(No ITVIC)	-12.1(3.9)	-20.0(2.8)	-10.2(2.5)	-8.8(2.9)	D
	4		-9.0(3.2)	-13.8(2.0)	-6.2(2.1)	-6.5(1.4)	
	5	AUTO:ED-2	-5.4(2.9)	-8.7(3.4)	-5.7(1.6)	-6.0(3.0)	C
F-124	1	RATE:ED-2	INSUFFICIENT DATA		0.8(1.8)	-8.0(1.5)	A
	2		3.9(3.5)	-10.2(3.7)	0.8(2.8)	-7.2(2.5)	
	3	AUTO:ED-1	4.9(2.6)	-19.1(1.9)	-1.7(2.3)	-10.6(2.8)	B
	4		11.0(1.6)	-11.6(2.0)	-3.6(3.9)	-13.3(2.3)	
F-128	1	ATT/RT:ED-3	17.6(3.4)	8.0(5.5)	3.5(2.7)	11.2(1.8)	D
	2		20.3(2.2)	16.0(4.0)	-2.8(2.0)	12.5(2.4)	
	3	ATT:ED-2(No ITVIC)	14.5(2.9)	14.7(2.9)	-1.7(2.5)	11.5(5.1)	C
	4		16.6(3.2)	14.8(3.2)	-2.0(2.2)	9.9(7.8)	

TABLE VII-1 (Cont.)

FLIGHT NO.	APPROACH	CONFIGURATION	GLIDE SLOPE INTERCEPT $V_{\omega X_e}$ ft/sec $\mu(\sigma)$	GLIDE SLOPE INTERCEPT $V_{\omega Y_e}$ ft/sec $\mu(\sigma)$	FLARE $V_{\omega X_e}$ ft/sec $\mu(\sigma)$	FLARE $V_{\omega Y_e}$ ft/sec $\mu(\sigma)$	TER
F-128	5	ATT/RT:ED-2+	15.5(1.5)	14.9(5.5)	-1.4(7.4)	6.3(4.9)	D
	6		10.8(2.7)	14.7(8.4)	-2.0(4.3)	9.5(6.3)	
F-130	1	RATE:ED-2+	-6.9(3.7)	-11.5(5.4)	-10.5(1.8)	-11.3(2.2)	A
	2		-4.5(1.7)	-16.8(3.5)	-6.8(3.7)	-12.4(4.6)	
	3	RATE:ED-1/FD	-10.2(3.4)	-19.1(5.2)	-8.9(2.2)	-13.3(6.1)	B
	4		-8.6(2.7)	-21.6(5.4)	-7.7(2.3)	-14.7(8.9)	
	5	RATE:ED-3	-12.8(2.1)	-22.7(5.8)	-10.1(2.0)	-10.5(6.1)	B
	6		-7.1(2.5)	-18.0(5.0)	-12.0(2.1)	-11.0(7.2)	
F-131	1	ATT:ED-3	1.9(1.7)	-22.3(2.6)	-5.6(1.9)	4.2(1.9)	A
	2		4.8(2.5)	-20.4(3.0)	-6.4(2.5)	2.0(2.4)	
	3	ATT:ED-2+	12.7(5.9)	-20.5(3.6)	-3.1(2.5)	4.6(1.7)	A
	4		9.2(2.2)	-16.5(3.0)	-5.7(1.3)	4.9(2.7)	
	5	AUTO:ED-2+	INSUFFICIENT DATA		-2.6(2.2)	4.0(3.0)	A
	6		10.9(2.0)	-14.5(3.2)	-5.5(1.8)	-2.7(1.8)	
F-132	1	ATT/RT:ED-2+	22.2(3.3)	-5.3(4.2)	15.3(2.5)	-9.0(4.2)	D
	2		22.8(2.0)	-5.8(4.8)	10.1(5.6)	-6.3(6.4)	
	3	RATE:ED-2+	22.7(1.9)	-5.1(3.9)	10.8(3.0)	-6.1(4.3)	D
	4		11.5(2.9)	-13.0(4.2)	10.2(3.3)	-5.8(3.5)	
F-133	1	AUTO:ED-2	10.2(1.5)	-16.1(2.0)	6.5(1.8)	4.7(2.5)	A
	2		8.7(2.2)	-16.4(2.9)	1.4(1.6)	5.4(2.1)	
	3	ATT/RT:ED-2	8.7(1.2)	-11.3(1.9)	1.5(1.7)	8.8(3.1)	B
	4		9.8(1.9)	-15.6(4.3)	5.3(1.9)	4.7(2.1)	
	5	ATT/RT:ED-3	7.2(2.3)	-13.0(1.1)	1.8(2.4)	4.5(2.7)	B
	6		8.5(1.8)	-13.3(2.6)	3.9(3.4)	3.3(1.7)	

TABLE VII-1 (Concl.)

FLIGHT NO.	APPROACH	CONFIGURATION	GLIDE SLOPE INTERCEPT		FLARE		TER
			$V_{w_{X_e}}$ ft/sec $\mu(\sigma)$	$V_{w_{Y_e}}$ ft/sec $\mu(\sigma)$	$V_{w_{X_e}}$ ft/sec $\mu(\sigma)$	$V_{w_{Y_e}}$ ft/sec $\mu(\sigma)$	
F-134	1	ATT:ED-2+	26.1(3.2)	-2.0(6.7)	12.0(2.9)	8.1(7.0)	E
	2		23.6(2.5)	-4.8(6.3)	12.9(3.1)	10.1(7.6)	
	3	RATE:ED-2+	21.4(3.6)	-2.3(4.4)	19.5(1.9)	2.7(10.2)	F
	4		21.1(1.6)	-6.0(11.3)	8.4(4.4)	0.9(3.7)	
	5	AUTO:ED-2+	24.0(3.7)	-2.8(5.4)	8.7(2.5)	6.6(5.6)	D
	6		19.8(2.0)	-7.3(8.6)	7.2(3.7)	2.6(7.7)	
F-139	1	ATT:ED-3	-5.1(2.9)	-22.5(3.1)	-4.7(4.6)	-13.0(4.3)	D
	2		-7.5(3.7)	-21.3(3.7)	-7.6(1.6)	-12.0(2.1)	
F-140	1	ATT:ED-2+	5.6(3.3)	-23.0(2.9)	-3.9(3.7)	-12.3(3.3)	C
	2		2.7(3.8)	-27.9(3.9)	1.2(2.8)	-15.1(3.2)	
	3	RATE:ED-3	-7.6(3.7)	-14.9(3.3)	3.5(2.2)	-9.8(1.8)	C
	4		-2.1(5.1)	-21.4(3.6)	5.7(3.5)	-3.9(2.5)	
F-141	1	DVC:ED-2	11.1(2.8)	-14.8(6.6)	6.6(2.4)	-9.0(2.9)	B
	2		11.7(2.3)	-18.4(3.4)	7.7(2.5)	-10.4(2.7)	
	3	DVC:ED-1	11.4(2.1)	-16.4(2.1)	10.3(1.8)	-15.4(2.9)	B
	4		19.1(2.3)	-20.5(2.2)	6.5(2.7)	-10.0(4.5)	
	5	DVC:ED-2	10.2(2.0)	-10.0(2.3)	6.3(6.4)	-6.5(3.1)	B
	6		15.1(2.4)	-14.1(3.1)	9.8(3.9)	-8.7(2.8)	
F-142	1	DVC:ED-2+	-0.8(2.1)	-22.5(2.2)	-1.7(4.4)	-7.7(4.4)	C
	2	ATT/RT:ED-3	0.0(4.4)	-22.5(4.4)	-2.2(1.8)	-14.1(4.2)	C
	3		-1.0(1.9)	-25.8(2.8)	-3.4(4.1)	-7.3(3.1)	
	4	DVC/ED-3	-0.7(2.4)	-21.9(3.2)	-3.2(2.5)	-10.1(3.3)	C
	5		-0.2(1.6)	-29.3(3.1)	-5.9(3.4)	-12.5(4.3)	

An example of the raw and processed wind data is presented as Figure VII-1. The data were taken from Flight F-132, Approach #1 during which the tower wind measurement was: 15 gusting to 20 knots from 15^{o} to the right (as seen by the pilot) of the desired approach course; this measurement yields a headwind component ($V_{\omega_{X_e}}$) of 25 ~ 33 ft/sec and a crosswind component ($V_{\omega_{Y_e}}$) of -7 ~ -9 ft/sec. The means and standard deviations of the two wind components measured on-board and the resultant wind speed and direction were:

	$V_{\omega_{X_e}}$, ft/sec $\mu(\sigma)$	$V_{\omega_{Y_e}}$, ft/sec $\mu(\sigma)$	Wind Speed/Direction Kts/Deg
Glide Slope Intercept	22.2(3.3)	-5.3(4.2)	13.5/13.4R
Flare	15.3(2.5)	-9.0(4.2)	10.5/30.5R

As discussed previously, it appears that $V_{\omega_{X_e}}$ at glide slope intercept is a more accurate measure of the headwind component and, likewise, that $V_{\omega_{Y_e}}$ at the flare better reflects the crosswind component. The use of these two quantities yields a measured wind speed and direction of 14.2 Kts from 22^{o} to the right of the approach course. Finally, the mean of the four measured turbulence levels is 3.6 ft/sec; the assigned TER for both approaches of the evaluation of this configuration (ATT/RT:ED-2+) was a D. This sample of the turbulence analysis carried out for this experiment therefore provides an indication of the general validity of using the division between TER of C and D as the boundary between "low" (≤ 3.2 ft/sec RMS) and "high" (>3.2 ft/sec RMS) turbulence levels for the purpose of the analysis of the flying qualities, performance, and workload data.

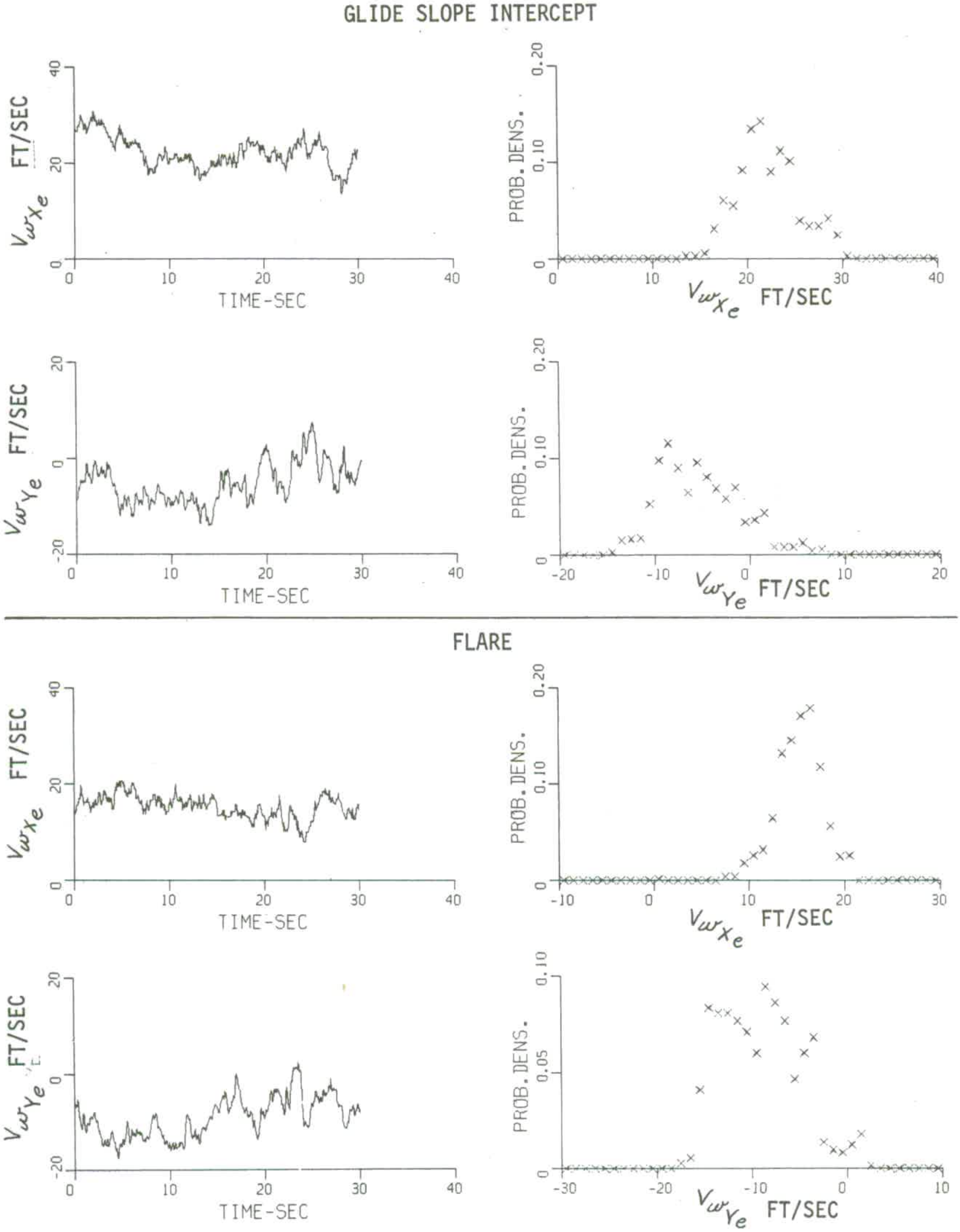


Figure VII-1 EXAMPLE OF WINDS/TURBULENCE MEASUREMENT

APPENDIX VIII

EQUIPMENT

Basic X-22A

The X-22A aircraft was developed by the Bell Aerosystems Company during a seven-year effort managed by the Naval Air Systems Command (NASC) and was designed to be a variable stability aircraft from the start with Calspan responsible for the variable stability system. In 1970, the Naval Air Systems Command awarded a contract to Calspan to begin flying qualities research with the X-22A.

As is evident from Figure VIII-1, the X-22A has four ducted propellers and four engines. The engines are connected to a common system of rotating shafts which distribute propulsive power to the four propellers. Changes in the direction of the thrust vector are accomplished by rotating the ducts, which are interconnected so that all rotate through the same angle. Thrust magnitude is determined by the collective pitch of the four propellers and this is controlled by either one of two levers, selectable in flight. One lever is very similar to a conventional helicopter "collective stick" and the other lever can be moved fore and aft similar to a throttle (Figure VIII-2). Normal-looking pitch, roll and yaw controls in the cockpit provide the desired control moments by differentially positioning the appropriate control elements (propeller pitch or elevon deflection) in each duct (Figure VIII-3).

In hovering flight, the X-22A employs fore and aft differential blade pitch for pitching moments, left and right differential blade pitch for rolling moments, and left and right differential elevon deflection for yawing moments. In forward flight, fore and aft differential elevon deflection is used for pitching moments, left and right differential elevon deflection for rolling moments, and left and right differential blade pitch for yawing moments. A mechanical mixer directs and proportions the pilot's commands to the appropriate propellers and elevons as a function of the duct angle.

X-22A Variable Stability System (VSS)

There are four VSS controllers - thrust, pitch, roll and yaw - and three artificial feel servos for the evaluation pilot cockpit controls, each employing electrohydraulic servos. When rigged for VSS flight the left hand flight controls are mechanically disconnected from the right hand flight controls and connected to the set of VSS pitch, roll and yaw feel servos. The VSS thrust servo operates the boost servo for the collective pitch system. VSS pitch, roll and yaw servos operate the right hand flight controls, moving the same linkages which are moved manually by the right hand pilot in normal non-VSS flight. (In fact, these same actuators serve a dual role by providing artificial feel for the primary flight control system when the VSS is not engaged.) Phasing of these control motions to the blades and elevons is accomplished by the mechanical mixer as for normal flight.

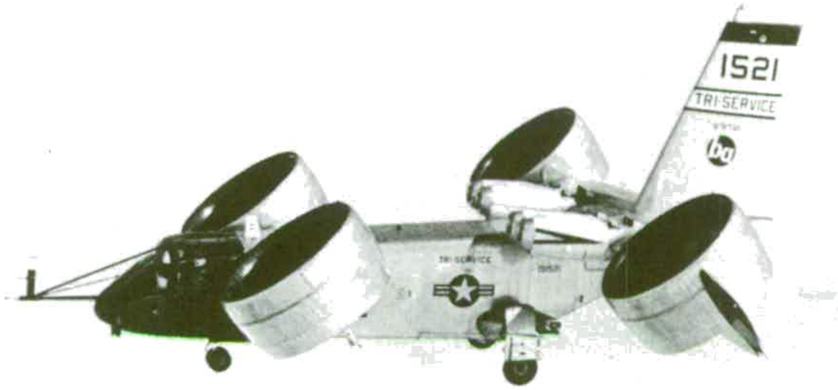


Figure VIII-1 X-22A VARIABLE STABILITY V/STOL AIRCRAFT

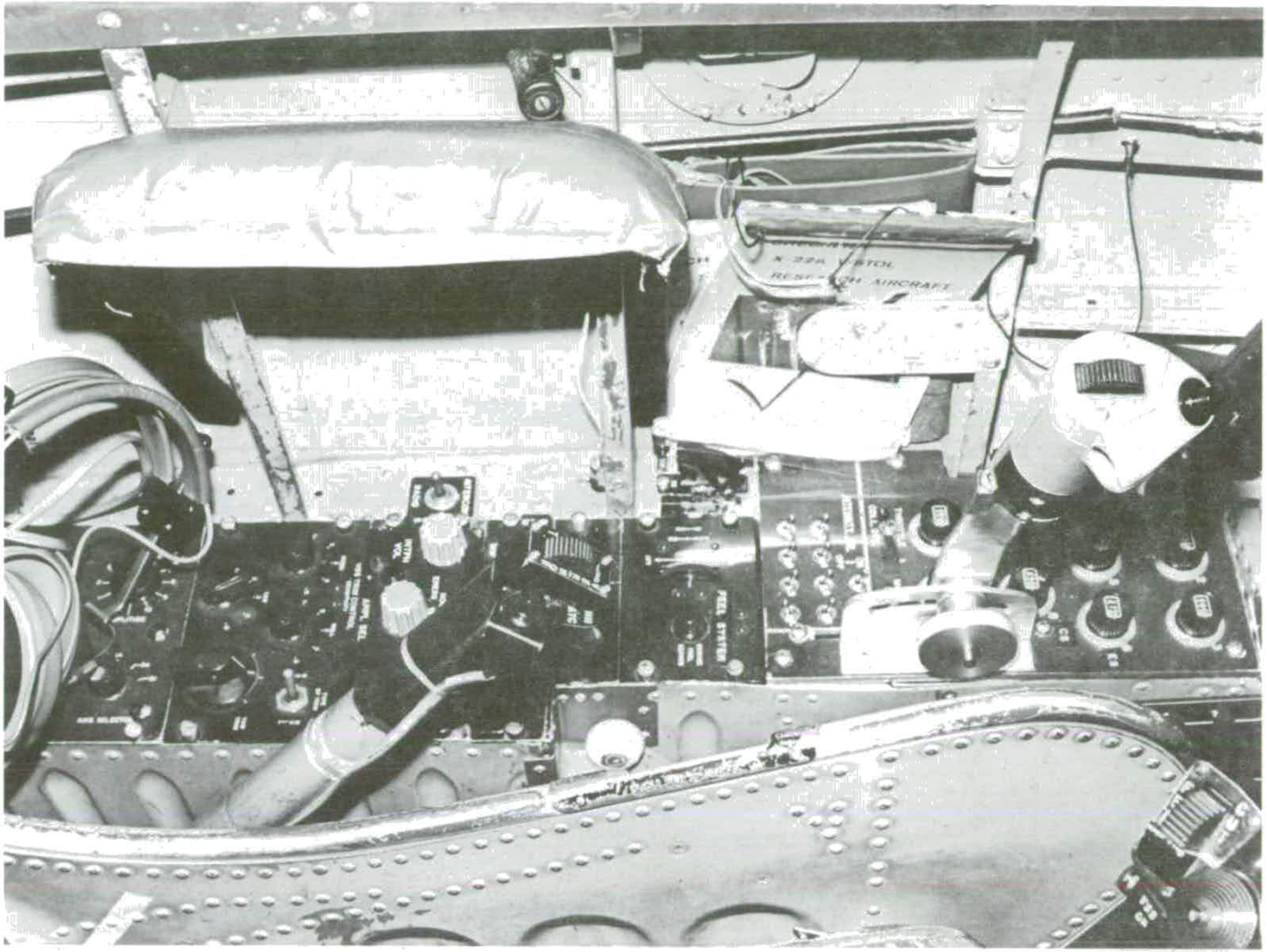


Figure VIII-2 EVALUATION PILOT COLLECTIVE AND THROTTLE STICKS PLUS DISPLAY SELECTION PANEL

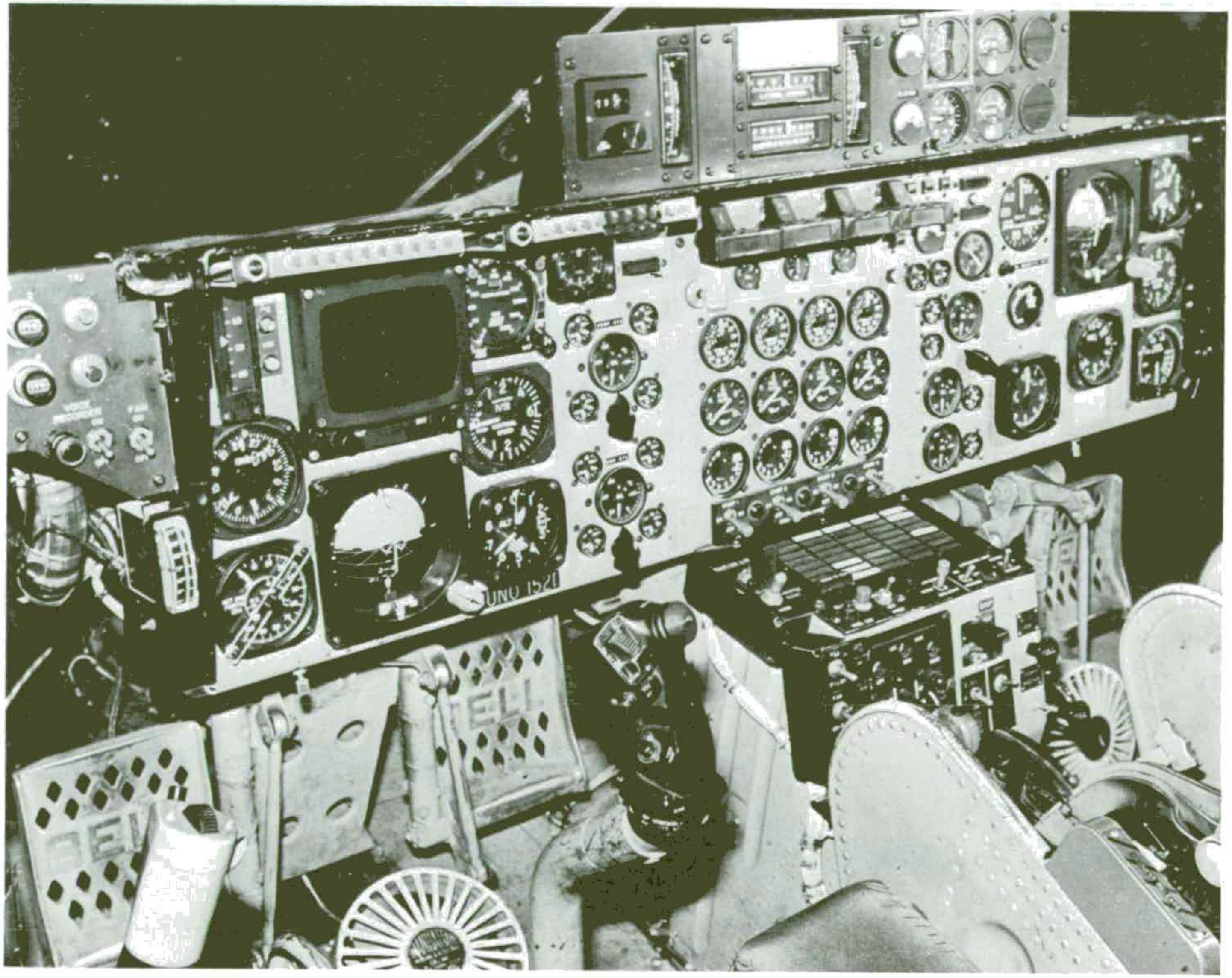


Figure VIII-3 EVALUATION PILOT STATION

During VSS operation, the evaluation pilot occupies the left hand seat in the cockpit. The system operator, who also serves as the safety pilot, occupies the right hand seat. The evaluation pilot's inputs, in the form of electrical signals, operate the appropriate right hand flight controls through the electrohydraulic servos. In addition to the evaluation pilot's inputs, signals proportional to aircraft motion and relative wind variables (for example, angle of attack and pitch rate) are fed back to move the right hand controls in the required manner and thus modify the aircraft's response characteristics as desired. The response-feedback and input gain controls are located beside the safety pilot and are used to set up the simulation configurations in flight. (Figure VIII-4). Note that the evaluation pilot cannot feel the basic X-22A control motions caused by the variable stability system.

Figure VIII-5 shows schematically a simplified example of the X-22A variable stability mechanization. This example illustrates how the desired values of the derivatives $M_{\delta_{es}}$ and M_{α} are achieved with this response feedback technique. Figure VIII-6 shows the full schematic for the roll channel of the VSS, including the artificial feel system.

Unique Features of the X-22A VSS

One unique feature of the X-22A VSS is that the response feedback gains are programmable with velocity throughout the full range of airspeeds, from -30 knots rearward through zero to 150 knots forward airspeed. This is accomplished by a multi-channel function generator which receives its airspeed input from the LORAS (Linear Omnidirectional Resolving Airspeed System). LORAS was developed by Calspan specifically for the X-22A. Recently, a second LORAS - much smaller than the original - was added to the nose boom to measure the vertical component of airspeed, specifically for VSS work in the hover.

Another unique feature of the X-22A is the Feedforward Flight Control System (FFCS). This is a limited authority, precision control system which acts like a vernier on the basic X-22A flight control system during VSS operation. The FFCS makes it possible to achieve extremely high precision in positioning the actuators for the X-22A aerodynamic controls - propeller pitch and elevon angle. Such control system precision is required for the satisfactory operation of the "closed-loop" VSS airplane.

A special Test Input Unit (TIU), which is a part of the X-22A VSS, greatly facilitates in-flight calibration procedures. This unit generates electrical step, doublet, or pulse inputs (whose magnitude and time scale are selectable) which can be inserted into any of the four VSS channels. Thus calibration records can be taken with repeatable, easily controlled, inputs.

On-Board Analog Computer

For this experiment, the capabilities of the basic X-22A variable stability system were considerably enhanced by the addition of an airborne analog computer, designed and built by Calspan. This computer, which works in conjunction with the VSS, was used to generate the guidance relationships

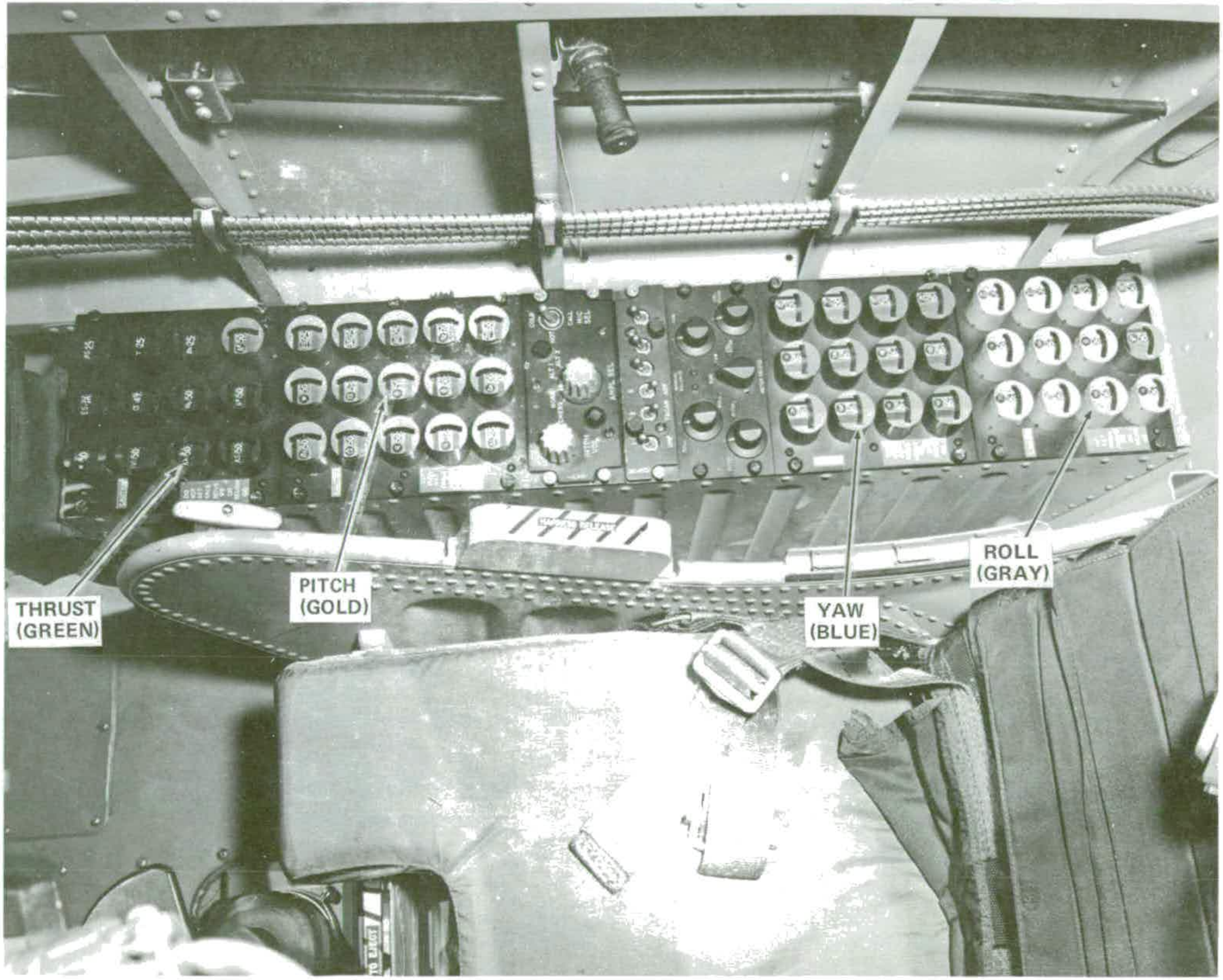
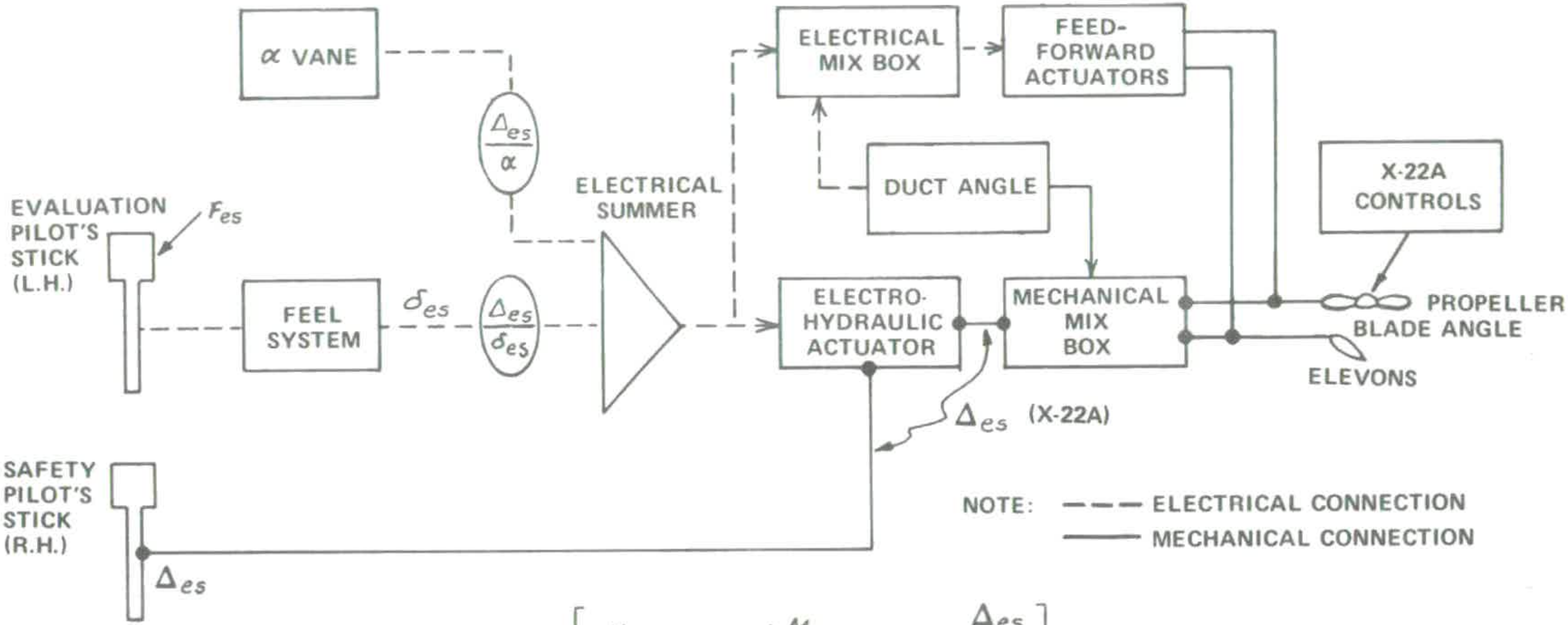


Figure VIII-4 VSS GAIN CONTROLS IN X-22A COCKPIT



$$M_{\alpha\,(\text{SIMULATED})} = \left[M_{\alpha(X-22A)} \pm M_{\Delta_{es}(X-22A)} \frac{\Delta_{es}}{\alpha} \right]$$

$$M_{\delta_{es}\,(\text{SIMULATED})} = \left[M_{\Delta_{es}(X-22A)} \frac{\Delta_{es}}{\delta_{es}} \right]$$

Figure VIII-5 SIMPLIFIED EXAMPLE OF THE X-22A VARIABLE STABILITY SYSTEM MECHANIZATION

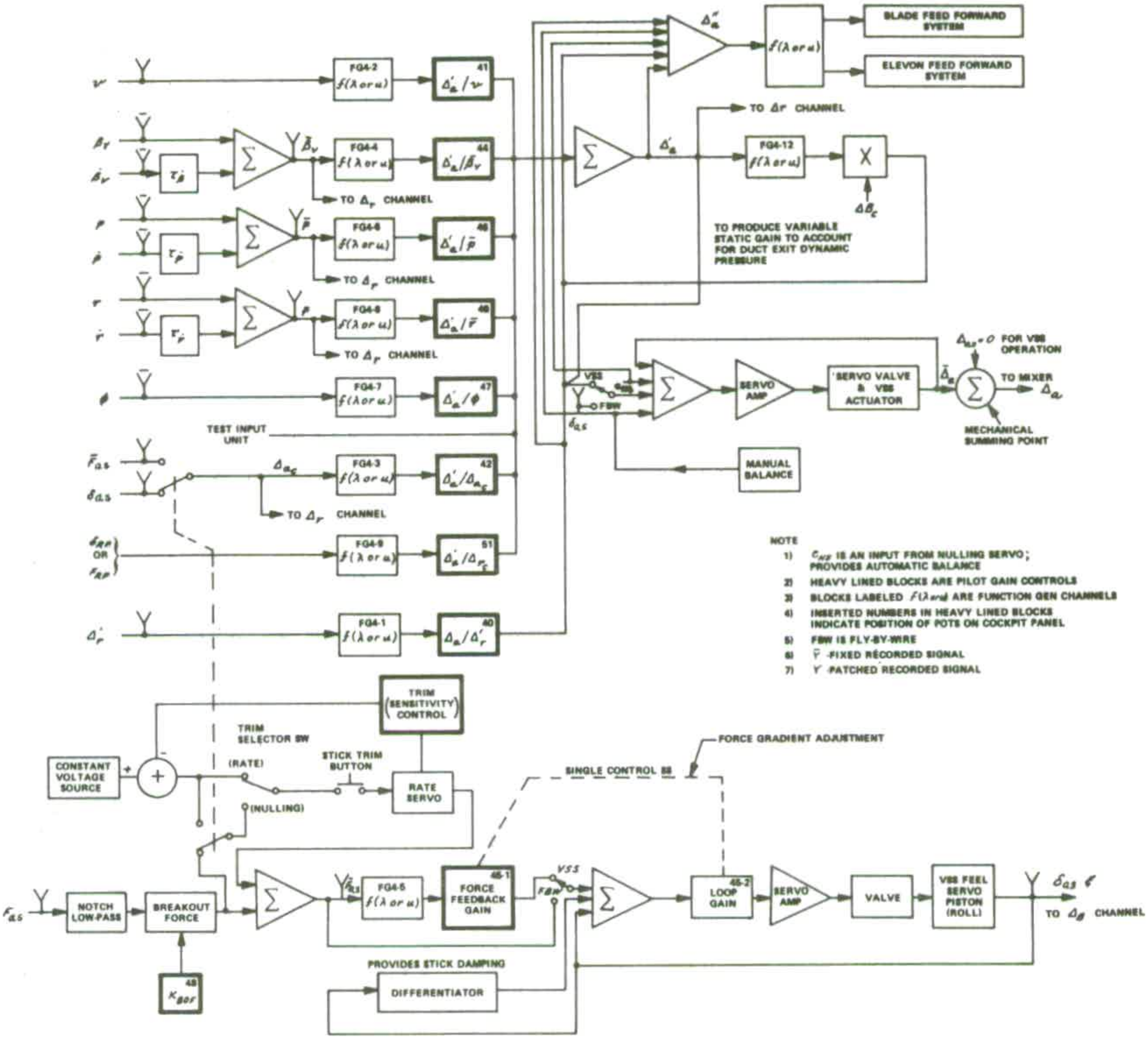


Figure VIII-6 X-22A VSS BLOCK DIAGRAM - ROLL CONTROL discussed in Section IV, to provide the quasi-model following control systems discussed in Section V, and to compute the flight director logic discussed in Section VI. The functional elements of the computer are summarized in Table VIII-1 below.

Table VIII-1

ANALOG COMPUTER FUNCTIONAL ELEMENTS

Quantity	Computing Element
20	Integrators
76	Summer/Inverters
32	Multipliers
12	Balance-Holds
10	Diode Function Generators
10	Special Circuits
10	Filters
76	Grounded Potentiometers
20	Floating Potentiometers
62	Resistor Groups
10	Relays

Ten of the potentiometers are remotely located on a panel next to the evaluation pilot (Figure VIII-2) to provide in-flight flexibility for the control of some of the computations.

Figures VIII-7 through VIII-12 are the programming diagrams for the computer as implemented in this experiment; Table VIII-2 provides a representative set of potentiometer values (taken from flight F-142). A more complete description of the computer design is given in Reference 25.

Analog Symbol Generator

The programmable symbol generator, designed and built by Calspan, is an analog device which is capable of producing as many as 32 different calligraphic symbils for display on a CRT instrument (Figure VIII-13). The symbol generator can easily be installed in the aircraft or in the ground simulator. It combines the simplicity and ease of programming available in an analog computer with an in-flight flexibility exceeding that of more complex digital devices. The design of display formats involves the following straightforward procedure.

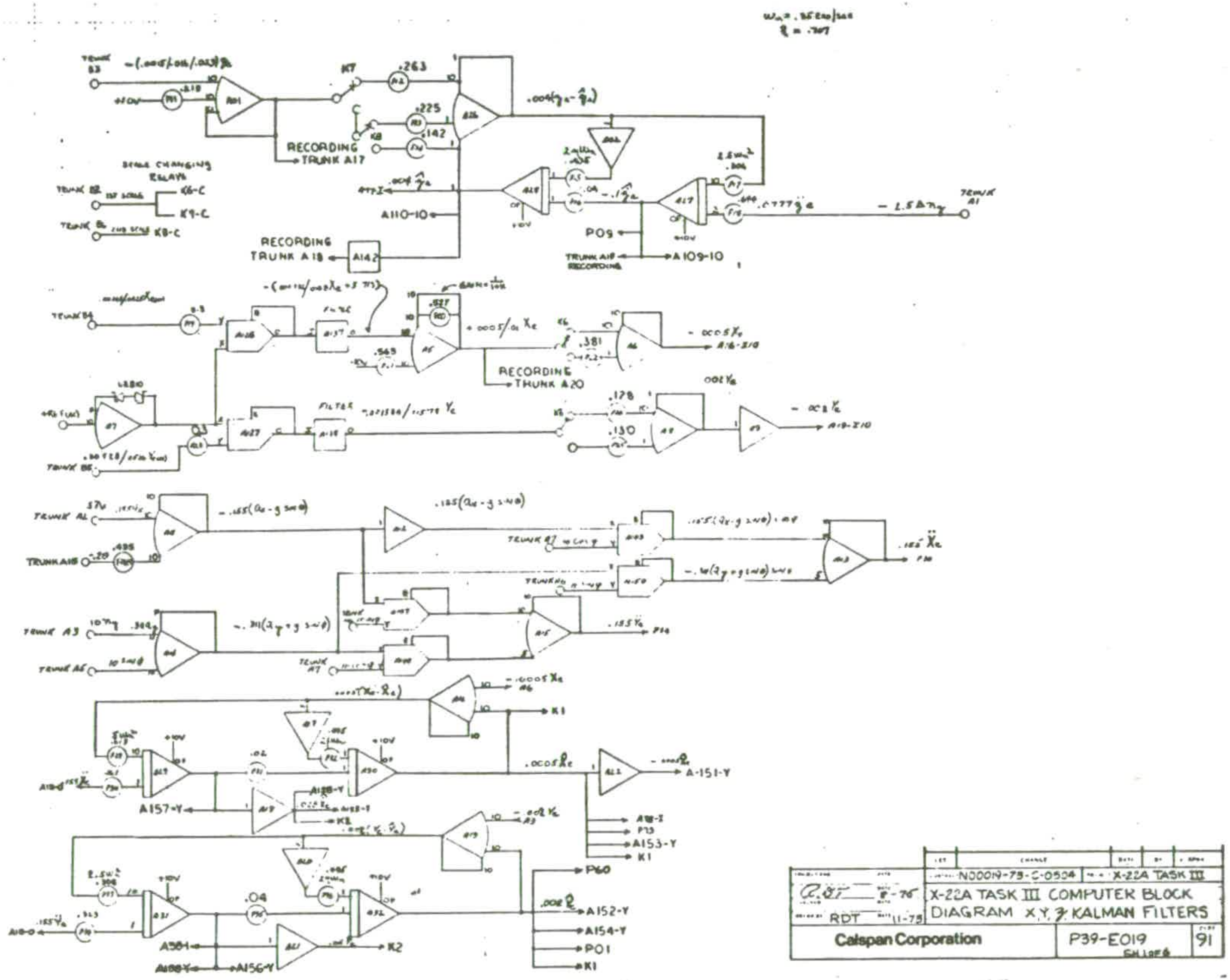


Figure VIII-7 ANALOG COMPUTER PROGRAM DIAGRAM (COMPLEMENTARY FILTERS)

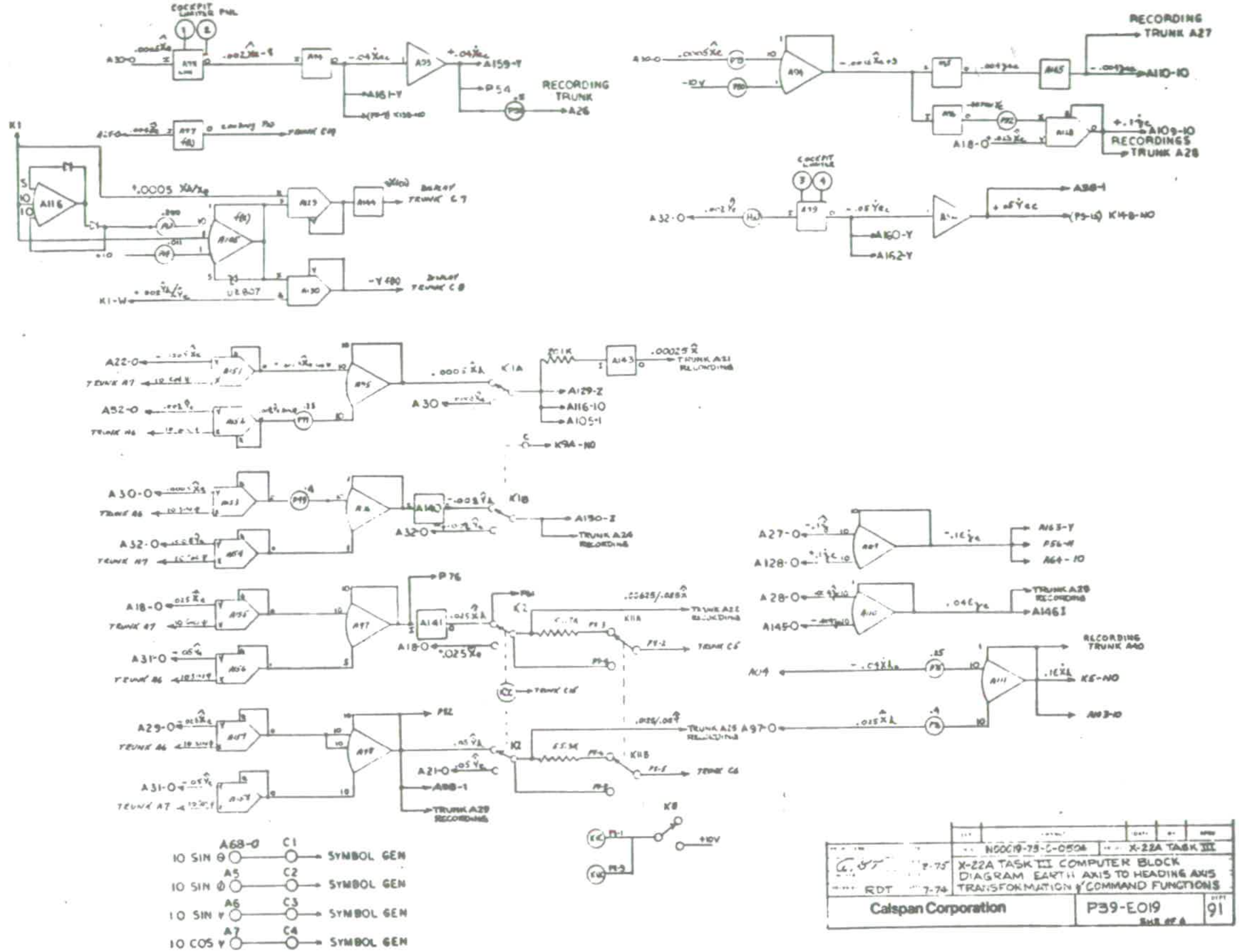


Figure VIII-8 ANALOG COMPUTER PROGRAM DIAGRAM (AXIS RESOLUTION)

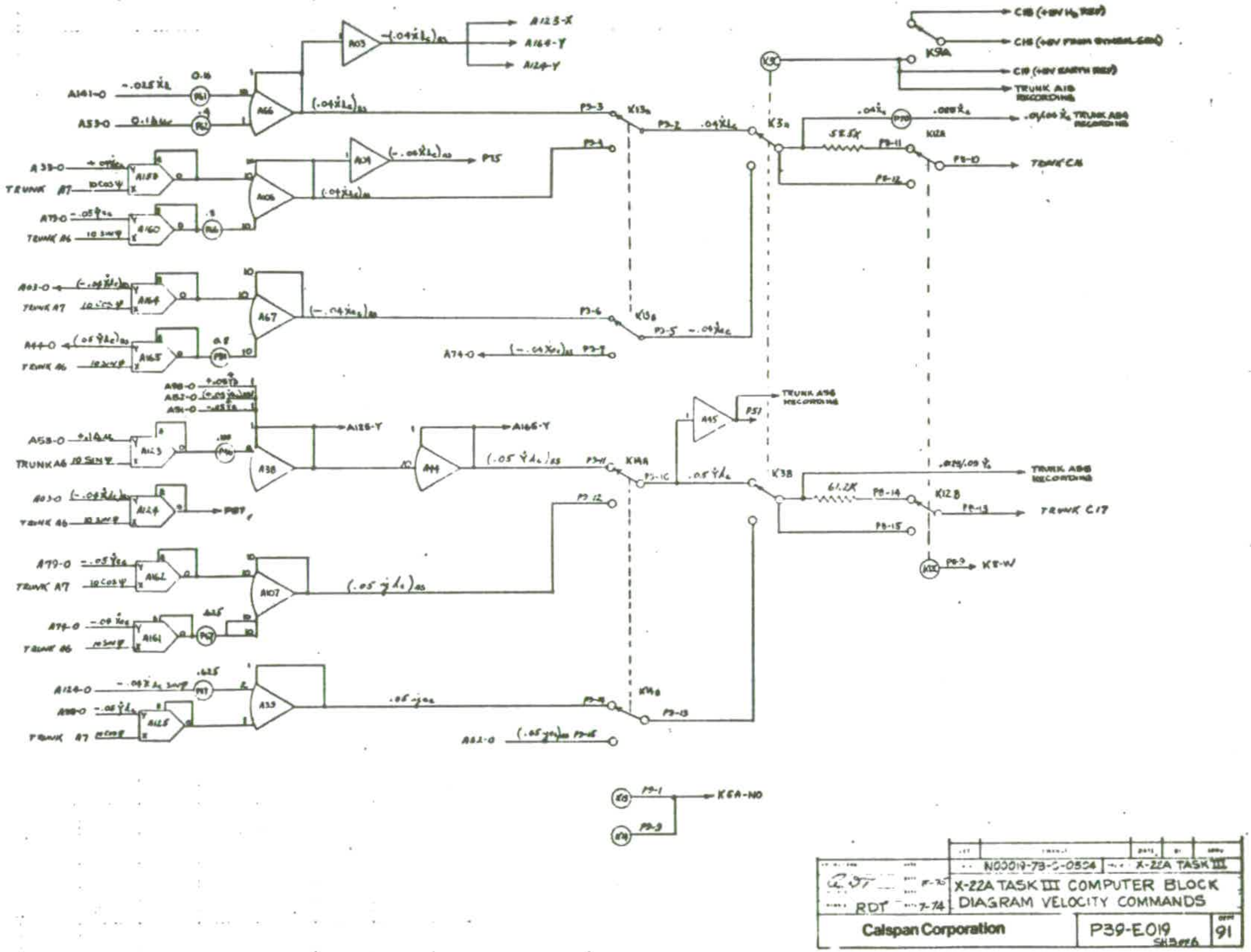


Figure VIII-9 ANALOG COMPUTER PROGRAM DIAGRAM (GENERATION OF COMMANDS)

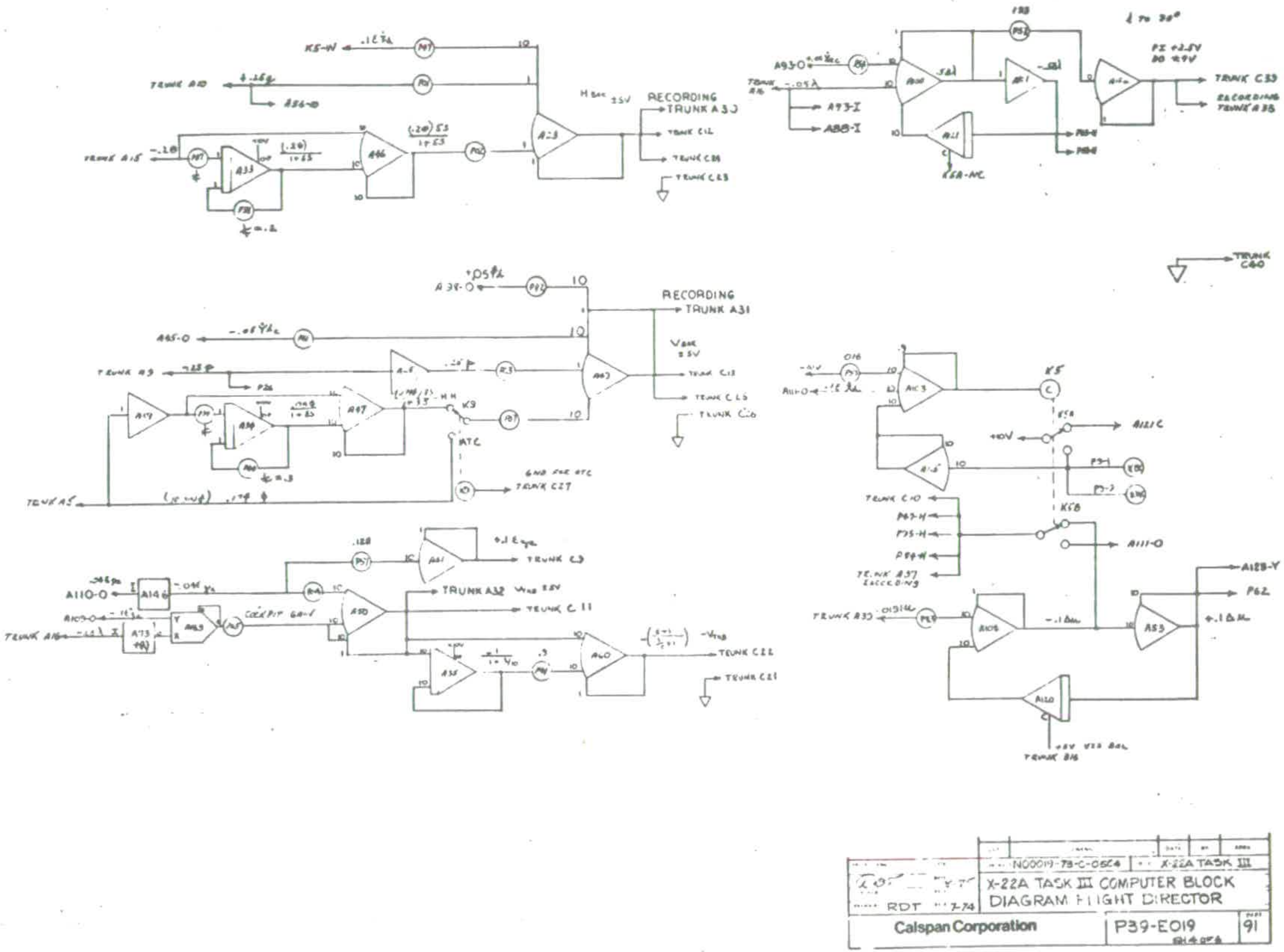


Figure VIII-10 ANALOG COMPUTER PROGRAM DIAGRAM (CONTROL AUGMENTATION)

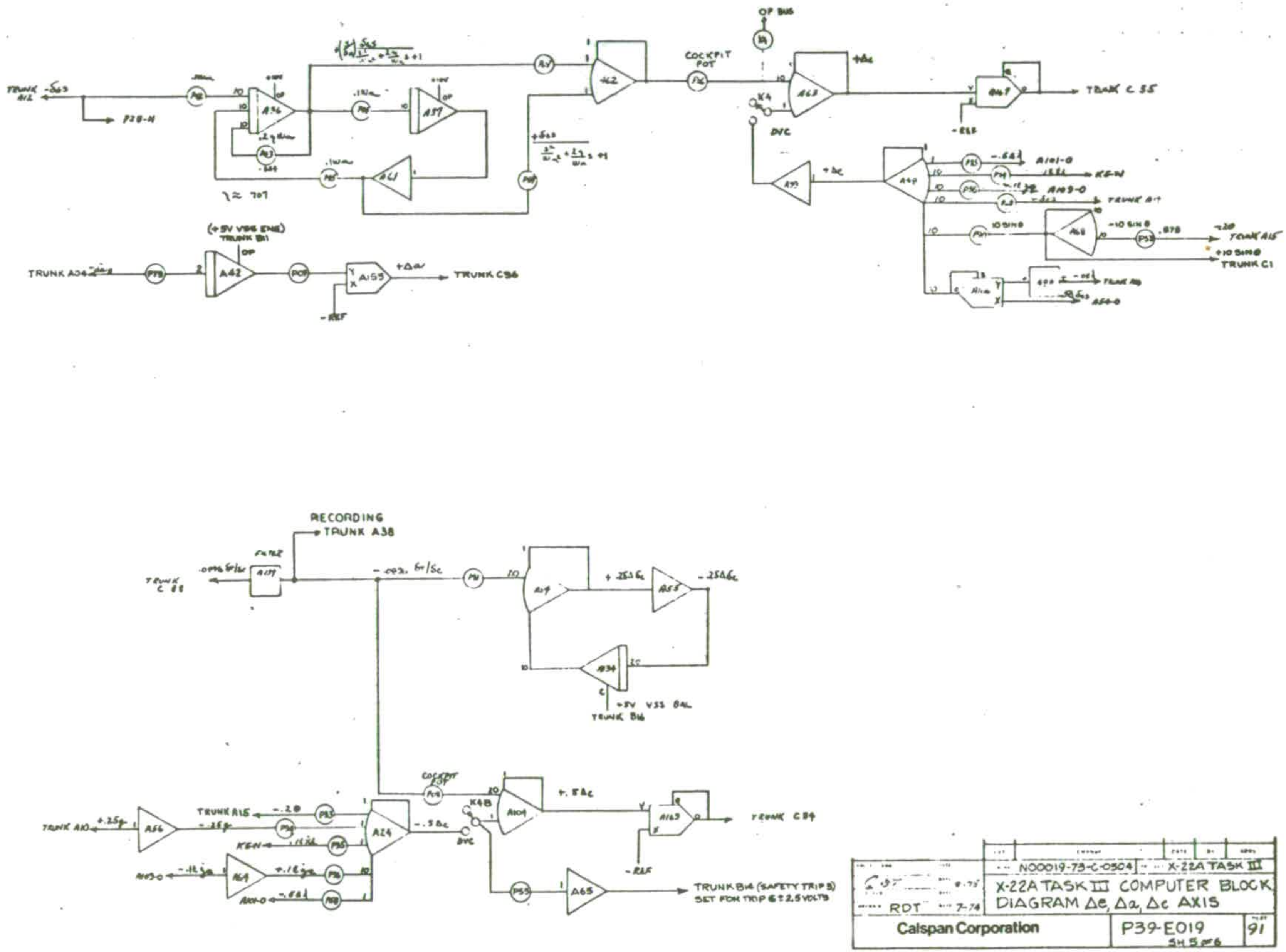


Figure VIII-11 ANALOG COMPUTER PROGRAM DIAGRAM (CONTROL AUGMENTATION

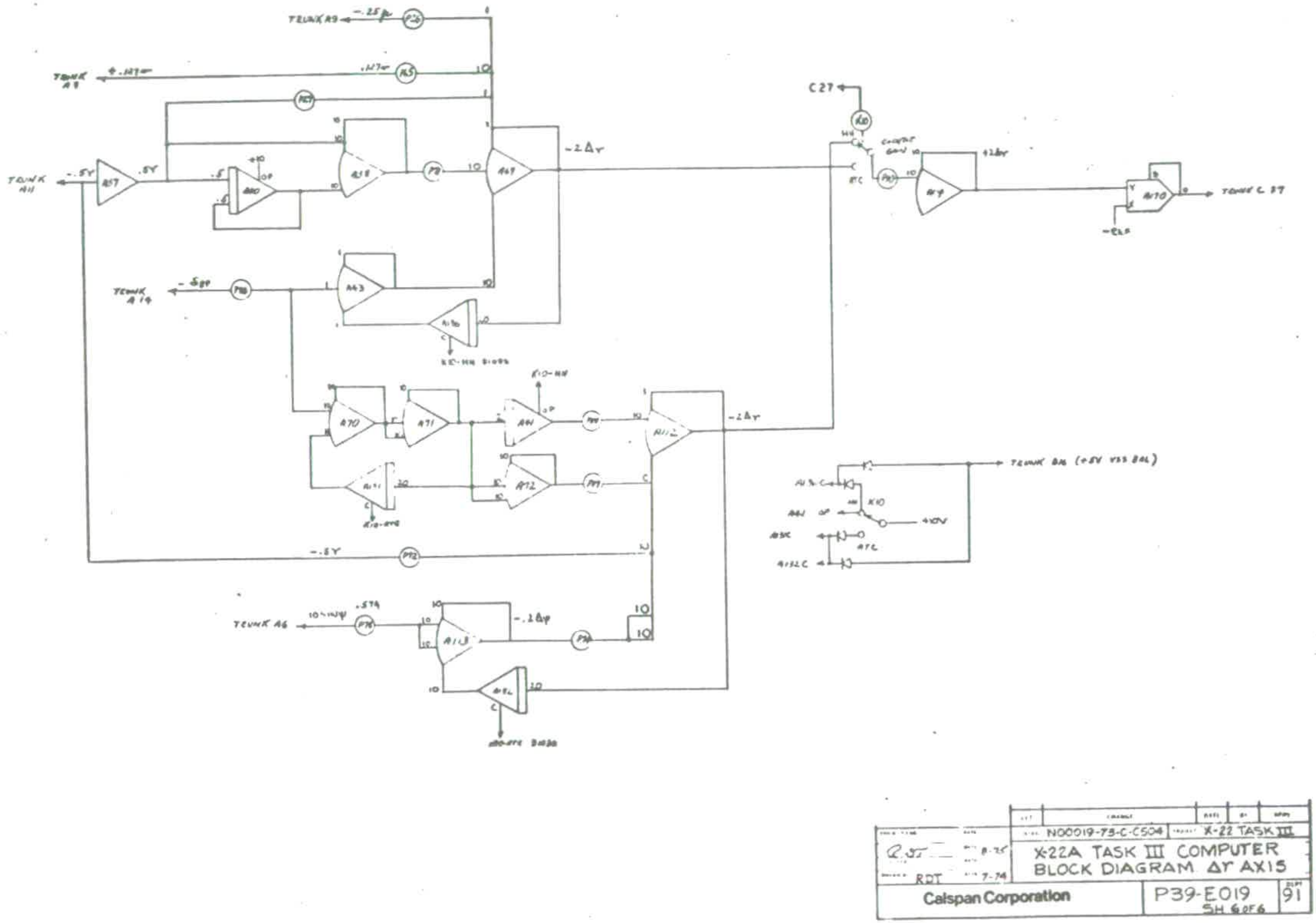


Figure VIII-12 ANALOG COMPUTER PROGRAM DIAGRAM (CONTROL AUGMENTATION)

TABLE VIII-2

X-22A ANALOG COMPUTER POT LIST

*DVC

POT NO.	PARAMETER SCALE	RATIO	POT SET	← LOAD	LOAD →	POT NO.	PARAMETER SCALE	RATIO	POT SET
P01	-.25 q/HBAR	.086	086	100K	10K	P55	DVC SAF TRIP		750
P02	(.20)5s/1 + 5s	.345	349	100K	10K	P56	$-\Delta_e/\epsilon_{\dot z}$	.190	205
P03	.25 p	.068	068	100K	10K	P57	VTAB /.4 ϵ_z	.125	132
P04	VTAB/.04 ϵ_z	.125	132	10K	100K	P58	$-\Delta_c/\Delta_\lambda$	.145	146
P05	.1$\dot\epsilon_z$ GAIN	.999	999	10K	10K	P59	-.01ϵ_{x_h} +1.5	.016	016
P06	δ_{es} MODEL	.000/.250	000/275	10K	5.9K	P60	.05 $\dot Y_{ec}$ / .002 Y_e	.283	337
P07	.174ϕ/.174$\phi\frac{3s}{1+3s}$ |VBAR	.026	026	10K	10K	P61	.16 (-.025$\dot X_h$)	.160	171
P08	δ_T/δ_c gain	*.78/.279	*869/342	5K	100K	P62	.4(.1$\Delta\alpha$)	.400	405
P09	δ_{as} INTEG		000	10K	10K	P63	.0005 $\hat X_h/\hat X_e$ gain	.200	217
P10	2Δ_r gain	000/1000	000/1000	10K	100K	P64	1/(X_e+K) OFFSET	.011	011
P11	z_e (OFFSET)		220	10K	10K	P65	-2Δ_r / .127v	.216	235
P12	1st scale .004 z_e		275	10K	10K	P66	.8(-.05 $\dot Y_{ec}$ sin ψ)	.800	851
P13	2nd scale .004 z_e		253¼	100K	5K	P67	.625(-.04 $\dot X_{ec}$ sin ψ)	.625	744
P14	3rd scale .004 z_e		128	100K	100K	P68	$-\frac{3}{\omega_n}\delta_{es}$ /(lag)	.707	714
P15	2$\zeta\omega_n$	.495	500	100K	100K	P69	$-\delta_{es}$/lag	1.000	1000
P16	(.04)(-.1$\hat{\dot z}_e$)	.04	040	100K	10K	P70	.625(.04 $\dot X_c$)	.625	628
P17	2.5 ω_n^2 .35 rad/sec	.306	340	10K	10K	P71	.5r /1 +2s	.091	095
P18	.05 $\ddot z_e$	.644	658	50K	10K	P72	-20Δ_r/-.5r	.122	129
P19	X_{eAC}/X_{eDC}	.3	300	∞	50K	P73	2K/s δ_{as}	.999	999
P20	.0005/.01 X_e gain		574	10K	5K	P74	-20Δ_r/-.2$\Delta\psi$	.157	180
P21	X_e OFFSET		618	10K	10K	P75	(-.04 $\dot X_{h_c}$).25	.250	275
P22	.01X_e gain		504-3/4	100K	10K	P76	.4(.025 $\dot X_h$)	.400	450
P23	Y_{eAC}/Y_{eDC}	.3	300	∞	10K	P77	.25(.002 $\dot Y_e$ sin ψ)	.250	275
P24	.002 Y_e gain		140	10K	5K	P78	.574(10 sin ψ)	.574	696
P25	.002 Y_e gain		132	100K	10K	P79	.001$\hat X_e$ +9/.0005$\hat X_e$	.225	246
P26	2Δ_r/.25p	.295	298	100K	100K	P80	+9V OFFSET	.895	899
P27	-2Δ_r/.5r	.159	160	100K	5K	P81	-.0896 δ_T/δ_c	.140	159
P28	$-\delta_{es}$	.573	639	10K	10K	P82	VBAR/.05 $\dot Y_e$	.235	257
P29	5 ω_n^2 X_e	.613	680	10K	10K	P83	.524(.0191μ)	.524	587
P30	$\dot X_e/\dot X_e$	.161	162	100K	10K	P84	$-\Delta_e/\epsilon_{\dot x_h}$	.195	211
P31	$\ddot X_e/\dot X_e$	.02	020	100K	100K	P85	Δ_e/.5$\Delta\lambda$	.400	405
P32	2$\zeta\omega_n X_e$	.700	707	100K	10K	P86	$-\delta_{RP}$/2Δ_r	.364	408
P33	2.5 ω_n^2 Y_e	.306	340	10K	50K	P87	.625(-.04 X_{h_c} sin ψ)	.625	639
P34	$\ddot Y_e/\hat{\dot Y}_e$	.323	326	100K	10K	P88	-2Δ_r/5$\Delta\delta_{RP}$	.628	695
P35	$\ddot Y_e/\hat Y_e$	.04	040	100K	10K	P89	-2Δ_r /$\Delta\delta_{RP}$	.608	675
P36	2$\zeta\omega_n Y_e$	.495	500	100K	10K	P90	Δ_e /.2θ_{wo}	.335	374
P37	$\frac{1}{2}(\theta)$	.200	200	100K	10K	P91	.8(.05 $\dot Y_{h_c}$ sin ψ)	.800	851
P38	$\frac{1}{2}(\theta)$	.200	200	100K	∞	P92	-40 tan γ_c X.75	.750	750
P39	$\frac{1}{2}(\phi)$	.300	303	100K	100K	P93	.5Δ_c /.2θ	.593	600
P40	$\frac{1}{2}(\phi)$	.300	303	100K	100K	P94	.5Δ_c /.25q	.075	075
P41	(.9)-(1/1+$\frac{s}{10}$)(.1ϵ_z)	.900	929½	10K	100K	P95	.5Δ_c /.1$\epsilon_{\dot x_h}$	.350	354
P42	.1$\omega_n\delta_{es}$	.400	450	10K	10K	P96	.5Δ_c /$\epsilon_{\dot z}$	.260	287
P43	.2$\zeta\omega_n$	.283	313	10K		LIMITER			
P44	.1ω_n sδ_{es}	.200	217	10K		P1	.002 $\hat X_e$ + 8		000
P45	-.1$\omega_n\delta_{es}$	.200	217	10K		P2	-.002 $\hat X_e$ + 8		000
P46	0.1(.1$\Delta\alpha$ sin ψ)	.100	102	20K		P3	-.05 $\dot Y_{ec}$		641
P47	10(.1$\epsilon_{\dot x}$/HBAR)	.150	160	10K		P4	+.05 $\dot Y_{ec}$		641
P48	.435(.2θ)	.435	489	10K		SIGNAL CONDITIONER			
P49	.002 $\dot X_e$ sin ψ	.40	450	10K		P1			
P50	.5(.04 $\dot X_{ec}$)	.500	503	200K		P2	.5(.004 z_e)	.500	415
P51	.05 $\dot Y_{h_c}$	.235	257	10K		P3			
P52	ITVIC LITE λ CONT	.179	193	10K		P4	-.5(.004 z_{ec})	.500	472
P53	.873(11.46 sin θ)	.873	209	10K		P5	.4(.0005/.01X_e)	.400	190
P54	.04 $\dot X_{ec}/\lambda$	.590	657	10K					

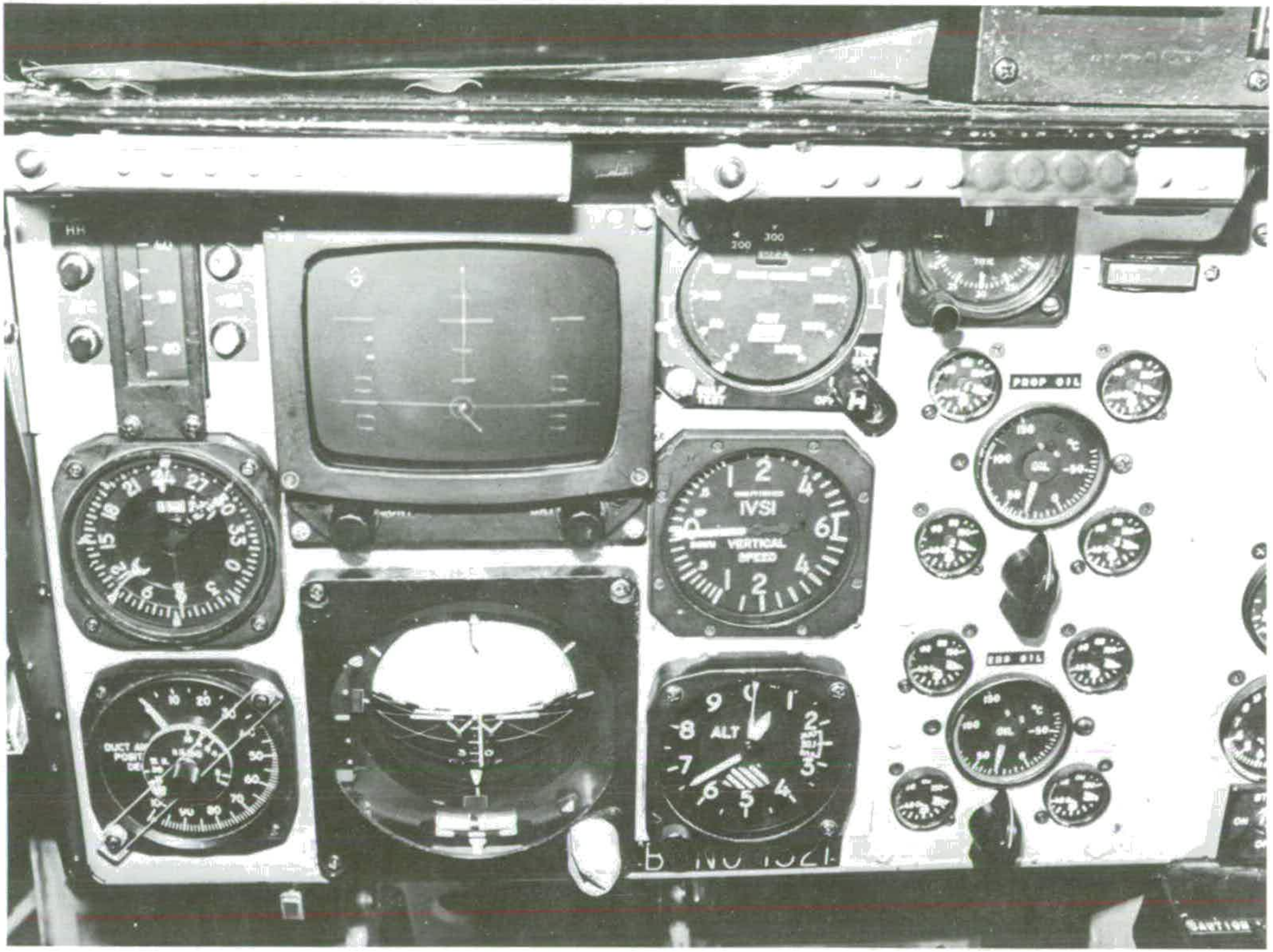


Figure VIII-13 EVALUATION PILOT INSTRUMENT PANEL

- Choice of symbology - The elementary symbols available to design a display format are:

  straight lines - variable length and rotation angle

  double lines - equal length and variable spacing

  circles - variable diameter

  diamonds

  chevrons

  Each of the 32 ouput channels can be patched and adjusted to provide any of the elementary symbols. The symbols may be statically positioned at any point on the display; individual intensity adjustment is available for all the output channels in order to selectively emphasize the importance of the various symbols. The symbol channels are multiplexed 50 times per second so that all 32 channels can be seen on a CRT without flicker.

- Definition of display dynamics - Each of the elementary symbols can be made to move horizontally and vertically on the display. In addition, the straight lines may be programmed as vectors with variable magnitude and direction; the diameter of the circles may be varied as a function of chosen variables. These symbol dynamics may be determined by any of the twenty-four available analog inputs. Forty-eight signal conditioning amplifiers are available for gain adjustment and sign inversion of the selected inputs. Twelve multipliers are provided to allow input gain changes as functions of twelve independent variables.

- Selection of display modes - Ten of the thirty-two output channels can be individually blanked through the use of cockpit switches. A display mode switch is also available to select different analog inputs to various symbols. This capability is very important for in-flight research experiments, as different display formats and presentations may be evaluated during flight without landing and reprogramming the symbol generator.

The initial programming and any necessary re-programing may be performed in an efficient manner since all of the symbol generator components are wired to a single patch panel for maximum flexibility of the system. Again, Reference 25 provides a more detailed description.

Data Acquisition and Processing System

Since the X-22A aircraft and variable stability systems are extremely complex, requiring monitoring during flight of many more variables than can be easily scanned by the pilot, a sophisticated system for data telemetry, acquisition, and processing was designed for the X-22A. A more complete description is given in Reference 52.

All data pertinent to the flight of the X-22A aircraft are telemetered to a ground station via a pulse-code-modulated "L-band" telemetry link. Eighty channels are provided, with the data sampled at a 200 Hz rate and encoded into 9-bit words. Of these 80 channels, five are required for time and synchronization, one is subcommutated to 64 additional channels, and one more is required to identify the subcommutated channel. There are, then, 137 channels available for data transmission.

Patch panels in the X-22A aircraft permit selection of the 137 variables to be telemetered from approximately 200 that are available. For the research experiments, approximately 80 flight safety variables (such as bearing hanger vibration levels and various oil temperatures and pressures) are telemetered and monitored; the remaining 57 variables (such as angle of attack, stick control positions, and VSS electrical commands) are of interest to the flying qualities experiment.

The data are telemetered to a ground station and experiment control center housed in a mobile van (Figures VIII-14, 15). The van contains the following equipment:

(a) an omnidirectional antenna and a steerable, directional antenna
(b) a telemetry receiver
(c) a PCM decommutator and signal simulator
(d) a tape recorder for recording the complete data stream
(e) a 32-channel digital-to-analog converter (DAC)
(f) four 6-channel chart recorders
(g) a panel of 9 meters for continuous display of a fixed set of flight safety variables
(h) a patch panel to select a desired set of 32 variables for the DAC's
(i) a paper printer
(j) a mini-computer with 24K storage capacity, 800 nanosecond effective cycle time, 36 channels of Digital-to-Analog converters and 12 channels of Analog-to-Digital converters
(k) a teletypewriter
(l) a high-speed paper tape unit
(m) a 9-channel digital tape recorder
(n) a 360-channel VHF transceiver
(o) a voice-actuated magnetic tape recorder
(p) a weather station
(q) two 5 kW 115-volt, 60 Hz generators

Figure VIII-14 MOBILE VAN, EXTERNAL VIEW

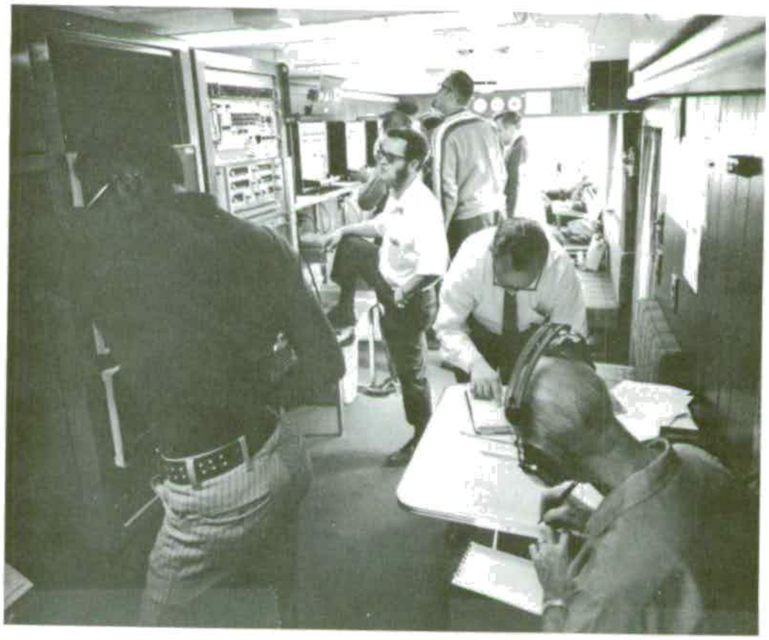


Figure VIII-15 MOBILE TELEMETRY VAN, INTERNAL VIEW

A simplified block diagram of the functions of this equipment during a flight is shown in Figure VIII-16. The primary purposes of the equipment include flight safety monitoring, experiment control, and data processing, each of which is briefly described below.

As has been discussed, the complexity of the X-22A aircraft requires constant monitoring of a large number of flight safety variables. This function is performed by the mini-computer in the mobile van. High and/or low limit values for the variables are stored in the computer; the telemetered data is processed through the computer on-line and compared continuously with these limits. In the event of a variable exceeding these preset limits, the teletypewriter unit immediately prints out the variable in question and its value. The high speed paper tape unit acts as an independent backup by printing out on command the values of all the telemetered variables.

The mobile van is used as the experiment control center during a flight. Pilot input and aircraft response variables are monitored on-line with four six-channel chart recorders. The flight test director is in continuous communication with the aircraft and, on the advice of the engineers monitoring the flight variables, can (for example) request the repeat of a calibration record.

The equipment in the van also serves to process the flight data digitally "off-line" after a flight. All telemetered data during a flight are recorded continuously on the bit-stream recorder. For digital data analysis, the appropriate portions of the appropriate channels are selected from the bit-stream recorder, and the format changed to be compatible with the IBM 370/165 computer used for the analyses. This is accomplished through use of the van computer and equipment to produce the required digital tape which is then processed by the IBM 370/165 computer.

X-22A Ground Simulator

The fixed-base X-22A ground simulator (Figure VIII-17) is designed to supplement the X-22A aircraft operation in the following manner:

- Perform preliminary tests of experimental programs prior to flight tests in the actual aircraft.
- Develop new experimental hardware and systems, such as control systems and displays prior to installation in the actual aircraft.
- Ground test new equipment and check experimental setups in the aircraft prior to actual flight test.
- Provide pilot training as required.

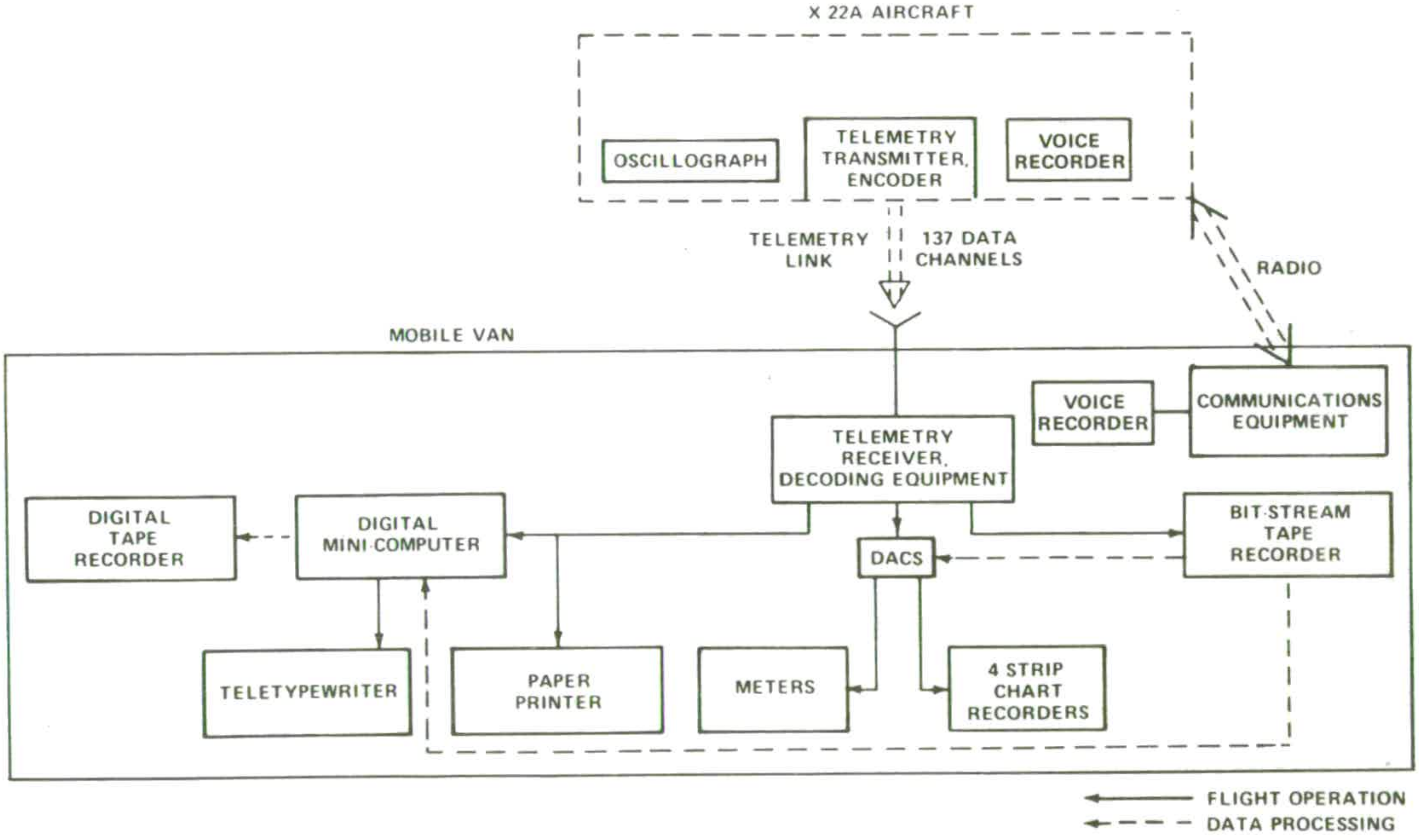


Figure VIII-16 SCHEMATIC DIAGRAM OF DIGITAL DATA ACQUISITION SYSTEM

Figure VIII-17 X-22A GROUND SIMULATOR

The ground simulator is composed of the following functional components:

- Digital computer - solves the computer model equations (housed in X-22A mobile van).
- Variable feel system - provides force-position characteristics for pilot's stick and rudder pedal controls.
- Variable stability system electronics - combines inputs from pilot's controls with feedback of computed responses to provide control inputs to computer model.
- Cockpit displays - flight instruments used by pilot to fly under instrument conditions (including CRT).
- Interface - patch boards, signal conversion, filtering, and scaling between simulator components.

The feel system, variable stability system electronics, and flight instruments duplicate those found in the X-22A aircraft; the analog symbol generator from the aircraft may also be readily moved to the simulator to provide the same CRT displays investigated in flight. All other elements associated with the aircraft including its airframe equations of motion, power plant characteristics, flight control system, and guidance system are simulated by the computer. As an option, the actual X-22A aircraft can be tied in with the simulator so that some of its components can be incorporated directly. For example, the complete flight control system can be employed with measured propeller blade and elevon signals used as inputs to the computer model for studying problems associated with the flight control system itself.

The X-22A ground simulator can also be used as a general aircraft instrument flight simulator. The use of a digital computer, with complete programming flexibility and tape storing of programs, greatly enhances the capability of the ground simulator for general simulation. Complex and nonlinear aerodynamic characteristics for either V/STOL or conventional aircraft can be readily incorporated, as can nonlinear control characteristics, or simple linearized equations of motion. Auxiliary systems, such as an ILS approach system or a sophisticated digital adaptive flight control system, can be readily included in the simulation.

AN/SPN-42T1 Radar System

For this experiment, the raw X,Y,Z position data were provided by an AN/SPN-42T1 tracking radar manufactured by the Bell Aerospace Company. The unit used was the prototype AN/SPN-42T1 Automatic Carrier Landing System (ACLS), and as such differed in some elements from the production systems used by the U.S. Navy (e.g. the computer was a UNIVAC 1218 instead of 1219, and the uplink modulator-demodulator was a USW2 instead of USW1); in general, however, the functional elements of the system corresponded to the description given in Reference 46 for land-based installations, with all the equipment housed in two mobile trailers.

Simplified greatly, the functional elements can be considered to be the tracking radar, a digital computer which operates on the radar measurements, and a telemetry uplink which transmits the results of these operations to the aircraft. For the X-22A application, the radar measurements are resolved into X,Y,Z components relative to one of five selectable course directions, with the origin of the axes being one of two selectable touchdown points. Four channels of information are telemetered to the aircraft: three of these are the X,Y,Z information, and the fourth contains commands for switching the resolution in the on-board complementary filters (see Section IV).

Two modes of operation are controlled by the UNIVAC computer: radar search and radar tracking. In the search mode, a computer-controlled search pattern is followed by the radar until the aircraft flies through a "capture window"; when the aircraft is within the window, "LOCK-ON" occurs, and the computer switches to the tracking mode. In the tracking mode, the resolution of the radar information and telemetry of the data to the aircraft occurs, which continues until "WAVE-OFF".

The overall characteristics of the AN/SPN-42T1 ACLS are summarized in Table VIII-3 below:

Table VIII-3

AN/SPN-42T1 CHARACTERISTICS

Frequency Band	33.0 - 33.4 GHz
Environment	Tested to MIL-E-16400
Coverage	
Minimum Range	150 feet (from SPN-42 position)
Maximum Range	To 8 nautical miles
Azimuth	$\pm$ 45 degrees
Elevation	$\mp$ 30 degrees
Auto Search	1^{o} Elevation by 25^{o} Azimuth x 1200 foot range
Search Rate	20 Scans per minute
Search Center	Adjustable Within Angular Coverage
Resolution	
Range	2 feet
Azimuth	0.022 degrees
Elevation	0.022 degrees

As set-up for this experiment, the location of the AN/SPN-42T1 was approximately 2200 feet from the primary touchdown point, and provided course directions of 220, 230, 255, 280, and 300 degrees.

Appendix IX

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Appendix X

GLOSSARY OF SYMBOLS AND ABBREVIATIONS

Symbol	
a_X, a_Y, a_Z	acceleration along body X, Y, Z axis, respectively (ft/sec^2)
a_{ij}, a_{ij}	design parameters for decoupled velocity control system (Section V)
c	number of columns
d	displayed position (cm)
F	equations-of-motion characteristic matrix (1/sec)
F_{ES}	pitch stick force gradient (lb/in.)
g	acceleration due to gravity (32.2 ft/sec^2)
G	equations-of-motion control matrix
G_2	partitioned control matrix (Section V)
h	altitude (ft)
HBAR	horizontal bar control director deflection (volts)
$I_{(\ )}$	moment of inertia about body ( )-axis (ft-lb/sec^2)
I_{XZ}	product of inertia in body axes (ft-lb/sec^2)
J	control gain matrix (Section V)
J_2	partitioned control gain matrix
K	{ linear gain { state feedback gain matrix (Section V)
$K_{(\ )}$	control director gain (volts/( ))
K_d	display position constant (cm)
K_L	non-dimensional inertia coupling in roll $\left(= \frac{I_Y - I_Z}{I_X}\right)$
K_N	non-dimensional inertia coupling in yaw $\left(= \frac{I_X - I_Y}{I_Z}\right)$
K_v	v-measurement calibration factor
K_α	α-measurement calibration factor
K_Γ	lateral guidance gain (deg/ft)
K_1, K_2	complementary filter gains (Section 4.2)
K_1, K_2, K_3	guidance gains (Section 4.3.3)
ℓ_{x_n}	length from aircraft center-of-gravity to α-vane (ft)
ℓ_{x_t}	length from aircraft center-of-gravity to tail LORAS (ft)
ℓ_{z_t}	height from aircraft center-of-gravity to tail LORAS (ft)
L	aerodynamic moment about body X-axis (ft-lb)

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Symbol

$L'_{(\ )}$	dimensional rolling moment derivative $= \frac{1}{I_X}\left(1 - I_{XZ}^2 / I_X I_Z\right)^{-1}\left[\frac{\partial L}{\partial (\ )} + \frac{I_{XZ}}{I_Z}\frac{\partial N}{\partial (\ )}\right] \left(\frac{\text{rad/sec}^2}{(\ )}\right)$
M	aerodynamic moment about body Y-axis (ft-lb)
$M_{(\ )}$	dimensional pitching moment derivative $= \frac{1}{I_Y}\frac{\partial M}{\partial (\ )}\left(\frac{\text{rad/sec}^2}{(\ )}\right)$
n_y, n_z	acceleration along body X and Y axes, respectively (g's)
N	aerodynamic moment about body Z-axis (ft-lb)
$N'_{(\ )}$	dimensional yawing moment derivative $= \frac{1}{I_Z}\left(1 - I_{XZ}^2 / I_X I_Z\right)^{-1}\left[\frac{\partial N}{\partial (\ )} + \frac{I_{XZ}}{I_X}\frac{\partial L}{\partial (\ )}\right] \left(\frac{\text{rad/sec}^2}{(\ )}\right)$
N_j^i	numerator of the i/j (s) transfer function
p	body axis roll rate (deg/sec, rad/sec)
P	steady-state augmented control gain matrix (Section V)
q	body axis pitch rate (deg/sec, rad/sec)
Q	optimal control state weighting matrix (Section V)
r	body axis yaw rate (deg/sec, rad/sec)
r	number of rows (Appendix VI)
R	optimal control weighting matrix (Section V)
$\dot{R}_a$	angular rate of line of sight (rad/sec)
s	Laplace operator $\sigma \pm j\omega$
s	sample standard deviation
t	time (sec)
T_1	control director numerator zero (sec)
u	velocity along body X-axis (ft/sec)
u_L	velocity along body X-axis measured by u-LORAS (ft/sec)
u_2	partitioned control vector (Section V)
v	velocity along body Y-axis (ft/sec)
v_L	velocity along body Y-axis measured by v-LORAS (ft/sec)
V	velocity (ft/sec, kt)
V_e	horizontal inertial velocity vector (ft/sec)
V_W	horizontal wind velocity vector (ft/sec)

Symbol	
$V_{W_{( )}}$	wind velocity component in ( ) direction (ft/sec)
$V_{X_a}, V_{Y_a}, V_{Z_a}$	earth-referenced velocity components with respect to the air mass (ft/sec)
VBAR	vertical bar control director deflection (volts)
VTAB	vertical tab control director deflection (volts)
w	velocity along body Z -axis (ft/sec)
X, Y, Z	generalized position coordinates (ft)
$X_{( )}, Y_{( )}, Z_{( )}$	dimensional longitudinal, lateral, and vertical force derivatives $= \frac{1}{M} \frac{\partial X, Y, \text{ or } Z}{\partial ( )} \left(\frac{\text{ft/sec}^2}{( )}\right)$
X	position (Section VI) (ft)
$\bar{X}$	sample mean
Y_{ijk}	generalized performance/workload measure
Z_Y	height of accelerometer package above aircraft center of gravity (ft)
α	angle of attack (deg,rad) level of significance (Section X)
β	angle of sideslip (deg,rad)
γ	flight path angle (deg)
γ_{ij}	additive interactive effect
Γ	course (deg)
$\delta_{( )}$	evaluation pilot's controller position as - lateral stick (in.), positive right rp - rudder pedal (in.), positive right es - longitudinal stick (in.), positive aft cs - collective stick (deg), positive up λ - duct angle (ON-OFF)
$\delta'_{( )}$	$\delta_{( )}$ including control crossfeeds (Figure 5-5a)
$\Delta( )$	perturbation term $( )-( )_o$, units of ( )
$\Delta(s)$	characteristic equation

Symbol	
$\Delta_{( )}$	safety pilot's controller position as - lateral stick (in.), positive right rp - rudder pedal (in.), positive right es - longitudinal stick (in.), positive aft cs - collective stick (deg), positive up
$\epsilon( )$	error term = $( )_c - ( )$, units of ( )
ϵ_{ijk}	additive random error in performance/workload model
ζ	damping ratio
ζ_θ	damping ratio of pitch attitude command prefilter
ζ_ϕ	damping ratio of numerator roots in ϕ/δ_{as} transfer function
ζ_d	damping ratio of Dutch roll characteristic roots
θ	pitch attitude (deg,rad)
θ_j	additive column effect in performance/workload model
K	display position constant (ft)
λ	X-22A duct angle measured from horizontal (deg)
μ	mean value
$\mu_{( )}$	mean value of ( ), units of ( )
σ	{standard deviation real portion of Laplace operator
$\sigma_{( )}$	standard deviation of ( ), units of ( )
σ_x, $\sigma_{\ddot{x}}$	radar and accelerometer noise standard deviations, respectively (ft and ft/sec^2, respectively)
τ	generalized time constant (sec)
τ_{ij}	additive row effect in performance/workload model
τ_R	roll mode time constant (sec)
τ_S	spiral mode time constant (sec)
ϕ	roll angle (deg, rad)
ψ	heading angle $\triangleq \psi_N - \psi_A$ (deg)
ψ_A	approach course heading with respect to North (deg)
ψ_N	aircraft heading with respect to North (deg)
ω	{generalized angular frequency imaginary portion of Laplace operator (rad/sec)

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Symbol

ω_n	undamped natural frequency (rad/sec)
ω_d	undamped natural frequency of Dutch roll mode (rad/sec)
ω_θ	undamped natural frequency of pitch attitude command prefilter (rad/sec)
ω_ϕ	undamped natural frequency of numerator roots in ϕ / δ_{as} transfer function (rad/sec)
ω_2	partitioned control vector (Section V)
$(\dot{\ })$	time rate of change of ( ), ( )/sec
$(\hat{\ })$	estimate of ( ), units of ( )
$(\ )^T$	transpose of matrix ( )
$(\ )_{AS}, (\ )_{BS}$	"after-switching" and "before switching" values of ( ) respectively, units of ( )
$(\ )_b$	aircraft body axis (Figure 4-2)
$(\ )_c$	commanded value of ( ), units of ( )
$(\ )_D$	design value of matrix ( ) (Section V)
$(\ )_e$	approach-course up (or "earth") axis (Figure 4-2)
$(\ )_F$	feedback signals for decoupled velocity control (Figure 5-5a)
$(\ )_h$	heading-up axis (Figure 4-2)
$(\ )_m$	measured value of ( ), units of ( )
$(\ )_{MAX}$	maximum value of quantity $\mu_{(\ )} \pm 2\sigma_{(\ )}$, units of ( )
$\|(\ )\|^2_Q$	$= (\ )^T Q (\ )$
$(\ )_{WO}$	washed-out value of ( ), units of ( )
$(\ )_o$	initial or trim value of ( ), units of ( )

Abbreviation

A/C	aircraft
ADI	attitude/director indicator
AGARD	Advisory Group for Aerospace Research and Development
AGL	above ground level
ANOVA	analysis of variance
A/S	airspeed
ATC	automatic turn coordination
CRT	cathode ray tube

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Abbreviation	
CTOL	conventional take-off and landing
CW	crosswind
DAC	digital-to-analog converter
dB	decibel
deg	degrees
DME	distance measuring equipment
ED	electronic display
F-( )	flight number ( )
FFCS	Feedforward Flight Control System
fpm	feet per minute
ft	feet
G/S	ground speed
GM	gain margin in decibels
H_a, H_0	alternate and null hypothesis, respectively
HH	heading hold
Hz	Hertz
IAS	indicated airspeed
ICL	Instrumentation and Control Laboratory
IFR	Instrument Flight Rules
ILS	Instrument Landing System
in	inches
ITED	Integrated Trajectory Error Display
ITVIC	Independent Thrust Vector Inclination Command
IVSI	Instantaneous Vertical Speed Indicator
JANAIR	Joint Army-Navy Aircraft Instrumentation Research
K	Thousands
KIAS	knots indicated airspeed
Kt	Knots
KW	Kilowatts
LORAS	Linear Omnidirectional Resolving Airspeed System

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Abbreviation	
MLS	Microwave Landing System
MS( )	mean square: E-error R-row C-column I-interaction
N/A	Not applicable
NI	no ITVIC
NASA	National Aeronautics and Space Administration
P	primary
PCM	pulse code modulation
PR	Cooper-Harper pilot rating
PI	performance index
PM	phase margin in degrees
rad	radian
RAE	Royal Aircraft Establishment
RMI	Remote Magnetic Indicator
RMS	root mean square
SAS	stability augmentation system
sec	second
SS ( )	sum of the squares: E-error R-row C-column I-interaction
STOL	short takeoff and landing
TAGS	Tactical Aircraft Guidance System
TER	turbulence effect rating
TIU	test input unit
VALT	VTOL Approach and Landing Technology
VBAR	vertical bar control director
VFR	Visual Flight Rules
VHF	Very High Frequency
VSS	variable stability system
V/STOL	vertical/short takeoff and landing
VTAB	vertical tab control director
VTOL	vertical takeoff and landing