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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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PREPARED BY

W. W. Powell, Sr.

W. W. Powell, Sr.
Lockheed Electronics Company, Inc.

APPROVED BY

A. T. Hiemer

A. T. Hiemer, Analysis Manager
Aerosurface Actuation Subsystems

O. P. Littleton

O. P. Littleton, Head
Flight Control Section

D. H. Shelton

D. H. Shelton, Chief
Navigation and Control Branch

J. F. Hanaway

J. F. Hanaway, Chief
Avionics Systems Division

Engineering and Development Directorate

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
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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 "deadspace" 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 unbypassed 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 funtionally 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	Servovalve (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	Servovalve flapper displacement	radians
Q_f	Servovalve 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_p	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	Servovalve (second stage) amplification area	0.0368	-	in^2
B_e	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	$in\text{-}lbs\text{-}sec^2$
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	Servovalve net stiffness	58	–	(in-lb)/rad
K_{fb}	Actuator position transducer sensitivity	0.683	1.173	V/in
K_p	Servovalve 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	$in^3/(sec\text{-}\sqrt{lb})$
K_{qs}	Servovalve (second stage) flow gain	652	–	cis/in
K_s	Local (backup) structure stiffness external to actuator	233000*	170000*	lb/in
K_{tm}	Servovalve 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_w	Servovalve first stage differential flow gain	45.3	–	cis/rad
M_p	Power spool mass	0.001	–	$(lb\text{-}sec^2)/in$
P_s	Hydraulic supply pressure to actuator interface (supply minus return)	2800	–	psi
R	"Average" actuator moment arm [see table 2-4 for $R(\delta_e)$]	14.46	8.42	in
R_f	Actuator pressure drop coefficient	0.0212	0.0397	$psi/(cis)^2$
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	DPS 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	DPS 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(δ_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	-Arm retraction
-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	-Arm extension
+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	

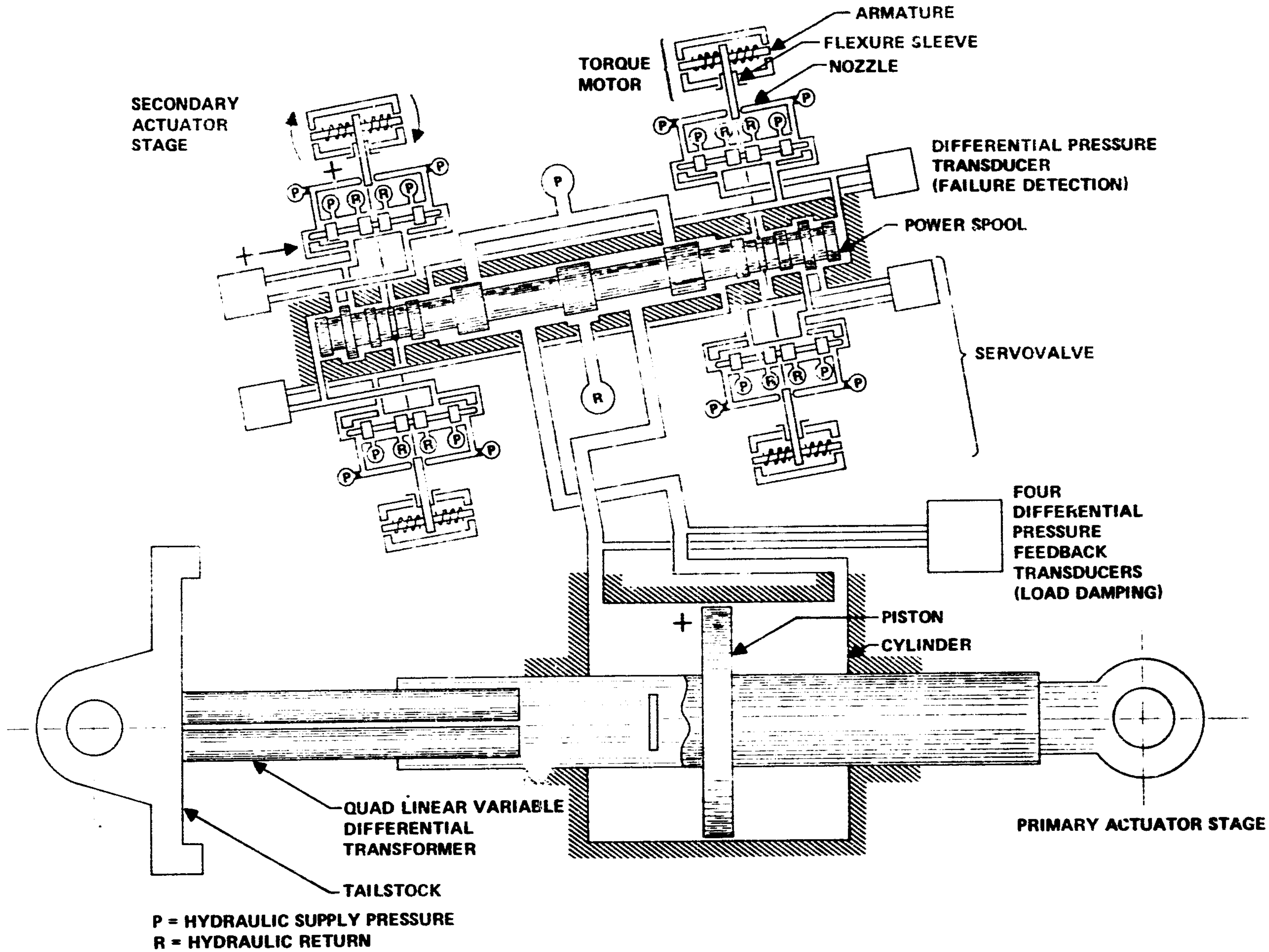


Figure 2-1.— Simplified hydraulic schematic of inboard or outboard actuator.

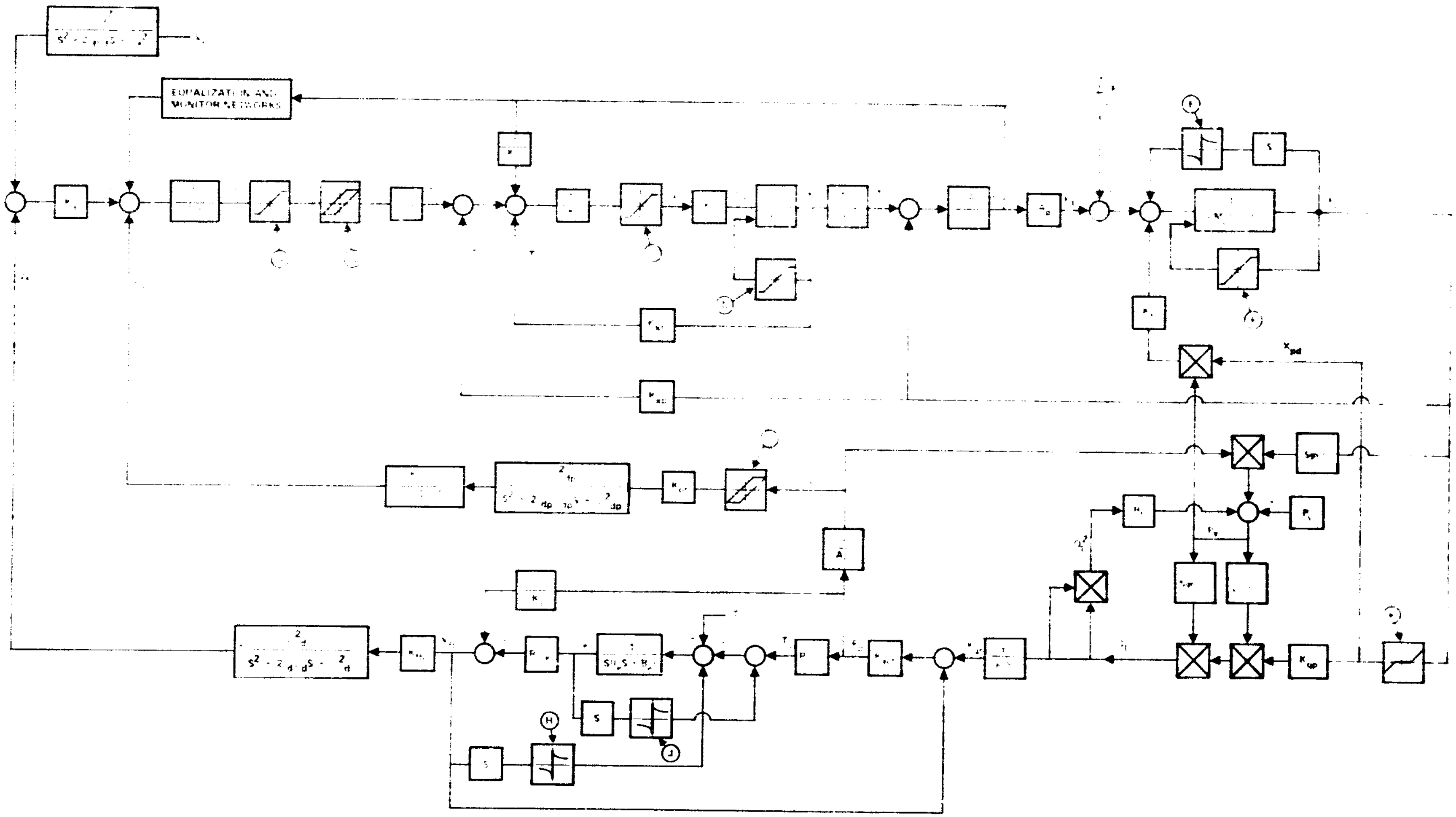


Figure 2-2.— Nonlinear OV102 elevon actuation subsystem math model.

```
$$$CONTINUOUS SYSTEM MODELING PROGRAM  III    V1M2    TRANSLATOR OUTPUT$$$
TITLE   625-30 MOOG INBOARD ELEVON ACTUATOR FOR SSV-OV102
*       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 = SMAL (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 = LIMA (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  Z, ZDOT = LIM2 (ZDDOT, P3, P4)
PROCEDURE ZDDOT1, ZDOT1 = LIMB (Z, 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 RESET1 THROUGH RESET4 CONTROL RESET CONDITIONS
*      IN ASA CHANNELS 1 THROUGH 4 RESPECTIVELY.....................
*          SET RESETN = -1 FOR NORMAL OPERATION.
*          SET RESETN = +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   THR1=7.56,        THR2=7.56,        THR3=7.56,        THR4=7.56
CONST   TA1=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)
        KAB2 = 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 = KFB * XLZERO
          VZERO1 = KAA1 * XLZERO
          VZERO2 = KAA2 * XLZERO
          VZERO3 = KAA3 * XLZERO
          VZERO4 = KAA4 * XLZERO
*
CONST     DELEIN = 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     KTHTA1=45.3,      KTHTA2=45.3,      KTHTA3=45.3,      KTHTA4=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     VS1=0.08,         VS2=0.08,         VS3=0.08,         VS4=0.08
CONST     XSLIM1=0.015,     XSLIM2=0.015,     XSLIM3=0.015,     XSLIM4=0.015
*
*
CONST     AP=21.82,         BF=4.5E4,         BP=6.5,           CPUL=10.0
CONST     ELSTK=6000.0,     IE=7588.0,        KACT=4.57E5,      KB=0.943
CONST     KQP=162.1,        KRAD=57.3,        KS=2.33E5,        MP=0.001
CONST     OVLAP=0.0004
CONST     PS=2800.0,        RAMSTK=3750.0,    RF=0.0212,        STIK=25.0
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, 0.680), ( 0.00, 1.989), ( 5.00, 3.230), ...
     ( 10.0, 4.547), ( 15.0, 5.779), ( 20.0, 6.972), ( 21.5, 7.320)
*
*
DYNAMIC
*
NOSORT
        VAN1 = LIMIT (-INTLM1, INTLM1, VAN1)
        VAN2 = LIMIT (-INTLM2, INTLM2, VAN2)
        VAN3 = LIMIT (-INTLM3, INTLM3, VAN3)
        VAN4 = LIMIT (-INTLM4, INTLM4, VAN4)
        VAT1 = LIMIT (LIMM1, LIMP1, VAT1)
        VAT2 = LIMIT (LIMM2, LIMP2, VAT2)
        VAT3 = LIMIT (LIMM3, LIMP3, VAT3)
        VAT4 = LIMIT (LIMM4, LIMP4, 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)
        DELED = LIMIT (-36.5, 21.5, DELED)
SORT
*
*
*
*
***************  COMMAND GENERATION  ***************
*
*       ASA COMMANDS ARE RATE LIMITED TO 20 DEGREES/SECOND
*****   DELEIN 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 = DELEIN * 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
        VAW1A = KAJ1 * VCMD1
        VAW1 = FILTER (VAW1A, KAK1, KAL1, VZERO1)
        VAA1 = REALPL (XLZERO, TA1, XFB)
        VAB1A = KAA1 * VAA1
        VAB1 = FILTER (VAB1A, KAB1, KAC1, VZERO1)
        VAC1 = HSTRSS (0.0, -HA1, HA1, 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, THI, 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 - KAHI * VANI
         DVANI = KAGI * VAMI
         VANI = LIMI (DVANI, -INTLMI, INTLMI)
         VAPI = KAPI * VANI
         VAXI = KAMI * (VAWI - VARI - VAFI - VAPI)
         II = LIMIT (-LAI, LAI, VAXI)
*
********  FAILURE MONITOR SECTION ... ASA CHANNEL 1  ********
*
PROCEDURE VARI = CNTRLI (VAJI, DETI, UPREFI, DNREFI)
         VARI = -DNREFI
         IF (ABS(VAJI).GE.DETI) VARI = UPREFI - DNREFI
ENDPROCEDURE
*
PROCEDURE DVATI = AAAAI (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 = LIMI (DVATI, LIMNI, LIMPI)
*
PROCEDURE VAVI, PFAILI = BBBBI (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.OR.RESETI.GT.0.0) GO TO 1113
         IF (VAVI.GT.0.0.OR.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 - VZEROI
         VAWMI = VAWI - VZEROI
         VAAMI = VAAI - XLZERO
         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 = HSTRSS (0.0, -HA4, HA4, FL)
        VAD4 = REALPL (0.0, TA4, VAC4)
        VAF4A = KAD4 * VAD4
        VAE4 = FILTER (VAE4A, KAR4, KAT4, 0.0)

        VAF4A = REALPL (0.0, TB4, VAE4)
        VAF4 = DERIV (0.0, VAF4A)
        PS4 = P4
        VAG4 = HSTRSS (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 = KAG4 * VAM4
        VAN4 = LIMI (DVAN4, -INTLM4, INTLM4)
        VAP4 = KAP4 * VAN4
        VAX4 = KAM4 * (VAW4 - VAB4 - VAF4 - VAP4)
        I4 = 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 VAT4 = 0.0
        DVAT4 = 0.0
   4442 CONTINUE
ENDPROCEDURE
*
        VAT4 = LIMI (DVAT4, LIMN4, LIMP4)
*
PROCEDURE VAV4, PFAIL4 = BBBB4 (VAT4, THR4, RESET4, BYPAS4, TIME)
         VAV4 = -1.
         IF (VAT4.GE.THR4) VAV4 = +1.
         IF (BYPAS4.GT.0.0) GO TO 4444
         IF (TIME.EQ.0.0.OR.RESET4.GT.0.0) GO TO 4443
         IF (VAV4.GT.0.0.OR.PFAIL4.GT.1.5) GO TO 4444
   4443 PFAIL4 = 0.
         GO TO 4445
   4444 PFAIL4 = +2.
```

Figure 2-3.— Continued.

```
  4445 CONTINUE
ENDPROCEDURE
*
*
*  .....THE FOLLOWING VARIABLES SHOW CHANGES FROM INITIAL CONDITIONS.....
*
       VCMDM4 = VCMD4 - VZERO4
       VAWM4 = VAW4 - VZERO4
       VAAM4 = VAA4 - XLZERO
       VABM4 = VAB4 - VZERO4
*
       ERROR4 = VAW4 - VAB4
*
*  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
*
       VCMDM = VCMD - VZERO
       XFBM = XFB - XLZERO
       XLM = XL - XLZERO
       XQRM = XQR - XLZERO
*
*
***************  ACTUATOR CHANNELS 1-3  ***************
*
       IL1 = I1
          IH1 = 0.0075 + 0.015 * ABS (IL1)
       IHYS1 = HSTRSS (0.0, -IH1, IH1, IL1)
       THFA1 = (KTM1*IHYS1 - KXP1*XPOSP - KXS1*XSD1 - P1/KP1) / KE1
       THTAF1 = LIMIT (-THLIM1, THLIM1, THFA1)
       QF1 = KTHTA1 * THTAF1
       DXX1 = QF1/AS1
       FXC1A = KX * (DXX1 - DXS1)
       FXC1 = LTDINT (FXC1A)
       DDXS1 = (FXC1 - AX*P1 - BX*DXS1) / MX
       DXS1 = LTDINT (DDXS1)
       XS1 = LIMI (DXS1, -XSLIM1, XSLIM1)
       XSD1 = DEADSP (-DDSP, DDSP, XS1)
       XQP1A = XS1 * KQS1 / AP1
       XQP1B = XQP1A * SQRT(ABS(PVS1/PSD)) * SIGN(1.0,PVS1)
          PVS1 = PSD - P1 * SIGN(1.0, XS1)
       XQP1 = INTGRL (0.0, XQP1B)
       P1A = (XQP1 - XP1) * 2.0 * BETA1 * AP1 / VS1
PROCEDURE P1 = AA1 (PFAIL1, PSD, P1A)
       IF (PFAIL1) 12,14,16
   12  P1 = -PSD
       GO TO 19
   14  P1 = LIMIT (-PSD, PSD, P1A)
       GO TO 19
   16  P1 = PSD
       IF (PFAIL1.GE.1.5) P1 = 0.0
   19  CONTINUE
ENDPROCEDURE
       F1 = P1 * AP1
*
*
***************  ACTUATOR CHANNEL 4  ***************
*
       IL4 = I4
          IH4 = 0.0075 + 0.015 * ABS (IL4)
       IHYS4 = HSTRSS (0.0, -IH4, IH4, IL4)
```

Figure 2-3.— Continued.

```
        THFA4 = (KTM4*IHYS4 - KXP4*XPDSP - KXS4*XSD4 - P4/KP4) / KE4
        THTAF4 = LIMIT (-THLIM4, THLIM4, THFA4)
        QF4 = KTHTA4 * THTAF4
        DXX4 = QF4/AS4
        FXC4A = KX * (DXX4 - DXS4)
        FXC4 = LTDINT (FXC4A)
        DDXS4 = (FXC4 - AX*P4 - BX*DXS4) / MX
        DXS4 = LTDINT (DDXS4)
        XS4 = LIMI (DXS4, -XSLIM4, XSLIM4)
        XSD4 = DEADSP (-DDSP, DDSP, XS4)
        XQP4A = XS4 * KQS4 / AP4
        XQP4B = XQP4A * SQRT(ABS(PVS4/PSD)) * SIGN(1.0,PVS4)
            PVS4 = PS) - P4 * SIGN(1.0, XS4)
        XQP4 = INTGRL (0.0, XQP4B)
        P4A = (XQP4 - XP) * 2.0 * BETA4 * AP4 / VS4
PROCEDURE P4 = AA4 (PFAIL4, PSD, P4A)
        IF (PFAIL4) 42,44,46
   42   P4 = -PSD
        GO TO 49
   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 * F1 + 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 = INTGRL (0.0, DDXP)
        XP = LIMI (DXP, -XPLIM, XPLIM)
        XPD = DEADSP (-OVLAP, OVLAP, XP)
```

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, FOFZ)
      PDAAA = RF * Z**2
      PVAAA = PS - PDAAA - PL*SIGN(1.0,XP)
   FOFZ = KQP * XPD * SQRT(ABS(PVAAA)) * SIGN(1.0,PVAAA)
*
      QL = Z
      QLSQD = QL**2
      PD = RF * QLSQD
      PSD = PS - PD
      PV = PSD - PL * SIGN (1.0, XP)
*
*
***************  LOAD DYNAMICS  ***************
*
*
      DXQR = QL / AR
      XQR = INTGRL (XLZERO, DXQR)
      FP = KACT * (XQR - XFB)
      PL = FP / AR
      R = AFGEN (MOMARM, DELED)
      TP = FP * R
*
* THE FOLLOWING PROCEDURE COMPUTES THE TOTAL TORQUE (TT) INCLUDING THE
* EFFECTS OF ACTUATOR STICTION AND ELEVON STICTION.
*
PROCEDURE TT = DDD (TP, TAERO, DDELED, DXFB, ELSTK, RAMSTK)
*
      IF (DXFB.NE.0.0) GO TO 500
      IF (DDELED.NE.0.0) GO TO 600
*  TO 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
*  TO 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
*
      DDDELE = (TT - BE*DDELE) / IE
```

Figure 2-3.— Continued.

```
         DELE, DDELE = LIM2 (DDDELE, -0.6369, 0.3752)
         DELED = KRAD * DELE
         DDELED = KRAD * DDELE
         XL  = AFGEN (STROKE, DELED)
         XFB = (KS*XL + KACT*XQR) / (KS + KACT)
         DXFB = DERIV (0.0, XFB)
*
TERMINAL
*
METHOD RKSFX
TIMER    DELT=0.00005, OUTDEL=0.002, PRDEL=0.01, FINTIM=1.0
RANGE    IL1, IHYS1, ILL, IL4, P1, P4, PL, QL, VAF1, VAF1, VAJ1, VAV1,...
         VAX1, VCMD1, XFB, XL, XP, XPD, XQR, XS1, DELED, DDELED, DMDELE
LABEL    625-30 MOOG ELEVON ACTUATOR (INBOARD) WITH ASA-1
LABEL    STABILITY TEST
LABEL    15 NOVEMBER 1978
OUTPUT   VCMDM1
LABEL    RAM POSITION COMMAND VOLTAGE, LESS OFFSET (VOLTS)
OUTPUT   VARM1
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   DDELED
LABEL    ELEVON SURFACE RATE (DEGREES/SECOND)
OUTPUT   XS1
LABEL    SECOND-STAGE SPOOL DISPLACEMENT IN CHANNELS 1-3 (INCHES)
OUTPUT   XP
LABEL    POWER SPOOL DISPLACEMENT (INCHES)
PRINT    IL, I4, DXS1, DXS4, P1A, P4A, P1, P4, DXP
END
STOP
```

Figure 2-3.— Continued.

```
OUTPUT VARIABLE SEQUENCE
KAB1   KAB2   KAB3   KAB4   KAC1   KAC2   KAC3   KAC4   KAK1   KAK2
KAK3   KAK4   KAL1   KAL2   KAL3   KAL4   KAR1   KAR2   KAR3   KAR4
KAT1   KAT2   KAT3   KAT4   KAV1   KAV2   KAV3   KAV4   KAW1   KAW2
KAW3   KAW4   VZERO  VZERO1 VZERO2 VZERO3 VZERO4 VAN1   VAN2   VAN3
VAN4   VAT1   VAT2   VAT3   VAT4   XS1    XS2    XS3    XS4    XP
DELED  CMDA   CMDB   BLIP   CMDELE VCMDA  VCMD   VCMD1  VAW1A  ZZ1003
ZZ1000 ZZ1001 ZZ1002 VAW1   DLLED  XL     XFB    ZZ1006 VAA1   VAB1A
ZZ1012 ZZ1009 ZZ1010 ZZ1011 VAB1   FP     PL     VAC1   ZZ1018 VAD1
VAF1A  ZZ1022 ZZ1019 ZZ1020 ZZ1021 VAF1   ZZ1029 VAF1A  VAV1   PFAIL1
XPF    ZZ1128 PDAAA  PVAAA  FOLZ   Z      QL     CLSQC  PD     PSC
P1A    P1     PS1    VAG1   ZZ1030 ZZ1031 VAH1   VAJ1A  ZZ1037 ZZ1034
ZZ1035 ZZ1036 VAJ1   VAK1   VAL1   VAM1   DVAN1  ZZ1042 ZZ1043 VAN1
VAR1   DVAT1  ZZ1046 VAT1   VCMD4  VAW4A  ZZ1052 ZZ1049 ZZ1050 ZZ1051
VAA4   ZZ1057 VAA4   VAB4A  ZZ1061 ZZ1058 ZZ1059 ZZ1060 VAB4   VAC4
ZZ1067 VAD4   VAF4A  ZZ1071 ZZ1068 ZZ1069 ZZ1070 VAF4   ZZ1073 VAF4A
VAV4   PFAIL4 P4A    F4     PS4    VAG4   ZZ1079 ZZ1080 VAH4   VAJ4A
ZZ1086 ZZ1083 ZZ1084 ZZ1085 VAJ4   VAK4   VAL4   VAM4   DVAN4  ZZ1091
ZZ1092 VAN4   VAR4   DVAT4  ZZ1095 VAT4   VAF1   VAP1   VAX1   I1
H1     IH1    THYS1  XPDSP  XSD1   THFA1  THTAF1 QF1    DXX1   FXC1A
ZZ1098 FXC1   DDXS1  ZZ1101 DXS1   ZZ1104 ZZ1105 XS1    XQP1A  P/S1
XQP1B  XQP1   VAF4   VAP4   VAX4   I4     IL4    IH4    THYS4  XSD4
THFA4  THTAF4 QF4    DXX4   FXC4A  ZZ1110 FXC4   DDXS4  ZZ1113 DXS4
ZZ1116 ZZ1117 XS4    XQP4A  PVS4   XQP4B  XQP4   F1     F4     PV
FE     FT     COULF  DDXPA  DDXP   DXP    ZZ1124 ZZ1125 XP     DXQR
XQR    K      TP     DDELED DXFB   TT     DODELE ZZ1131 DDELE  ZZ1132
DELE   VCMDM1 VAWM1  VAAM1  VABM1  ERROR1 VCMDM4 VAWM4  VAAM4  VABM4
ERROR4 VCMDM  XFBM   XLM    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.

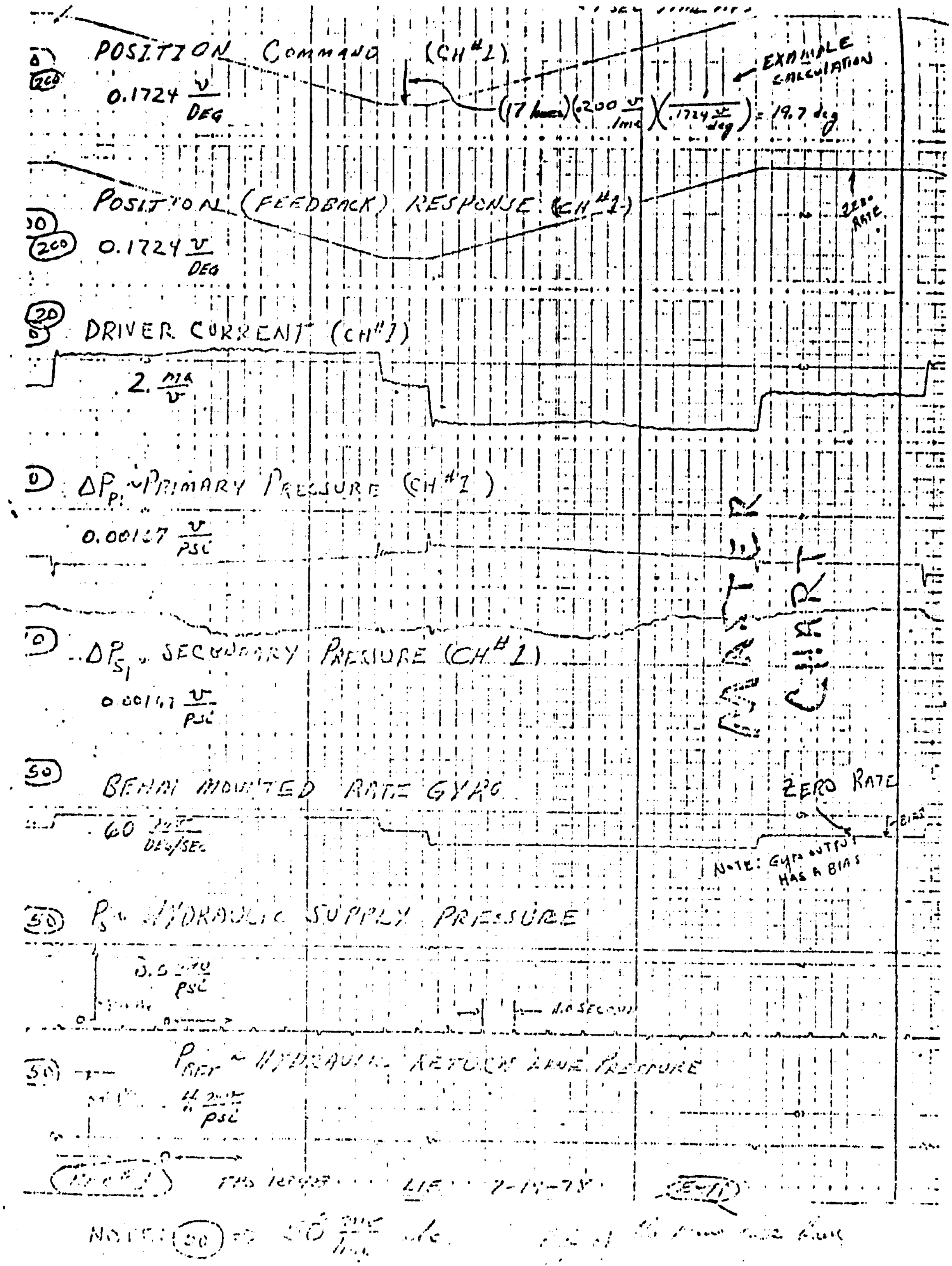


Figure 2-4.— FCHL master chart.

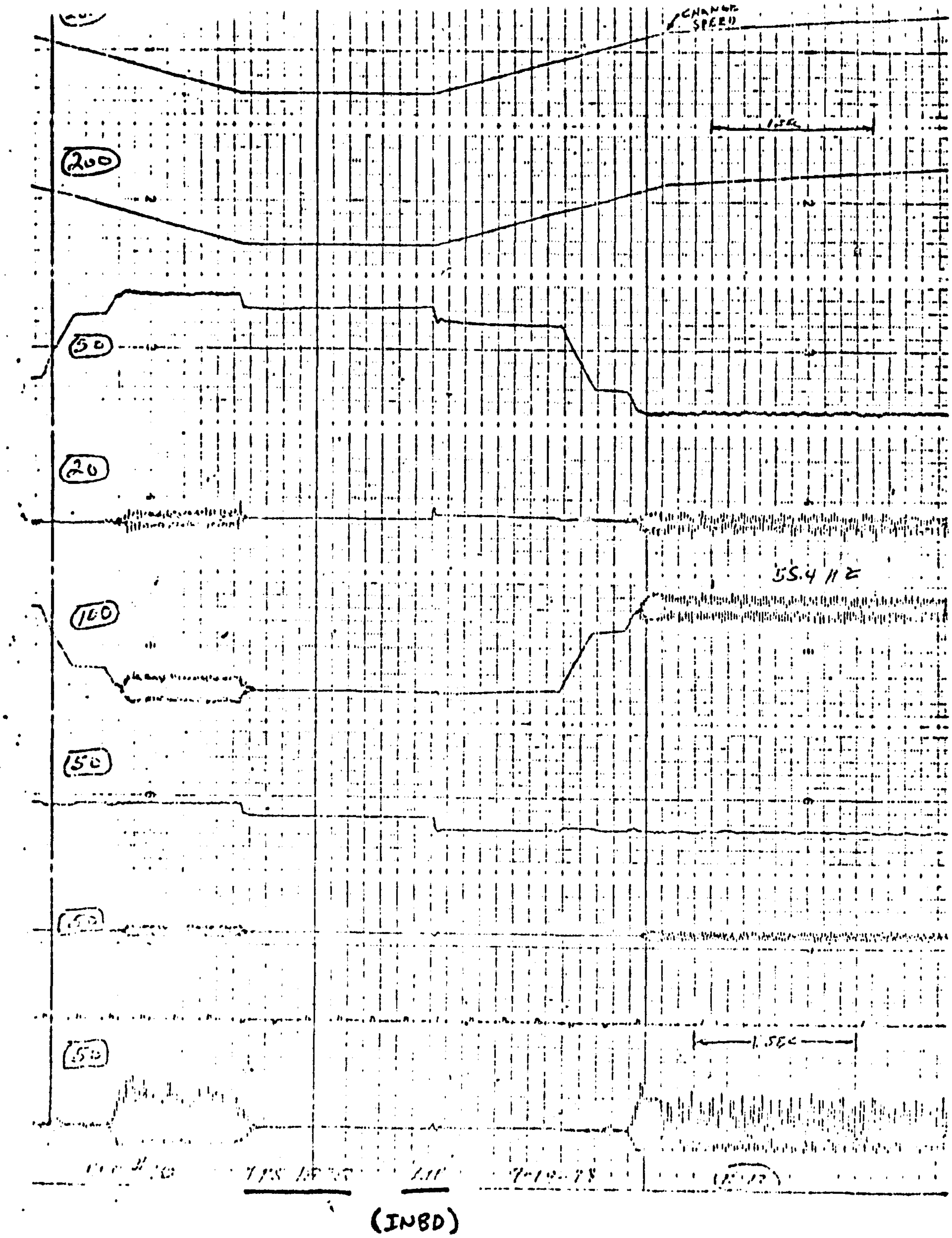


Figure 2-5.— Strip chart (E-12).

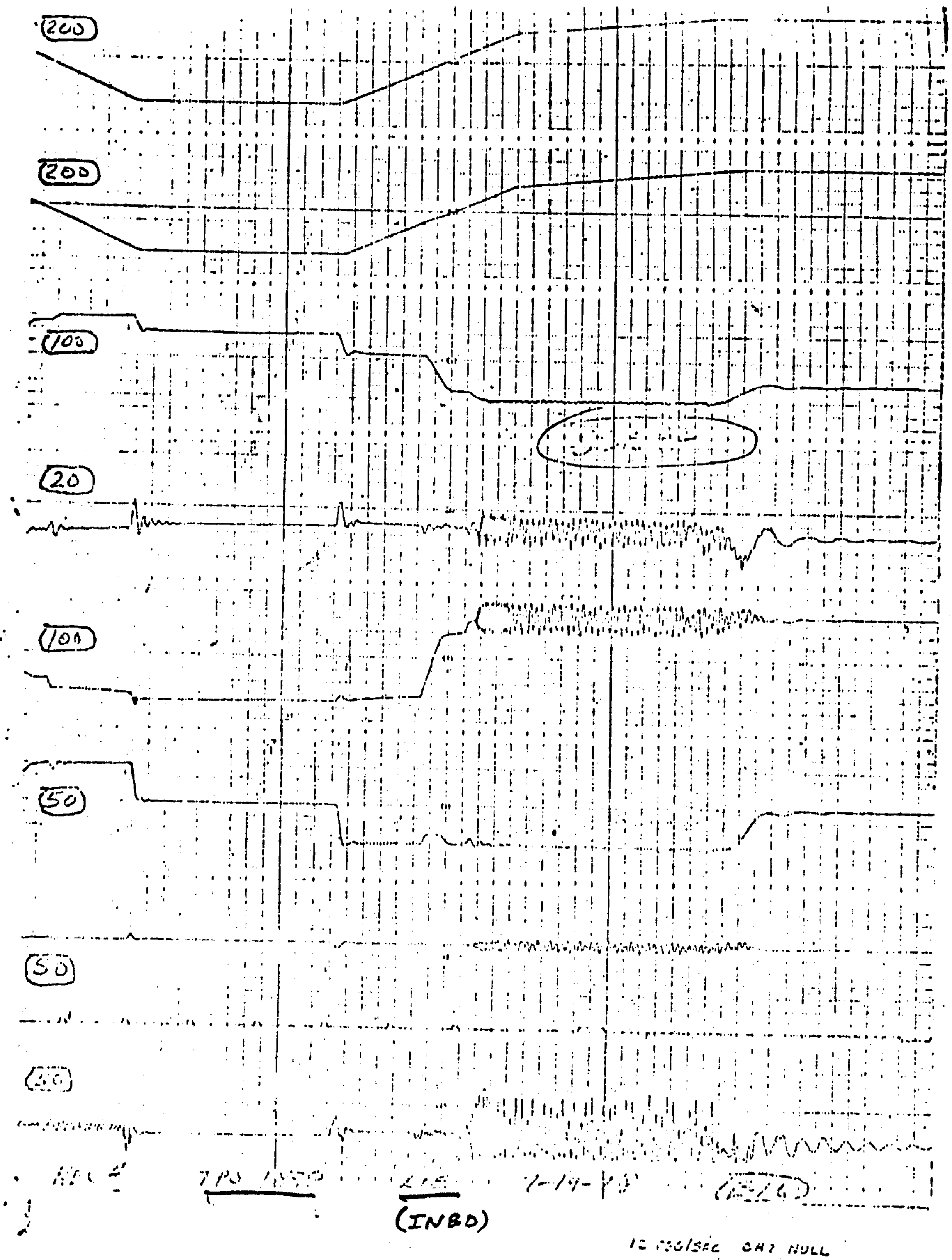


Figure 2-6.— Strip chart (E-16).

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

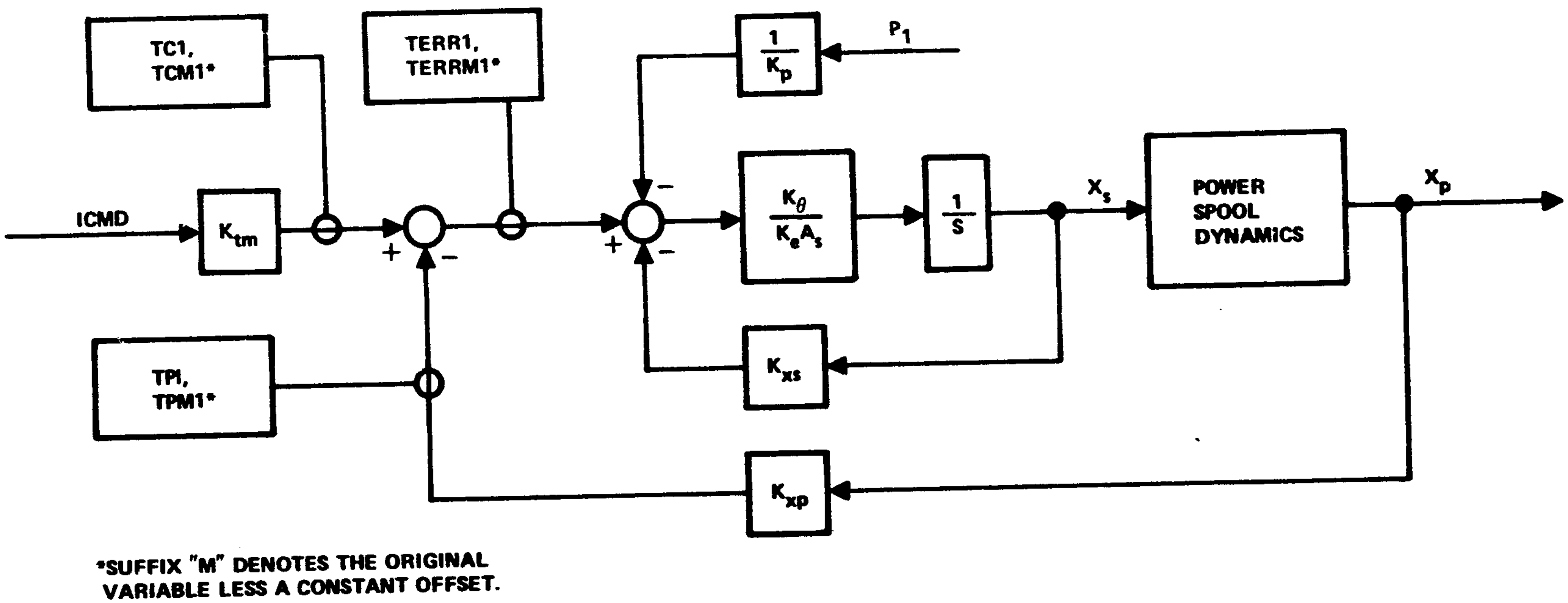


Figure 3-1.— Definition of variables for secondary actuator frequency response measurements.

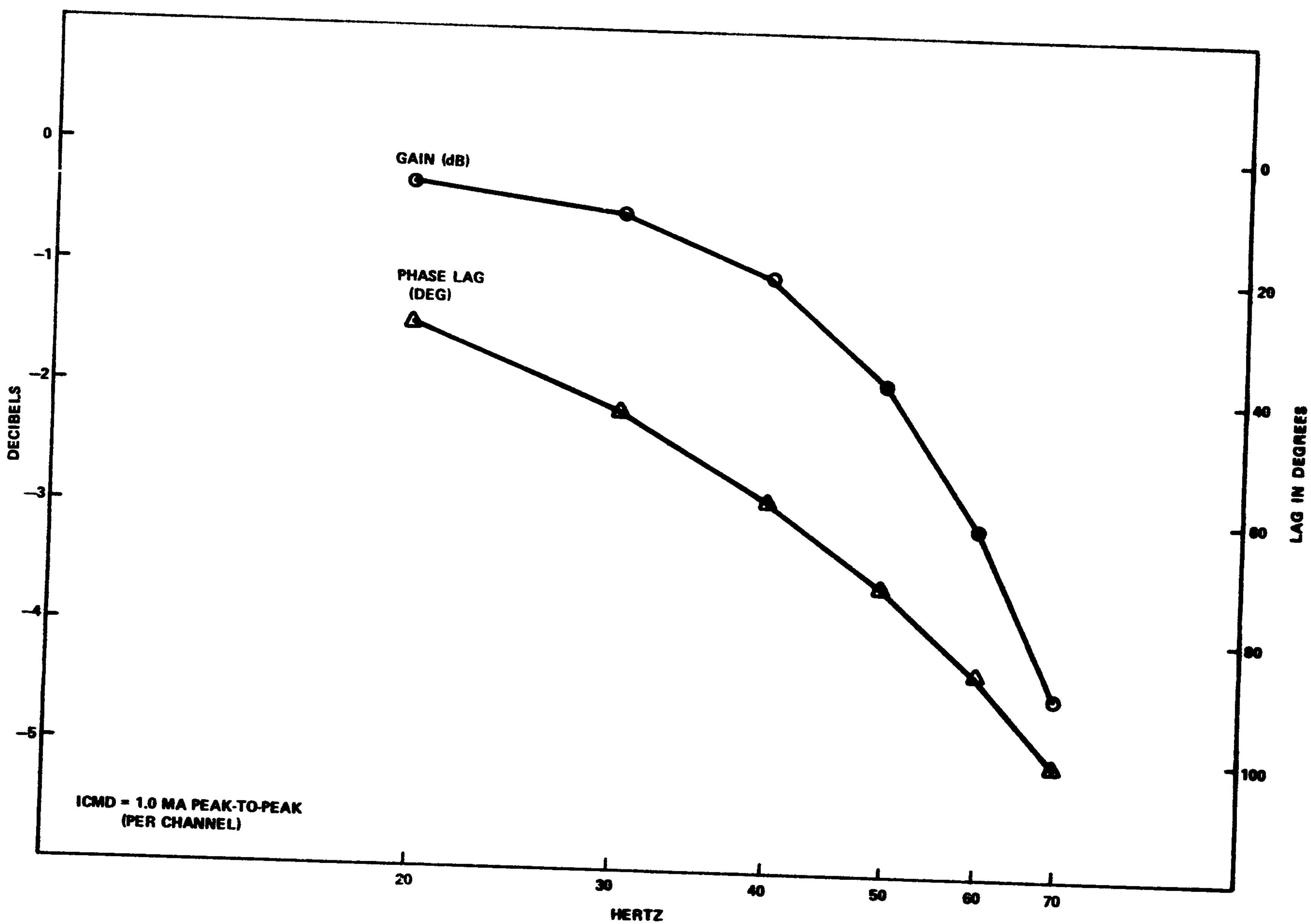


Figure 3-2.– Inboard secondary actuator closed-loop response (TP1/TC1), no faults.

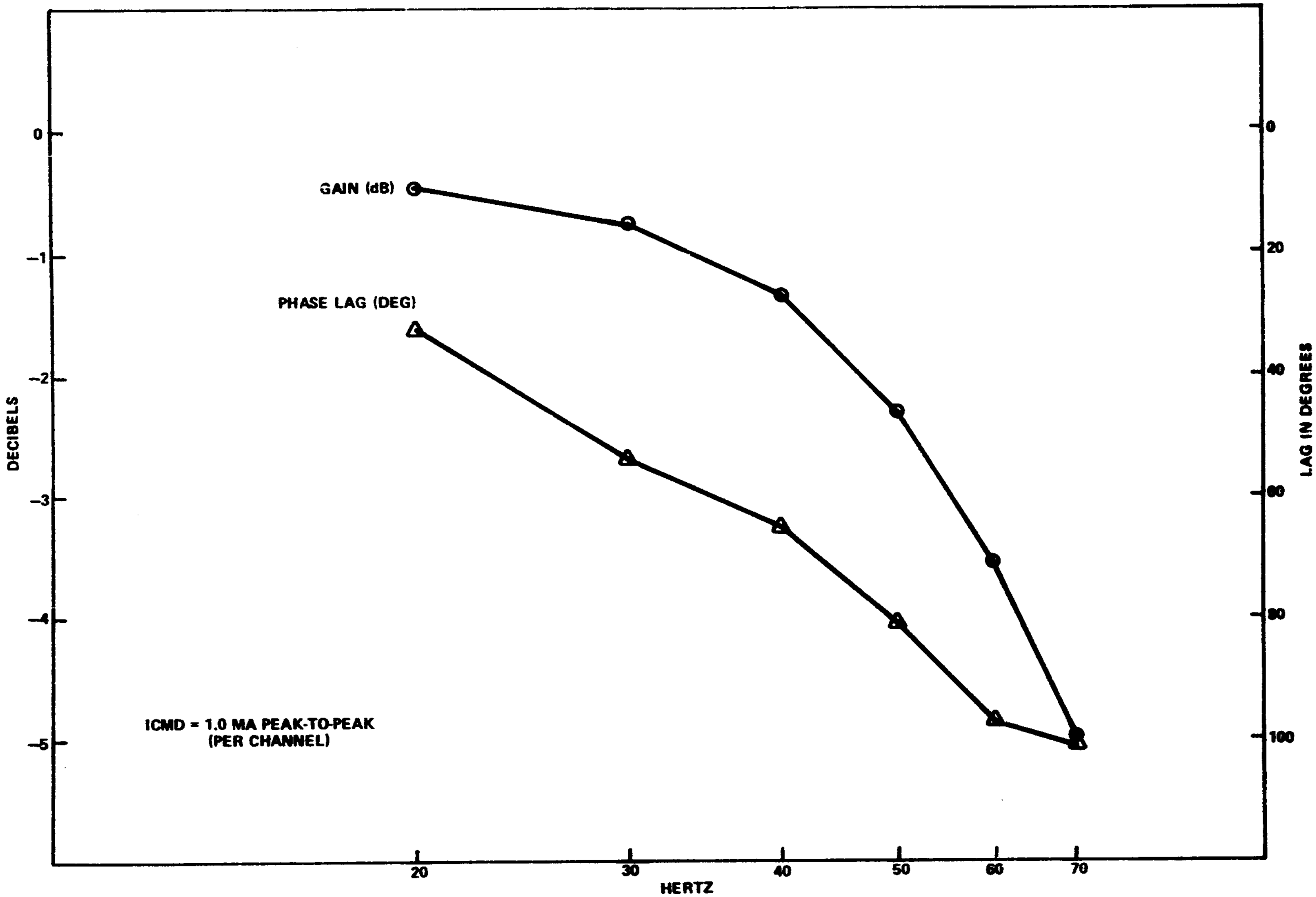


Figure 3-3.— Inboard secondary actuator closed-loop response (TPM1/TCM1), single channel hardover.

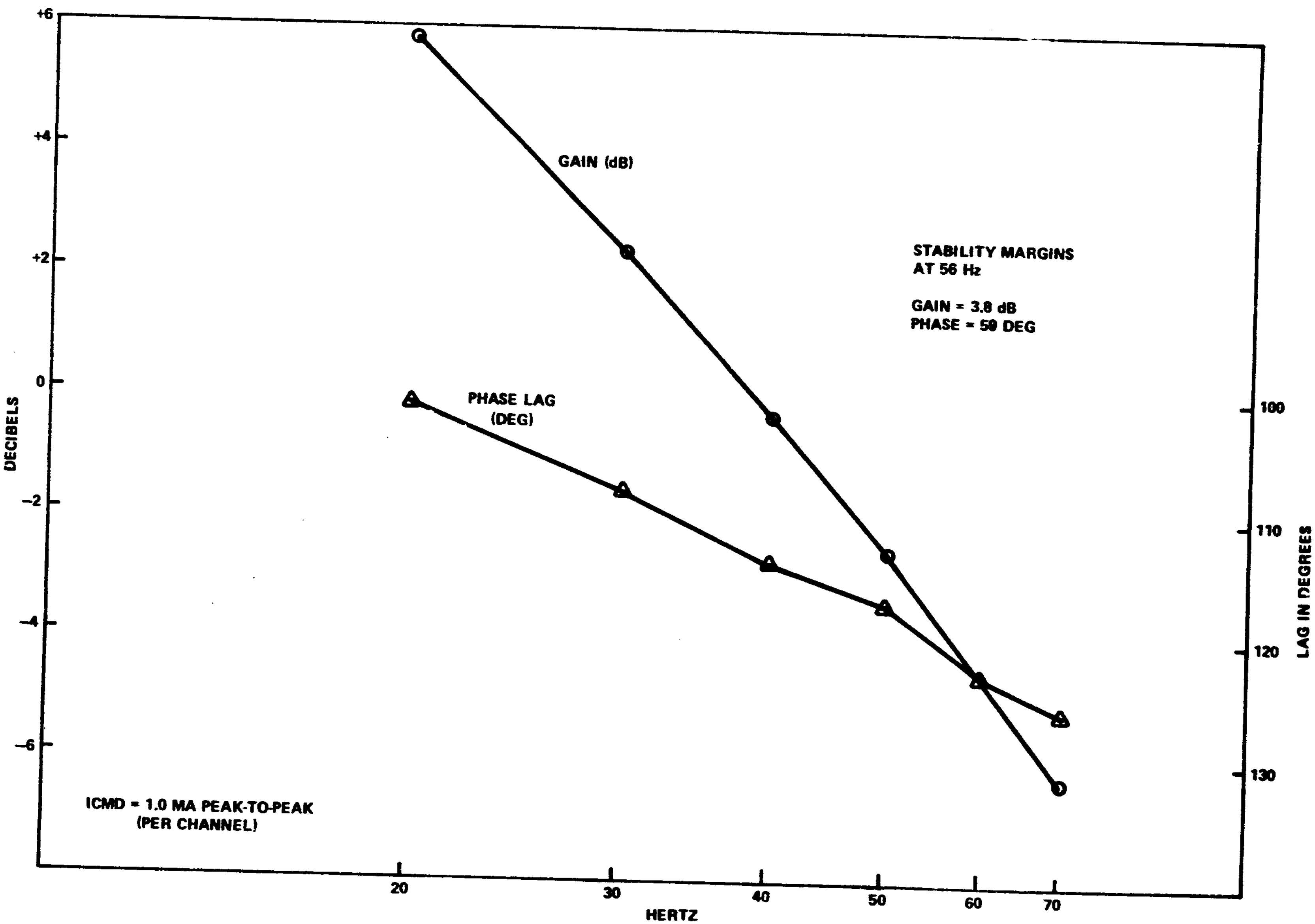


Figure 3-4.— Inboard secondary actuator open-loop response (TP1/TERR1), no faults.

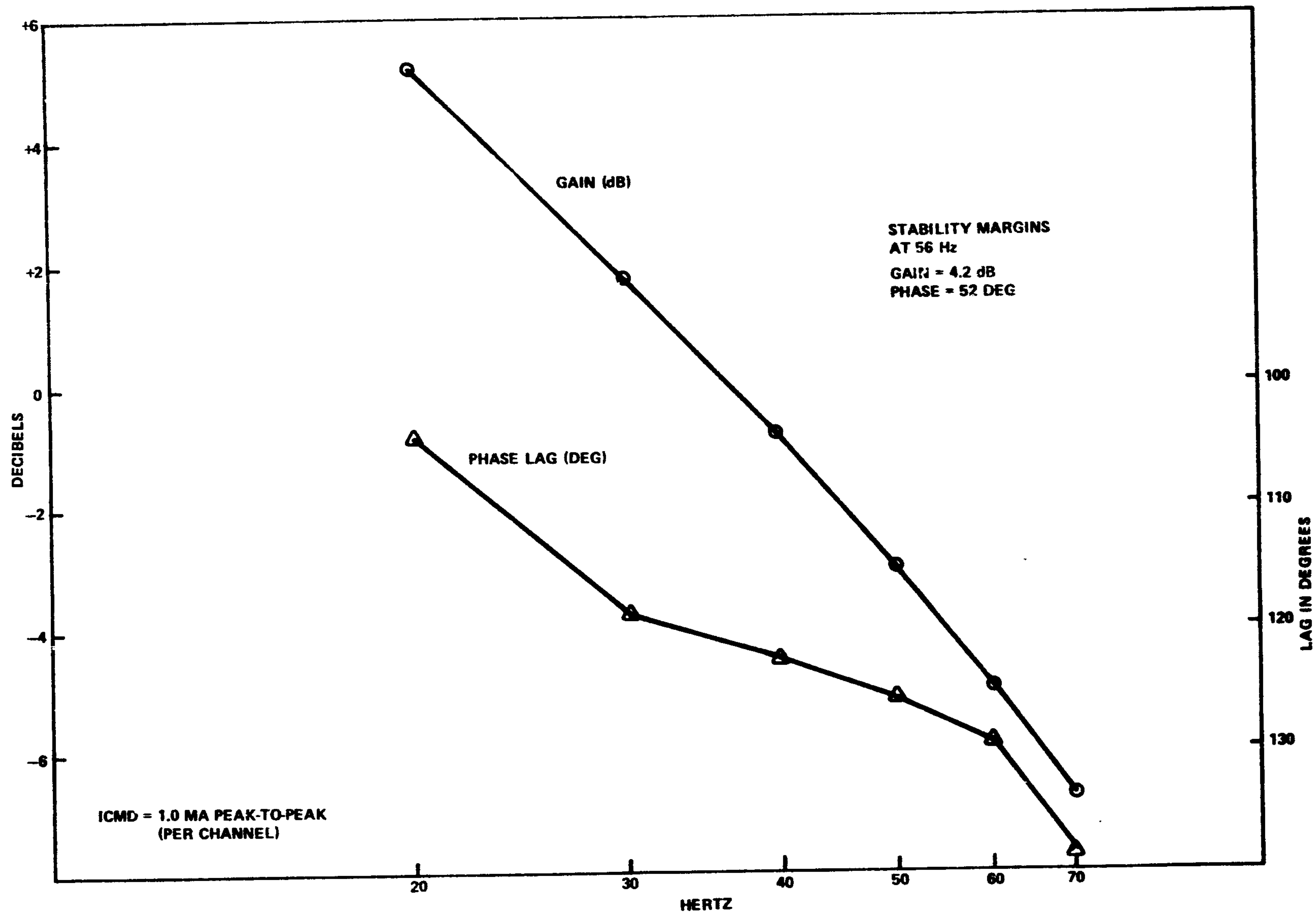


Figure 3-5.— Inboard secondary actuator open-loop response (TPM1/TERRM1), single channel hardover.

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 (η) 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.

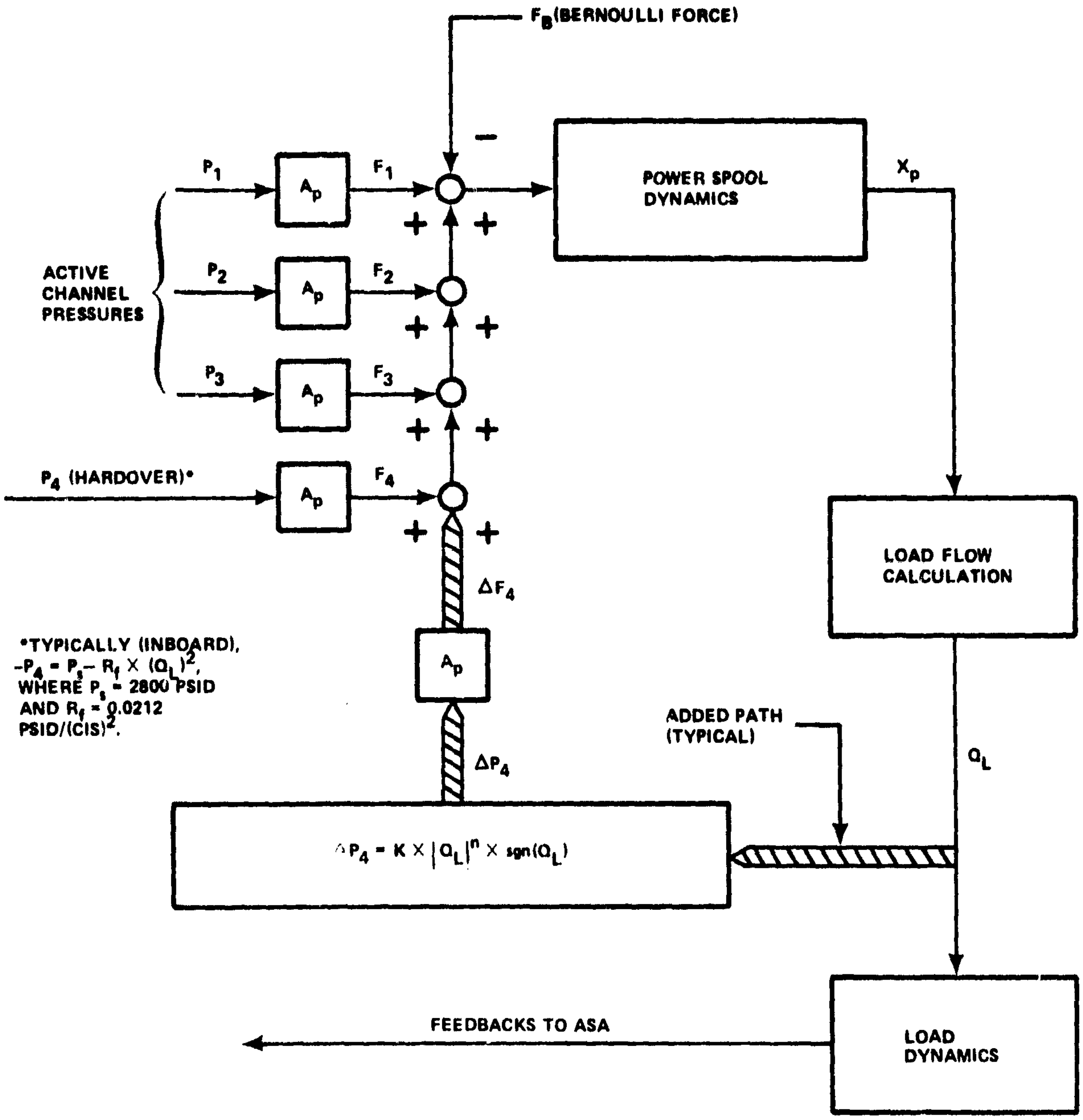


Figure 3-6.— Addition of flow-dependent pressure coupling to power spool dynamics for hardover feedback theory tests.

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 psid/(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)$^{\eta}$]	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 elevon 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 (fn) and damping ratios (ζ) which led to their selection as outlined in the following paragraphs.

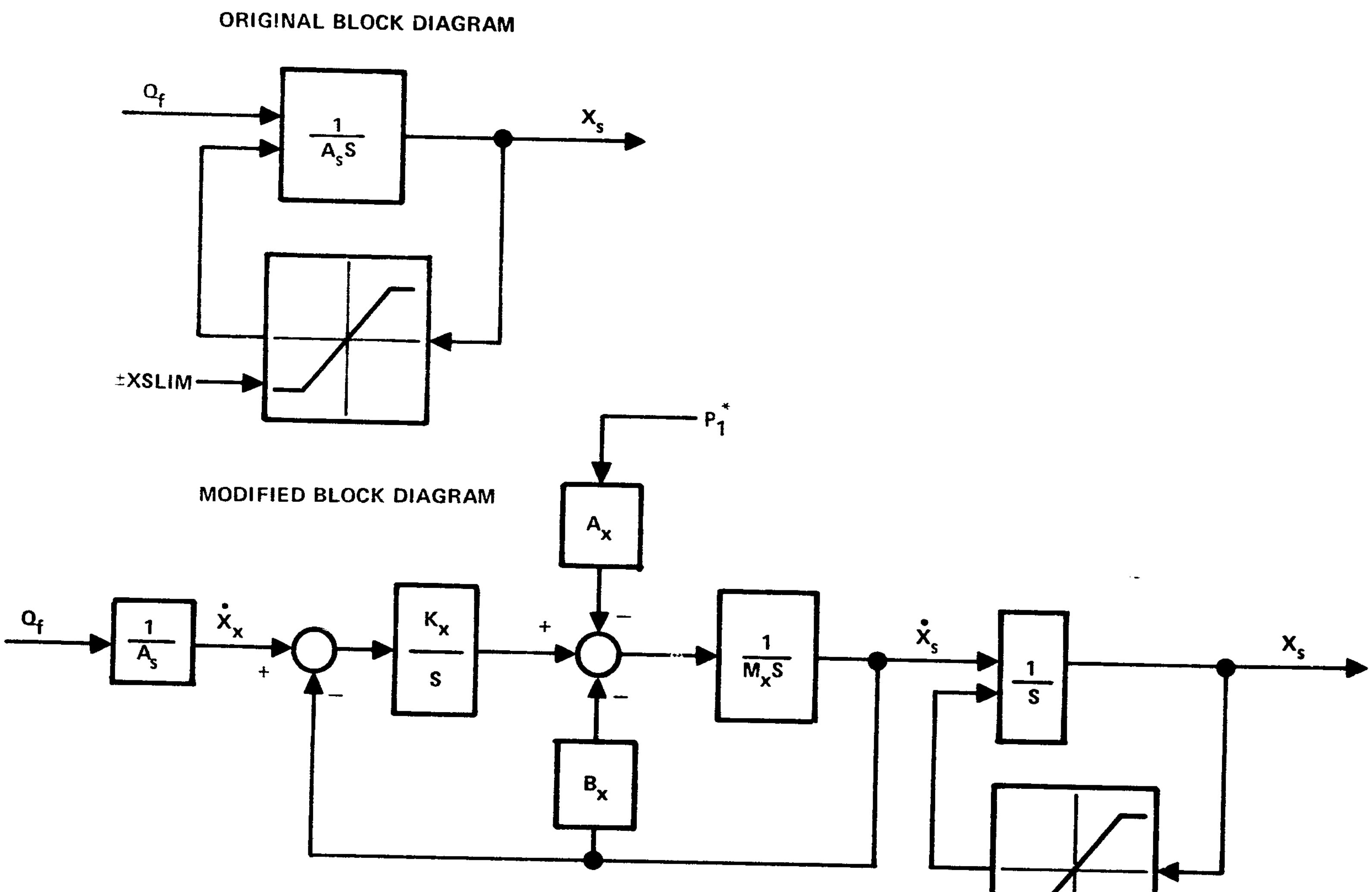
TABLE 3-2.— NEW VARIABLES AND PARAMETERS

Symbol	Units	Description
$\dot{X}_x$	inch/sec	Second-stage spool rate (ideal)
$\dot{X}_s$	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 $\left(\frac{\text{lb-sec}^2}{\text{in}}\right)$	B_x $\left(\frac{\text{lb-sec}}{\text{in}}\right)$	A_x (in^2)	Calculated f_η (Hz)	Calculated 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.



*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.

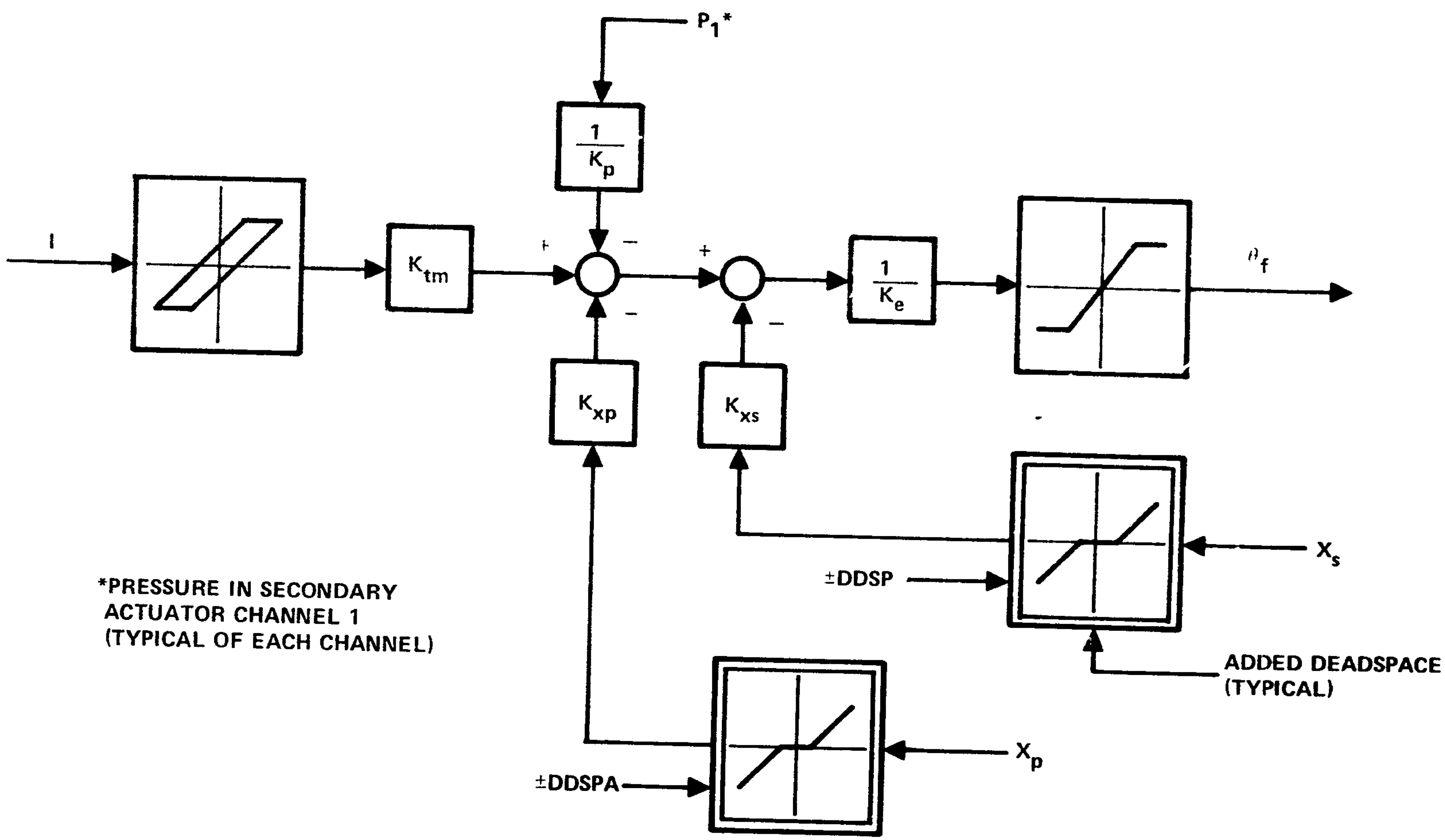


Figure 3-8.— Addition of deadspaces DDSP and DDSPA for deadspace theory tests.

The value used for M_x (1.5 E-5 lb-sec^2/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 $f\eta = (1/2\pi)\sqrt{K_x/M_x}$ and the damping ratio $\zeta = B_x/4\pi f\eta M_x$. These equations were solved to find K_x and B_x:

$$K_x = 4\pi^2 f\eta^2 M_x$$

$$B_x = 4\pi f\eta\zeta M_x$$

Values for deadspaces DDSP and DDSPA were determined by experimentation. The total throw of each second-stage spool was limited to ±XSLIM = ±0.015 inch, and that of the power spool was limited to ±XPLIM = ±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 se. of reference data for verification purposes.

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

Run no.	Printout (1978)	ω_n (KHz)						ζ				Ramp		DDSPA (in)				DDSP (in)						Oscil- lations		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	0.003	0.005	0	0.001	0.002	0.003	0.005	Blip in	< 40 Hz	> 40 Hz	All inboard subsystem. All with force fighting.
01	22 Sep. 26	X						X					X	X				X					X			No spool dynamics and K_{XS} 1-4 = 0
02	22 Sep. 27	X						X				X		X				X					X			No spool dynamics reference run
03	71 Sep. 27						X				X	X		X				X					X			MOD A is no good (no pressure feedback)
04	71 Oct. 17		X								X	X		X				X					X			B-0 verified no good
05	72 Oct. 23					X					X	X		X				X					X			B-1 verified excellent
06	72 Oct. 24					X					X		X	X								X	X			$\lvert X_{S1} \rvert$ << DDSP
07	72 Oct. 27			X							X	X		X				X					X			B-2 verified fair
08	72 Oct. 26			X							X		X	X								X	X		X	B-2 shows 55.5 Hz
09	72 Oct. 30				X						X	X		X				X					X			B-3 verified excellent
10	72 Oct. 31				X						X		X	X								X	X		X	B-3 shows 59.5 Hz
11	72 Nov. 01				X						X		X	X					X				X			B-3 rings at 55.5 Hz
12	72 Nov. 01				X						X		X	X							X		X			
13	72 Nov. 03				X				X				X	X					X				X			B-4 is no good (oscillates at 250 × 17 Hz)
14	72 Nov. 03				X				X				X	X							X		X			
15	72 Nov. 06				X					X			X	X					X				X			B-5 rings at 50.0 Hz
16	72 Nov. 06				X					X			X	X							X		X			
17	72 Nov. 07				X						X		X				X		X				X	X		DDSPA is too large (B-3). Some 55.5 Hz oscillations
18	72 Nov. 07				X						X		X				X				X		X	X	X	
19	72 Nov. 13				X						X		X			X					X			X		Note no blip (B-3)
20	72 Nov. 14				X						X		X			X					X		X	X	X	Blip → oscillations
21	72 Nov. 14				X						X		X		X						X		X		X	(B-3) 55.5 Hz only
22	72 Nov. 15				X						X		X		X					X			X		X	(B-3) 55.5 Hz only*
23	72 Nov. 15				X						X		X		X				X				X	X		12 Hz at plateau only No 55.5 Hz (B-3)

*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] [VABM1]	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

[a]Onset defined as first appearance of oscillations in PL.
[b]Onset defined as first appearance of oscillations in IL1.

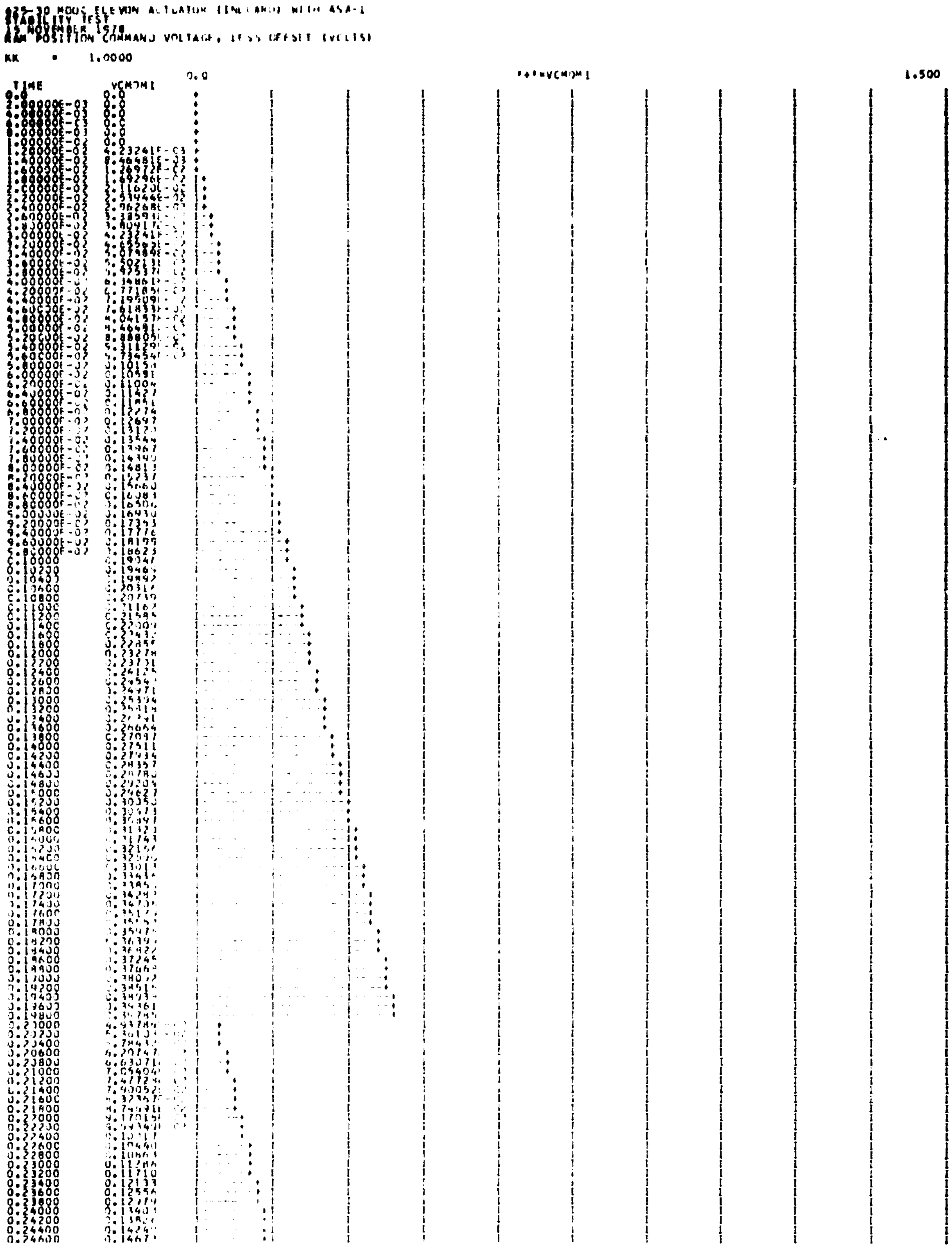


Figure 3-9.— Ram position command voltage, less offset (volts).

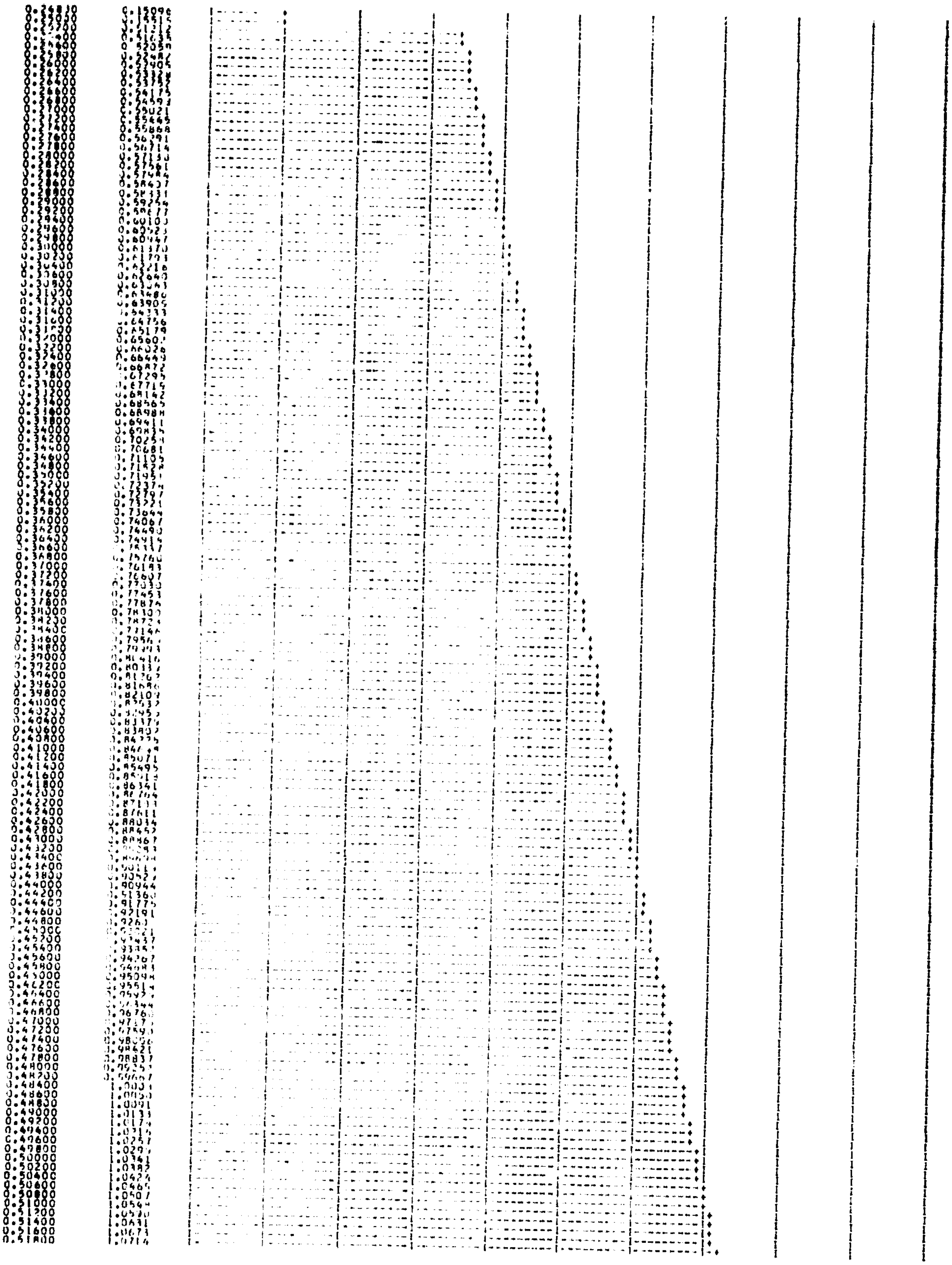


Figure 3-9.– Continued.

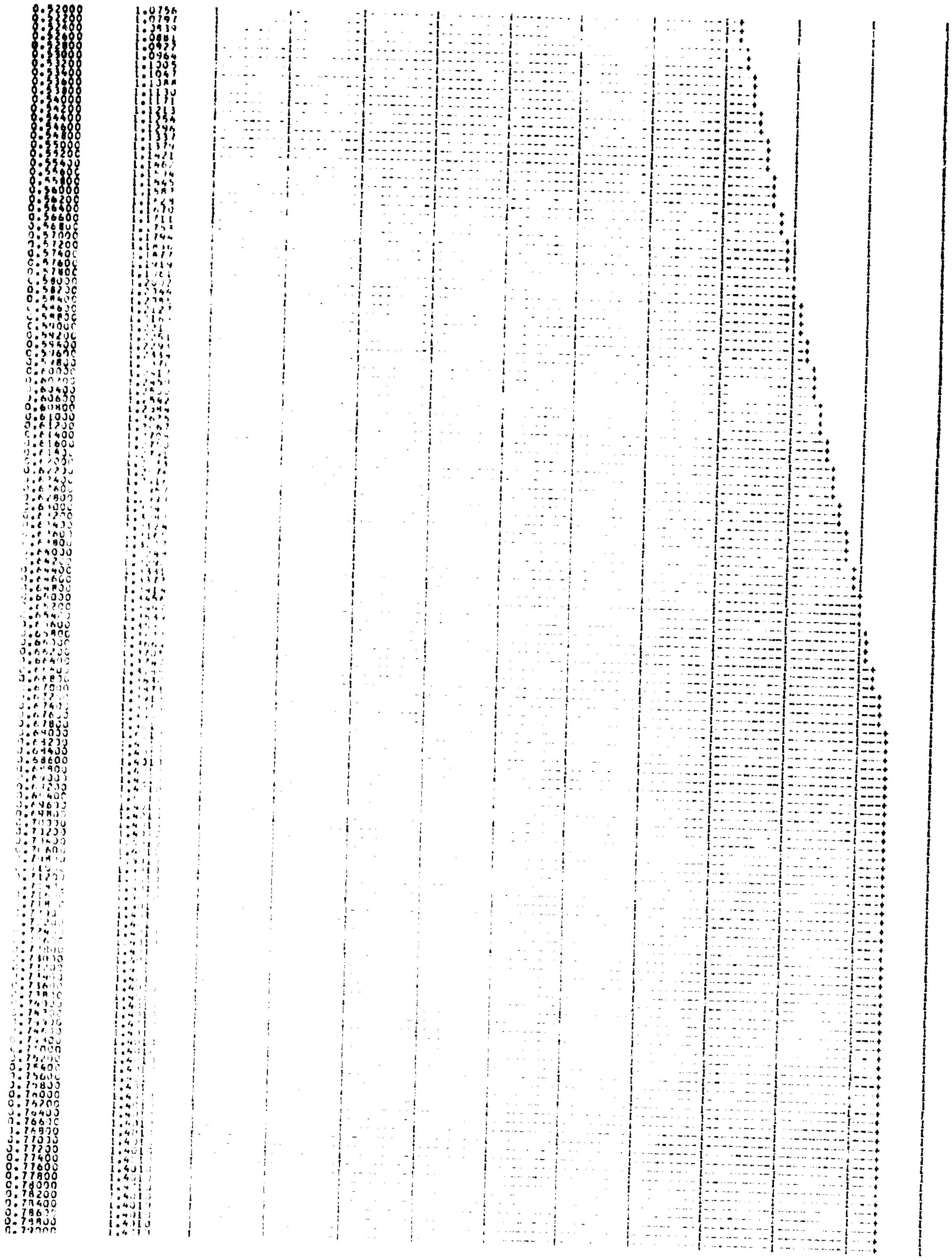


Figure 3-9.— Continued.

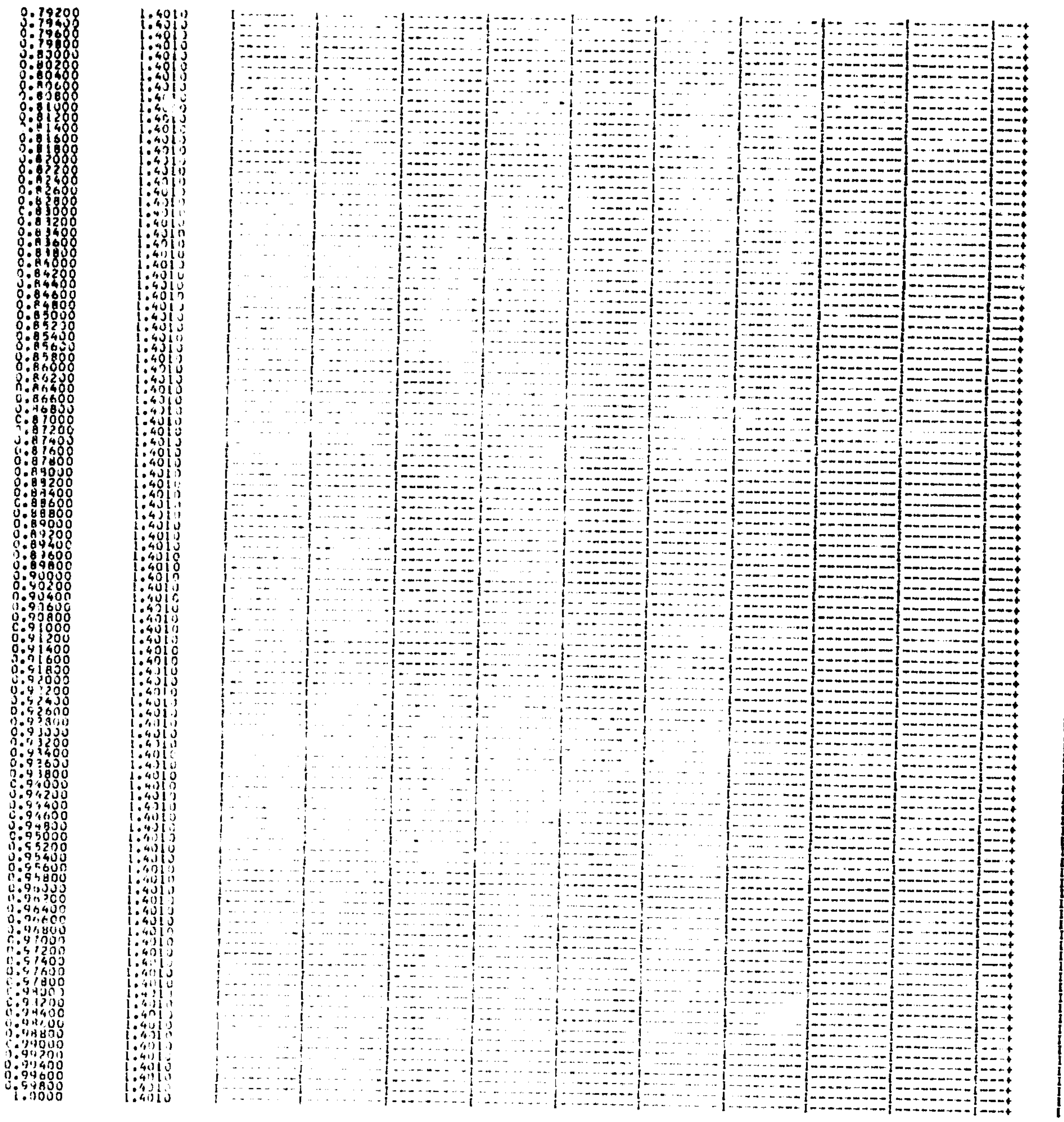


Figure 3-9.— Concluded.

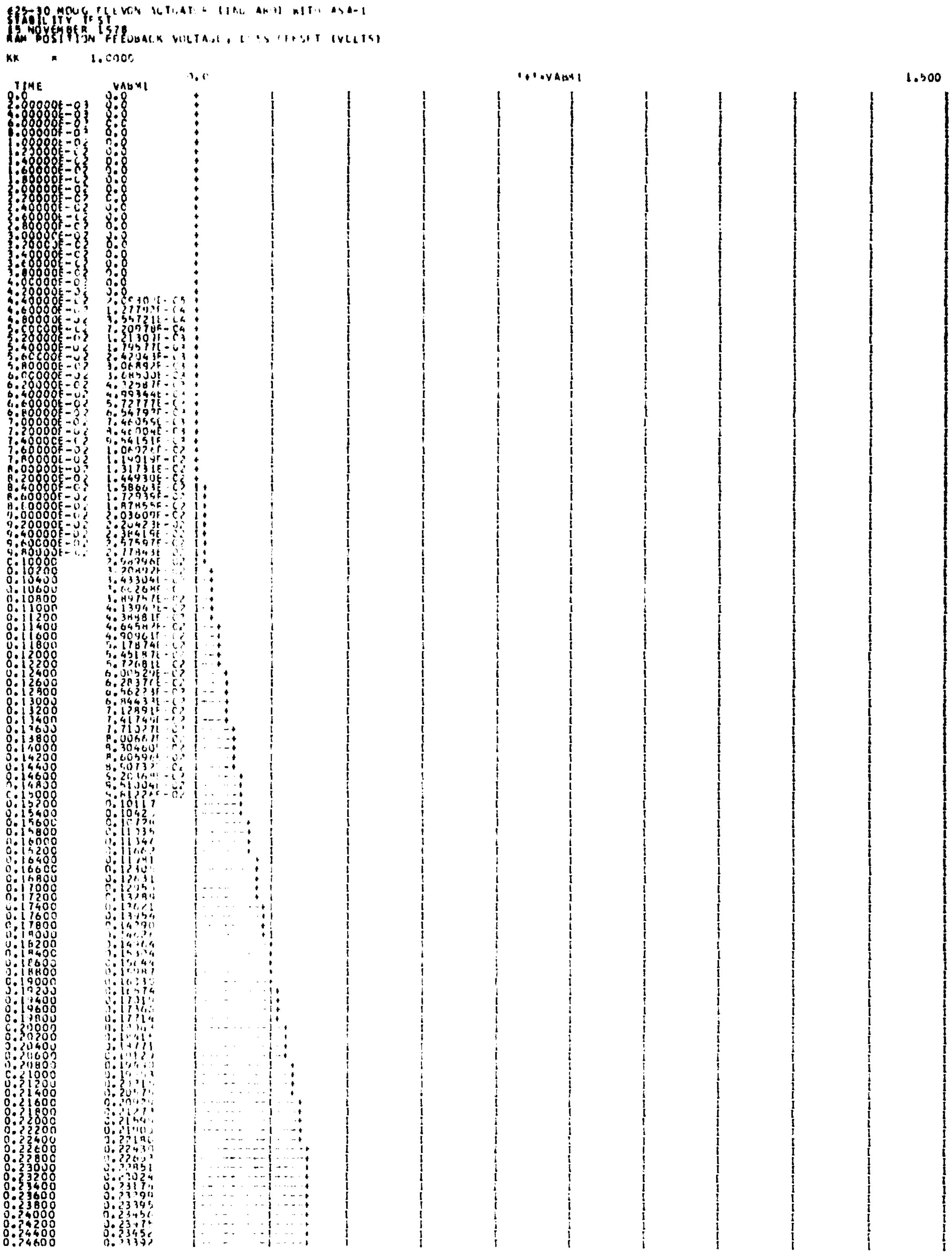


Figure 3-10.— Ram position feedback voltage, less offset (volts).

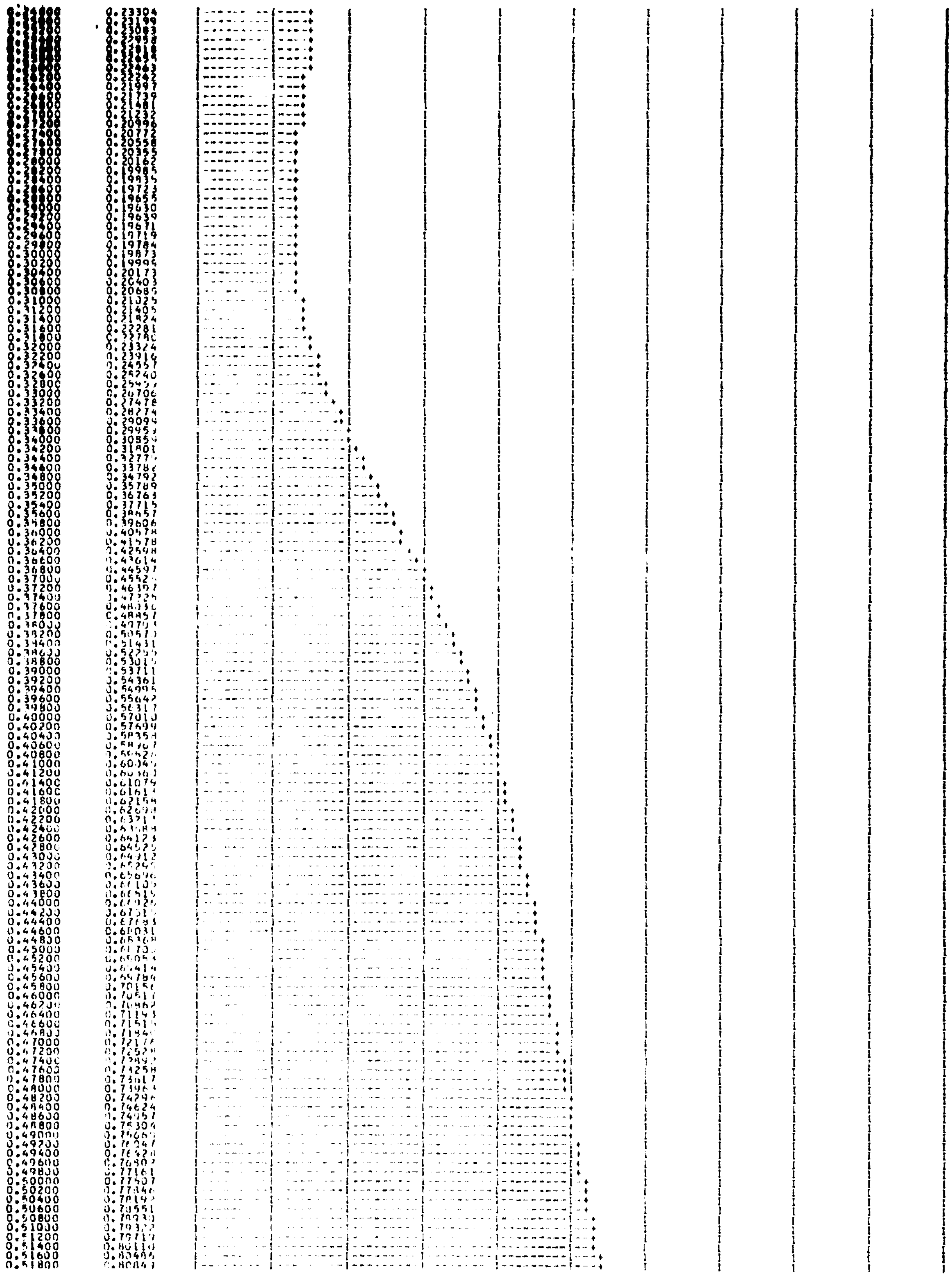


Figure 3-10.— Continued.

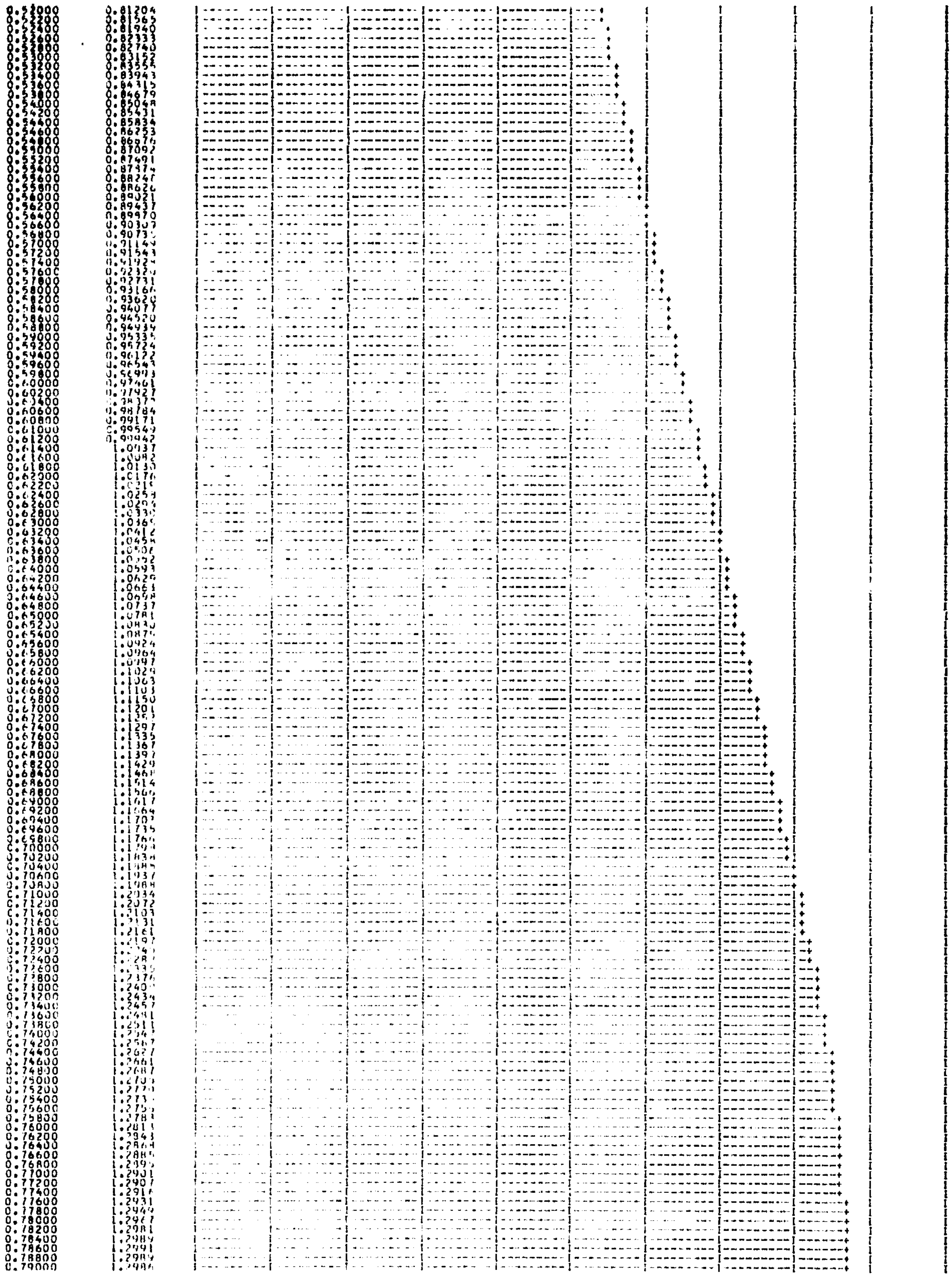


Figure 3-10.— Continued.

0.79200	1.2986
0.79400	1.2991
0.79600	1.2999
0.79800	1.3007
0.80000	1.3014
0.80200	1.3016
0.80400	1.3014
0.80600	1.3009
0.80800	1.3002
0.81000	1.2997
0.81200	1.2995
0.81400	1.2996
0.81600	1.3000
0.81800	1.3003
0.82000	1.3005
0.82200	1.3004
0.82400	1.3000
0.82600	1.2994
0.82800	1.2987
0.83000	1.2981
0.83200	1.2973
0.83400	1.2977
0.83600	1.2977
0.83800	1.2979
0.84000	1.2980
0.84200	1.2979
0.84400	1.2976
0.84600	1.2971
0.84800	1.2965
0.85000	1.2958
0.85200	1.2952
0.85400	1.2949
0.85600	1.2944
0.85800	1.2942
0.86000	1.2940
0.86200	1.2937
0.86400	1.2938
0.86600	1.2936
0.86800	1.2934
0.87000	1.2930
0.87200	1.2925
0.87400	1.2919
0.87600	1.2912
0.87800	1.2906
0.88000	1.2900
0.88200	1.2896
0.88400	1.2892
0.88600	1.2889
0.88800	1.2887
0.89000	1.2884
0.89200	1.2882
0.89400	1.2881
0.89600	1.2879
0.89800	1.2877
0.90000	1.2876
0.90200	1.2874
0.90400	1.2872
0.90600	1.2871
0.90800	1.2869
0.91000	1.2868
0.91200	1.2867
0.91400	1.2866
0.91600	1.2865
0.91800	1.2864
0.92000	1.2863
0.92200	1.2863
0.92400	1.2862
0.92600	1.2862
0.92800	1.2861
0.93000	1.2861
0.93200	1.2860
0.93400	1.2860
0.93600	1.2859
0.93800	1.2859
0.94000	1.2859
0.94200	1.2858
0.94400	1.2857
0.94600	1.2857
0.94800	1.2856
0.95000	1.2856
0.95200	1.2855
0.95400	1.2854
0.95600	1.2854
0.95800	1.2853
0.96000	1.2853
0.96200	1.2852
0.96400	1.2851
0.96600	1.2851
0.96800	1.2850
0.97000	1.2849
0.97200	1.2848
0.97400	1.2848
0.97600	1.2847
0.97800	1.2847
0.98000	1.2846
0.98200	1.2845
0.98400	1.2844
0.98600	1.2844
0.98800	1.2843
0.99000	1.2842
0.99200	1.2841
0.99400	1.2841
0.99600	1.2840
0.99800	1.2839
1.0000	1.2838

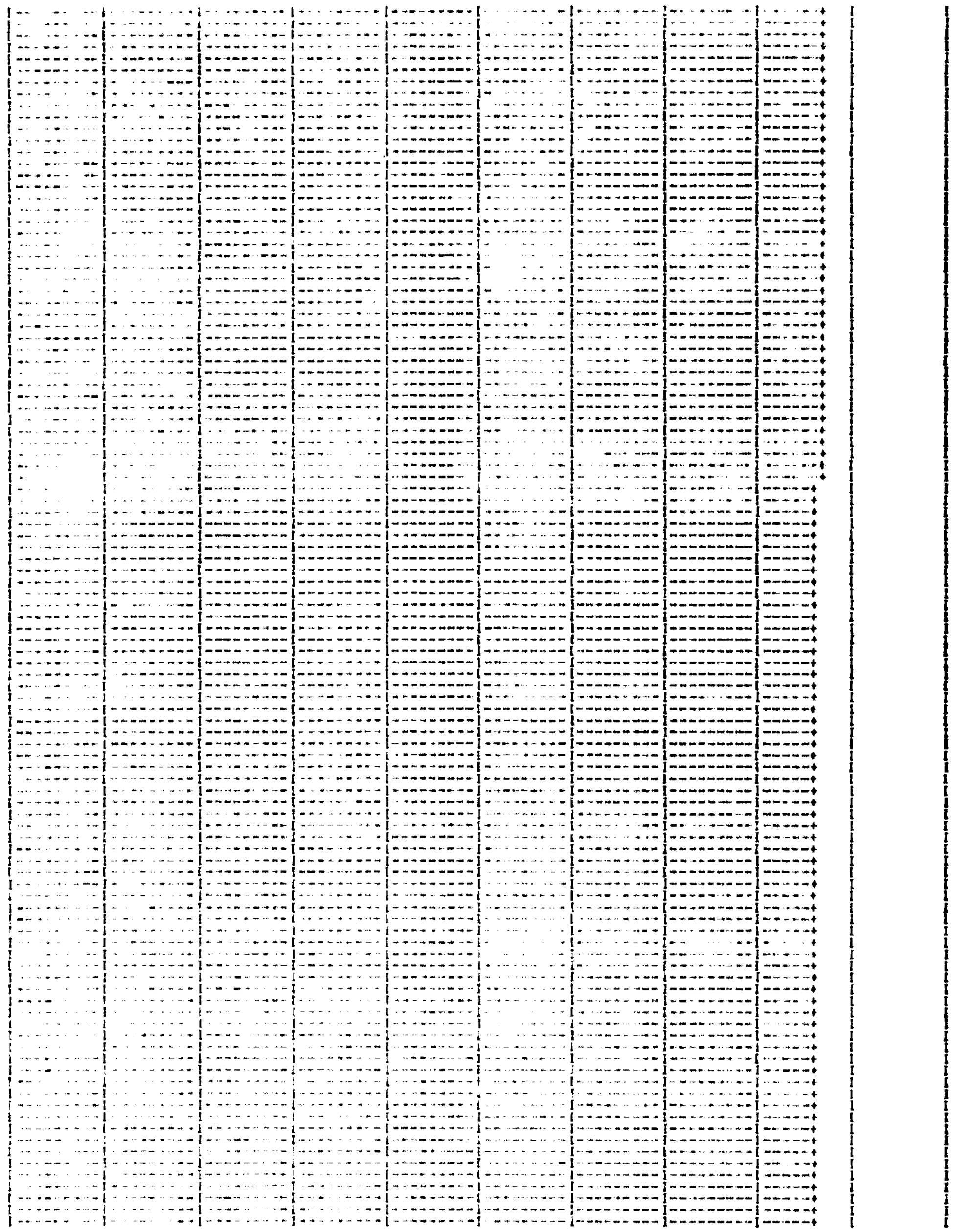


Figure 3-10.— Concluded.

Figure 3-11.— Second-stage spool displacement in inches
in channels 1-3 (no force fighting).

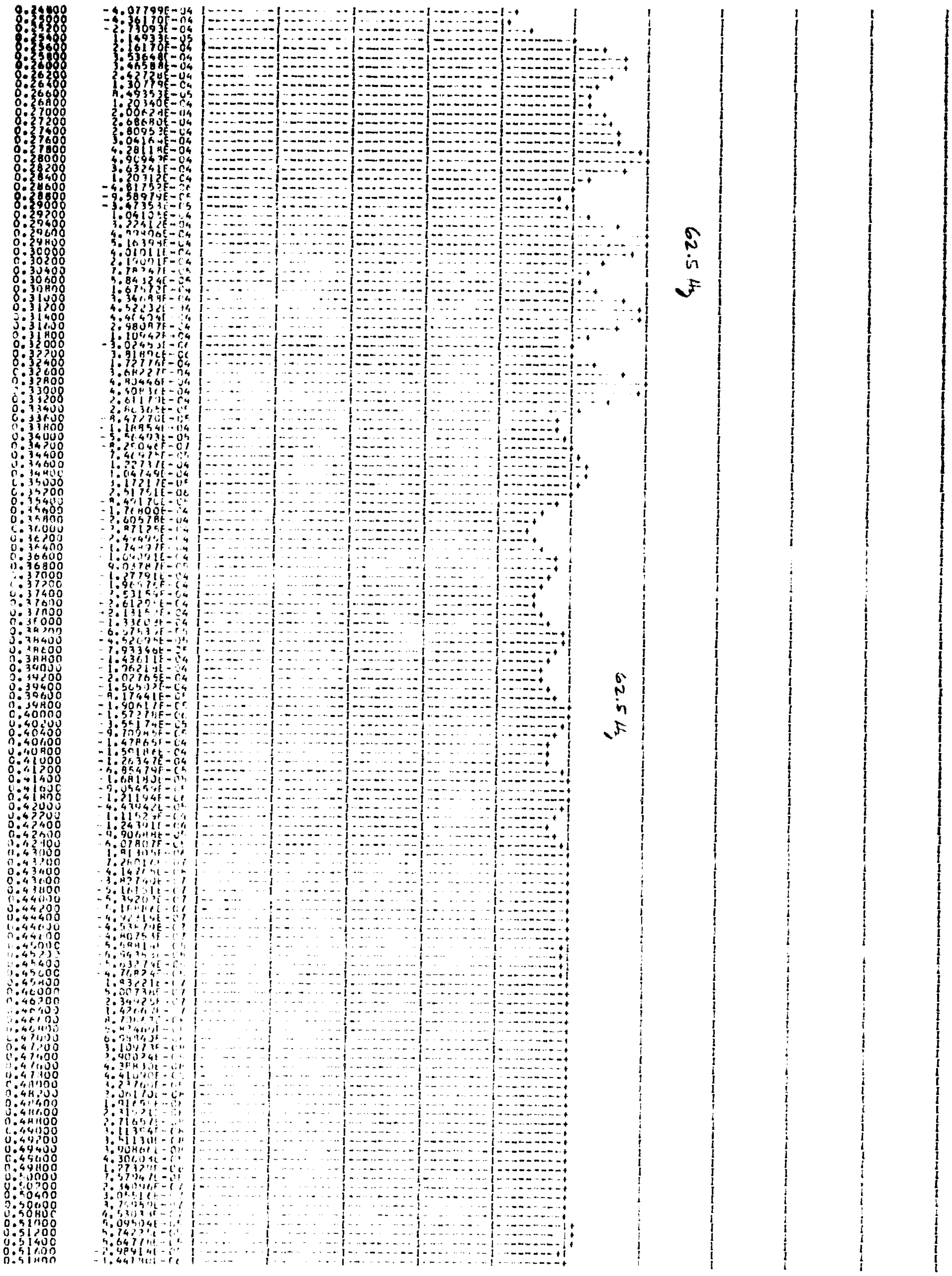


Figure 3-11.— Continued.

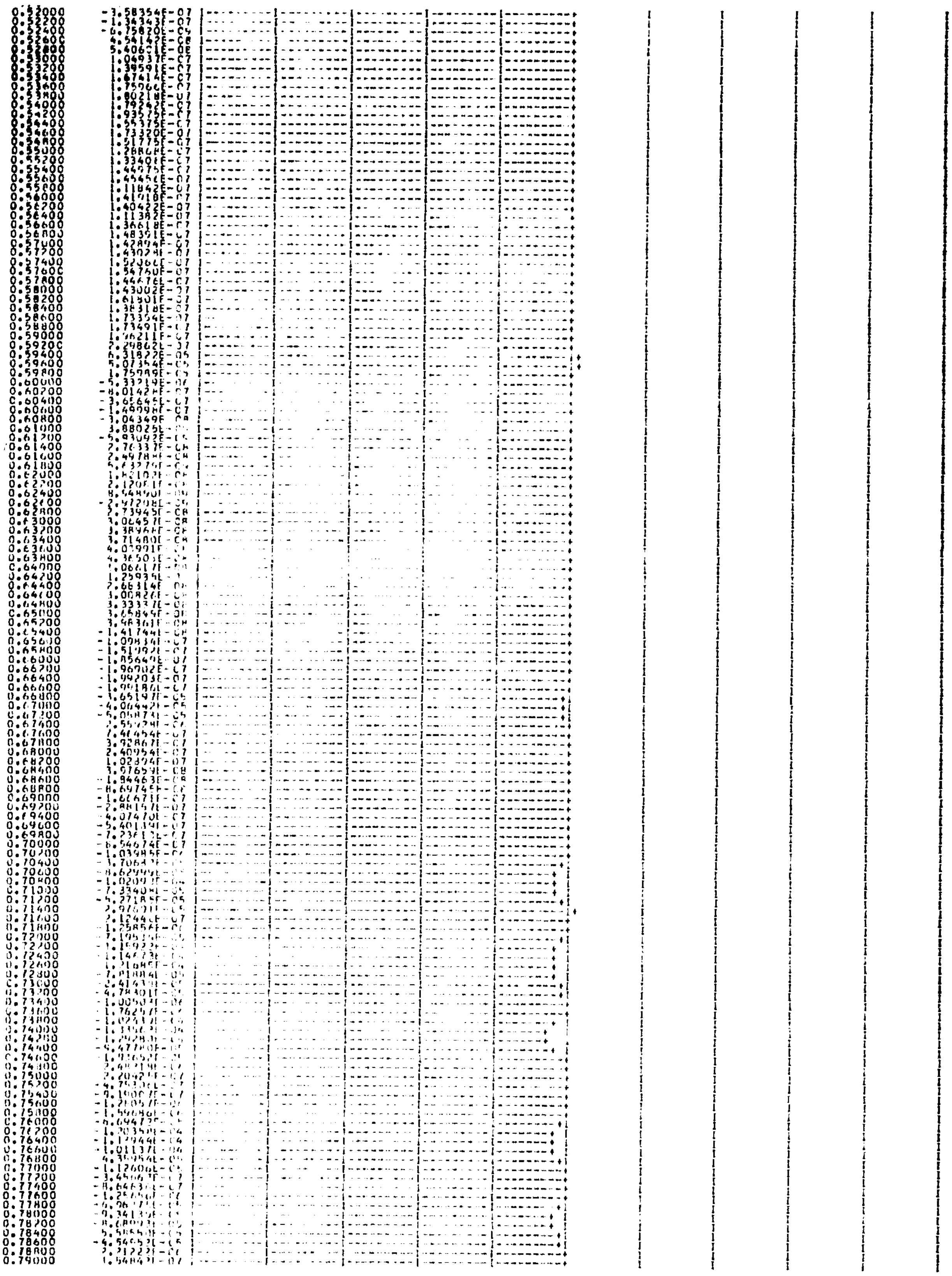


Figure 3-11.— Continued.

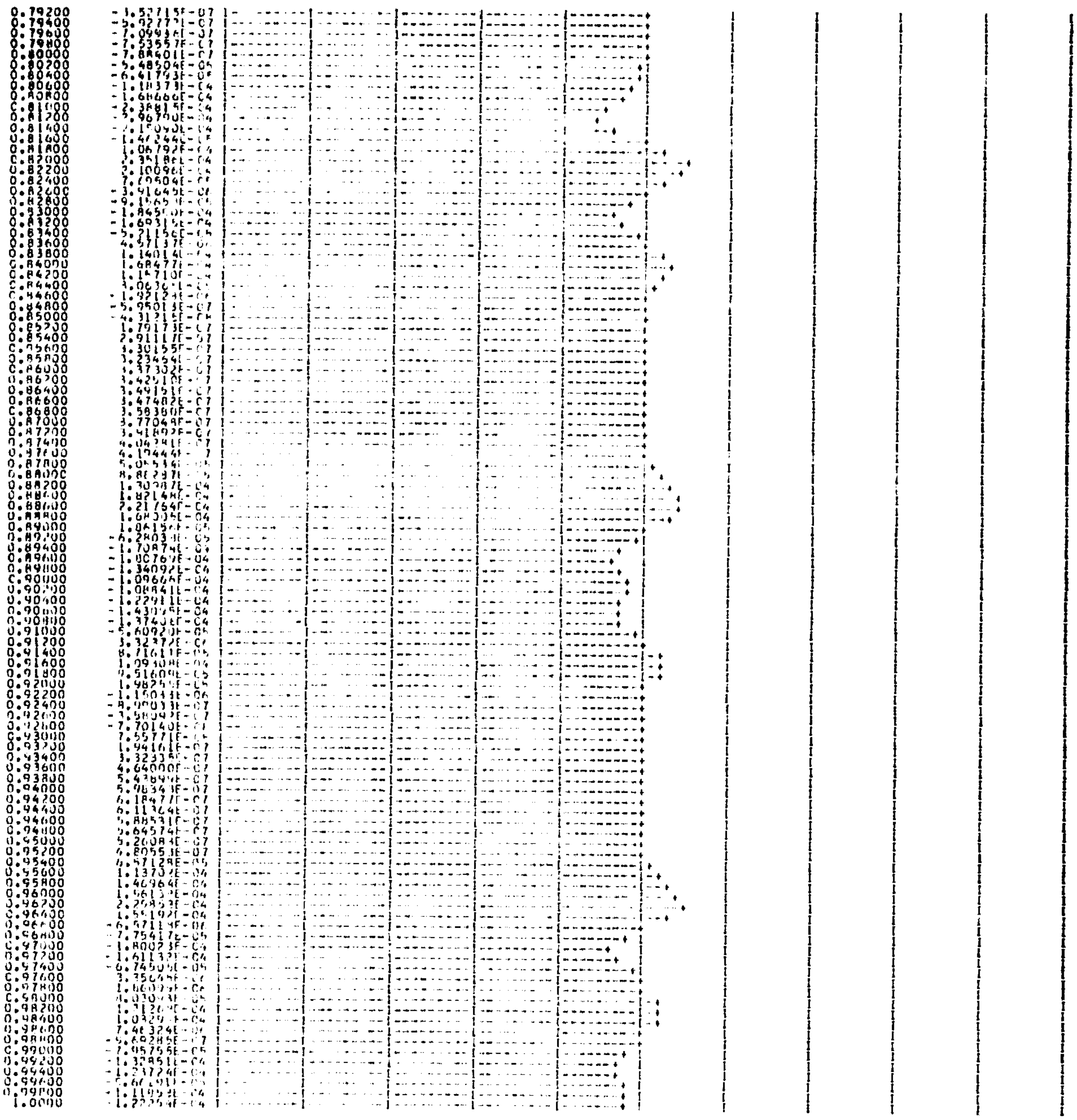


Figure 3-11.— Concluded.

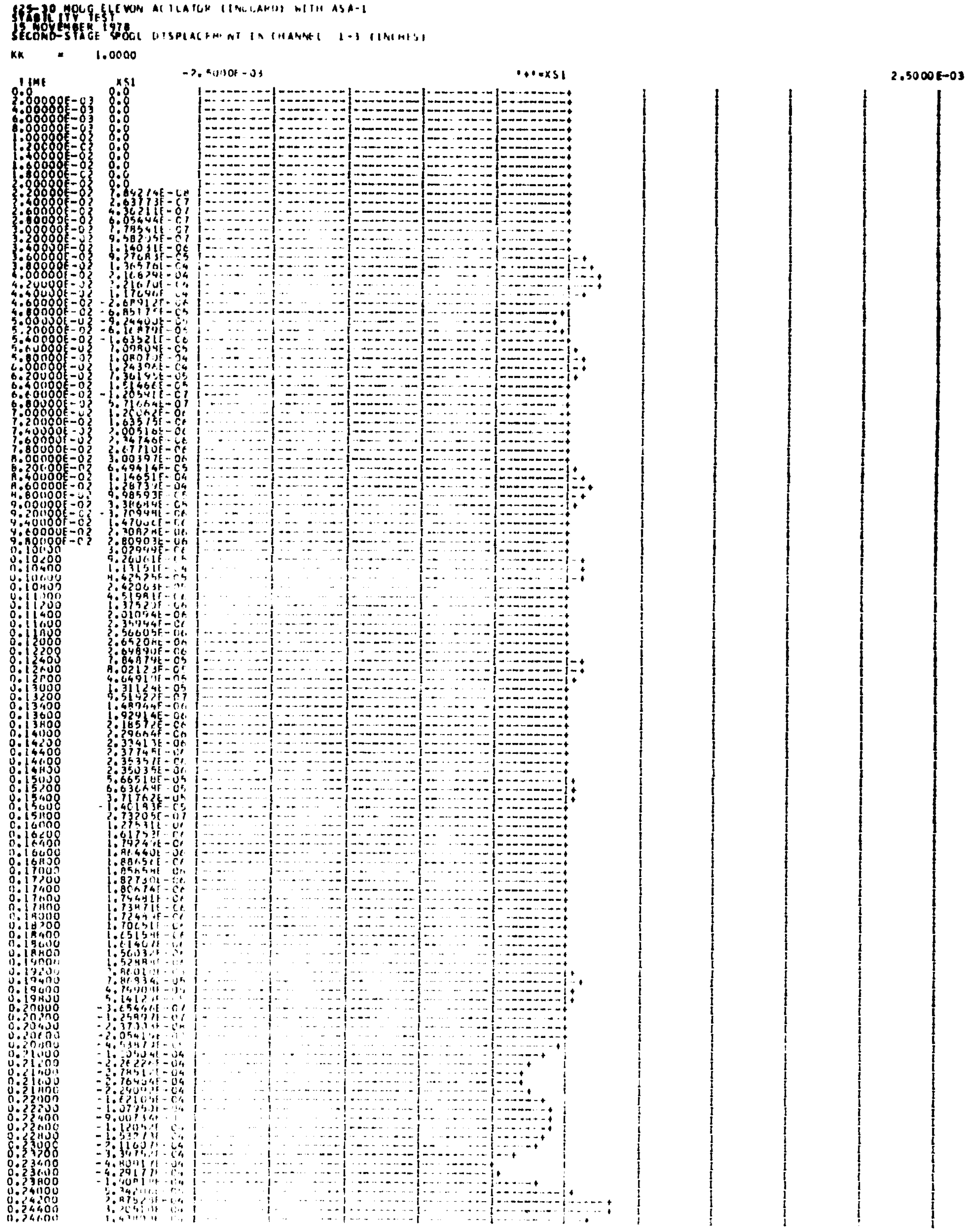


Figure 3-12.– Second-stage spool displacement in inches in channels 1-3 (with force fighting).

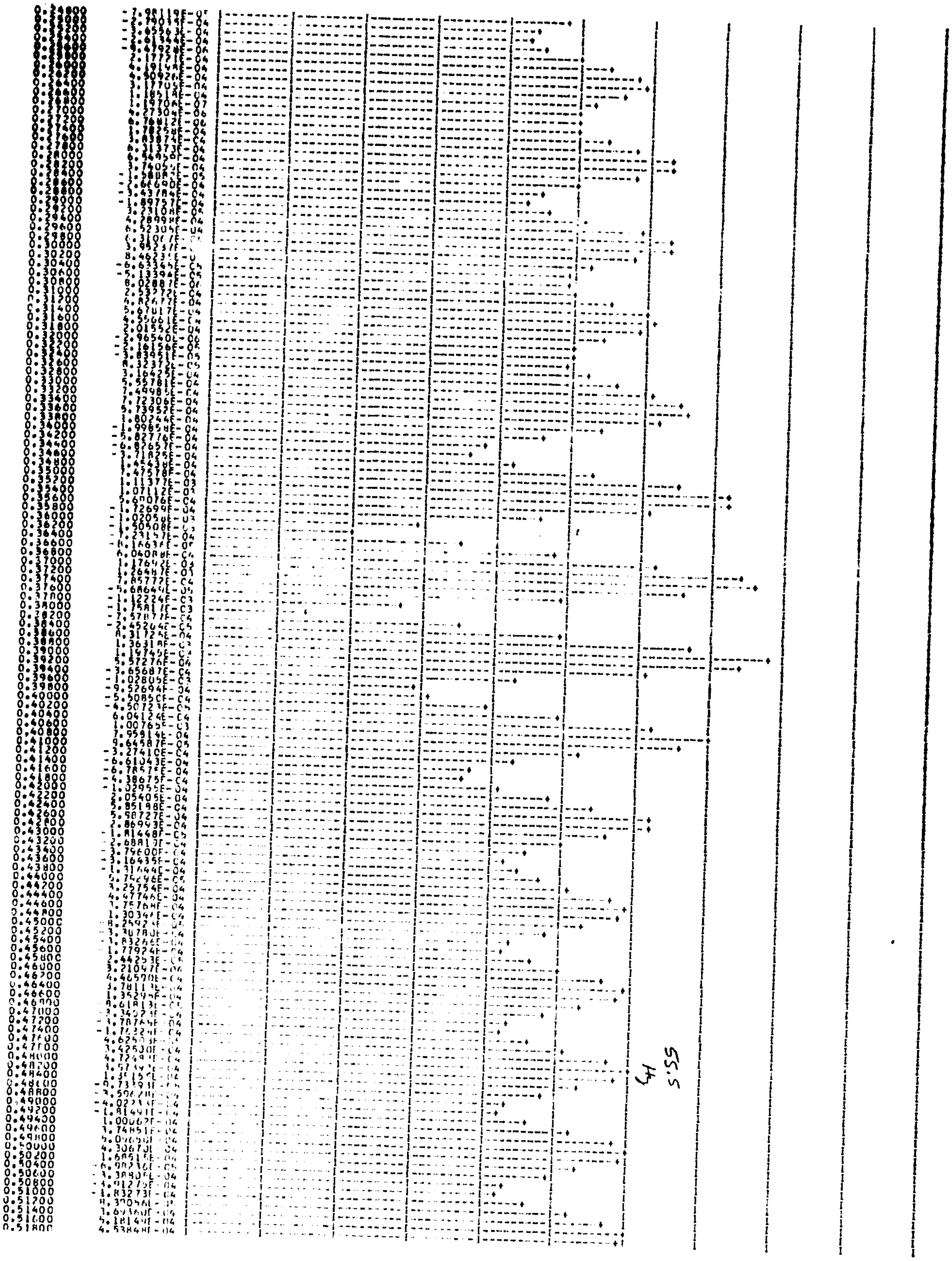


Figure 3-12.— Continued.

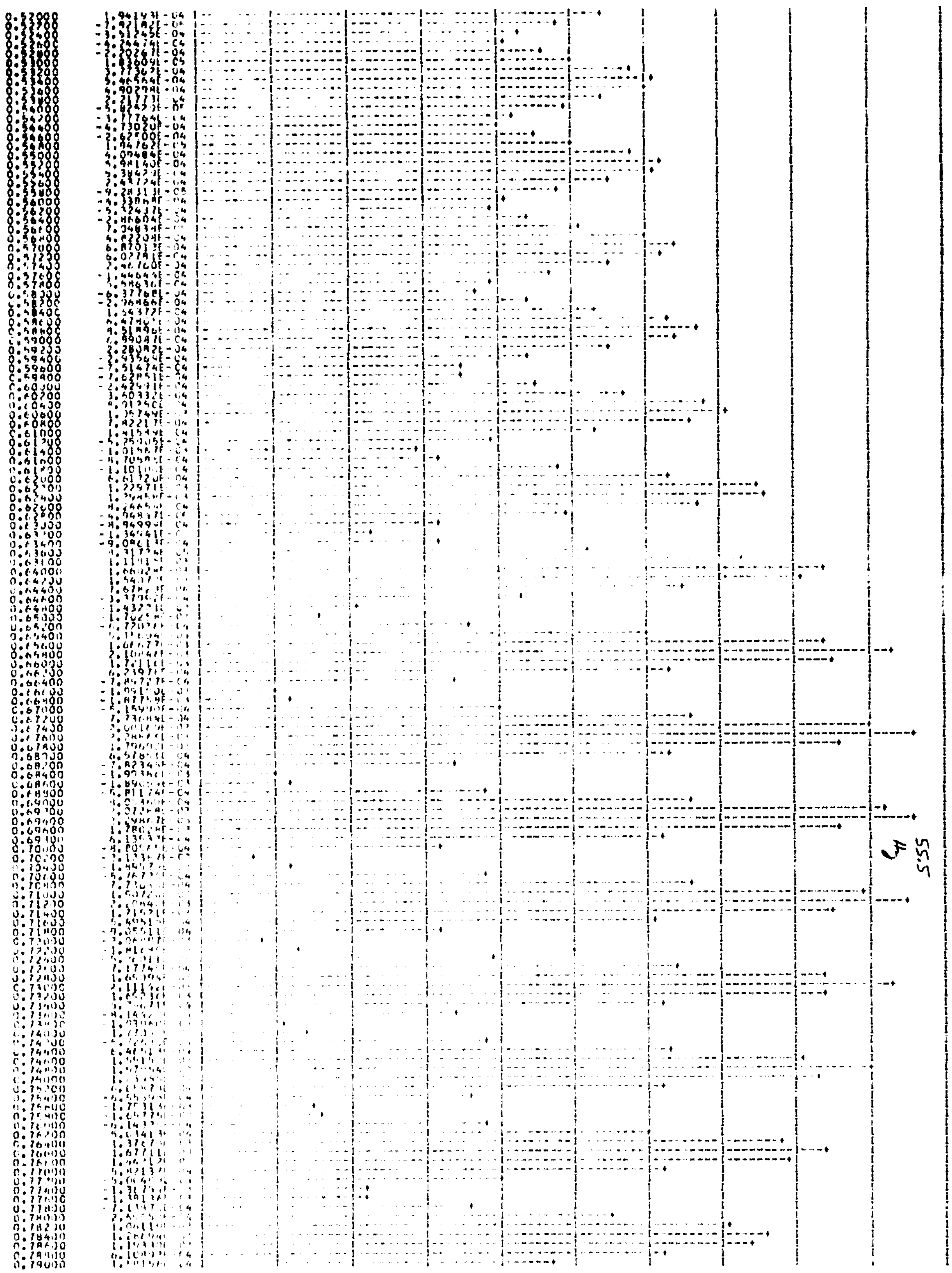


Figure 3-12.— Continued.

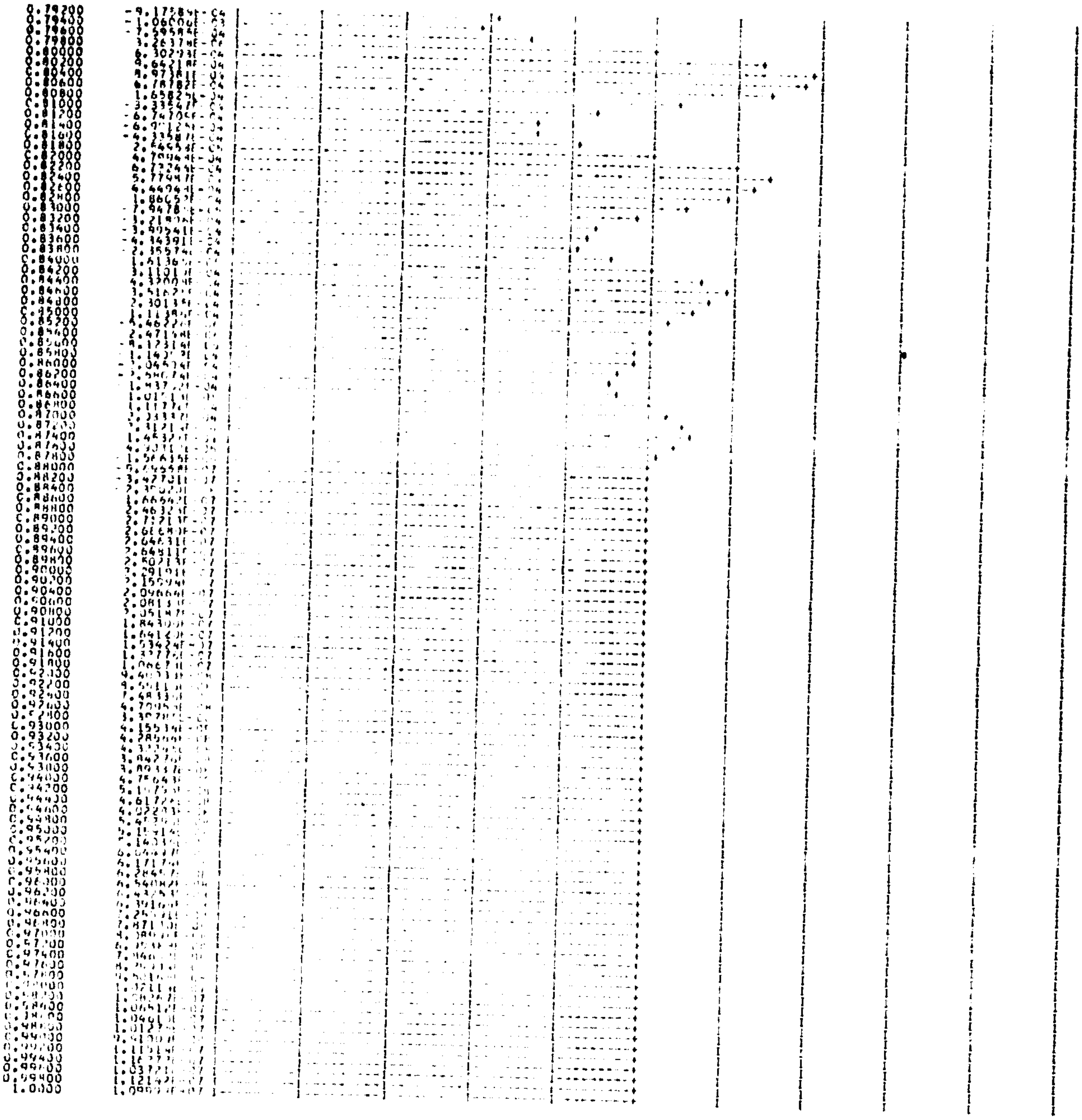


Figure 3-12.– Concluded.

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 E-5 lbs-sec^2/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.