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AVIONICS SYSTEMS DIVISION

INTERNAL NOTE 79-EH-05

INVESTIGATION OF HIGH FREQUENCY OSCILLATIONS
IN THE OV102 ELEVON ACTUATION SUBSYSTEMS USING
CONTINUOUS SYSTEM MODELING PROGRAM SIMULATION

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		12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lyndon B. Johnson Space Center Houston, Texas 77058	
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16. Abstract Undesired oscillations at frequencies between 40 and 60 Hz occurred in the Orbiter Vehicle inboard and outboard elevon actuation subsystems during hardware testing at the Rockwell/Space Division Flight Control Hydraulics Laboratory facility in July 1978. Two theories emerged as to the cause: the "hardover feedback" and "dead-space" theories. These were tested at the Lyndon B. Johnson Space Center using Continuous System Modeling Program Simulation. Results did not support the "hardover feedback" theory but showed that deadspace in the torque feedback spring connections to the servospools must be considered to be a possible cause of the oscillations. Further investigation is recommended.			
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1. SUMMARY

During recent testing of the hardware elevon actuation subsystems, undesired oscillations above 40 Hz were first observed at the Rockwell International/Space Division (R/SD) Flight Control Hydraulics Laboratory (FCHL). These oscillations occurred at different frequencies in both the inboard and the outboard elevon subsystems. They occurred only in the presence of an unby-passed channel failure and then only while force fighting was present in the secondary actuator stage.

Two possible causes, hardover feedback and deadspace, were investigated using Continuous System Modeling Program (CSMP) simulation. Tests of the hardover feedback theory were completely negative. No sustained oscillations above 40 Hz were observed. Tests of the deadspace theory produced data matching certain key characteristics of the hardware oscillations including inboard actuator oscillation frequency (55.5 Hz). The oscillations occurred only in the presence of force fighting and damped out at a position plateau. It was concluded that deadspace must be considered to be a possible cause of the oscillations. Modification of the actuator math model followed by further investigation of this theory is recommended.

2. INTRODUCTION

Undesired oscillations, occurring at 56 and 46 Hz in the inboard and outboard elevon actuation subsystems, respectively, with amplitudes sufficient to cause loud audible vibrations in the hydraulics were observed under certain conditions during hardware tests conducted at the R/SD FCHL. These were reported to the National Aeronautics and Space Administration/Lyndon B. Johnson Space Center (NASA/JSC) about 15 August 1978. Because the cause of the oscillations is unknown, their occurrence may prevent the elevon actuation subsystems from meeting the fail-safe requirement for second failures in the Space Shuttle Orbiter Vehicle (OV) 102.

Two theories emerged as to the oscillations' cause: the hardover feedback and the deadspace theories. The hardover feedback theory asserted that the oscillations were caused by a flow-dependent positive pressure feedback force acting on the power valve spool, presumably through a hardover channel. The deadspace theory asserted that the oscillations were caused by deadspace existing in the couplings between the second-stage valve spools and their associated torque feedback springs.

These two theories were investigated using Continuous System Modeling Program (CSMP) simulation. Attempts were made to duplicate certain FCHL test data by discovering which particular combination of added nonlinearities best reproduced the FCHL data. Any such combination, while not definitely the cause of these oscillations, would be at least a possible cause.

2.1 ACTUATOR BACKGROUND

The elevon actuators for the OV102 are four-channel hydraulic actuators having redundancy concentrated in a secondary actuator stage which acts to position a single power valve spool in proportion to the command current inputs. Redundancy is achieved through force summing at the power spool. The power ram or primary actuator stage is nonredundant. The inboard and outboard actuators are functionally identical and differ only in the size of certain

components. A simplified hydraulic schematic diagram typical of either actuator is shown in figure 2-1.

The CSMP simulation used in making this investigation was derived from a math model of these actuators that was developed by R/SD. This math model is shown in figure 2-2. Identified variables, constants, and nonlinearities are listed in tables 2-1 through 2-4. A CSMP listing typical of those used in making this investigation is shown in figure 2-3.

2.2 OSCILLATION BACKGROUND

About 15 August 1978, NASA/JSC was advised by R/SD of undesired oscillations occurring in the hardware elevon actuation subsystems that were then being tested at the R/SD FCHL facility. These oscillations at 56 and 46 Hz in the inboard and outboard subsystems, respectively, reportedly occurred only in the presence of an unbypassed channel failure.

Copies of some of the FCHL test data were received at NASA/JSC before 1 September 1978. Examination of this data, which consisted of analog strip charts, confirmed the presence of the previously reported high-frequency oscillations (above 40 Hz) and showed that other oscillations also were occurring near 14 Hz. These lower-frequency oscillations had been previously investigated extensively at Honeywell, Inc., and at NASA/JSC and were believed to be too small in amplitude to cause operational problems. Conversely, the high-frequency oscillations were new and were severe enough to cause loud audible vibrations in the hydraulics.

A copy of the master chart received from FCHL is shown in figure 2-4. This chart indicates scale factors applicable to the two strip charts that were selected for special study in this investigation (see figs. 2-5 and 2-6). For practical reasons related to computer run times, figure 2-6 (FCHL test no. E-16) was singled out as being more desirable for study using CSMP simulation.

TABLE 2-1. - ELEVON MODEL VARIABLES

Parameter	Description	Units
V_c	Actuator position command signal	volts
V_f	Actuator position feedback signal	volts
V_p	Primary pressure feedback signal	mA
I	ASA driver current	mA
T_c	Servo valve (torque motor) torque	in-lb
T_p	Power spool wire-feedback torque	in-lb
T_s	Second stage wire-feedback torque	in-lb
θ_f	Servo valve flapper displacement	radians
Q_f	Servo valve first stage differential flow rate	cis
X_s	Second stage spool displacement	in
X_{qp}	Commanded second stage spool displacement (ideal)	in
P_1	Secondary differential pressure (typical)	psi
F_1	Secondary summing force corresponding to P_1	lbs
X_D	Power spool displacement	in
X_{pd}	Power spool displacement beyond overlap	in
Q_ℓ	Load flow rate	cis
X_{qr}	Commanded ram displacement (ideal)	in
F_p	Differential force across ram piston	lbs
P_ℓ	Load pressure (equivalent to F_p)	psi
T_a	Actuator torque applied to elevon	in-lbs
δ_e	Elevon angular displacement	radians
X_{fb}	Linear ram motion (piston with respect to cylinder)	in

TABLE 2-2. - ELEVON MODEL CONSTANTS

Constant	Description	Value		Units
		Inboard	Outboard	
A_p	Power spool amplification area	0.3927	-	in ²
A_r	Power ram piston area	21.82	18.04	in ²
A_s	Servo valve (second stage) amplification area	0.0368	-	in ²
B_p	Elevon viscous friction (mechanical)	45000	15000	in-lb-sec
B_p	Power spool viscous friction	6.5	-	(lb-sec)/in
I_e	Elevon moment of inertia (about hinge line)	7588	1876	in-lbs-sec ²
K_a	Servo amplifier position gain	16.5	19.5	mA/V
K_{act}	Elevon actuator stiffness	457000	621000	lb/in
K_b	Power spool flow force coefficient	0.943	0.355	in
K_c	Dynamic load damping gain coefficient	1.4	2.4	mA/V
K_e	Servo valve net stiffness	58	-	(in-lb)/rad
K_{fb}	Actuator position transducer sensitivity	0.683	1.173	V/in
K_p	Servo valve pressure gain	17544	-	psi/(in-lb)
K_{pt}	Primary and secondary pressure transducer sensitivities	0.00167	-	V/psi
K_{qp}	Power spool flow gain	162.1	61.0	in ³ /(sec-√lb)
K_{qs}	Servo valve (second stage) flow gain	652	-	cfs/in
K_s	Local (backup) structure stiffness external to actuator	233000*	170000*	lb/in
K_m	Servo valve torque motor gain	0.0285	-	(in/lb)/mA
K_{xp}	Wire feedback stiffness (power spool-to-flapper)	4.464	-	(in-lb)/in
K_{xs}	Wire feedback stiffness (second stage spool-to-flapper)	26.6	-	(in-lb)/in
K_{ii}	Servo valve first stage differential flow gain	45.3	-	cfs/rad
M_s	Power spool mass	0.001	-	(lb-sec ²)/in
P_s	Hydraulic supply pressure to actuator interface (supply minus return)	2800	-	psi
R	Average actuator moment arm [see table 2-4 for $R(\psi_p)$]	14.46	8.42	in
R_f	Actuator pressure drop coefficient	0.0212	0.0397	psi/(cfs) ²
S	Laplace transform operator	-	-	sec ⁻¹
V_s	Load volume to second stage orifice (one side)	0.08	-	in ³
β	Hydraulic fluid bulk modulus	172000	-	psi
ζ_d	Demodulator filter damping factor	0.707	-	none
ζ_f	IPS filter damping factor	0.707	-	none
ζ_{dp}	Demodulator filter damping factor	0.707	-	none
T_a	ASA time constant	0.00187	-	sec
T_c	Dynamic load damper time constant	0.10	-	sec
ω_d	Demodulator filter break frequency (position feedback)	314	-	rad/sec
ω_f	IPS filter break frequency	36	-	rad/sec
ω_{dp}	Demodulator filter break frequency (primary pressure transducer)	628	-	rad/sec

* ± 25 percent tolerance.

TABLE 2-3.-- ELEVON MODEL NONLINEARITIES (NL)

NL	Description	Value	Tolerance	Units
A	Servoamplifier current limiter	8.5		mA
B	Torque motor hysteresis characteristic (full band)	$0.03 I + b^*$		mA
C	Torque motor flapper angular limit	0.00353		radians
D	Second stage spool stroke limit	0.015		in
E	Power spool stiction force	10.0		lbs
F	Power spool stroke limit (inboard/outboard)	0.05/0.0507		in
G	Pressure transducer hysteresis characteristic (full band)	100.0		psi
H	Actuator ram stiction (inboard/outboard)	3750/2200		in-lbs
J	Elevon hinge and seal stiction force	6000	±3000	in-lbs
K	Effective power spool overlap	0.0004		in

*b = 0.015 mA (typical)
 = 0.075 mA (worst case)

TABLE 2-4.— EFFECTIVE ACTUATOR MOMENT ARM $R(\delta_E)$

Elevon position (deg)	Inboard actuator		Outboard actuator	
	Effective arm length (in)	Stroke (in)	Effective arm length (in)	Stroke (in)
-36.5	13.160	-7.320	7.767	-4.266
-35	13.377	-6.973	7.884	-4.061
-30	14.002	-5.777	8.223	-3.358
-25	14.480	-4.533	8.481	-2.628
-20	14.816	-3.254	8.661	-1.880
-15	15.020	-1.951	8.766	-1.119
-10	15.098	-0.636	8.800	-0.352
-7.709	—	—	8.793	0
-7.585	15.094	0	—	—
-5	15.061	+0.680	8.767	+0.415
0	14.915	+1.989	8.671	+1.176
+5	14.669	+3.280	8.517	+1.927
+10	14.331	+4.547	8.307	+2.661
+15	13.908	+5.779	8.047	+3.375
+20	13.407	+6.972	7.740	+4.064
+21.5	13.242	+7.320	7.639	+4.266

-Arm retraction

-Arm extension

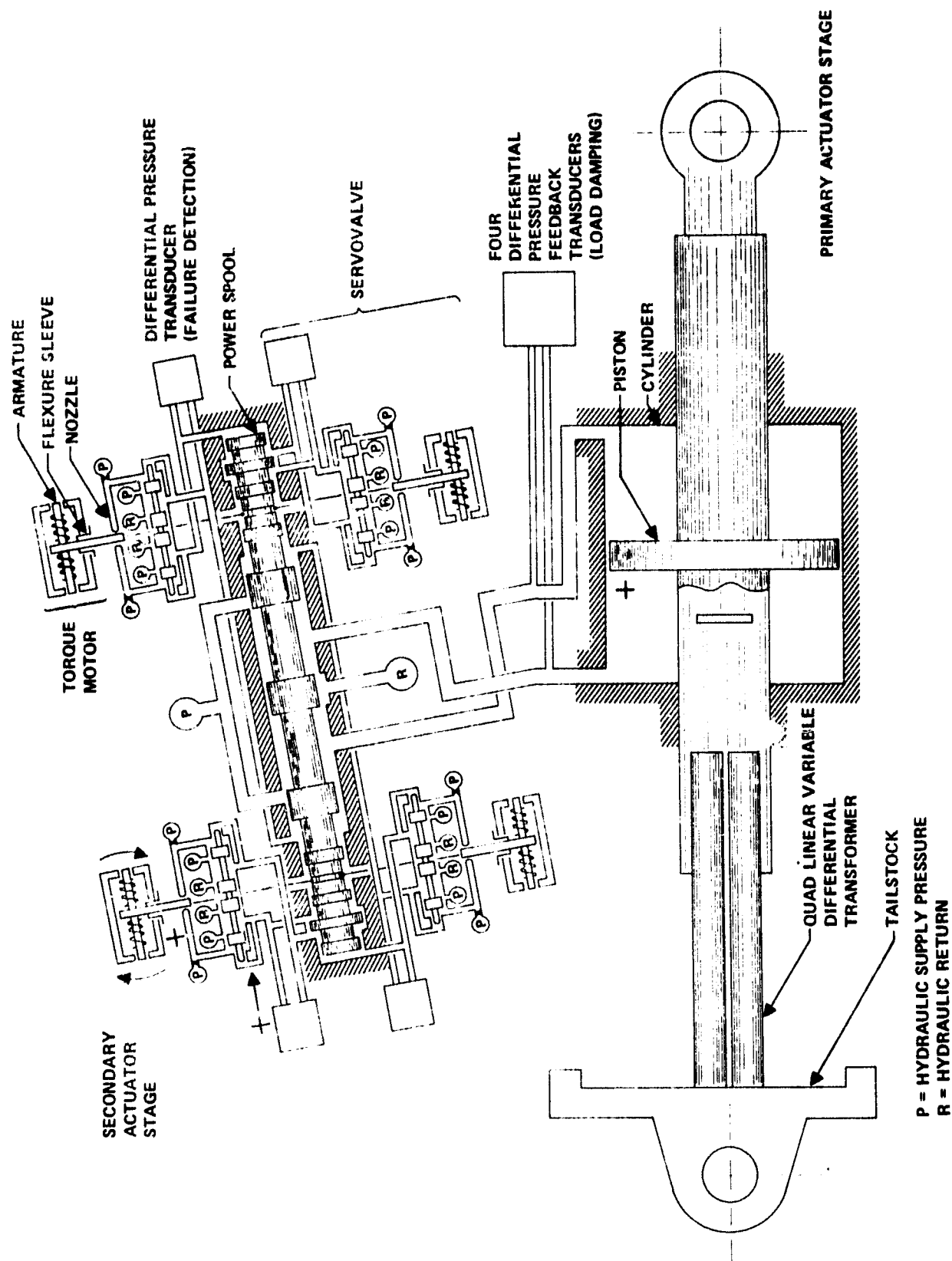


Figure 2-1.— Simplified hydraulic schematic of inboard or outboard actuator.

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR


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$$$CONTINUOUS SYSTEM MODELING PROGRAM III   VM2   TRANSLATOR OUTPUT$$$
TITLE  625-30 400G INBOARD ELEVON ACTUATOR FOR SSV-0V102
*      FULL-UP HOKE MODEL WITH ASA-1
TITLE  STABILITY TEST
TITLE  15 NOVEMBER 1978
*
*      SYSTEM MACROS
*
*      LTDINT IS A LOW-LEVEL-LIMITED INTEGRATOR
*
MACRO  T = LTDINT (DT)
PROCEDURE DR = SMALL (DT)
      DR = DT
      IF (ABS(DT).LT.1.0E-50) DR = 0.0
ENDPROCEDURE
      T = INTGRL (0.0, DR)
ENDMACRO
*
*      LIMLAG IS A LIMITED LAG FUNCTION (P IS INPUT)
*
MACRO  V = LIMLAG (P, TC)
*
      DVA = (P-V)/TC
*
      PROCEDURE DV = SMALL (DVA)
      DV = DVA
      IF (ABS(DVA).LT.1.0E-50) DV = 0.0
      ENDPROCEDURE
*
      V = INTGRL (0.0, DV)
*
ENDMACRO
*
*      FILTER IS A UNITY-GAIN SECOND-ORDER LOW-PASS FILTER (W IS INPUT)
*
MACRO  X = FILTER (W, A, B, IC)
*
      DDXA = B * (W - X) - A * DX
*
      PROCEDURE DDX = SMALLA (DDXA)
      DDX = DDXA
      IF (ABS(DDXA).LT.1.0E-50) DDX = 0.0
      ENDPROCEDURE
*
      DXA = INTGRL (0.0, DDX)
*
      PROCEDURE DX = SMALLB (DXA)
      DX = DXA
      IF (ABS(DXA).LT.1.0E-50) DX = 0.0
      ENDPROCEDURE
*
      X = INTGRL (IC, DX)
*
ENDMACRO
*
*      LIM1 IS A LIMITED FIRST ORDER SYSTEM
*
MACRO  Y = LIM1 (YDOT, P1, P2)
PROCEDURE DYDT = LINA (Y, YDOT, P1, P2)

```

Figure 2-3.-- Typical CSMP listing.

```

          DYDT = YDOT
          IF (Y.LE.P1) DYDT = AMAX1 (0.0, YDOT)
          IF (Y.GE.P2) DYDT = AMIN1 (0.0, YDOT)
ENDPROCEDURE
      Y = INTGRL (0.0, DYDT)
ENDMACRO
*
* LIM2 IS A LIMITED SECOND ORDER SYSTEM
*
MACRO 7, ZDOT = LIM2 (ZDDOT, P3, P4)
PROCEDURE ZDDOT1, ZDOT1 = LIMB (7, ZDOT, ZDDOT, P3, P4)
      IF (Z.LE.P3) GO TO 330
      IF (Z.GE.P4) GO TO 331
      ZDDOT1 = ZDDOT
      ZDOT1 = ZDOT
      GO TO 332
330  ZDDOT1 = AMAX1 (0.0, ZDDOT)
      ZDOT1 = AMAX1 (0.0, ZDOT)
      GO TO 332
331  ZDDOT1 = AMIN1 (0.0, ZDDOT)
      ZDOT1 = AMIN1 (0.0, ZDOT)
332  CONTINUE
ENDPROCEDURE
      ZDOT = INTGRL (0.0, ZDDOT1)
      Z = INTGRL (0.0, ZDOT1)
ENDMACRO
*
* PFAIL DISCRETES
*
* DISCRETE SIGNALS PFAIL1 THROUGH PFAIL4 CONTROL PRESSURE FAILURE
* CONDITIONS IN CHANNELS 1 THROUGH 4 RESPECTIVELY.....
* SET PFAILN = -1 FOR NEGATIVE HARDOVER
*              0 FOR NO FAILURE
*              +1 FOR POSITIVE HARDOVER
*              +2 FOR BYPASSED CHANNEL.
*
* RESET DISCRETES
*
* DISCRETE SIGNALS RESE11 THROUGH RESE14 CONTROL RESET CONDITIONS
* IN ASA CHANNELS 1 THROUGH 4 RESPECTIVELY.....
* SET RESE1N = -1 FOR NORMAL OPERATION.
* SET RESE1N = +1 TO FORCE PFAILN = 0 (UNLESS BYPASN = +1).
*
* BYPAS DISCRETES
*
* DISCRETE SIGNALS BYPAS1 THROUGH BYPAS4 CONTROL OVERRIDING BYPASS
* CONDITIONS IN CHANNELS 1 THROUGH 4 RESPECTIVELY.....
* SET BYPASN = -1 FOR NORMAL OPERATION.
* SET BYPASN = +1 TO FORCE PFAILN = +2.
*
*
INITIAL
*****
↓
* SIMPLIFIED ASA MODEL ASA-1
*
*****

```

Figure 2-3.— Continued.

```

****
CONSTANTS ARE FOR THE INBOARD ACTUATOR SYSTEM
****
CONST DB1=2.148, DB2=2.148, DB3=2.148, DB4=2.148
CONST DET1=3.781, DET2=3.781, DET3=3.781, DET4=3.781
CONST DNREF1=1.7, DNREF2=1.7, DNREF3=1.7, DNREF4=1.7
CONST HA1=50.0, HA2=50.0, HA3=50.0, HA4=50.0
CONST HB1=50.0, HB2=50.0, HB3=50.0, HB4=50.0
CONST INTLM1=0.926, INTLM2=0.926, INTLM3=0.926, INTLM4=0.926
CONST KAA1=0.683, KAA2=0.683, KAA3=0.683, KAA4=0.683
CONST KAD1=1.432E-5, KAD2=1.432E-5, KAD3=1.432E-5, KAD4=1.432E-5
CONST KAE1=1.718E-3, KAE2=1.718E-3, KAE3=1.718E-3, KAE4=1.718E-3
CONST KAF1=0.4883, KAF2=0.4883, KAF3=0.4883, KAF4=0.4883
CONST KAG1=8.53, KAG2=8.53, KAG3=8.53, KAG4=8.53
CONST KAH1=0.0326, KAH2=0.0326, KAH3=0.0326, KAH4=0.0326
CONST KAJ1=1.0, KAJ2=1.0, KAJ3=1.0, KAJ4=1.0
CONST KAM1=16.5, KAM2=16.5, KAM3=16.5, KAM4=16.5
CONST KAN1=10.0, KAN2=10.0, KAN3=10.0, KAN4=10.0
CONST KAP1=0.393, KAP2=0.393, KAP3=0.393, KAP4=0.393
CONST LA1=8.523, LA2=8.523, LA3=8.523, LA4=8.523
CONST LIMN1=-0.6, LIMN2=-0.6, LIMN3=-0.6, LIMN4=-0.6
CONST LIMP1=15.0, LIMP2=15.0, LIMP3=15.0, LIMP4=15.0
CONST THP1=7.56, THP2=7.56, THP3=7.56, THP4=7.56
CONST TAI=0.004, TA2=0.004, TA3=0.004, TA4=0.004
CONST TB1=0.1, TB2=0.1, TB3=0.1, TB4=0.1
CONST UPREF1=8.5, UPREF2=8.5, UPREF3=8.5, UPREF4=8.5
*
CONST RESET1=-1., RESET2=-1., RESET3=-1., RESET4=+1.
*
**** NOTE RESET4 NOT EQUAL TO -1. FOR TEST ****
*
CONST BYPAS1=-1., BYPAS2=-1., BYPAS3=-1., BYPAS4=-1.
*
* * * * *
KAB1 = 2.0 * (0.707) * (314.0)
KAF2 = 2.0 * (0.707) * (314.0)
KAB3 = 2.0 * (0.707) * (314.0)
KAB4 = 2.0 * (0.707) * (314.0)
KAC1 = (314.0) ** 2
KAC2 = (314.0) ** 2
KAC3 = (314.0) ** 2
KAC4 = (314.0) ** 2
KAK1 = 2.0 * (0.707) * (36.0)
KAK2 = 2.0 * (0.707) * (36.0)
KAK3 = 2.0 * (0.707) * (36.0)
KAK4 = 2.0 * (0.707) * (36.0)
KAL1 = (36.0) ** 2
KAL2 = (36.0) ** 2
KAL3 = (36.0) ** 2
KAL4 = (36.0) ** 2
KAR1 = 2.0 * (0.707) * (628.0)
KAR2 = 2.0 * (0.707) * (628.0)
KAR3 = 2.0 * (0.707) * (628.0)
KAR4 = 2.0 * (0.707) * (628.0)
KAT1 = (628.0) ** 2
KAT2 = (628.0) ** 2
KAT3 = (628.0) ** 2

```

Figure 2-3.— Continued.

```

KAT4 = (628.0) ** 2
KAV1 = 2.0 * (0.707) * (615.0)
KAV2 = 2.0 * (0.707) * (615.0)
KAV3 = 2.0 * (0.707) * (615.0)
KAV4 = 2.0 * (0.707) * (615.0)
KAW1 = (615.0) ** 2
KAW2 = (615.0) ** 2
KAW3 = (615.0) ** 2
KAW4 = (615.0) ** 2
*
* * * * *
*
VZERO = KFA * XLZERO
VZERO1 = KAA1 * XLZERO
VZERO2 = KAA2 * XLZERO
VZERO3 = KAA3 * XLZERO
VZERO4 = KAA4 * XLZERO
*
CONST DELTIM = 12.0
CONST DDSP = 0.002, DDSPA = 0.001
PARAMETER KK = (-1.0, +1.0)
*
*****
*
* FULL-UP HOKE MODEL OF MOOG ELEVON ACTUATOR *
*
*****
*
*****
CONSTANTS AND FUNCTIONS ARE FOR THE INBOARD ACTUATOR SYSTEM *****
*
CONST AP1=3.927E-1, AP2=3.927E-1, AP3=3.927E-1, AP4=3.927E-1
CONST AS1=3.68E-2, AS2=3.68E-2, AS3=3.68E-2, AS4=3.68E-2
CONST BETA1=1.72E5, BETA2=1.72E5, BETA3=1.72E5, BETA4=1.72E5
CONST KE1=58.0, KE2=58.0, KE3=58.0, KE4=58.0
CONST KP1=17544.0, KP2=17544.0, KP3=17544.0, KP4=17544.0
CONST KQS1=652.0, KQS2=652.0, KQS3=652.0, KQS4=652.0
CONST KHTA1=45.3, KHTA2=45.3, KHTA3=45.3, KHTA4=45.3
CONST KTM1=2.85E-2, KTM2=2.85E-2, KTM3=2.85E-2, KTM4=2.85E-2
CONST KXP1=4.464, KXP2=4.464, KXP3=4.464, KXP4=4.464
CONST KXS1=26.6, KXS2=26.6, KXS3=26.6, KXS4=26.6
CONST THLIM1=3.53E-3, THLIM2=3.53E-3, THLIM3=3.53E-3, THLIM4=3.53E-3
CONST VSI=0.08, VSP=0.08, VSI3=0.08, VSI4=0.08
CONST XSLIM1=0.015, XSLIM2=0.015, XSLIM3=0.015, XSLIM4=0.015
*
CONST AP=21.82, NF=4.5E4, BP=6.5, CCUL=10.0
CONST ELSTK=6000.0, IR=7588.0, KACT=4.57E5, MP=0.943
CONST KOP=162.1, KRAD=57.3, KS=2.33E5, MP=0.001
CONST OVIAP=0.0004, RAMSTK=3750.0, RF=0.0212, STIK=25.0
CONST PS=2000.0,
CONST XPLIM=0.05
*
CONST DXPL=0.0, TAERO=0.0, KFB=0.683, XLZERO=1.989
*
Rev 3 -> CONST AX=0.01629, BX=0.33, KX=3701.0, MX=1.5E-5
*
FUNCTION MOMARM = (-36.5,13.160), (-35.0,13.377), (-30.0,14.002), ...
(-25.0,14.480), (-20.0,14.816), (-15.0,15.020), (-10.0,15.098), ...

```

Figure 2-3.— Continued.

```

(-7.585,15.094), (-5.00,15.061), ( 0.00,14.915), ( 5.00,14.659), ...
( 10.0,14.331), ( 15.0,13.908), ( 20.0,13.407), ( 21.5,13.242) ...
*
*
*
FUNCTION STROKE = (-36.5,-7.320), (-35.0,-6.973), (-30.0,-5.777), ...
(-25.0,-4.533), (-20.0,-3.254), (-15.0,-1.951), (-10.0,-0.636), ...
(-7.585, 0.000), (-5.00, 0.690), ( 0.00, 1.989), ( 5.00, 3.230), ...
( 10.0, 4.547), ( 15.0, 5.779), ( 20.0, 5.972), ( 21.5, 7.320)
*
*
DYNAMIC
*
NOSORT
VAN1 = LIMIT (-INLM1, INLM1, VAN1)
VAN2 = LIMIT (-INLM2, INLM2, VAN2)
VAN3 = LIMIT (-INLM3, INLM3, VAN3)
VAN4 = LIMIT (-INLM4, INLM4, VAN4)
VAT1 = LIMIT (LIM1, LIM1, VAT1)
VAT2 = LIMIT (LIM2, LIM2, VAT2)
VAT3 = LIMIT (LIM3, LIM3, VAT3)
VAT4 = LIMIT (LIM4, LIM4, VAT4)
XS1 = LIMIT (-XSLIM1, XSLIM1, XS1)
XS2 = LIMIT (-XSLIM2, XSLIM2, XS2)
XS3 = LIMIT (-XSLIM3, XSLIM3, XS3)
XS4 = LIMIT (-XSLIM4, XSLIM4, XS4)
XP = LIMIT (-XPLIM, XPLIM, XP)
CELED = LIMIT (-36.5, 21.5, CELED)
*
SORT
*
*
*
***** COMMAND GENERATION *****
*
*   ASA COMMANDS ARE RATE LIMITED TO 20 DEGREES/SECOND
**** DELE IN IS AMPLITUDE OF COMMAND SIGNAL IN DEGREES ****
*
PROCEDURE BLIP = KICK (TIME)
  BLIP = -2.0
  IF (TIME.LT.0.2.OR.TIME.GT.0.25) BLIP = 0.0
ENDPROCEDURE
*
  CMDA = DELE IN * RAMP (0.01)
  CMDB = LIMIT (-8.0, 8.0, CMDA)
  CMDELE = CMDB * BLIP
  VCMDA = AFGEN (STROKE, CMDELE)
  VCMD = KFB * VCMDA
*
*
***** ASA CHANNELS 1-3 *****
*
  VCMD1 = VCMD
  VAK1A = KAJ1 * VCMD1
  VAW1 = FILTER (VAK1A, KAK1, KAL1, VZERC1)
  VAA1 = REALPL (XUZERC, TAL, KFB)
  VAB1A = KAA1 * VAA1
  VAB1 = FILTER (VAB1A, KAB1, KAC1, VZERC1)
  VAC1 = HSTRSS (O.G, -HAL, HAL, PL)

```

Figure 2-3.— Continued.

```

VADI = REALPL (0.0, TAI, VACI)
VAEIA = KADI * VADI
VAFI = FILTER (VAEIA, KARI, KATI, 0.0)
VAFIA = REALPL (0.0, TBI, VAEI)
VAFI = DERIV (0.0, VAFIA)
PSI = PI
VAGI = HSTPSS (0.0, -HBI, HBI, PSI)
VAHI = LIMLAG (VAGI, TAI)
VAJIA = KAEI * VAHI
VAJI = FILTER (VAJIA, KAVI, KAWI, 0.0)
VAKI = DEADSP (-DBI, DBI, VAJI)
VALI = KAFI * VAKI
VAMI = VALI - KAH1 * VANI
DVANI = KACI * VAMI
VANI = LIM1 (DVANI, -INTLMI, INTLMI)
VAPI = KAPI * VANI
VAXI = KAMI * (VANI - VARI - VAFI - VAPI)
II = LIMIT (-LAI, LAI, VAXI)
***** FAILURE MONITOR SECTION ... ASA CHANNEL I *****
*
* PROCEDURE VARI = CNTRL1 (VAJI, DETI, UPREFI, DNREFI)
  VARI = -DNREFI
  IF (ABS(VAJI).GE.DETI) VARI = UPREFI - DNREFI
* ENDPROCEDURE
*
* PROCEDURE DVATI = AAAA1 (VARI, RESETI, KANI)
  IF (RESETI.GT.0.0) GO TO 1111
  DVATI = KANI * VARI
  GO TO 1112
  1111 VATI = 0.0
  DVATI = 0.0
  1112 CONTINUE
* ENDPROCEDURE
*
  VATI = LIM1 (DVATI, LIMNI, LIMPI)
*
* PROCEDURE VAVI, PFAILI = BBBB1 (VATI, THRI, RESETI, BYPASI, TIME)
  VAVI = -1.
  IF (VATI.GE.THRI) VAVI = +1.
  IF (BYPASI.GT.0.0) GO TO 1114
  IF (TIME.EQ.0.0.CK.RESETI.GT.0.0) GO TO 1113
  IF (VAVI.GT.0.0.CK.PFAILI.GT.1.5) GO TO 1114
  1113 PFAILI = 0.
  GO TO 1115
  1114 PFAILI = +2.
  1115 CONTINUE
* ENDPROCEDURE
*
* .....THE FOLLOWING VARIABLES SHOW CHANGES FROM INITIAL CONDITIONS.....
*
  VCMDMI = VCMDI - VZERCI
  VAWMI = VAWI - VZEROI
  VAAWI = VAAI - XZERCI
  VABMI = VABI - VZEROI
*
  ERRORI = VAWI - VABI
*

```

Figure 2-3.— Continued.

```

***** ASA CHANNEL 4 *****
*
PROCEDURE VCMD4 = SEL4 (KK, VCMD, VZERC)
  VCMD4 = VCMD
  IF (KK.GT.0.0) VCMD4 = VZERC
ENDPROCEDURE
  VAW4A = KAJ4 * VCMD4
  VAW4 = FILTER (VAW4A, KAK4, KAL4, VZERC4)
  VAA4 = REALPL (XLZERL, TA4, XFB)
  VAB4A = KAA4 * VAA4
  VAB4 = FILTER (VAB4A, KAB4, KAC4, VZERC4)
  VAC4 = HSTPSS (0.0, -HA4, HA4, PL)
  VAD4 = REALPL (0.0, TA4, VAC4)
  VAF4A = KAD4 * VAD4
  VAF4 = FILTER (VAF4A, KAR4, KAT4, 0.0)

  VAF4A = REALPL (0.0, TB4, VAF4)
  VAF4 = DERIV (0.0, VAF4A)
  PS4 = P4
  VAG4 = HSTPSS (0.0, -HB4, HB4, PS4)
  VAH4 = LIMLAG (VAG4, TA4)
  VAJ4A = KAE4 * VAH4
  VAJ4 = FILTER (VAJ4A, KAV4, KAW4, 0.0)
  VAK4 = DEADSP (-DB4, DB4, VAJ4)
  VAL4 = KAF4 * VAK4
  VAM4 = VAL4 - KAH4 * VAN4
  DVAN4 = KAS4 * VAM4
  VAN4 = LIM1 (DVAN4, -INTLM4, INTLM4)
  VAP4 = KAP4 * VAN4
  VAX4 = KAM4 * (VAH4 - VAB4 - VAF4 - VAP4)
  L4 = LIMIT (-LA4, LA4, VAX4)
*
***** FAILURE MONITOR SECTION ... ASA CHANNEL 4 *****
*
PROCEDURE VAR4 = CNTRL4 (VAJ4, DET4, UPREF4, DNREF4)
  VAR4 = -DNREF4
  IF (ABS(VAJ4).GE.DET4) VAR4 = UPREF4 - DNREF4
ENDPROCEDURE
*
PROCEDURE DVAT4 = AAAA4 (VAR4, RESET4, KAN4)
  IF (RESET4.GT.0.0) GO TO 4441
  DVAT4 = KAN4 * VAR4
  GO TO 4442
  4441 DVAT4 = 0.0
  DVAT4 = 0.0
  4442 CONTINUE
ENDPROCEDURE
*
  VAT4 = LIM1 (DVAT4, LIMN4, LIMP4)
*
PROCEDURE VAV4, PFAIL4 = BBBB4 (VAT4, THR4, RESET4, EYPAS4, TIME)
  VAV4 = -1.
  IF (VAT4.GE.THR4) VAV4 = +1.
  IF (EYPAS4.GT.0.0) GO TO 4444
  IF (TIME.F0.0.0.CR.RESET4.GT.0.0) GO TO 4443
  IF (VAV4.GT.0.0.CR.PFAIL4.GT.1.5) GO TO 4444
  4443 PFAIL4 = 0.
  GO TO 4445
  4444 PFAIL4 = +2.

```

Figure 2-3.— Continued.


```

4445 CONTINUE
ENCPROCEDURE
*
*
* .....THE FOLLOWING VARIABLES SHOW CHANGES FROM INITIAL CONDITIONS.....
*
VCM4 = VCM4 - VZERO4
VAV4 = VAV4 - VZERO4
VAA4 = VAA4 - XLZERO
VAB4 = VAB4 - VZERO4
*
ERROR4 = VAV4 - VAB4
*
* * * * *
*
VCM4 = VCM4 - VZERO
XFB4 = XFB4 - XLZERO
XLM4 = XLM4 - XLZERO
XQM4 = XQM4 - XLZERO
*
***** ACTUATOR CHANNELS 1-3 *****
*
IL1 = I1
IH1 = 0.0075 + 0.015 * ABS (I1)
IHYS1 = HSTRSS (C.O, -IH1, IH1, I1)
THFA1 = (KTM1 * IHYS1 - KXP1 * PSD - KXS1 * XSD1 - PI / KPI) / KE1
THFA1 = LIM1 (-THLIM1, THLIM1, THFA1)
QF1 = KTHA1 * THFA1
DXX1 = QF1 / ASI
FXC1A = AX * (DXX1 - DXS1)
FXC1 = LTDINT (FXC1A)
DDXS1 = (FXC1 - AX * PI - BX * DXS1) / MX
DXS1 = LTDINT (DDXS1)
XS1 = LIM1 (DXS1, -XSLIM1, XSLIM1)
XSD1 = DDSP (-DDSP, DDSP, XS1)
XQPIA = XS1 * KQSI / API
XQPIB = XQPIA * SQRT (ABS (PVS1 / PSD)) * SIGN (1.0, PVS1)
PVS1 = PSD - PI * SIGN (1.0, XS1)
XQPI = INTGR (J.O, XQPIB)
PIA = (XQPI - XP) * 2.0 * BETAL * API / VSI
PROCEDURE P1 = AAL (PFAIL1, PSD, PIA)
IF (PFAIL1) 12, 14, 16
12 P1 = -PSD
GO TO 19
14 P1 = LIMIT (-PSD, PSD, PIA)
GO TO 19
16 P1 = PSD
IF (PFAIL1.GE.1.5) P1 = 0.0
19 CONTINUE
ENCPROCEDURE
P1 = P1 * API
*
*
***** ACTUATOR CHANNEL 4 *****
*
IL4 = I4
IH4 = 0.0075 + 0.015 * ABS (I4)
IHYS4 = HSTRSS (C.O, -IH4, IH4, I4)

```

Figure 2-3.— Continued.

```

THFA4 = (KTM4*IHYS4 - KXP4*XPDSP - KXS4*XSD4 - P4/KP4) / KE4
THTA4 = LIMIT (-THLIM4, THLIM4, THFA4)
CF4 = KTHTA4 * THTA4
DXX4 = QF4/AS4
FXC4A = KX * (DXX4 - DXS4)
FXC4 = LIMIT (FXC4A)
DDXS4 = (FXC4 - AX*P4 - BX*DXS4) / MX
DXS4 = LIMIT (DDXS4)
XS4 = LIMIT (DXS4, -XSLIM4, XSLIM4)
XSD4 = DEADSP (-DVLAP, DDSP, XS4)
XQP4A = XS4 * QS4 / AP4
XQP4B = XQP4A * SQRT (ABS (PVS4/PSD)) * SIGN (1.0, PVS4)
PVS4 = PS) - P4 * SIGN (1.0, XS4)
XQP4 = INTGR (0.0, XQP4B)
P4A = (XQP4 - XPI) * 2.0 * BETA4 * AP4 / VS4
PROCEDURE P4 = AA4 (PFAIL4, PSD, P4A)
  IF (PFAIL4) 42,44,46
  42 P4 = -PSD
  GO TO 44
  44 P4 = LIMIT (-PSD, PSD, P4A)
  GO TO 49
  46 P4 = PSD
  IF (PFAIL4.GE.1.5) P4 = 0.0
  49 CONTINUE
ENDPROCEDURE
F4 = P4 * AP4
*
***** POWER SPOOL DYNAMICS *****
*
FB = KB + PV * XPD
FT = 3.0 * FL + F4 - FB
*
PROCEDURE COULF = BBB (DXP, COUL)
COULF = 0.0
IF (DXP.NE.0.0) COULF = COUL * SIGN (1.0, DXP)
ENDPROCEDURE
*
DDXPA = (FT - BP*DXP - COULF) / MP
*
PROCEDURE DDXP = CCC (DDXPA, DXP, STIK, FT)
DDXP = DDXPA
DXPF = DXPL * DXP
DXPL = DXP
IF (DXPF.GT.0.0) GO TO 200
IF (ABS (FT).LE.STIK) GO TO 100
DDXPB = DEADSP (-STIK, STIK, FT)
DDXP = DDXPB / MP
GO TO 200
100 DXP = 0.0
DXPL = 0.0
DXPF = 0.0
DDXP = 0.0
200 CONTINUE
ENDPROCEDURE
*
DXP = INTGR (0.0, DDXP)
XP = LIMIT (DXP, -XPLIM, XPLIM)
XPD = DEADSP (-DVLAP, DVLAP, XPI)

```

Figure 2-3.— Continued.

```

XPDSP = DEADSP (-DDSPA, DDSPA, XP)
*
***** LOAD FLOW EQUATIONS *****
*
* IMPLICIT VARIABLE Z WILL BE SET EQUAL TO QL AFTER CALCULATION
*
Z = IMPL (0.0, 0.01, FDFZ)
PDAAA = PF * Z**2
PVAAA = PS - PDAAA - PL * SIGN(1.0, XP)
FDFZ = KQP * XPD * SQRT (ABS(PVAAA)) * SIGN(1.0, PVAAA)
*
QL = Z
QLSWD = QL**2
PC = RF * QLSWD
PSD = PS - PD
PV = PSD - PL * SIGN (1.0, XP)
*
***** LOAD DYNAMICS *****
*
DXQP = QL / AR
XQR = INTGRL (XLZEPG, DXQR)
FP = KACT * (XQR - XFB)
PI = FP / AR
R = AFGFN (MOMARM, DELED)
TP = FP * P
*
* THE FOLLOWING PROCEDURE COMPUTES THE TOTAL TORQUE (TT) INCLUDING THE
* EFFECTS OF ACTUATOR STICKION AND ELEVON STICKION.
*
PROCEDURE TT = DDG (TP, TAERO, DDELED, DXFB, ELSTK, RAMSTK)
*
IF (DXFB.NE.0.0) GO TO 500
IF (DDELED.NE.0.0) GO TO 600
* TC HERE IF DXFB.EQ.0 AND DDELED.EQ.0
TF = TP + TAERO
STCTN = ELSTK + RAMSTK
TT = DEADSP (-STCTN, STCTN, TF)
GO TO 800
* TO HERE IF DXFB.EQ.0 AND DDELED.NE.0
600 TF = TP + TAERO - FCNSW (DDELED, -ELSTK, 0.0, ELSTK)
TT = DEADSP (-RAMSTK, RAMSTK, TF)
GO TO 800
500 CONTINUE
IF (DDELED.NE.0.0) GO TO 700
* TC HERE IF DXFB.NE.0 AND DDELED.EQ.0
TF = TP + TAERO - FCNSW (DXFB, -RAMSTK, 0.0, RAMSTK)
TT = DEADSP (-ELSTK, ELSTK, TF)
GO TO 800
* TO HERE IF DXFB.NE.0 AND DDELED.NE.0
700 TT = TP + TAERO - FCNSW (DXFB, -RAMSTK, 0.0, RAMSTK) ...
- FCNSW (DDELED, -ELSTK, 0.0, ELSTK)
800 CONTINUE
ENDPROCEDURE
*
DDELE = (TT - BE * DDELE) / IE

```

Figure 2-3.— Continued.

```

DELE, DDELE = LIM2 (DDDELE, -0.6369, 0.3752)
DELEF = KKAD * DELE
DDELEF = KFAO * DDELE
XL = AFGEN (STROKE, DELE)
XFB = (KS*XL + KACT*XOR) / (KS + KACT)
DXFB = DERIV (D.C, XFB)
*
TERMINAL
*
METHOD RK SFX
TIME DELT=0.00005, NUTDEL=0.002, PRDEL=0.01, FINTIM=1.0
CAUSE IL1, IY51, IL4, P1, P4, PL, QL, VAF1, VAF1, VAF1, VAF1,...
VAX1, VAX1, XFA, XL, XP, XPD, XOR, XSI, LCLLE, CLLE, CMJLE
LABEL 625-30 MODG ELEVON ACTUATOR (INBOARD) WITH ASA-1
LABEL STABILITY TEST
LABEL 15 NOVEMBER 1978
OUTPUT VCMDM1
LABEL RAM POSITION COMMAND VOLTAGE, LESS OFFSET (VOLTS)
OUTPUT VARMI
LABEL RAM POSITION FEEDBACK VOLTAGE, LESS OFFSET (VOLTS)
OUTPUT IL1, IL4, PL
LABEL CURRENT IN CHANNELS 1-3 (IL1) AND 4 (IL4), MILLIAMPERES, AND ...
LOAD PRESSURE (PL), LBS/SQ INCH
OUTPUT P1, P4
LABEL PRESSURES IN CHANNELS 1-3 (P1) AND 4 (P4), LBS/SQ INCH
OUTPUT DDELE
LABEL ELEVON SURFACE RATE (DEGREES/SECOND)
OUTPUT XSI
LABEL SECOND-STAGE SPODE DISPLACEMENT IN CHANNELS 1-3 (INCHES)
OUTPUT XP
LABEL POWER SPODE DISPLACEMENT (INCHES)
PRINT IL, I4, DXSI, DXS4, P1A, P4A, P1, P4, DXP
END
STOP

```

Figure 2-3.— Continued.

OUTPUT	VAR	TABLE	SEQUENCE								
KAB1	KAB2	KAB3	KAB4	KAC1	KAC2	KAC3	KAC4	KAK1	KAK2		
KAB3	KAP4	KAL1	KAL2	KAL3	KAL4	KAR1	KAR2	KAR3	KAR4		
KAT1	KAT2	KAT3	KAT4	KAV1	KAV2	KAV3	KAV4	KAW1	KAW2		
KAW3	KAW4	VZLRC	VZERC1	VZERC2	VZERC3	VZERC4	VAN1	VAN2	VAN3		
VAN4	VAT1	VAT2	VAT3	VAT4	XSL	XSE	XSE	XSE	XSE		
DELED	CMCA	CMCR	BLIP	CMDEF	CMMA	VCMD	VCMD1	VAV1A	ZZ1003		
ZZ1000	ZZ1001	ZZ1002	VAV1	DELED	AL	XFR	ZZ1005	VAA1	VAB1A		
ZZ1012	ZZ1005	ZZ1010	ZZ1011	VAB1	FP	PL	VAC1	ZZ1012	VAD1		
VAF1A	ZZ1022	ZZ1015	ZZ1020	ZZ1021	VAF1	ZZ1023	VAF1A	VAV1	PFALL1		
XPI	ZZ1128	PVAAA	PVAAA	FORZ	Z	QL	CLSCD	PC	PSC		
PJA	PL	PSI	VAG1	ZZ1030	ZZ1031	VAH1	VAJ1A	ZZ1037	ZZ1034		
ZZ1035	ZZ1036	VAJ1	VAK1	VAL1	VAM1	DVAN1	ZZ1042	ZZ1043	VAN1		
VAR1	DVAT1	ZZ1045	VAT1	VCMD4	VAV4A	ZZ1052	ZZ1045	ZZ1053	ZZ1051		
VAV4	ZZ1057	VAA4	VAF4A	ZZ1061	ZZ1062	ZZ1068	ZZ1054	ZZ1060	VAP4	VAC4	
ZZ1067	VAF4	VAF4A	ZZ1071	ZZ1061	ZZ1069	ZZ1070	VAF4	ZZ1071	VAF4A		
VAV4	PF4IL4	P4A	P4	P54	VAG4	ZZ1075	ZZ1080	VAF4	VAJ4A		
ZZ1086	ZZ1083	ZZ1084	ZZ1085	VAJ4	VAK4	VAL4	VAN4	DVAN4	ZZ1091		
ZZ1092	VAN4	VAR4	DVA14	ZZ1095	VAF4	VAF1	VAP1	VAX1	IL		
IL	IHI	IHYS1	XDXSP	XSD1	IHFAL	IHTAF1	CF1	LXX1	FXC1A		
ZZ1098	FXC1	DXSI	ZZ1101	DXS1	ZZ1104	ZZ1105	XSI	XQPIA	PYS1		
XQPIA	XQP1	VAF4	VAP4	VAX4	IL4	IL4	IH4	IHYS4	XSD4		
TFA4	IHTAF4	QF4	DXX4	FXC4A	ZZ1110	FXC4	DXXS4	ZZ1113	DXS4		
ZZ1116	ZZ1117	XSD4	XQP4A	PVS4	XQP4B	XQP4	F1	F4	PV		
FE	FT	CMULF	DXXA	DXP	DXP	ZZ1124	ZZ1125	XP	DXQR		
XCR	K	TP	DELED	DXPB	TT	DEDEL	ZZ1131	DELE	ZZ1132		
CILE	VCMDM1	VAM1	VAM1	VABM1	ERRCR1	VCMDM4	VAM4	VAM4	VABM4		
ERRCP4	VCMDM	XFBM	XL4	XQRM							

\$\$\$ TRANSLATION TABLE CONTENTS \$\$\$

	CURRENT	MAXIMUM
MACRO AND STATEMENT OUTPUTS	277	600
STATEMENT INPUT WORK AREA	599	1900
INTEGRATORS+MEMORY BLOCK OUTPUTS	41 + 0	300
PARAMETERS+FUNCTION GENERATORS	186 + 2	400
STORAGE VARIABLES+INTEGRATOR ARRAYS	0 + 0/2	50
HISTORY AND MEMORY BLOCK NAMES	21	50
MACRO DEFINITIONS AND NESTED MACROS	11	50
MACRO STATEMENT STORAGE	56	125
LITERAL CONSTANT STORAGE	1	100
SORT SECTIONS	2	20
MAXIMUM STATEMENTS IN SECTION	332	600

Figure 2-3.- Concluded.

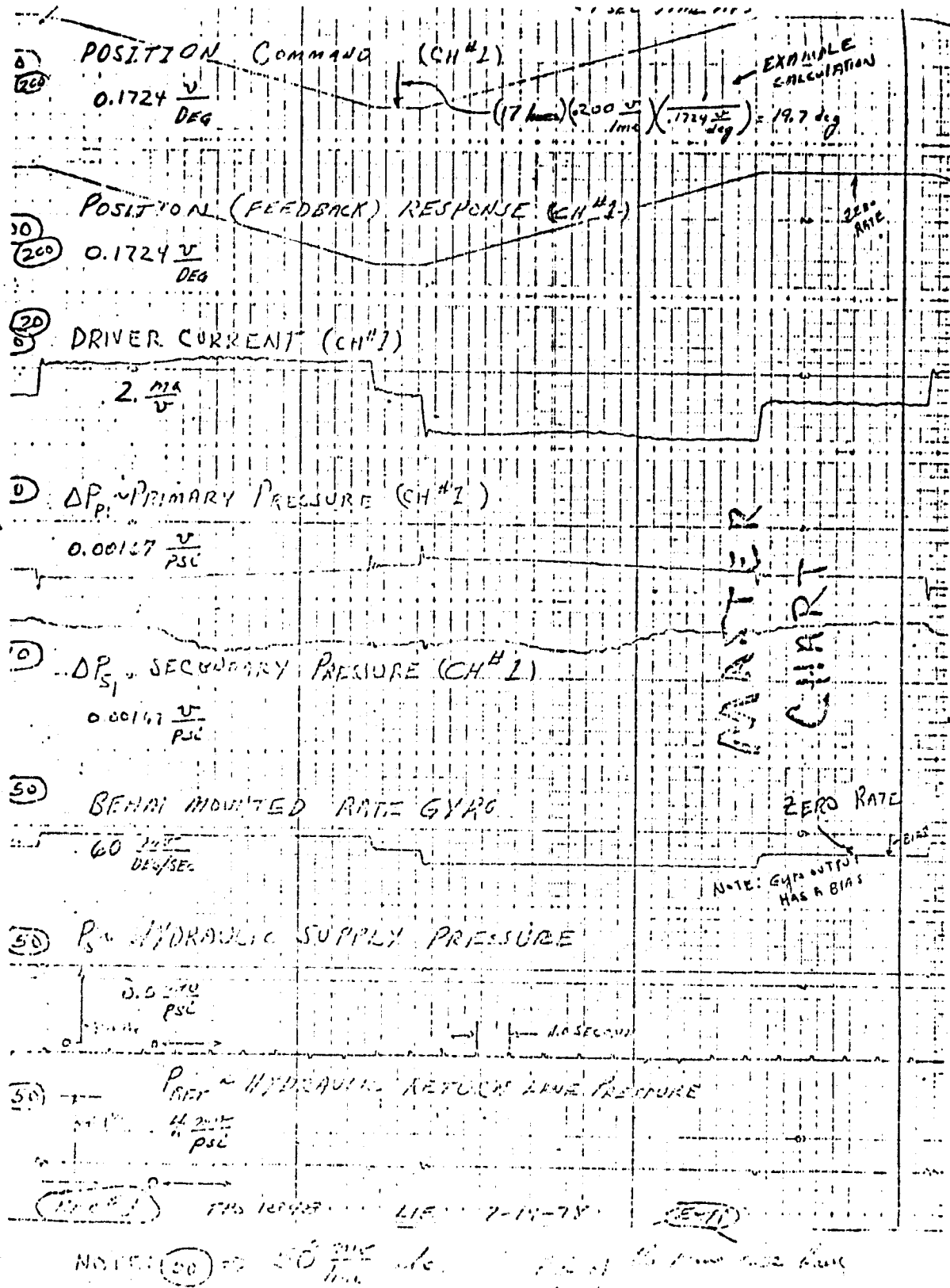
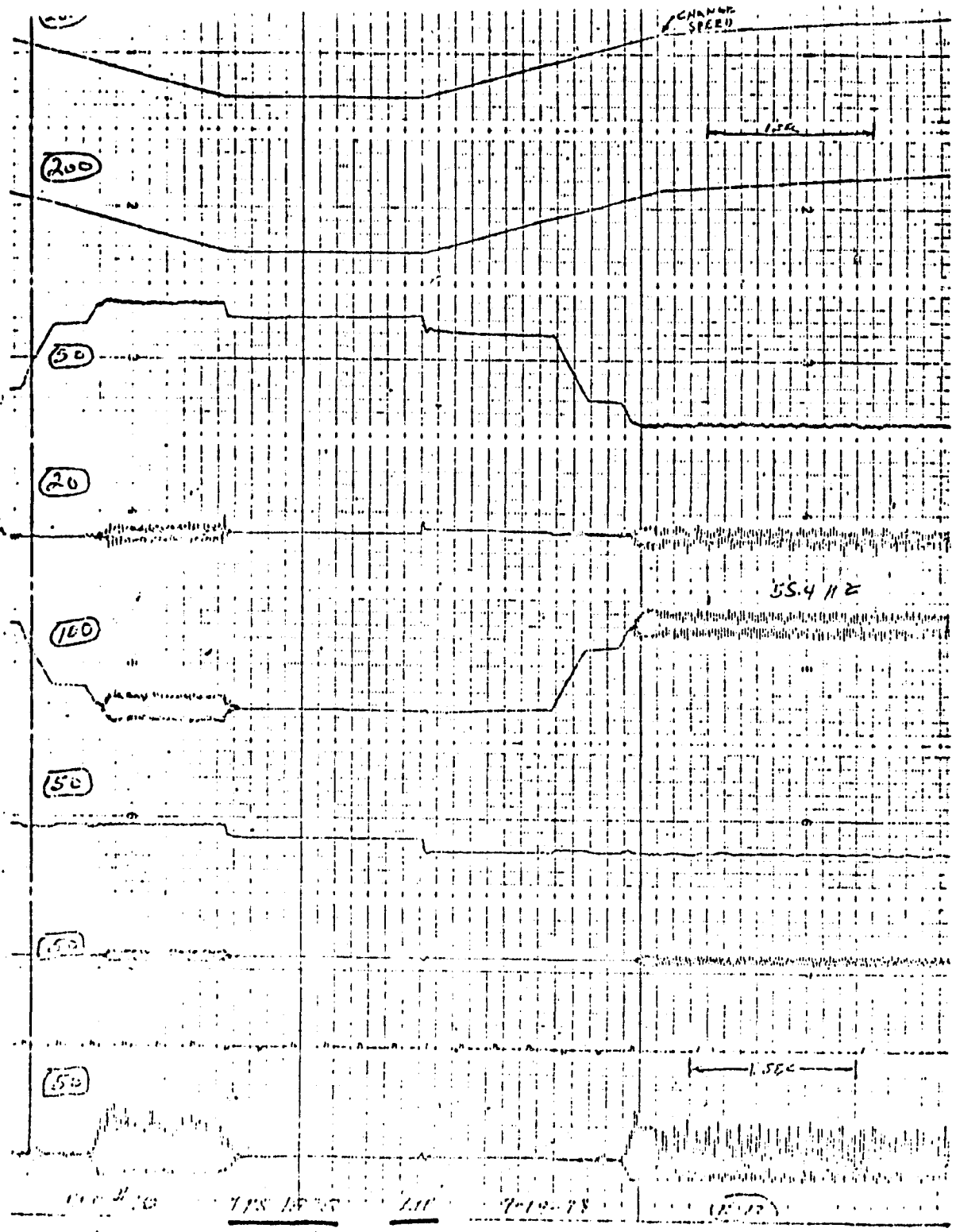


Figure 2-4.- FCHL master chart.



(INBD)

Figure 2-5.— Strip chart (E-12).

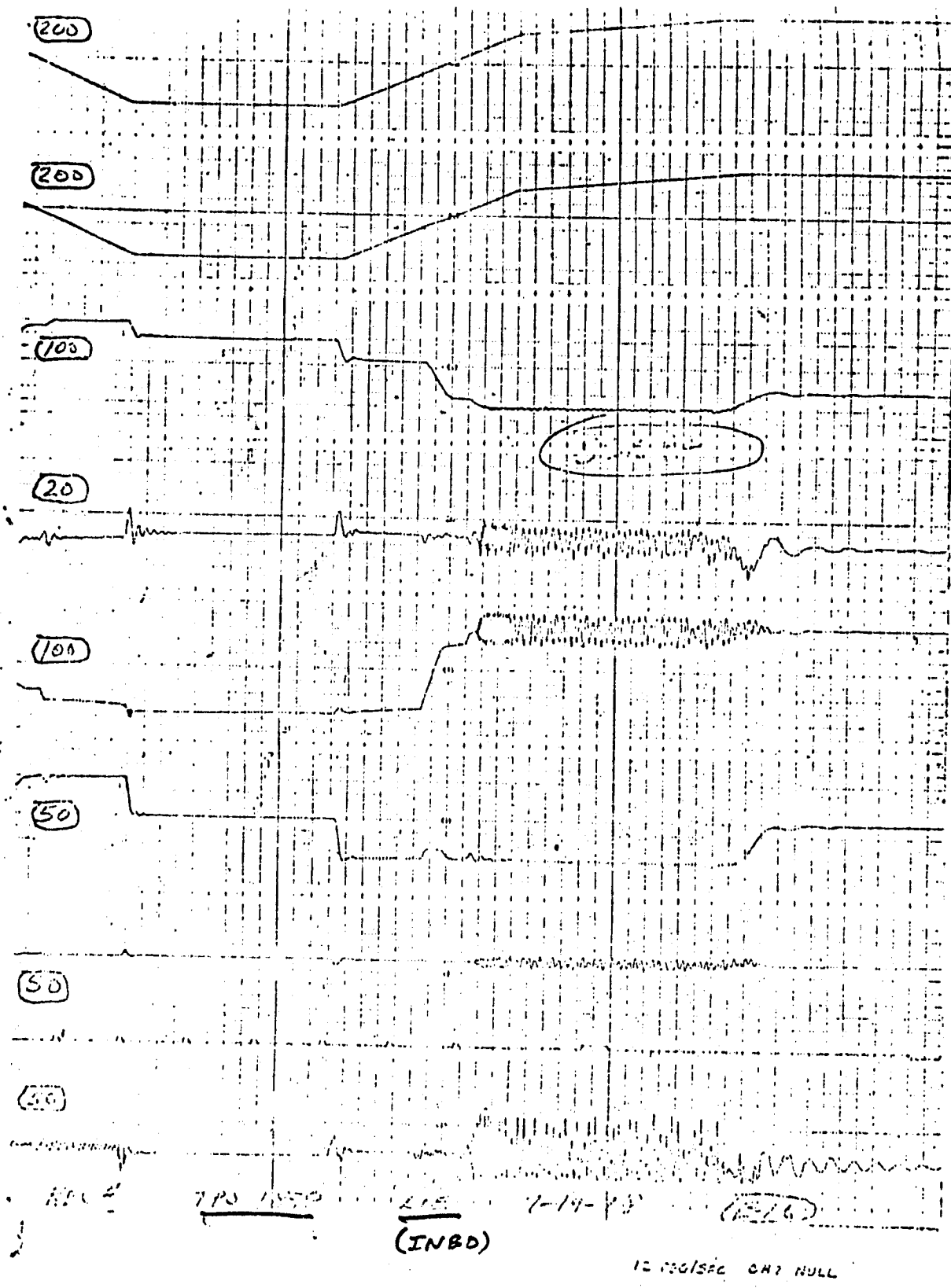


Figure 2-6.— Strip chart (E-16).

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

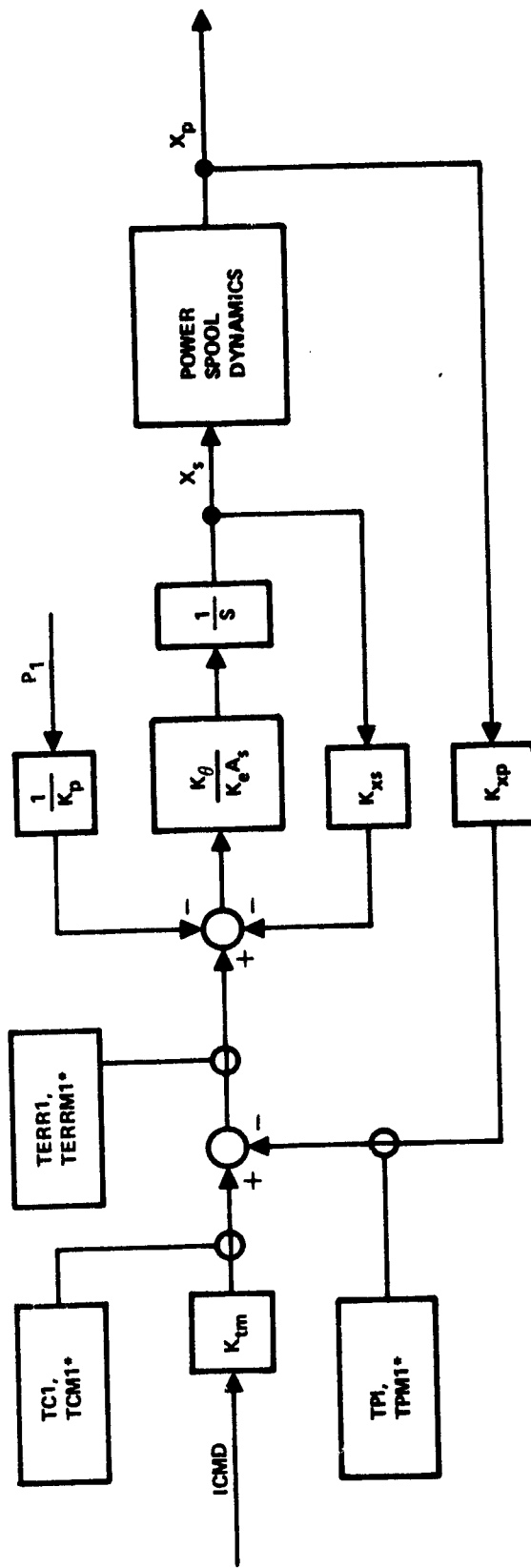
3. OSCILLATION INVESTIGATION

The objective of this investigation was to determine the probable cause of the high-frequency oscillations previously observed in the elevon actuators. The method employed (CSMP testing) was directed towards discovering which particular combination of added nonlinearities could best reproduce the problem oscillations. Any such combination, while not definitively the cause of these oscillations, would be at least a possible cause. If a really good match could be obtained between the hardware test data and CSMP printouts, that combination would have to be considered the probable cause at least in the absence of any contrary evidence.

3.1 PRELIMINARY ANALYSIS

Analysis of the test data received from FCHL revealed the following two facts regarding the high-frequency oscillations.

- a. The oscillations appeared to be confined to the actuator unit and did not significantly involve the Aerosurface Servo Amplifiers (ASA's). The FCHL data showed only enough current in the ASA-actuator drive lines to be accounted for by measured variations in the primary pressure feedbacks. These current levels were low on the order of the hysteresis thresholds of the actuator torque motors. Such levels might have influenced the oscillations but were probably too low to induce or support them.
- b. The oscillations occurred only when each ram was moving and only in the presence of an unbypassed command failure that produced force fighting in the secondary actuator. The frequency of oscillations pointed to the secondary actuator subassembly as the probable source. This subassembly has a calculated resonant frequency of 63 Hz and a damping ratio of 0.71 under no-fault conditions. Accordingly, a separate CSMP program modeling only the secondary actuator stage was set up, and frequency response data were taken to measure stability margins at 56 Hz. These data along with a sketch defining the terms used are shown in figures 3-1 through 3-5. Closed-loop data are plotted in figures 3-2 and 3-3, while the more important open-loop data are displayed in figures 3-4 and 3-5. The latter



*SUFFIX "M" DENOTES THE ORIGINAL VARIABLE LESS A CONSTANT OFFSET.

Figure 3-1.— Definition of variables for secondary actuator frequency response measurements.

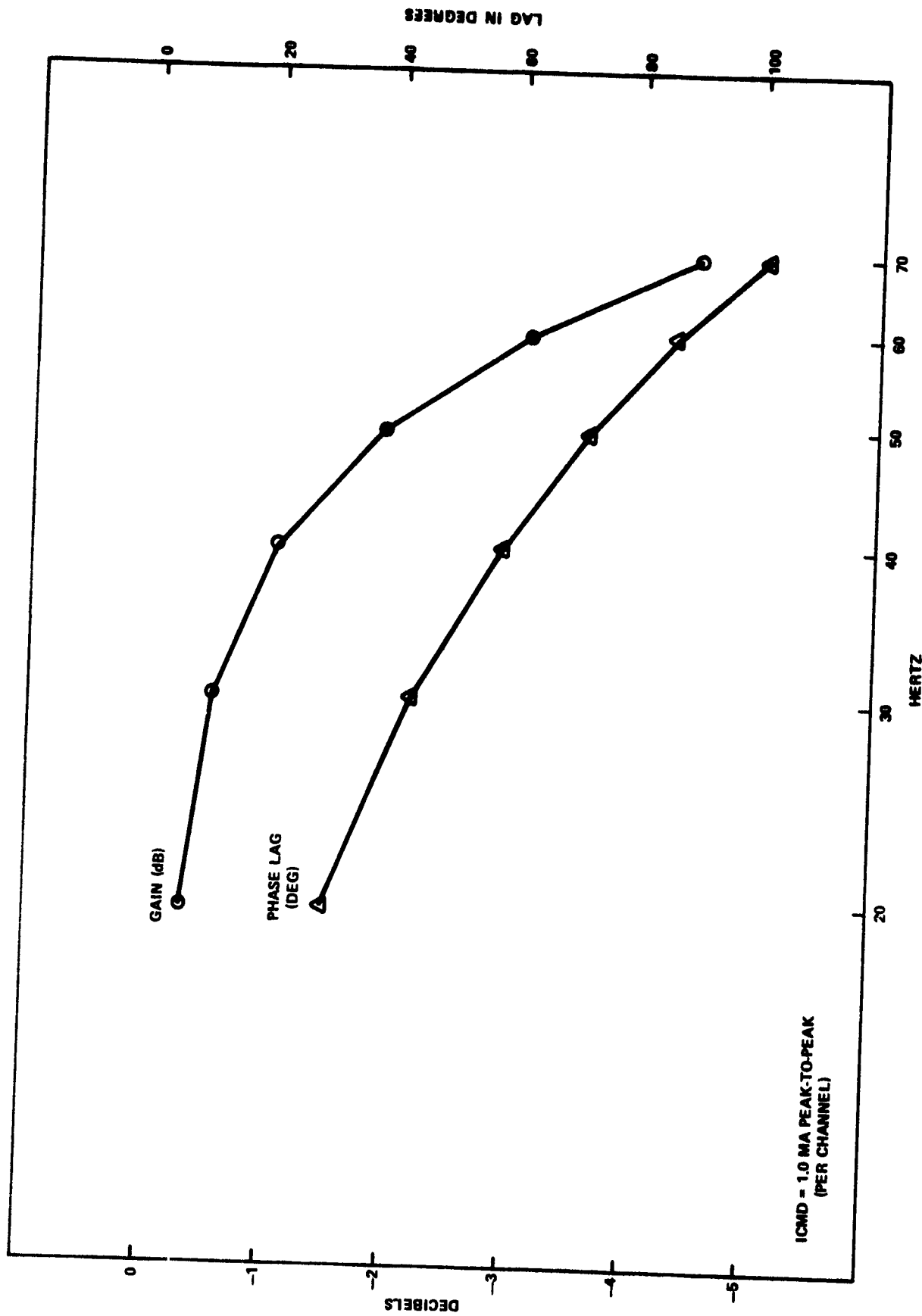


Figure 3-2.— Inboard secondary actuator closed-loop response (TP1/TC1), no faults.

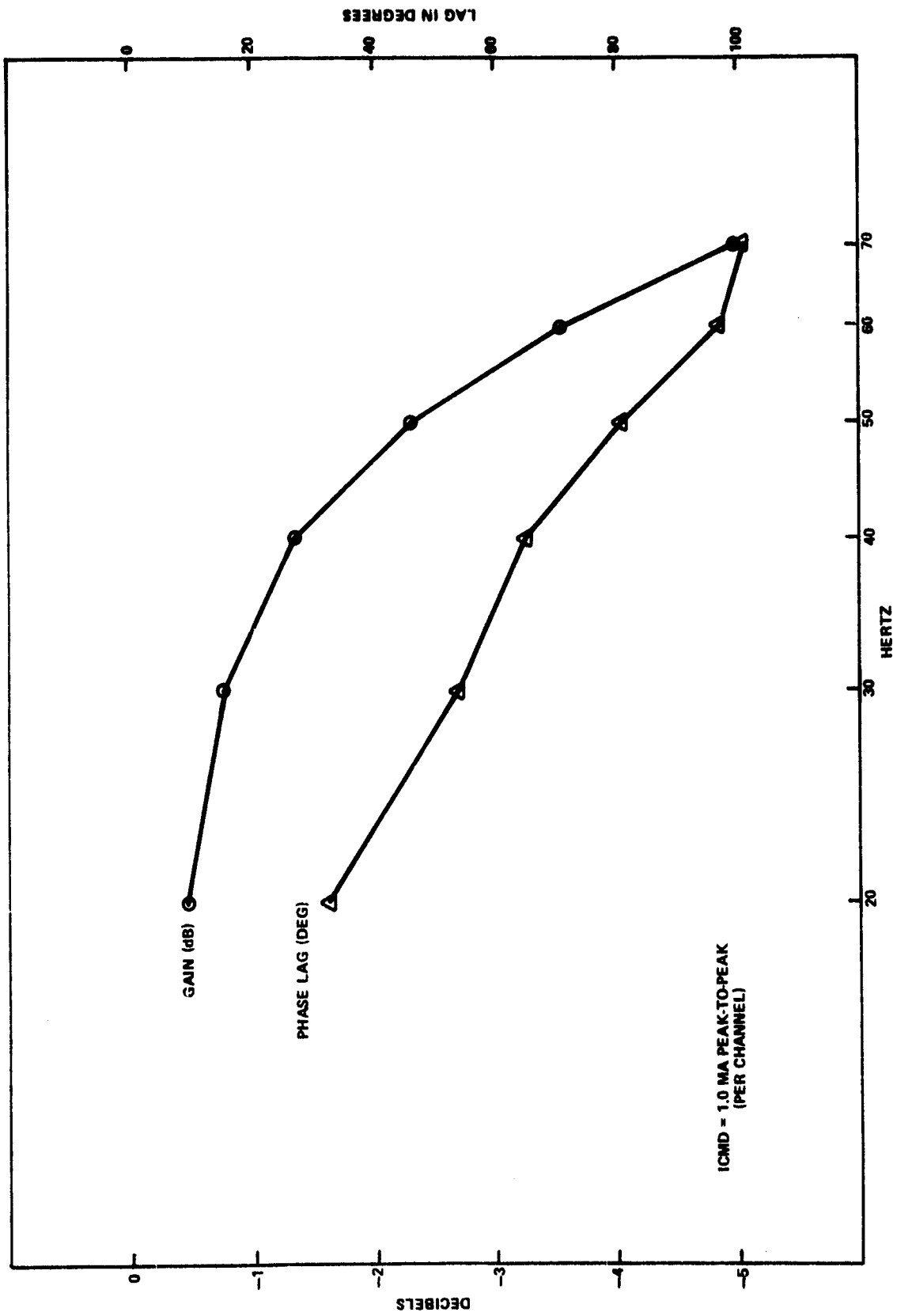


Figure 3-3.— Inboard secondary actuator closed-loop response (TPM1/TCM1), single channel hardover.

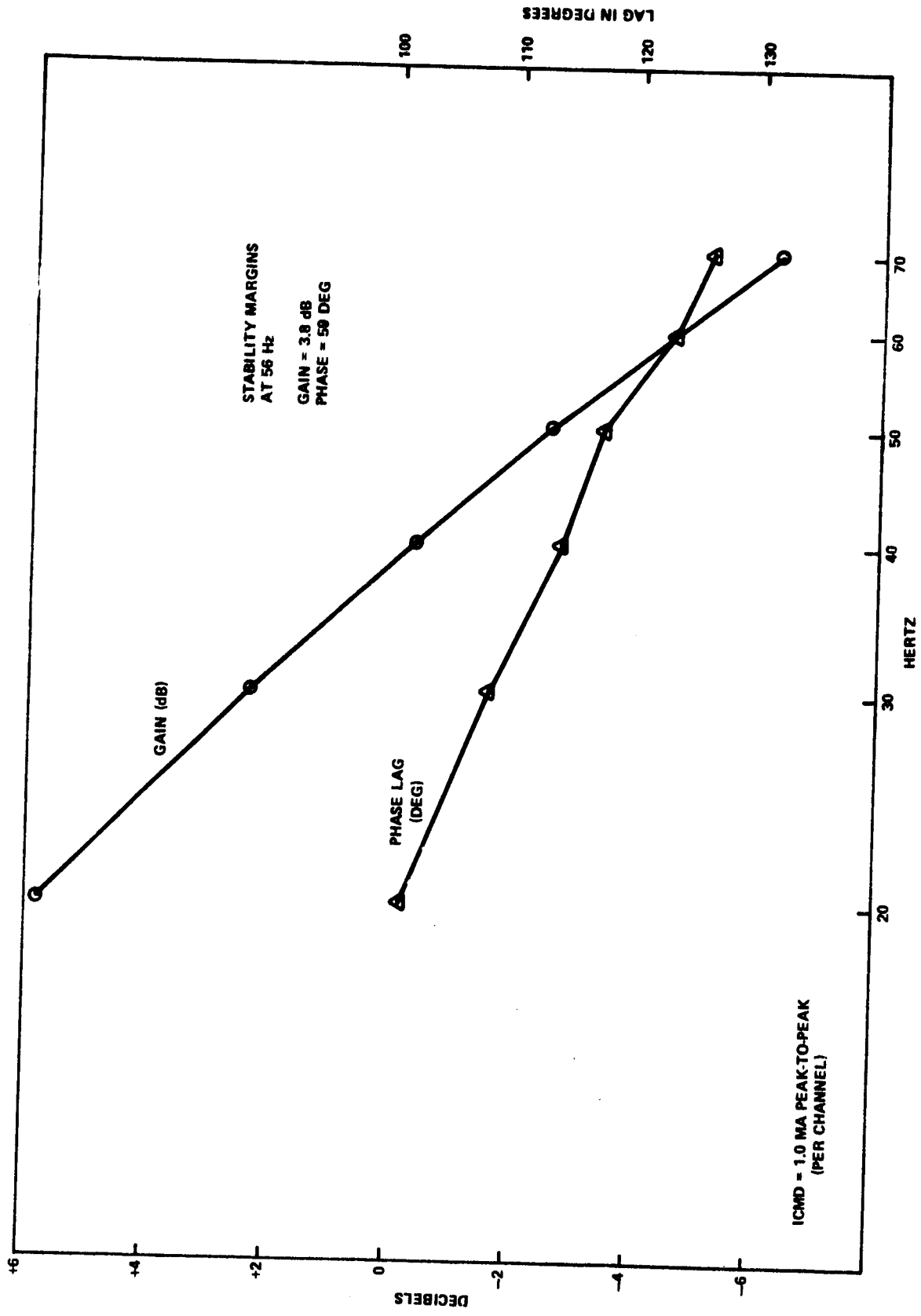


Figure 3-4.— Inboard secondary actuator open-loop response (TPI/TERR1), no faults.

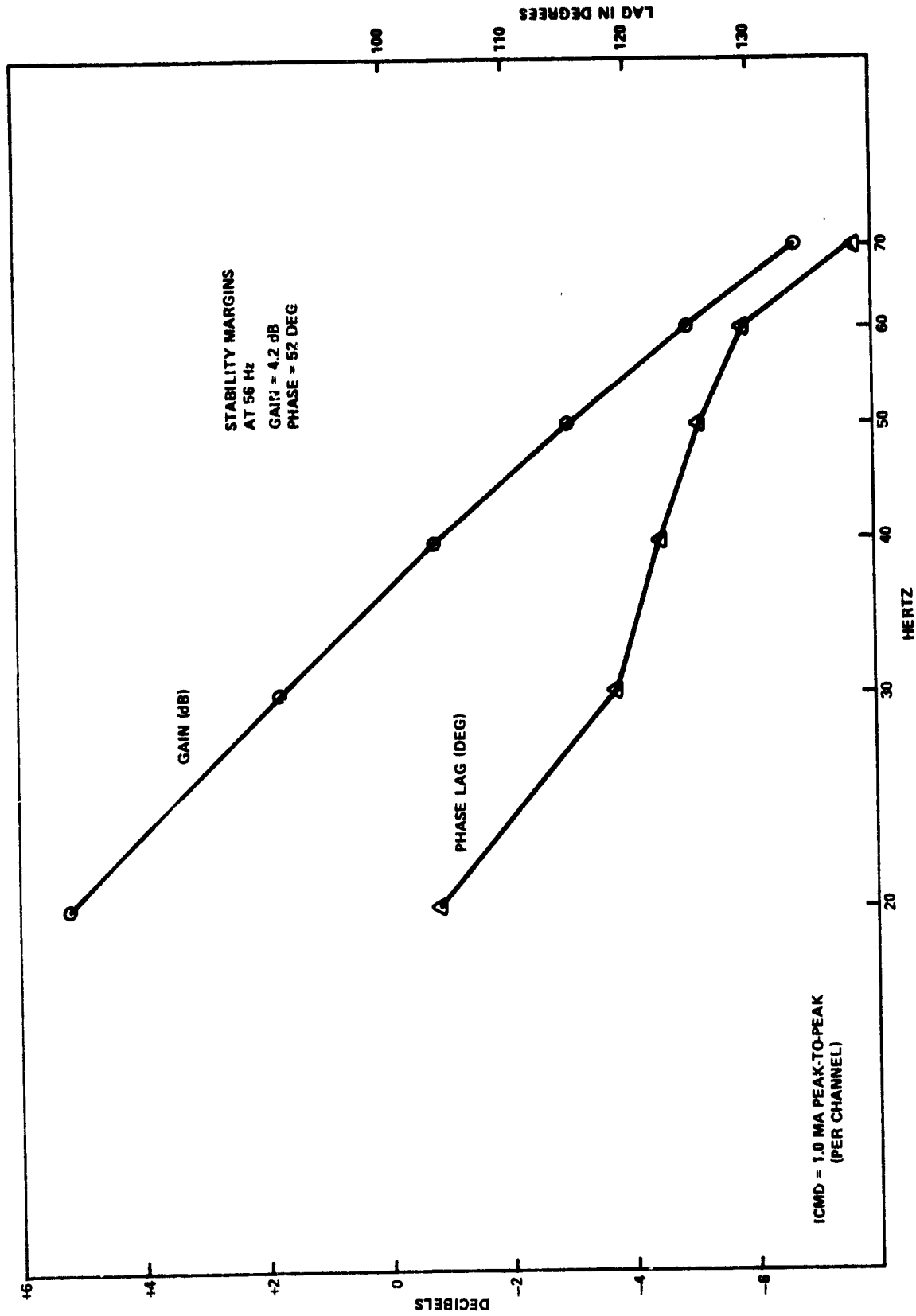


Figure 3-5.— Inboard secondary actuator open-loop response (TPM1/TERRM1), single channel hardover.

two figures also display calculated gain and phase margins at 56 Hz. Obviously, more loop gain (0.4 dB) but less phase shift (7°) would be required to force the secondary actuator stage into oscillation at 56 Hz with force fighting present (fig. 3-5) rather than with it absent (see fig. 3-4).

Another factor pointing to the secondary actuator stage as the probable source of the unwanted oscillations was that the actuator manufacturer Moog, Inc., had successfully stopped some similar high-frequency oscillations observed in a predecessor Thrust Vector Control (TVC) actuator by using an isolated hydraulic power supply to drive the hardover channel (only) in the secondary actuator stage.

After reviewing available FCHL test data and discussing the oscillations problem with R/SD and NASA/JSC engineers, two possible causes emerged for further investigation using CSMP simulation. One possible cause was flow-induced supply pressure drops acting on the power valve spool primarily through the hardover (faulted) channel. This theory was referred to as the hardover feedback theory. The other possible cause was deadspace in the couplings between the second-stage valve spools and their associated torque feedback springs. This was referred to as the deadspace theory.

3.2 HARDOVER FEEDBACK THEORY

The hardover feedback theory asserted that the problem oscillations were caused by a flow-dependent positive pressure feedback force acting on the power valve spool, presumably through a hardover channel. The basic idea is depicted in figure 3-6, which shows an added pressure drop term (ΔP_4) that is proportional (K) to some power (n) of the magnitude of the actuator flow rate (QL). Inclusion of the signum (sgn) function ensures positive feedback if K is positive and negative feedback if K is negative (both were tested).

As indicated in a note on figure 3-6, the typical pressure value in the hardover channel (channel 4) is also flow dependent, but there is no continuity of algebraic sign included in this dependency to ensure positive or negative feedback.

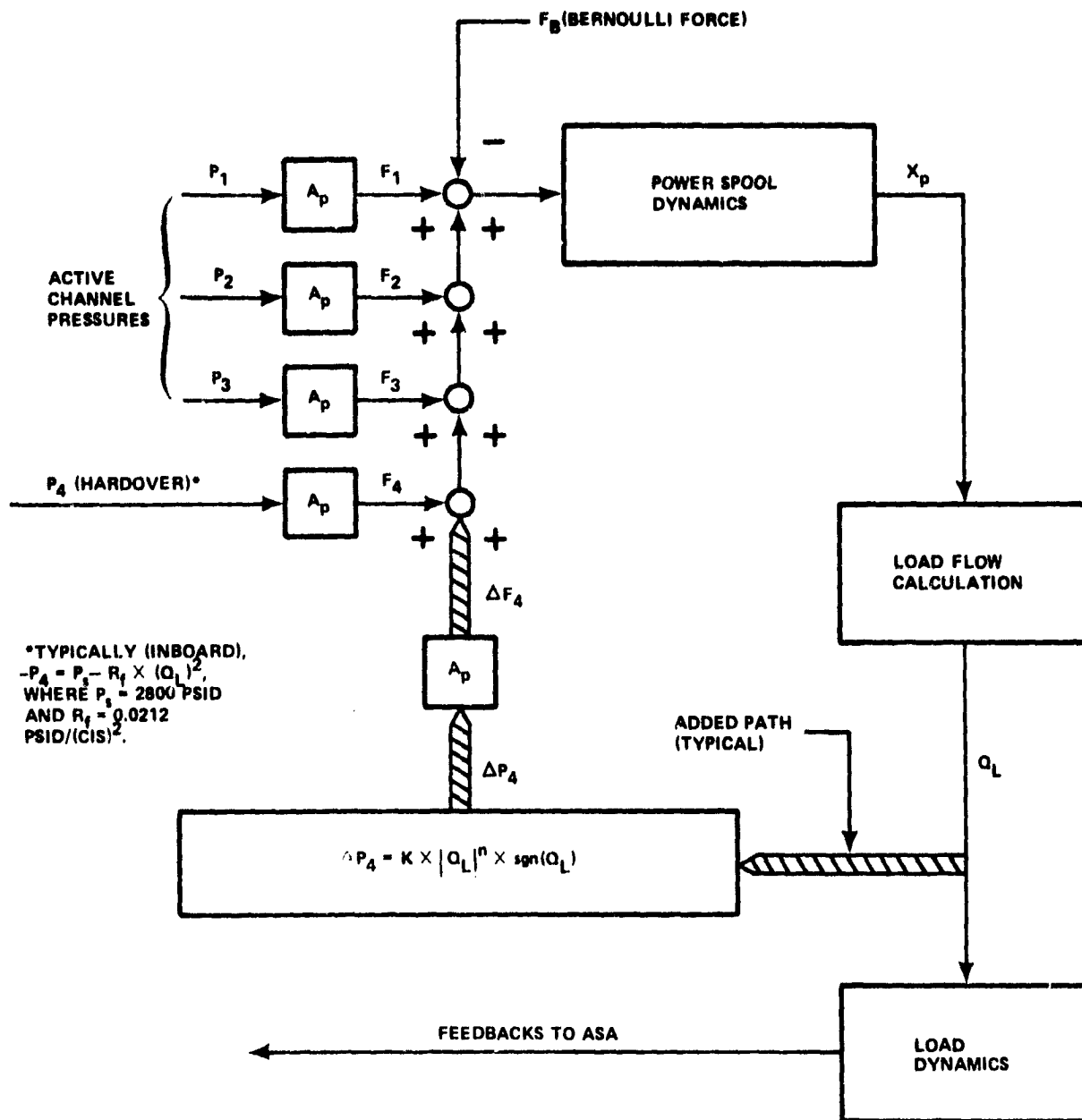


Figure 3-6.— Addition of flow-dependent pressure coupling to power spool dynamics for hardover feedback theory tests.

In accordance with the investigation objective, the CSMP program was rewritten to add the previously described pressure feedback term into the equations, and computer runs were performed using the parameter values listed in table 3-1. Referring to table 3-1, only four different computer runs actually were made to test this theory, although six printouts are listed. These runs are numbers 1, 2 and 3 with $K = +0.1297$; runs 2 and 3 with $K = -0.1297$; and runs 5 and 6. Runs 2 and 3 (and 5 and 6) were made using CSMP program listings that were identical except for the output calls, which were separated to avoid overloading the digital computers. Run 4 was exceptional in that it was made using incoherent feedback. This was accomplished by setting $K = 0$ and raising the value of the pressure drop coefficient R_F from 0.0212 to $0.1297 \text{ psid}/(\text{cis})^2$ for this one run only.

The CSMP test results were completely negative. No sustained oscillations were observed above 40 Hz, although the square-law runs with positive feedback quickly became exponentially unstable with very large self-quenched oscillations occurring at approximately 17 Hz.

3.3 DEADSPACE THEORY

The deadspace theory asserted that the problem oscillations were caused by deadspace existing in the couplings between the second-stage valve spools and their associated torque feedback springs. Whenever the feedback springs were positioned inside this deadspace, they were decoupled from the valve spools. Such decoupling immediately raised the forward-path gain of all contiguous outer servo loops and added phase shift, thus driving the outer loops towards instability.

Assuming the secondary actuator subassembly is principally responsible for producing the problem oscillations, the major outer loops affected are those for which the power spool displacement variable (X_p) provides the return signal. These loops are shown in figure 3-1. The stability margins shown in figures 3-4 and 3-5 are applicable. In order to make a quick check to see if opening the second-stage torque feedbacks entirely would cause an actuation subsystem to oscillate, a CSMP test run was made with all second-stage

TABLE 3-1.- COMPUTER RUNS FOR HARDOVER FEEDBACK THEORY TESTS

Run no.	Printout (1978)	Parameters			Comments*
		K [psid/(cis) ⁿ]	η	Source	
1	22 Sep 14	8.824	1	(1)	8.824 = 600/68
2	71 Sep 14	±0.1297	2	(1)	Common listings. Large oscillations at 17 Hz with K > 0.
3	72 Sep 18				
4	71 Sep 18	0	1	(1)	R _F = 0.1297
5	71 Sep 21	0.013058	1.75	(2)	Common listings
6	72 Sep 21				
Source of parameter values					
(1)	FCHL data for test no. E-16 with flow = 68 cis (approximately)				
(2)	Hydraulic line drop per R/SD internal letter 383-220-78-010				

*All tests were made on the inboard eleven actuation subsystem with force fighting induced in the secondary actuator to match FCHL test no. E-16.

For all tests, CMDELE (channels 1-3) = 12° ramp + (-2°) blip at T = 1.0 second. CMDELE (channel 4) = 0°.

feedback gain coefficients (K_{XS}) set to zero. No continuous oscillations resulted, although some ringing was observed at 62.5 Hz.

Referring to the hydraulic schematic diagram in figure 2-1, it is evident that mechanical coupling exists between the pressure developed in each channel of the secondary actuator and the flapper of the corresponding first-stage servo valve. This coupling passes through each second-stage servo valve via the torque feedback spring connection and logically would be affected by deadspace at this connection point. This coupling is not modeled explicitly in the R/SD math model (see fig. 2-2), because zero deadspace was assumed in deriving it. Obviously, it is necessary to develop and include the dynamics of the second-stage servo valves in the math model in order to make it suitable for use in testing the deadspace theory of oscillations.

The modifications developed to satisfy this requirement are shown in figure 3-7. Input flow (Q_F) and second-stage valve spool displacement (X_S) are related by the two block diagrams providing a before and after look at the math model. Observe that mechanical coupling from the secondary actuator pressure variable (P_1) to the second-stage valve spool is included explicitly in the modified block diagram. Further math model changes required to insert deadspace into the couplings between the second-stage and power valve spools and the corresponding torque feedback springs are shown in figure 3-8. These were the only changes made in the R/SD math model before making the deadspace theory CSMP runs.

New variables and parameters added for the deadspace theory runs are listed in table 3-2.

Different sets of numerical values assigned to parameters A_x , B_x , K_x and M_x during the course of testing were identified by a MOD (letter) REV (number) code for convenience, where MOD means modification and REV means revision. These sets of values are shown in table 3-3 along with the underlying resonant frequencies (f_n) and damping ratios (ζ) which led to their selection as outlined in the following paragraphs.

TABLE 3-2.— NEW VARIABLES AND PARAMETERS

Symbol	Units	Description
$\dot{\lambda}_x$	inch/sec	Second-stage spool rate (ideal)
$\dot{\lambda}_s$	inch/sec	Second-stage spool rate (actual)
A_x	inch ²	Stub spool area
B_x	lb-sec/inch	Viscous friction coefficient
K_x	lb/inch	Effective spring constant
M_x	lb-sec ² /inch	Mass of second-stage spool
DDSP	inches	Deadspace at connection to second-stage spool (half width)
DDSPA	inches	Deadspace at connection to power spool (half width)

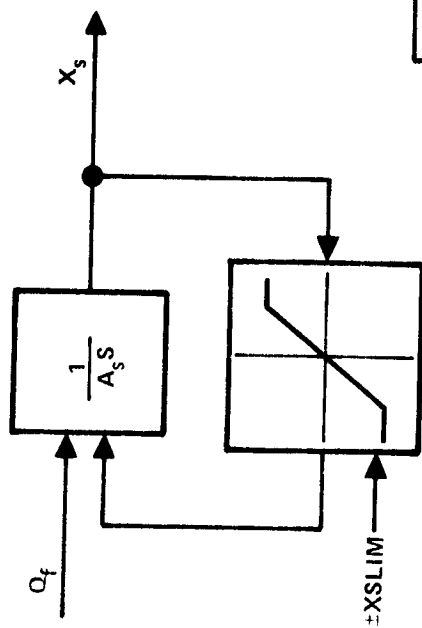
TABLE 3-3.— PARAMETER VALUES USED IN DEADSPACE THEORY TESTS

Actuator MOD/REV	K_x (lb/in)	M_x ($\frac{lb-sec^2}{in}$)	B_x ($\frac{lb-sec}{in}$)	A_x (in ²)	Calculated	
					f_n (Hz)	ζ
A/0*	7592	1.5 E-5	0.48	0.01629	3581	0.71
B/0	592	1.5 E-5	0.13	0.01629	1000	0.71
B/1	5330	1.5 E-5	0.40	0.01629	3000	0.71
B/2	2369	1.5 E-5	0.27	0.01629	2000	0.71
B/3**	3701	1.5 E-5	0.33	0.01629	2500	0.71
B/4	3701	1.5 E-5	0.047	0.01629	2500	0.10
B/5	3701	1.5 E-5	0.188	0.01629	2500	0.40

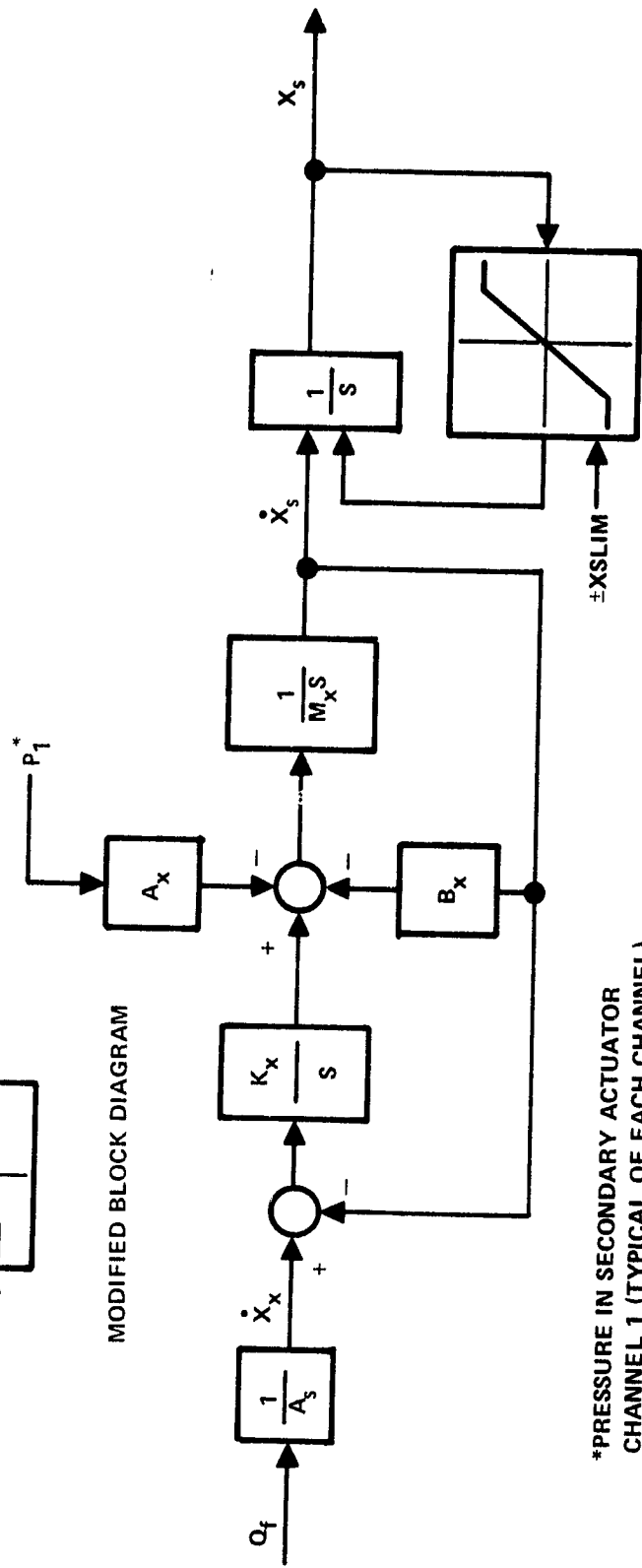
*MOD A was invalid (no pressure feedback).

**MOD B REV 3 was selected for use in further testing on 17 NOV 78.

ORIGINAL BLOCK DIAGRAM



MODIFIED BLOCK DIAGRAM



*PRESSURE IN SECONDARY ACTUATOR CHANNEL 1 (TYPICAL OF EACH CHANNEL)

Figure 3-7.— Modifications to R/SD actuator math model to include servo valve dynamics for deadspace theory tests.

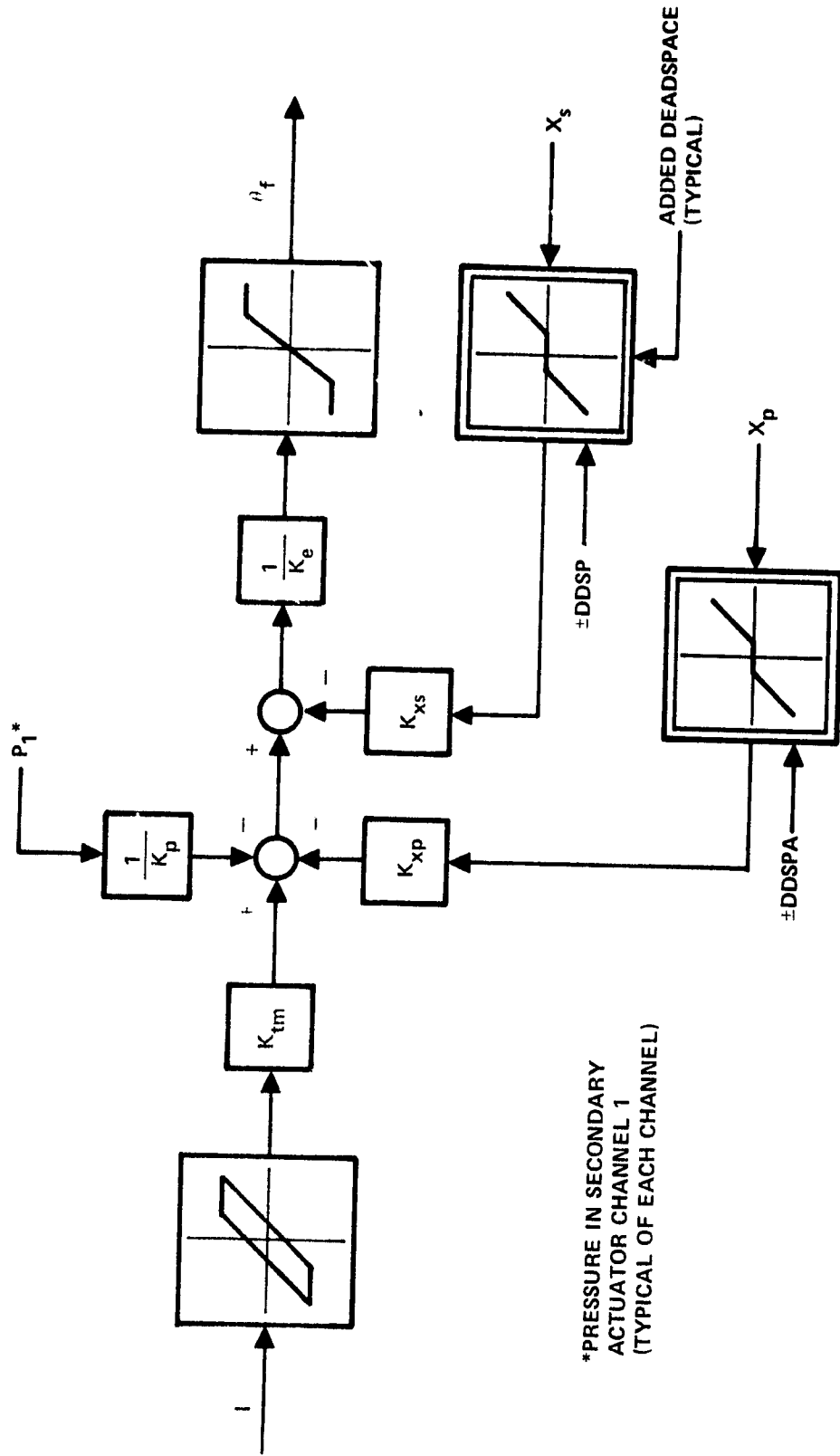


Figure 3-8.— Addition of deadspaces DDSP and DDSPA for deadspace theory tests.

The value used for M_x ($1.5 \text{ E-5 lb-sec}^2/\text{inch}$) was estimated by scaling physical dimensions with respect to the power valve spool using drawings included with the original Moog, Inc., proposal document. This same document provided the exact value used for A_x .

The values for K_x and B_x were chosen to provide the resonant frequencies and damping ratios indicated in table 3-3. Referring to figure 3-7 and neglecting pressure P_1 , the transfer function \dot{X}_s/\dot{X}_x is defined as T_x

$$T_x = \frac{K_x}{M_x S^2 + B_x S + K_x}$$

By inspection, the natural frequency $f_n = (1/2\pi)\sqrt{K_x/M_x}$ and the damping ratio $\zeta = B_x/4\pi f_n M_x$. These equations were solved to find K_x and B_x :

$$K_x = 4\pi^2 f_n^2 M_x$$

$$B_x = 4\pi f_n \zeta M_x$$

Values for deadspaces DDSP and DDSPA were determined by experimentation. The total throw of each second-stage spool was limited to $\pm XSLIM = \pm 0.015$ inch, and that of the power spool was limited to $\pm XPLIM = \pm 0.05$ inch.

The first 23 computer runs made to test the deadspace theory are listed in table 3-4. Referring to this table, notice that run 01 was the original run made with no spool dynamics included and all second-state feedback gain coefficients (K_{xs}) set to zero as discussed earlier in this section.

Before starting to test using nonzero deadspaces, it was necessary to verify that any set of MOD/REV (see table 3-3) numerical parameter values selected for use in testing would generate CSMP test data closely matching that obtained using the original R/SD math model with no second-stage spool dynamics included. Accordingly, run 02 was made using the original math model in order to generate a set of reference data for verification purposes.

TABLE 3-4.- COMPUTER RUNS FOR DEADSPACE THEORY TESTS

Run no.	Printout (1975)	ω_n (KHz)								ζ		Ramp		DDSPA (in)				DDSP (in)				Oscillations		Comments	
		N/A	1.0	2.0	2.5	3.0	3.581	N/A	0.1	0.4	0.71	6 deg/sec	12 deg/sec	0	0.001	0.002	0.003	0.005	0.005	0.005	0.005	Blip in	< 40 Hz		> 40 Hz
01	22 Sep. 26	X										X		X								X			All inboard subsystem. All with force fighting.
02	22 Sep. 27	X						X			X		X									X			No spool dynamics and $K_{XS} 1-4 = 0$
03	71 Sep. 27					X					X		X									X			No spool dynamics reference run
04	71 Oct. 17		X								X		X									X			MOD A is no good (no pressure feedback)
05	72 Oct. 23					X					X		X									X			B-0 verified no good
06	72 Oct. 24					X					X		X									X			B-1 verified excellent
07	72 Oct. 27					X					X		X									X			$ X_{ST} < DDSP$
08	72 Oct. 26			X							X		X									X			B-2 verified fair
09	72 Oct. 30			X							X		X									X			B-2 shows 55.5 Hz
10	72 Oct. 31										X		X									X			B-3 verified excellent
11	72 Nov. 01										X		X									X			B-3 shows 59.5 Hz
12	72 Nov. 01										X		X									X			B-3 rings at 55.5 Hz
13	72 Nov. 03								X		X		X									X			B-4 is no good (oscillates at 250 x 17 Hz)
14	72 Nov. 03								X		X		X									X			B-5 rings at 50.0 Hz
15	72 Nov. 06								X		X		X									X			B-5 rings at 50.0 Hz
16	72 Nov. 06								X		X		X									X			DDSPA is too large (B-3). Some 55.5 Hz oscillations
17	72 Nov. 07								X		X		X									X			Note no blip (B-3)
18	72 Nov. 07								X		X		X									X			Blip + oscillations
19	72 Nov. 13								X		X		X									X			(B-3) 55.5 Hz only
20	72 Nov. 14								X		X		X									X			(B-3) 55.5 Hz only*
21	72 Nov. 14								X		X		X									X			12 Hz at plateau only
22	72 Nov. 15								X		X		X									X			No 55.5 Hz (B-3)
23	72 Nov. 15								X		X		X									X			

*This set of parameter values was selected for further testing on 17 Nov. 78.

Run 03 was made to verify the MOD A REV 0 parameters but was unacceptable because direct pressure feedback was mistakenly removed from the torque summing junction. Predictably, the data obtained came nowhere near matching the reference data previously obtained in run 02.

Direct pressure feedback was restored to the R/SD math model producing actuator MOD B. This modification proved to be acceptable for all later testing.

Run 04 was made to verify MOD B REV 0 parameters, but the data obtained did not match that of the reference run (run 02) at all. In fact, it was highly oscillatory and jittery and completely unacceptable. The natural frequency (f_n) was 1000 Hz and probably too low. Accordingly, f_n was raised to 3000 Hz for run 05.

Run 05 was made to verify MOD B REV 1 parameters and was the first successful verification test run. The data obtained was an excellent match with that previously obtained in run 02. Consequently, nonzero deadspace was introduced into the simulation for the first time using MOD B REV 1 parameter values in run 06.

Run 06 was made with all second-stage deadspaces (DDSP) equal to ± 0.005 inch and with zero deadspace at the power spool connections (DDSPA = 0). A +12 degs/sec ramp command was applied to the three active channels. It was limited to +8 degrees maximum and augmented by a -2 degrees blip to excite any possible oscillations. A fixed (zero degrees) command was applied to the single failed channel (channel 4). No undesired oscillations were observed in the printouts. The magnitude of displacement of the second-stage valve spools in the three active channels never was great enough to move the feedback springs out of their deadspace regions during the entire test run. Apparently 3000 Hz was too high for f_n , and 1000 Hz was too low.

Accordingly, run 07 was made with f_n equal to 2000 Hz. The purpose was to verify MOD B REV 2 parameter values, but only a fair match was obtained

between the printout data and that previously obtained in the reference run, primarily because of excessive ringing at and above 62.5 Hz.

Run 08 was made with f_n equal to 2000 Hz (MOD B REV 2 parameter values) and DDSP equal to ± 0.005 inch (DDSPA = 0). For the first time, this run generated printouts matching certain key characteristics of the hardware oscillations observed in FCHL test no. E-16 (fig. 2-6) including oscillation frequency (55.5 Hz) and dampout at a position plateau.

Run 09 was made to verify MOD B REV 3 parameters, which were derived using f_n equal to 2500 Hz. Excellent agreement was achieved with the printouts from the reference run (run 02).

Run 10 was made using MOD B REV 3 parameter values along with DDSP equal to ± 0.005 inch (DDSPA = 0). Oscillations similar to those generated during run 08 were observed but with a frequency of 59.5 instead of 55.5 Hz.

Runs 11 and 12 were made using MOD B REV 3 parameters but with DDSP reduced to ± 0.001 and ± 0.003 inch, respectively (DDSPA = 0). No continuous oscillations appeared, although ringing at 55.5 Hz was observed during both runs. Both the amplitude and the duration of the ringing were greater using the larger DDSP value.

Before run 13, all deadspace-theory test runs had been made with the damping ratio (ζ) arbitrarily set equal to 0.71. Runs 13 and 14 were made with ζ equal to 0.1 (MOD B REV 4 parameter values) and with DDSP equal to ± 0.001 and ± 0.003 inch, respectively. Neither run was acceptable. Both produced strong oscillations in the secondary actuator stage at 250 Hz modulated at 17 Hz.

Runs 15 and 16 were made using the same values of DDSP and DDSPA but with ζ set equal to 0.4 (MOD B REV 5 parameter set). Continuous oscillations were not generated, but ringing at 50.0 Hz was observed during both runs.

Runs 17 through 23 were all made using the MOD B REV 3 set of parameter values with nonzero values of power spool deadspace DDSPA used for the first time. Runs 17 and 18 were made with DDSPA equal to ± 0.005 inch and DDSP equal to ± 0.001 and ± 0.003 inch, respectively. A variety of continuous oscillations appeared including some at 25, 45, and 55.5 Hz.

Continuous oscillations at 25 Hz were observed after the ram stopped moving in the plateau area where the +12 degs/sec ramp command was limited to +8 degrees. Apparently the deadspaces were too large.

Runs 19 and 20 were made with both DDSP and DDSPA equal to ± 0.003 inch, and the blip was deleted from the limited ramp position command signal for run 19 (only). No continuous high-frequency oscillations (above 40 Hz) were generated during run 19, but in run 20 continuous oscillations at 55.5 Hz were observed while the ram was in motion. When the ram stopped moving in the plateau area, the frequency of the continuous oscillations changed to 22.2 Hz. Apparently a blip was required to excite the high-frequency oscillations.

Runs 21 through 23 were made with DDSPA fixed at ± 0.001 inch and DDSP set equal to ± 0.003 , ± 0.002 and ± 0.001 inch, respectively. Runs 21 and 22 produced continuous oscillations at 55.5 Hz while the ram was moving and no oscillations at all inside the plateau area. Some ringing at 55.5 Hz was observed during run 23 while the ram was moving. This was followed by continuous oscillations at 12.0 Hz in the plateau area.

Along with the MOD B REV 3 parameter value set, the values of DDSP and DDSPA used in run 22 were selected for making further tests of the deadspace theory of oscillations. This was done because the data from run 22 matched that from FCHL test no. E-16 best of all the runs that had been made.

Little further testing was performed, however. Runs 24 and 25 (not listed in table 3-4) (printout 72 NOV 20) were made using DDSP set equal to ± 0.002 inch and DDSPA set equal to ± 0.001 inch to see whether or not oscillations would occur in the absence of force fighting in the secondary actuator

stage. They did not occur. Run 24 was made without force fighting, and run 25 included force fighting. The oscillations did not occur in run 24, and this pair of computer runs is considered the best obtained during this investigation. Some of the printouts from this pair of runs are displayed in figures 3-9 through 3-12, and a tabulated comparison of characteristics of the oscillations that were observed with force fighting present against those from FCHL test no. E-16 appears in table 3-5. The CSMP listing for these runs (a double-run case) is shown in figure 2-3.

Runs 26 and 27 were identical to runs 24 and 25 except a CSMP model of the outboard elevon actuator was substituted for that of the inboard actuator previously tested in runs 01 to 25. No continuous oscillations were observed in the printouts (74 NOV 27-78), although ringing at 55.5 Hz was observed especially after the blip. These two runs were the only ones made using the outboard actuator model.

Runs 28 and 29 were made to simulate FCHL test no. E-12. The three active channels were given a +4 degs/sec ramp command plus a -1 deg blip. The sum was limited to +2.7 degrees maximum. The MOD B REV 3 parameter set was used with the power spool deadspace DDSPA fixed at ± 0.001 inch. Second-stage spool deadspace (DDSP) values were ± 0.002 and ± 0.001 inch, respectively, in runs 28 and 29. No continuous high-frequency oscillations were observed in the printouts (75 NOV 27-78), but ringing at 50 Hz was observed following the blip. Continuous oscillations at 10 Hz were noted in the plateau region (only). The magnitude of differential pressure in the faulted channel (channel 4) never exceeded 1506 psid, because the commanded surface displacement was limited to +2.7 degrees in the three active channels. A constant command of 0 degrees was applied to channel 4.

The final CSMP run, run 30, was made under conditions similar to those for run 28 (DDSP = ± 0.002 inch and DDSPA = ± 0.001 inch) except an expanded maximum surface displacement of +10 degrees was used. Similar test results were obtained, although the magnitude of differential pressure in channel 4 quickly

TABLE 3-5.— COMPARISON OF OSCILLATION CHARACTERISTICS BETWEEN
 FCHL TEST E-16 AND RUN 72 NOV 20-78

No.	Characteristic	Units	FCHL	KK = 1.0 this run
1	Frequency	Hz	55.5	55.5
2	Feedback volts at onset ^a [VABM]	volts	1.000	0.36 (1.07) ^b
3	Stops at plateau?		Yes	Yes
4	I ₁ (IL1) ripple	mA p-p	0.16	0.17
5	ΔP_{p1} (PL)	psi p-p	120	159
6	ΔP_{s1} (P1)	psi p-p	600	139
7	Gyro rate (DDELED)	deg/sec p-p	(Very small)	0.7

^aOnset defined as first appearance of oscillations in PL.

^bOnset defined as first appearance of oscillations in IL1.

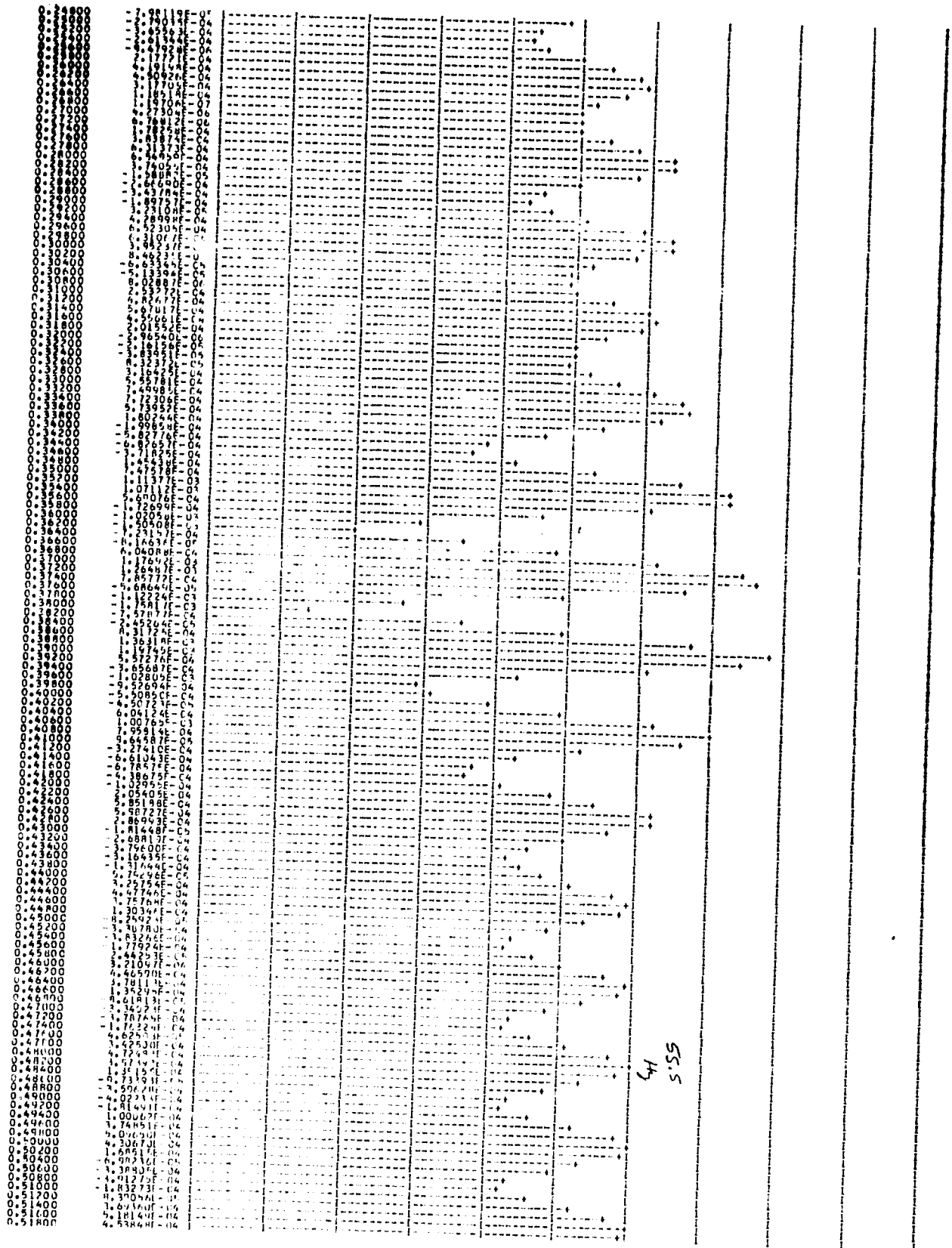


Figure 3-12.— Continued.

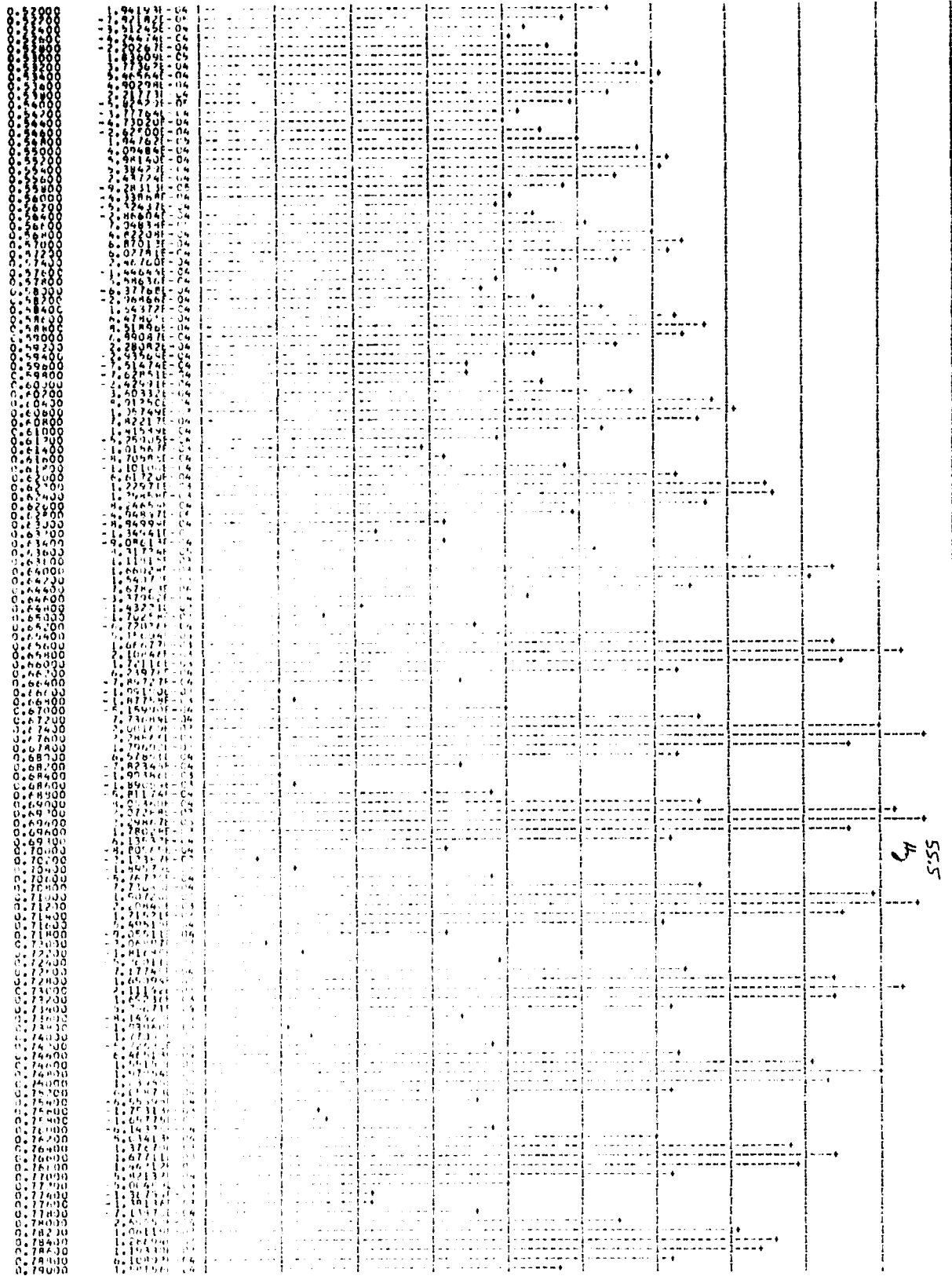


Figure 3-12.— Continued.

0.78200	-9.17284	C4
0.78400	-1.06604	C4
0.78600	7.59584	C4
0.78800	7.26374	C4
0.80000	6.30274	C4
0.80200	4.64274	C4
0.80400	2.97274	C4
0.80600	1.65874	C4
0.80800	-0.33274	C4
0.81000	-2.47074	C4
0.81200	-4.31474	C4
0.81400	-5.74474	C4
0.81600	-6.67474	C4
0.81800	-7.04474	C4
0.82000	-6.80474	C4
0.82200	-6.00474	C4
0.82400	-4.60474	C4
0.82600	-2.66474	C4
0.82800	-1.14474	C4
0.83000	0.00474	C4
0.83200	1.11474	C4
0.83400	2.15474	C4
0.83600	3.11474	C4
0.83800	3.99474	C4
0.84000	4.79474	C4
0.84200	5.51474	C4
0.84400	6.15474	C4
0.84600	6.71474	C4
0.84800	7.19474	C4
0.85000	7.59474	C4
0.85200	7.91474	C4
0.85400	8.15474	C4
0.85600	8.31474	C4
0.85800	8.39474	C4
0.86000	8.39474	C4
0.86200	8.31474	C4
0.86400	8.15474	C4
0.86600	7.91474	C4
0.86800	7.59474	C4
0.87000	7.19474	C4
0.87200	6.71474	C4
0.87400	6.15474	C4
0.87600	5.51474	C4
0.87800	4.79474	C4
0.88000	3.99474	C4
0.88200	3.11474	C4
0.88400	2.15474	C4
0.88600	1.11474	C4
0.88800	0.00474	C4
0.89000	-1.14474	C4
0.89200	-2.66474	C4
0.89400	-4.60474	C4
0.89600	-6.80474	C4
0.89800	-9.17284	C4
0.90000	-11.72084	C4
0.90200	-14.44884	C4
0.90400	-17.25684	C4
0.90600	-20.14484	C4
0.90800	-23.11284	C4
0.91000	-26.16084	C4
0.91200	-29.28884	C4
0.91400	-32.49684	C4
0.91600	-35.77484	C4
0.91800	-39.12284	C4
0.92000	-42.54084	C4
0.92200	-46.02884	C4
0.92400	-49.58684	C4
0.92600	-53.21484	C4
0.92800	-56.91284	C4
0.93000	-60.68084	C4
0.93200	-64.51884	C4
0.93400	-68.42684	C4
0.93600	-72.40484	C4
0.93800	-76.45284	C4
0.94000	-80.57084	C4
0.94200	-84.75884	C4
0.94400	-89.01684	C4
0.94600	-93.34484	C4
0.94800	-97.74284	C4
0.95000	-102.21084	C4
0.95200	-106.74884	C4
0.95400	-111.35684	C4
0.95600	-116.03484	C4
0.95800	-120.78284	C4
0.96000	-125.59084	C4
0.96200	-130.45884	C4
0.96400	-135.38684	C4
0.96600	-140.37484	C4
0.96800	-145.42284	C4
0.97000	-150.53084	C4
0.97200	-155.69884	C4
0.97400	-160.92684	C4
0.97600	-166.21484	C4
0.97800	-171.56284	C4
0.98000	-176.97084	C4
0.98200	-182.43884	C4
0.98400	-187.96684	C4
0.98600	-193.55484	C4
0.98800	-199.20284	C4
0.99000	-204.91084	C4
0.99200	-210.67884	C4
0.99400	-216.50684	C4
0.99600	-222.39484	C4
0.99800	-228.34284	C4
1.00000	-234.35084	C4

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Figure 3-12.-- Concluded.

became saturated at the supply limit (2800 psid). Continuous oscillations were noted at 11 Hz in the plateau region (only) in the printouts (75 NOV 28-78).

On 15 December 1978, a copy of the elevon servoactuators math model developed by C. J. Greaves at Moog, Inc., was received at NASA/JSC. This model includes a considerably greater amount of detail in modeling the flapper valve stage than does figure 2-2 (R/SD math model). Although making direct comparisons between the two math models generally is not feasible, there is a considerable amount of similarity between them. For instance, it was learned that the proper value of M_x was $2.85 \text{ E-5 lbs-sec}^2/\text{inch}$, rather than the 1.50 E-5 value that was used in this investigation. Because of the way the supporting values B_x and K_x were developed, it is believed that this difference in M_x does not significantly affect any interpretations of data that were arrived at in this study.

4. CONCLUSIONS AND RECOMMENDATIONS

Principally because of the similarity in test results achieved between CSMP runs 24 and 25 and FCHL test no. E-16, it is concluded that deadspace in the couplings between the second-stage valve spools and their associated torque feedback springs (with or without similar deadspace in the couplings between the power spool and associated torque feedback springs) must be considered to be a possible cause of the problem oscillations occurring above 40 Hz in the hardware elevon actuation subsystems.

It is recommended that the actuator manufacturer Moog, Inc., be made aware of the results of this investigation and that the comments of that company regarding the deadspace theory of oscillations be solicited.

It is further recommended that the R/SD actuator math model used in this investigation be modified especially around the flapper and second-stage (servo) valve stages to bring it into conformance with the Moog actuator math model and that a limited number of tests be repeated using this modified math model. If results warrant, further investigations incorporating different values of deadspace, different FCHL reference data, deadspace included in different amounts in different channels, outboard actuator models, and so forth can be considered.