N87-17831

Active Damping of Vibrations in SCOLE Excited by Slewing

by

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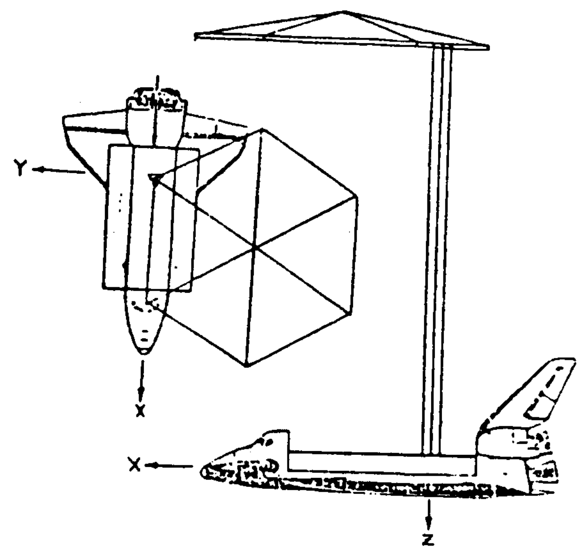
Control Research Corp.

ACTIVE DAMPING OF VIBRATIONS IN SCOLE

EXCITED BY MINIMUM-TIME RAPID SLEWING



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INTRODUCTION

HIGHLIGHTS OF NUMERICAL RESULTS

MINIMUM-TIME RAPID LOS POINTING SLEW FOR SCOLE

ADAPTATION OF LOS ERROR EXPRESSION

CONCEPT OF "MODAL DASHPOTS"

MODAL-DASHPOT VIBRATION CONTROLLERS
-- DESIGN AND SIMULATION RESULTS

CONCEPT OF "MODAL SPRINGS"

MODAL-SPRING VIBRATION CONTROLLERS
-- DESIGN AND SIMULATION RESULTS

COMBINED USE OF MODAL DASHPIOTS AND SPRINGS
-- MORE DESIGN AND SIMULATION RESULTS

CONCLUSIONS

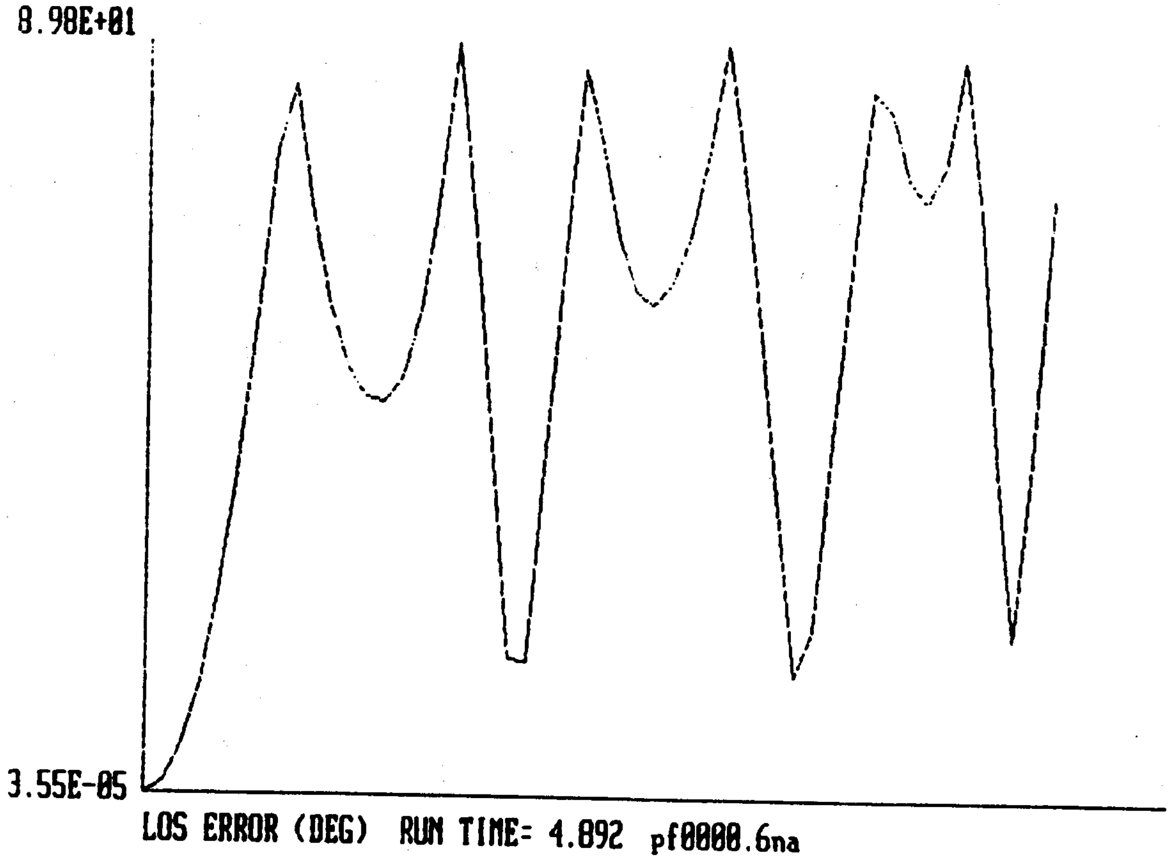
HIGHLIGHTS OF NUMERICAL SIMULATION RESULTS

F0000: BPB SLEW EXCITATION 10,000 lb-ft on Shuttle, 800 lb on Refle.
F0010: ACTIVE DAMPING AFTER EXCITATION 5 deg/sec rate lim

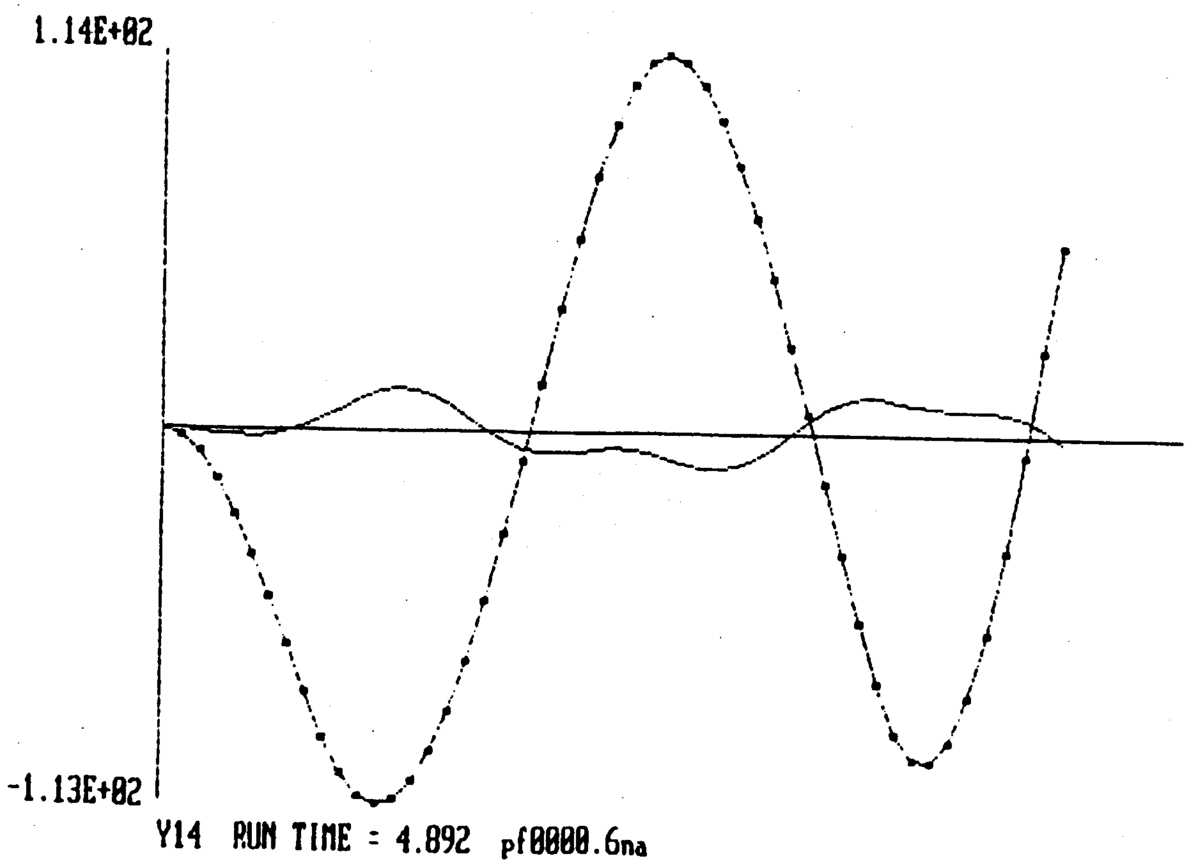
F0100: ACTIVE STIFFENING DURING EXCITATION
F2100: ACTIVE DAMPING & STIFFENING DURING EXCITATION
F3100: SAME

F0110: ACTIVE DAMPING & STIFFENING DURING AND AFTER EXCITATION
F2110: SAME
F3110: SAME

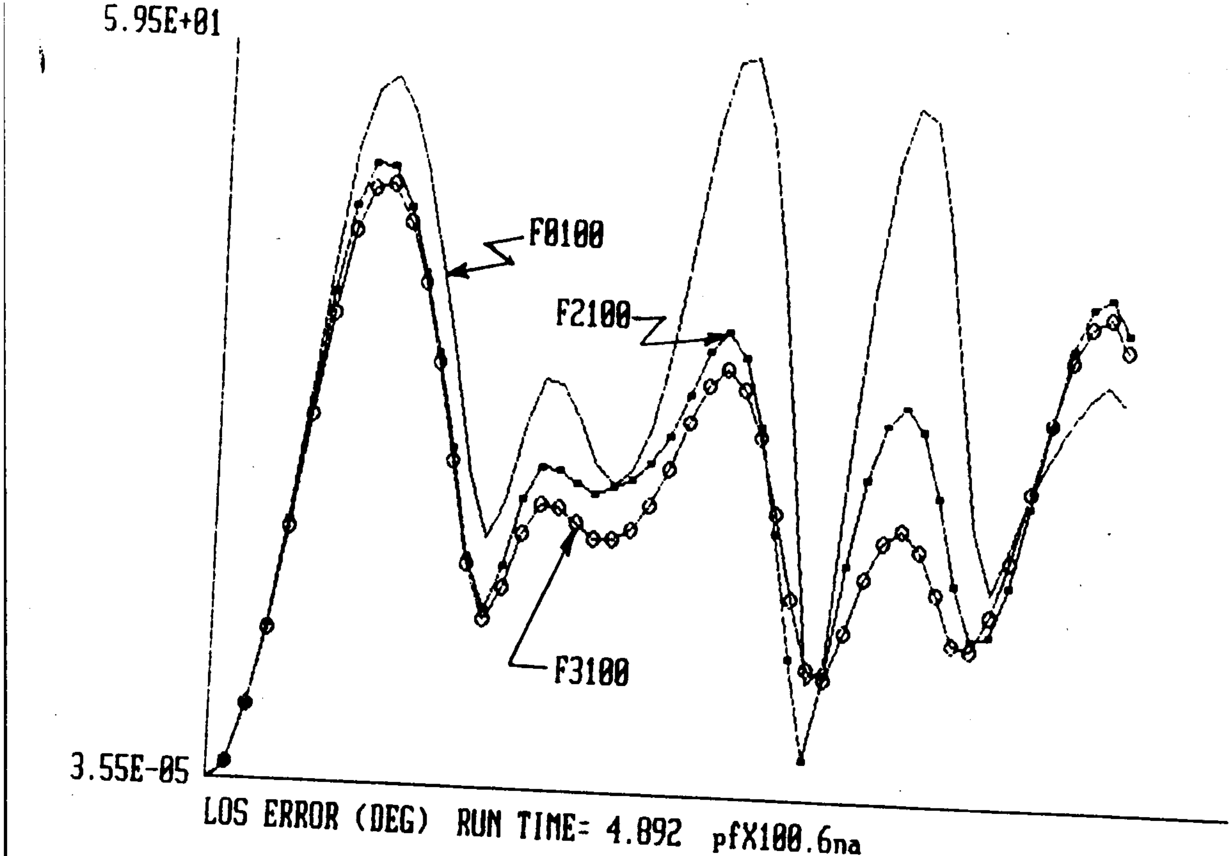
F125: BB SLEW EXCITATION; 10,000 lb-ft on Shuttle
25 lb on Reflector

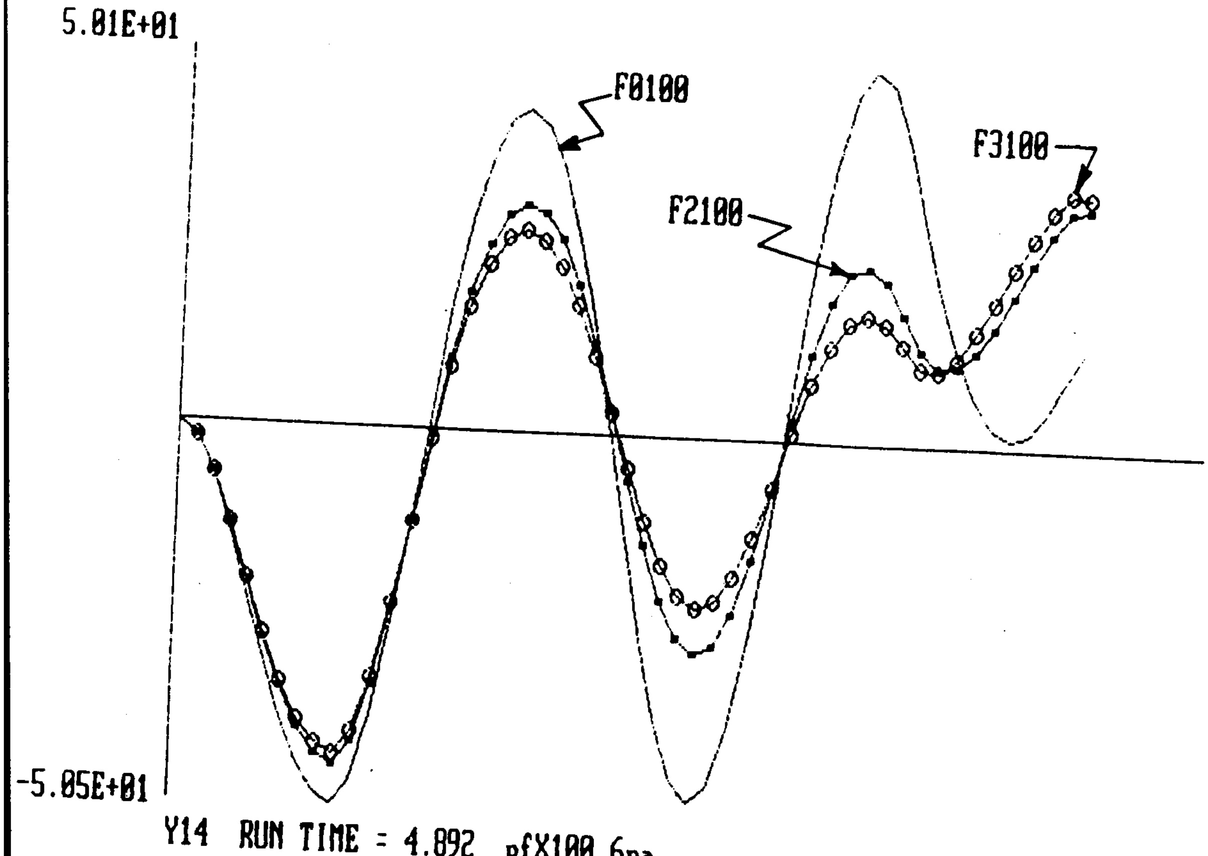

8.98E+01
3.55E-05
LOS ERROR (DEG) RUN TIME= 4.892 pf0000.6na

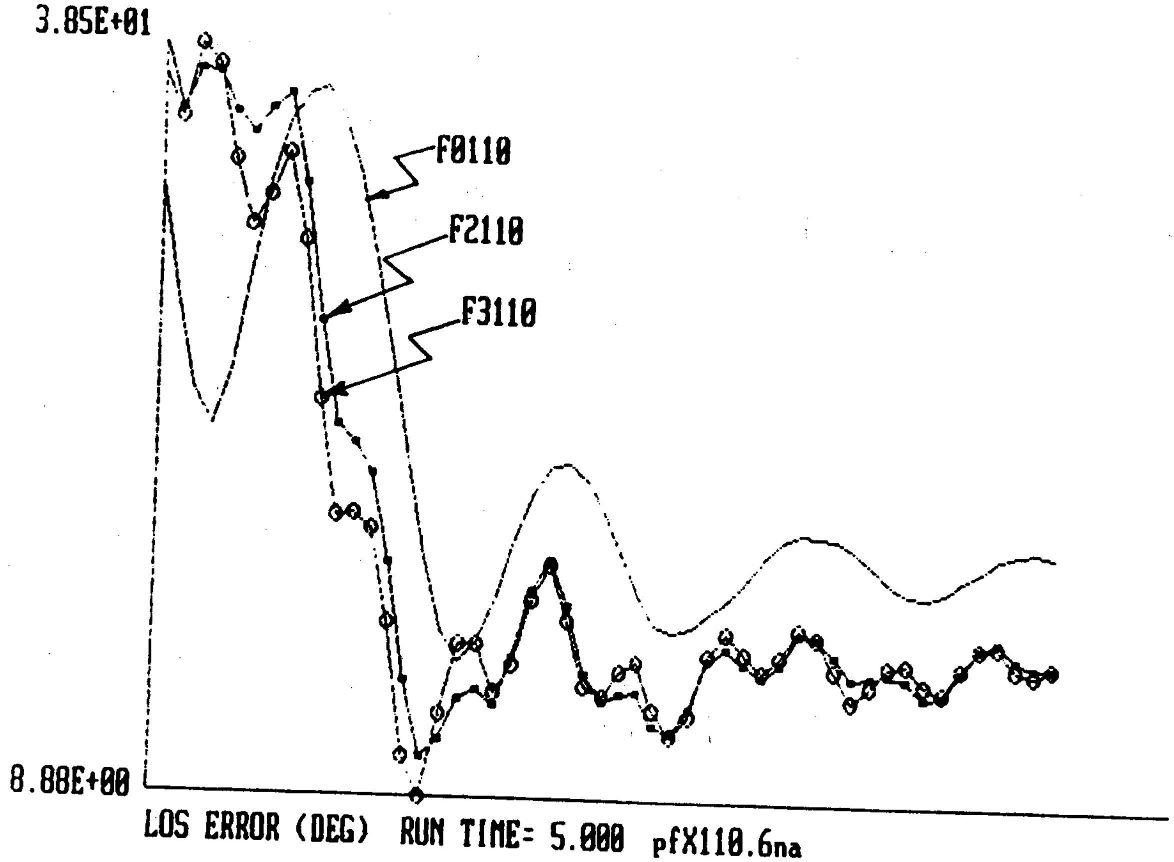
LCOPY

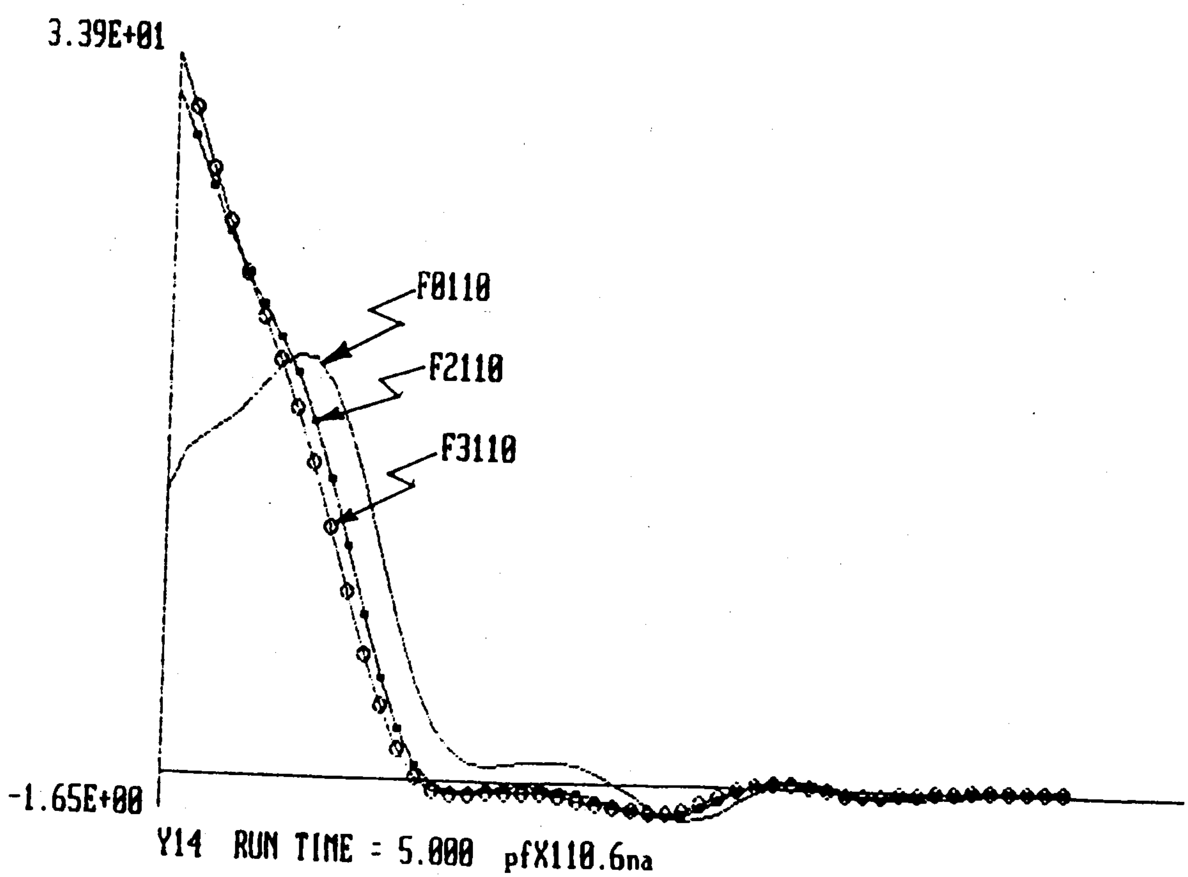

1.14E+02
-1.13E+02
Y14 RUN TIME = 4.892 pf0000.6na

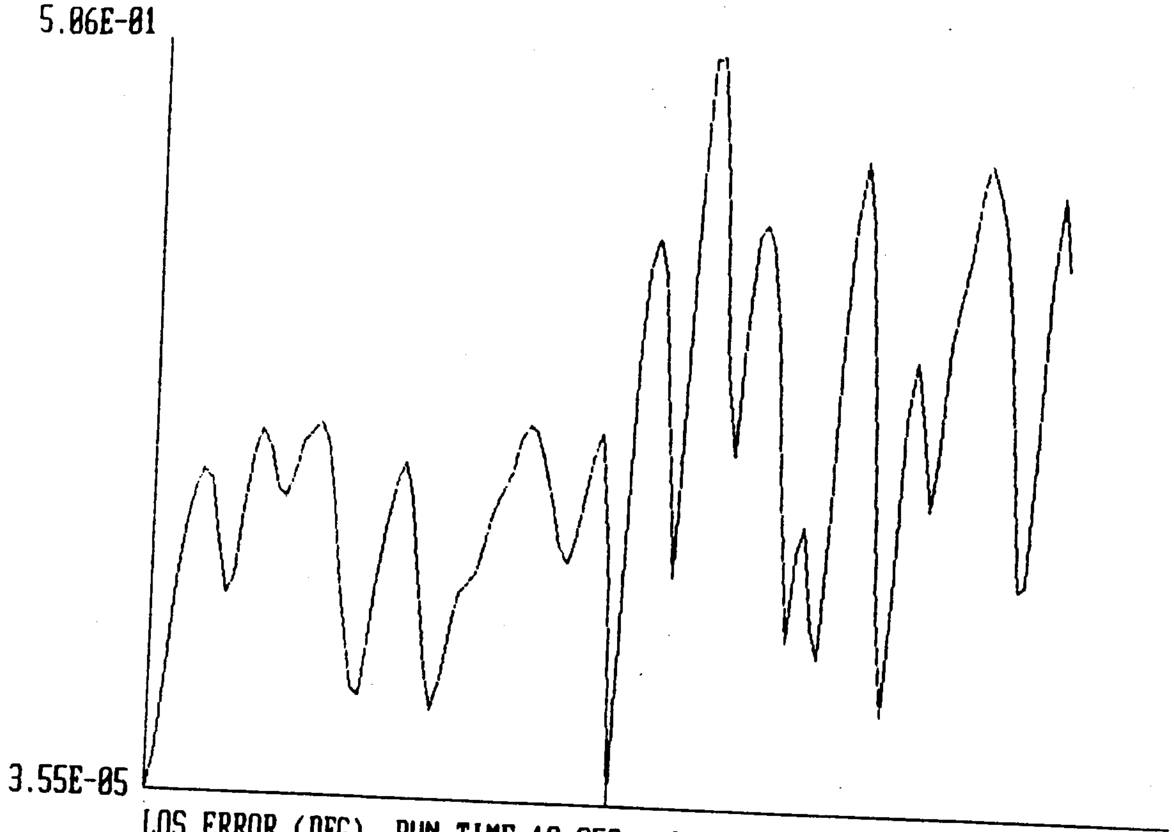
LCOPY


5.95E+01
F0100
F2100
F3100
3.55E-05
LOS ERROR (DEG) RUN TIME= 4.892 pfX100.6na


5.01E+01
F0100
F3100
F2100
-5.05E+01
Y14 RUN TIME = 4.892 pfX100.6na

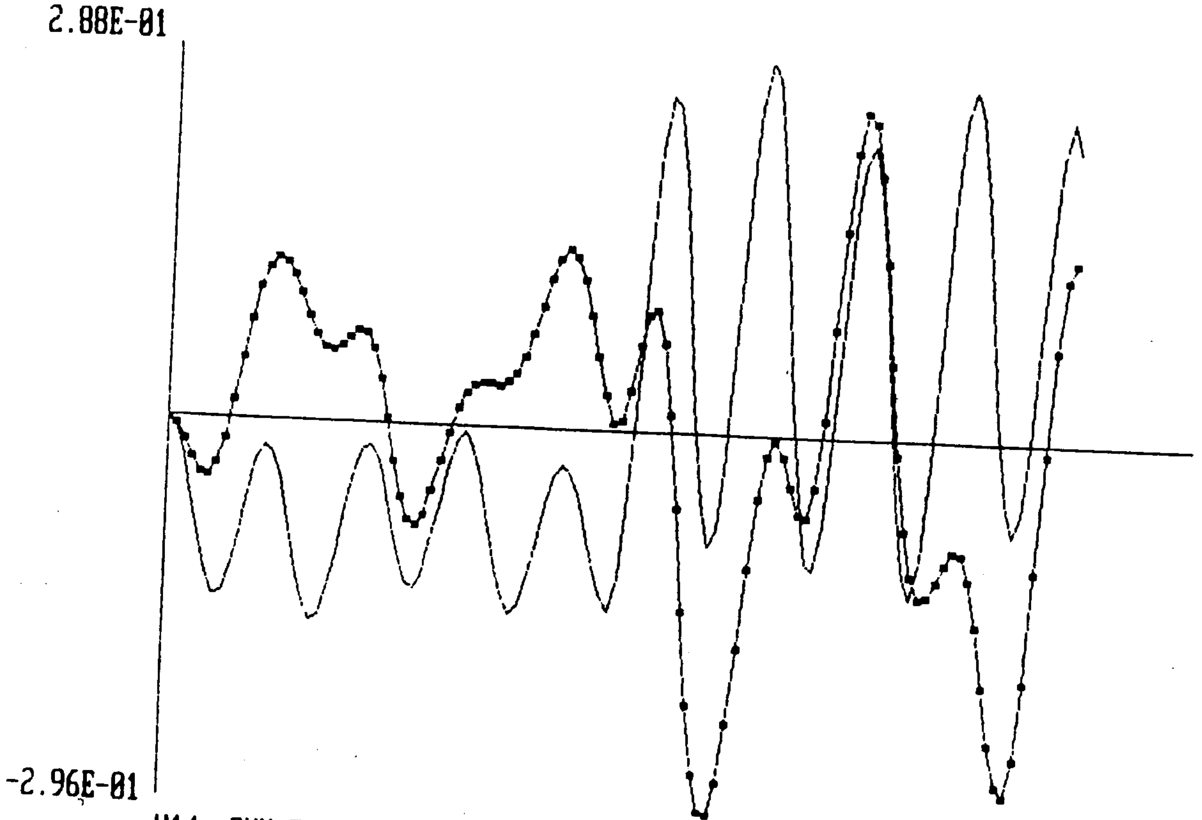

3.85E+01
F0110
F2110
F3110
8.00E+00
LOS ERROR (DEG) RUN TIME= 5.000 pfX110.6na


3.39E+01
F0110
F2110
F3110
-1.65E+00
Y14 RUN TIME = 5.000 pfX110.6na



LOS ERROR (DEG) RUN TIME=10.959 pf125.6na

LCOPY



Y14 RUN TIME =10.959 pf125.6na

LCOPY

LINE-OF-SIGHT ERROR--GENERAL VECTOR EXPRESSION

- $\underline{FR}$ = RAY OF EMISSION = $\mathbf{R}_R - \mathbf{R}_F$

  $\underline{F'R}$ = REFLECTED RAY = LOS VECTOR = $\mathbf{R}_{LOS}$

- $\underline{RF'} = \underline{FR} + 2\underline{RR'}$ SINCE

  $\underline{FR} + \underline{RF'} = \underline{FF'}$; $\underline{FR} + \underline{RR'} = \underline{FR'}$; $\underline{FF'} = 2\underline{FR'}$

- $RR' = (\underline{RF} \cdot \mathbf{R}_A)\mathbf{R}_A = -(\underline{FR} \cdot \mathbf{R}_A)\mathbf{R}_A$

- IN UN-NORMALIZED FORM:

$$\boxed{\mathbf{R}_{LOS} = RF' = \mathbf{R}_R - \mathbf{R}_F - 2\left[(\mathbf{R}_R - \mathbf{R}_F) \cdot \mathbf{R}_A\right]\mathbf{R}_A}$$

- TRANSFORMING TO INERTIAL FRAME,
  FORMING CROSS-PRODUCT WITH TARGET DIRECTION,

$$\|\mathbf{D}_T \times T_1\mathbf{R}_{LOS}\| = \|\mathbf{D}_T\| \cdot \|T_1\mathbf{R}_{LOS}\| \cdot |\sin e_{LOS}|$$
$$= \|\mathbf{R}_{LOS}\| \cdot |\sin e_{LOS}|$$

- TAKING PRINCIPAL VALUE

$$\boxed{e_{LOS} = \pm \sin^{-1}\left[\|\mathbf{D}_T \times T_1\mathbf{R}_{LOS}\| / \|\mathbf{R}_{LOS}\|\right]}$$

LINE-OF-SIGHT ERROR-- GENERAL MATRIX EXPRESSION

o $R_A = \begin{bmatrix} R_{Ax} \\ R_{Ay} \\ R_{Az} \end{bmatrix}$ IN REFLECTOR'S BODY AXES

o $$R_R - R_F = \begin{bmatrix} 18.75 \\ -32.5 \\ -130 \end{bmatrix} - \begin{bmatrix} 3.75 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 15 \\ -32.5 \\ -130 \end{bmatrix}$$

o $$(R_R - R_F)^T R_A = [15 \ -32.5 \ -130] \begin{bmatrix} R_{Ax} \\ R_{Ay} \\ R_{Az} \end{bmatrix}$$
$$= 15R_{Ax} - 32.5R_{Ay} - 130R_{Az}$$

$$\boxed{\begin{aligned} R_{LOS} &= \begin{bmatrix} 15 \\ -32.5 \\ -130 \end{bmatrix} - 2(15R_{Ax} - 32.5R_{Ay} - 130R_{Az}) \begin{bmatrix} R_{Ax} \\ R_{Ay} \\ R_{Az} \end{bmatrix} \\ &= \begin{bmatrix} -2(15R_{Ax} - 32.5R_{Ay} - 130R_{Az})R_{Ax} + 15 \\ -2(15R_{Ax} - 32.5R_{Ay} - 130R_{Az})R_{Ay} - 32.5 \\ -2(15R_{Ax} - 32.5R_{Ay} - 130R_{Az})R_{Az} - 130 \end{bmatrix} \end{aligned}}$$

o $$D_T = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \qquad [D_T \times] = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$[T_1 R_{LOS}] = \begin{bmatrix} (T_1 R_{LOS})_x \\ (T_1 R_{LOS})_y \\ (T_1 R_{LOS})_z \end{bmatrix} \qquad [D_T \times T_1 R_{LOS}] = \begin{bmatrix} -(T_1 R_{LOS})_y \\ (T_1 R_{LOS})_x \\ 0 \end{bmatrix}$$

$$\boxed{\| D_T \times T_1 R_{LOS} \| = \sqrt{[(T_1 R_{LOS})_x]^2 + [(T_1 R_{LOS})_y]^2}}$$

MORE ON LOS ERROR EXPRESSION -- INCLUSION OF MAST BENDING AND TORSION

$$R_R - R_F = R_T - T_1^T T_4 R_B - R_F$$

WHERE

$$R_T = \begin{bmatrix} BENDx \\ BENDy \\ -\sqrt{130^2 - BENDx^2 - BENDy^2} \end{bmatrix}$$

$$R_B = \begin{bmatrix} 18.75 \\ -32.5 \\ 0 \end{bmatrix} \qquad R_F = \begin{bmatrix} 3.75 \\ 0 \\ 0 \end{bmatrix}$$

$$BENDx = u_x(4) - u_x(1) \qquad BENDy = u_y(4) - u_y(1)$$

$\vdots$

$$LOS_x = -(T_1 R_{LOS})_y = -T_{1ry} R_{LOS}$$

$$= \left[2T_{4yz}T_{4xz},\ -1+2T_{4yz}^2,\ -2T_{4yz}T_{4zz}\right] T_1 \left[R_T - R_F\right] + T_{4ry} R_B$$

$$LOS_y = (T_1 R_{LOS})_x = T_{1rx} R_{LOS}$$

$$= \left[1-2T_{4xz}^2,\ -2T_{4xz}T_{4yz},\ -2T_{4xz}T_{4zz}\right] T_1 \left[R_T - R_F\right] + T_{4rx} T_B$$

DYNAMICS:

$$M \frac{d^2 x}{dt^2} + D \frac{dx}{dt} + K x = f$$

FORCE (TORQUE) ACTUATORS AND VELOCITY SENSORS:

$$f = B_F u$$

$$y = C_v \frac{dx}{dt}$$

NORMAL MODAL REPRESENTATION $x = \Phi \eta$:

$$\frac{d^2 \eta}{dt^2} + \Delta \frac{d\eta}{dt} + \Omega^2 \eta = \Phi^T B_F u$$

$$y = C_v \Phi \frac{d\eta}{dt}$$

WHERE

$$\Omega^2 = \mathrm{DIAG}\left[\omega_i^2\right] = \Phi^T K \Phi$$

$$\Delta = \Phi^T D \Phi$$

CONTROL LAW FOR CONSTANT-GAIN VELOCITY-OUTPUT FEEDBACK:

$$u = - G y$$

FULL-ORDER CLOSED-LOOP SYSTEM EQUATION:

$$\frac{d^2 \eta}{dt^2} + \underbrace{(\Delta + \Phi^T B_F G C_v \Phi)}_{\Delta^*} \frac{d\eta}{dt} + \Omega^2 \eta = 0$$

MODAL-DASHPOT APPROACH

DESIGN TO ACHIEVE **INDEPENDENT** DAMPING AUGMENTATION FOR EACH MODE IN A **REDUCED-ORDER** MODEL

LET ζ_i BE DAMPING RATIO DESIRED OF MODELED MODE i

SET $$\underbrace{\Phi_M^T B_F G C_v \Phi_M}_{\Delta_M^*} = \mathrm{DIAG}[\underbrace{2\zeta_i \omega_i}_{\delta_i^*}]$$

THEN SOLVE FOR FEEDBACK GAIN MATRIX G,

$$G = (\Phi_M^T B_F)^{\dagger}\ \mathrm{DIAG}[\underbrace{2\zeta_i \omega_i}_{\delta_i^*}]\ (C_v \Phi_M)^{\dagger}$$

USING THE PSEUDO-INVERSES $(\ )^{\dagger}$ DEFINED AS FOLLOWS

$$(\Phi_M^T B_F)^{\dagger} = (\Phi_M^T B_F)^T \left[(\Phi_M^T B_F)(\Phi_M^T B_F)^T\right]^{-1}$$

$$(C_v \Phi_M)^{\dagger} = \left[(C_v \Phi_M)^T (C_v \Phi_M)\right]^{-1} (C_v \Phi_M)^T$$

- <u>NEVER</u> DESTABILIZE LARGE FLEXIBLE SPACE STRUCTURES WHEN THE ACTUATORS ARE CO-LOCATED WITH THE SENSORS

- WITHIN THE REDUCED-ORDER DESIGN MODEL, <u>ANY</u> AMOUNT OF DAMPING DESIRED CAN BE ADDED TO <u>ANY</u> MODE <u>EXACTLY</u>

NUMERICAL ANALYSIS OF VIBRATION MODES

1. LOS ERROR DUE TO UNIT INITIAL MODAL DISPLACEMENT

MODE	1	2	3	4	5	6	7	8	9	10
PEAK	.37	.53	.54	.93	1.3	.14	.51	.002	.18	.03

====> 5, 4, 3, 2, 7, 1, 9, 6, 10, 8

2. MODAL DISPLACEMENT DUE TO RAPID POINTING SLEW

MODE	1	2	3	4	5
PEAK	21.6	603	41.2	13.7	0.49

====> 2, 3, 1, 4, 5, 6, 7, ...

WHICH MODES REALLY REQUIRE ACTIVE CONTROL?

NEED AN ALTERNATIVE AND MORE INDICATIVE MEASURE !!!

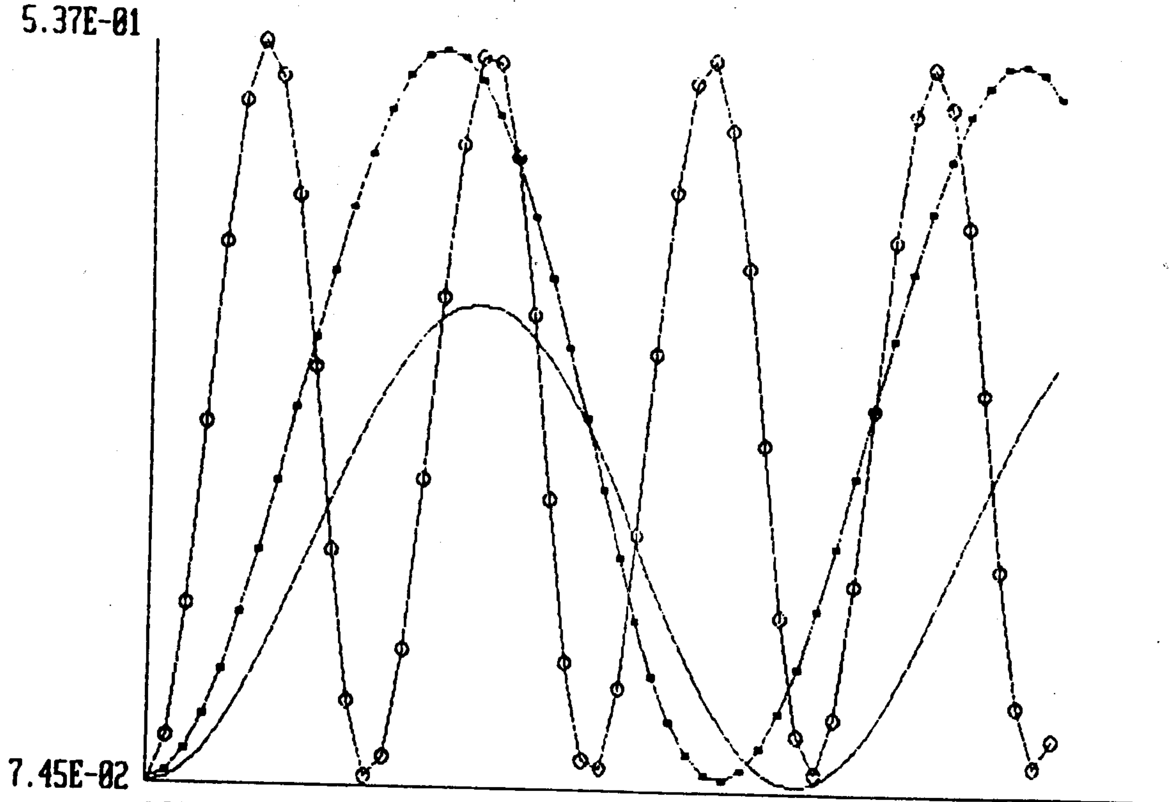
3. LOS ERROR SOLELY DUE TO EACH MODE EXCITED BY THE SLEW

MODE	1	2	3	4	5
PEAK	3.26	88.6(?)	9.57	6.53	0.33

====> 2, 3, 1, 4 (OR 4, 1), 5, 7, 6, ...

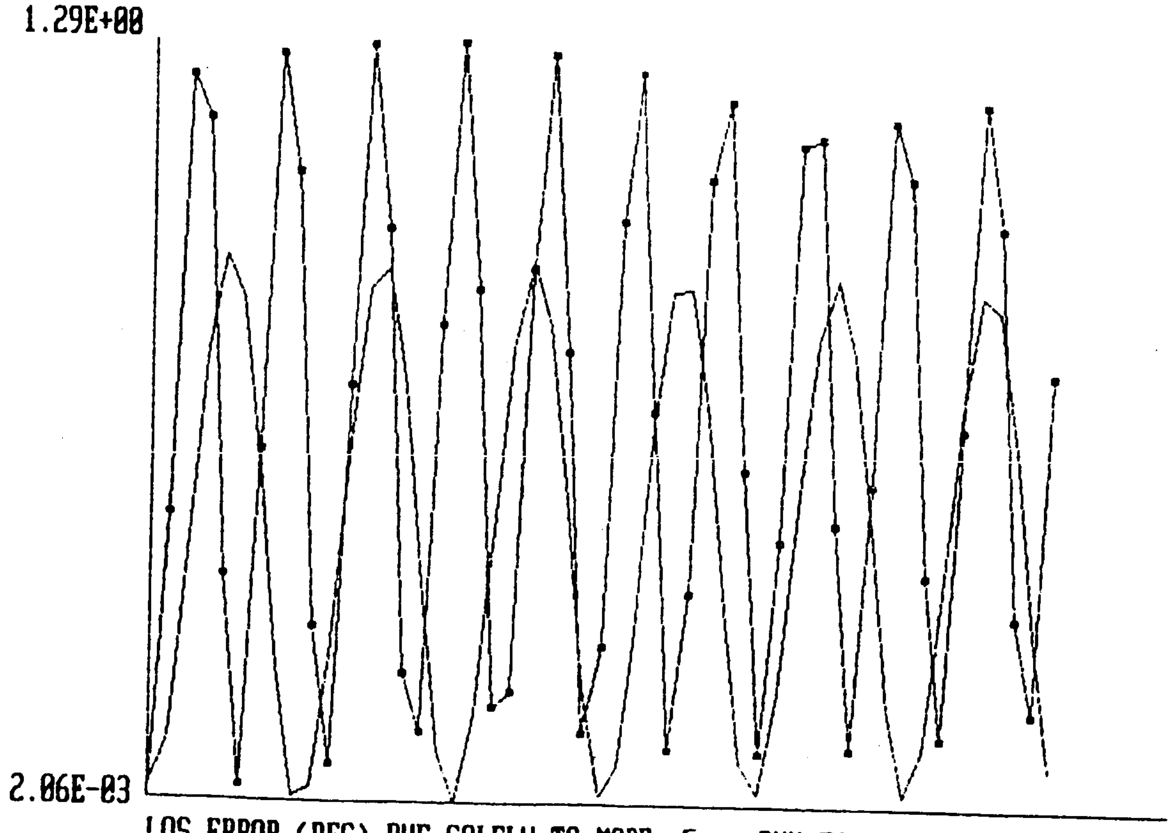
A SOUND MEASURE OF THE SIGNIFICANCE OF EACH MODE:

INPUT (SLEW EXCITATION) AND OUTPUT (LOS ERROR) DULY COMBINED



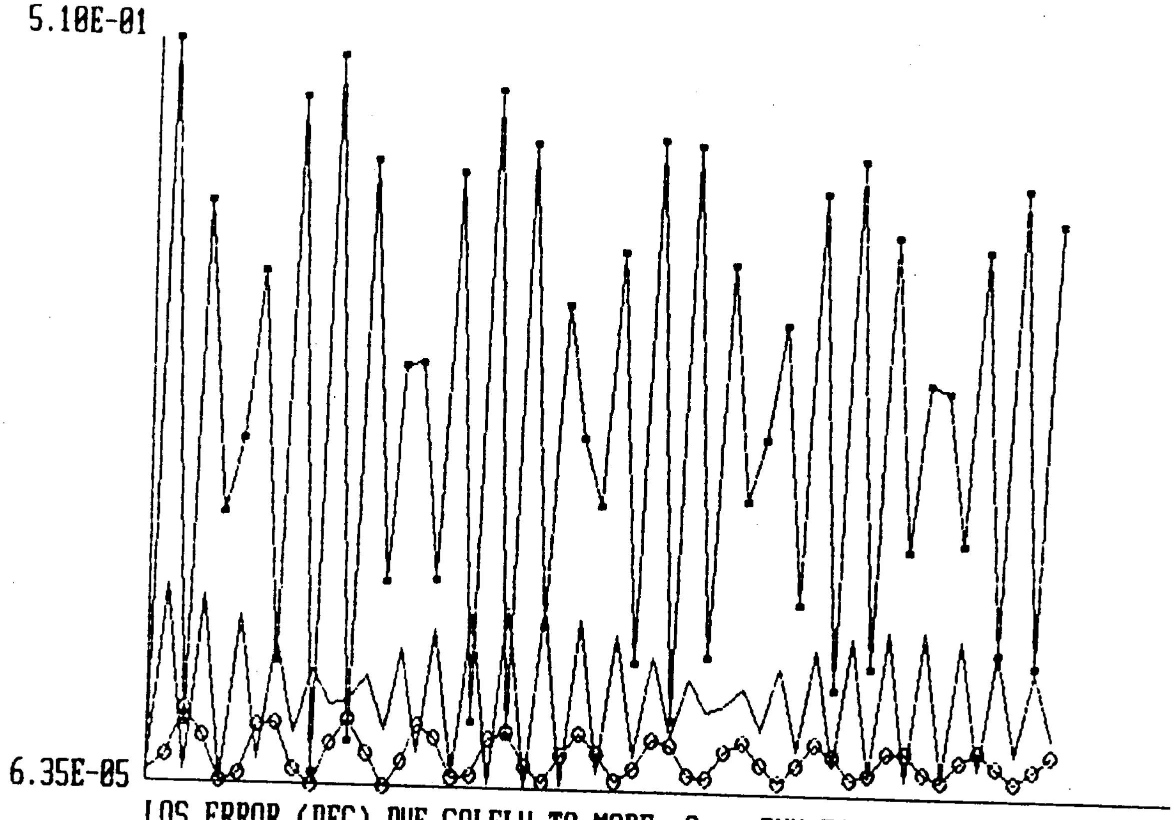
LOS ERROR (DEG) DUE SOLELY TO MODE 3 RUN TIME= 4.892 pf9az.6na

LCOPY



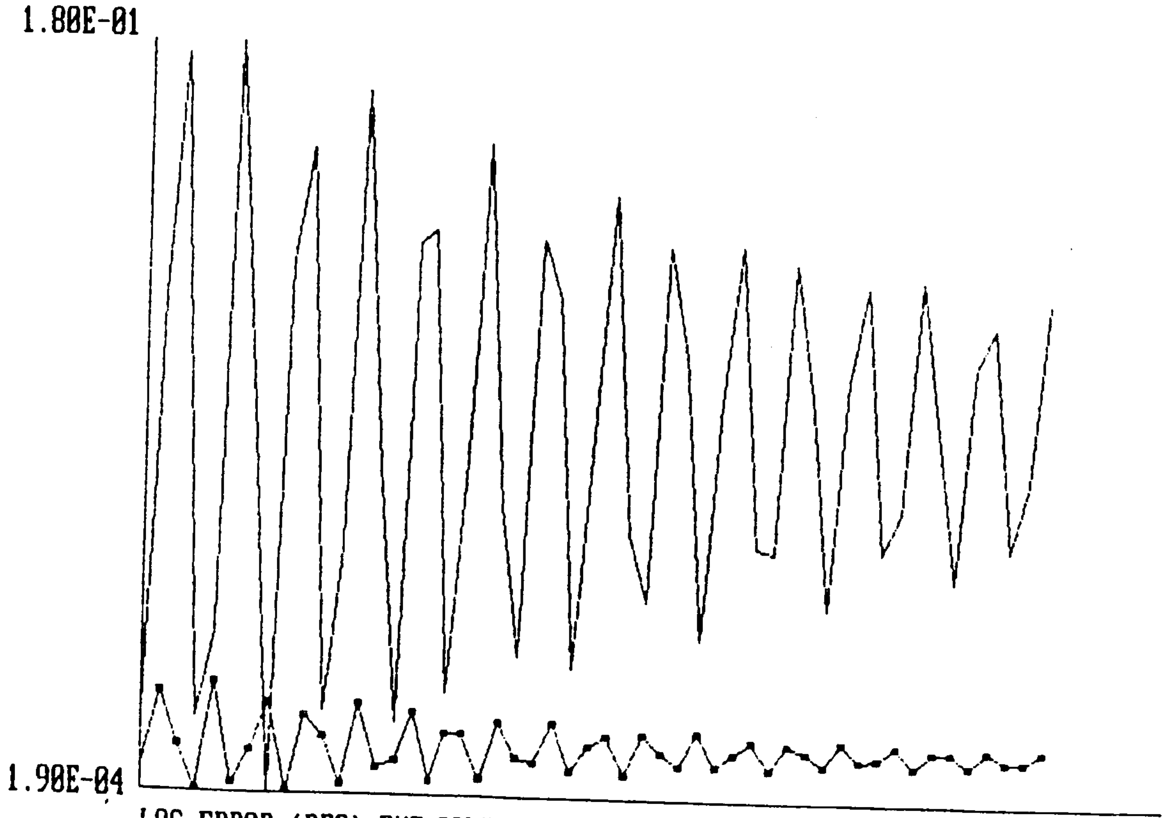
LOS ERROR (DEG) DUE SOLELY TO MODE 5 RUN TIME= 4.892 pf9az.6na

LCOPY



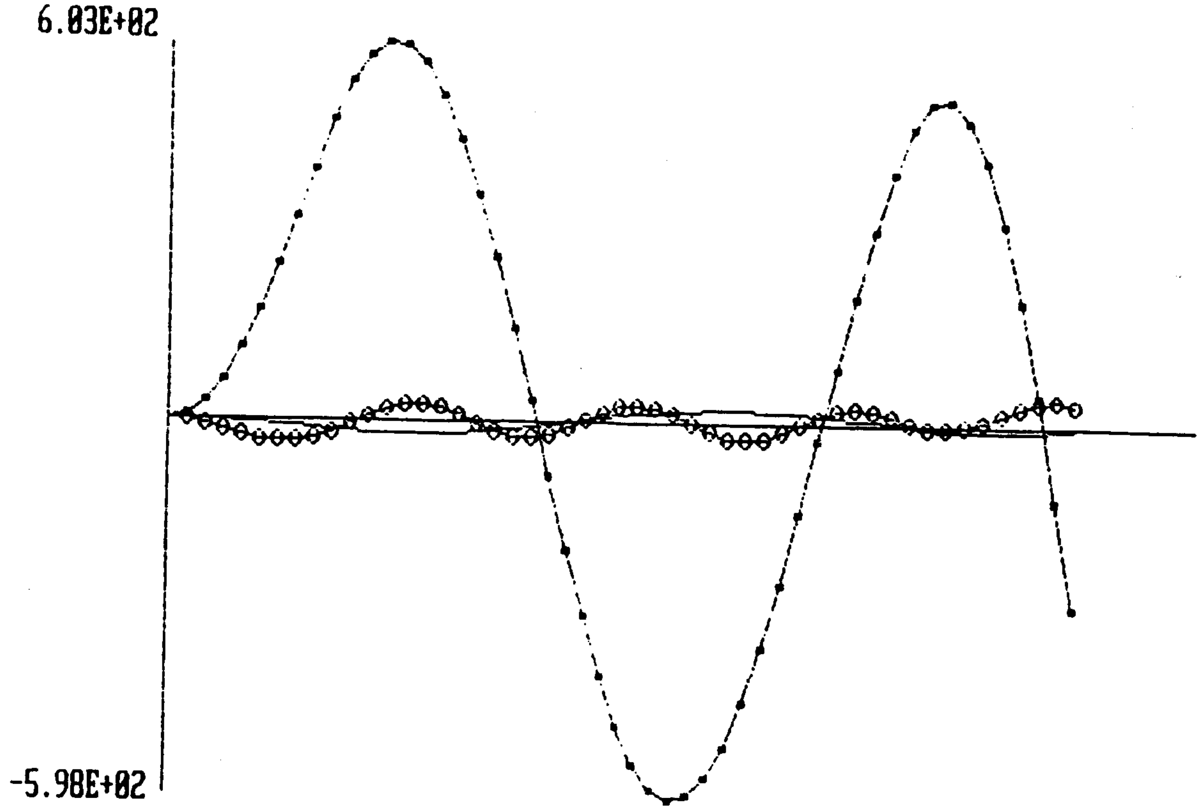
LOS ERROR (DEG) DUE SOLELY TO MODE 8 RUN TIME= 4.892 pf9az.6na

LCOPY



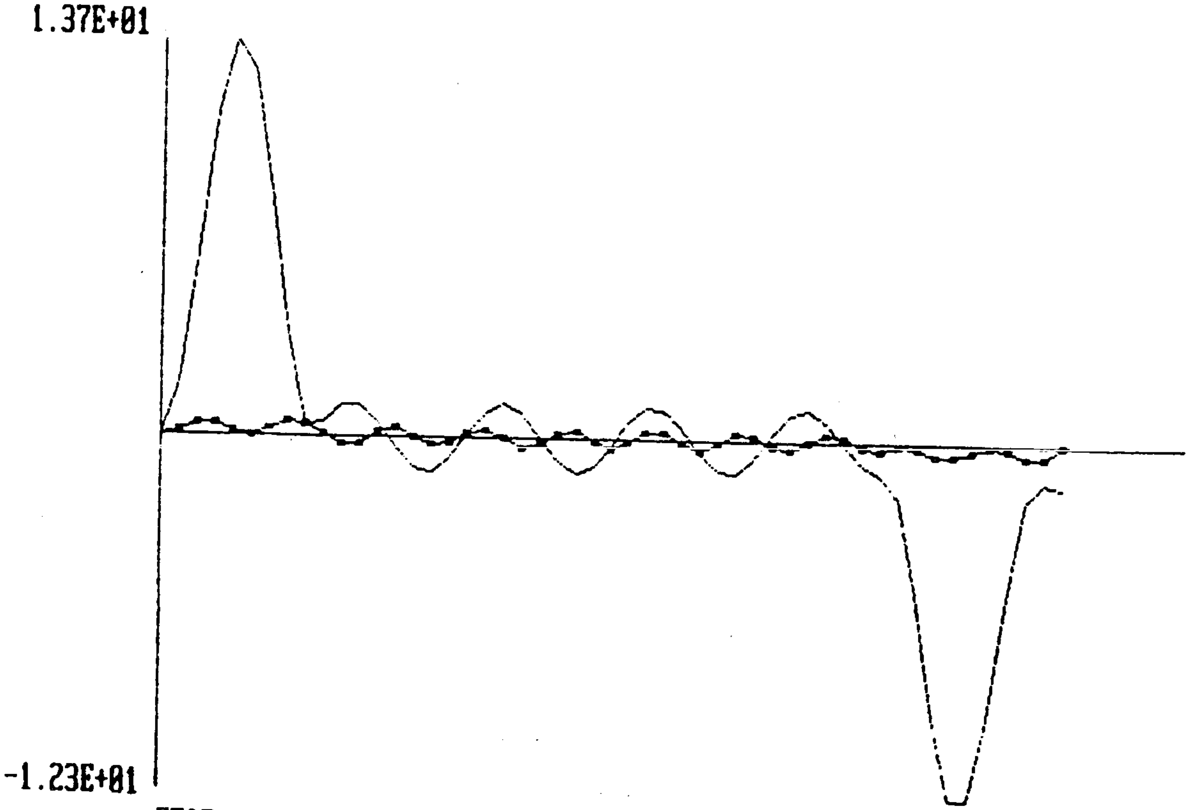
LOS ERROR (DEG) DUE SOLELY TO MODE 10 RUN TIME= 4.892 pf9az.6na

LCOPY



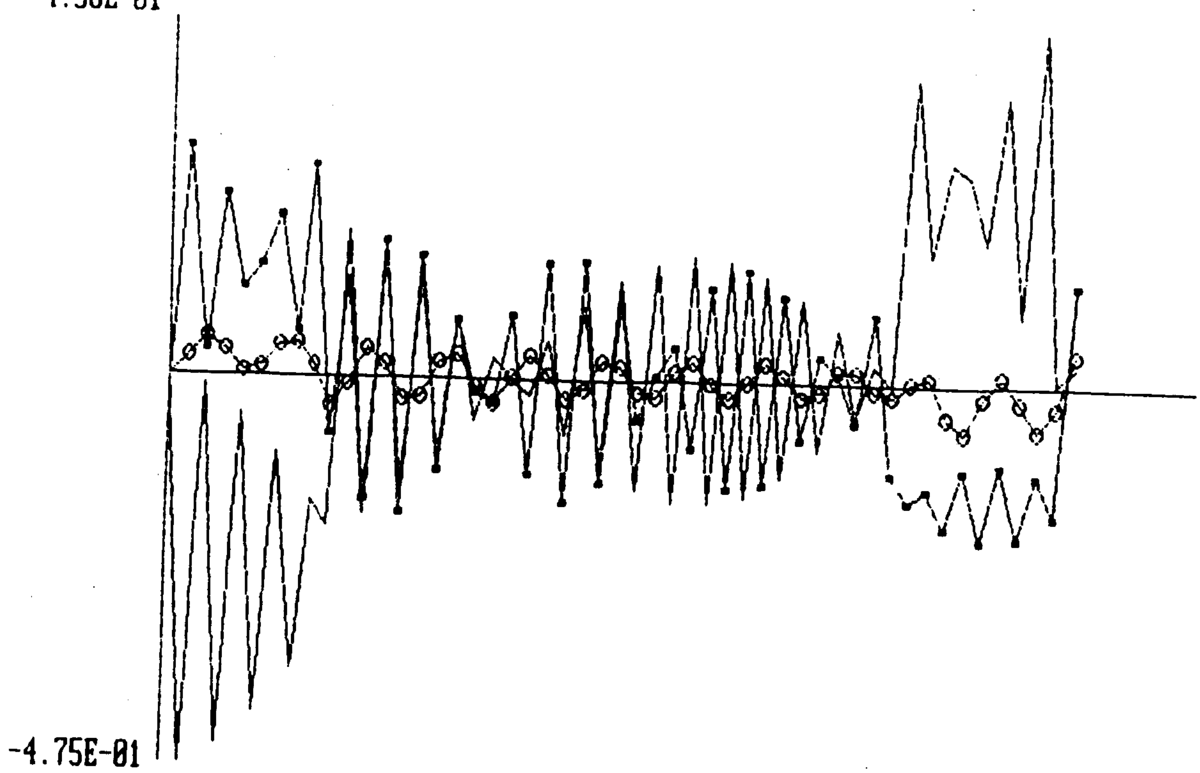
ETA3 RUN TIME = 4.892 pf0000.6na

LCOPY



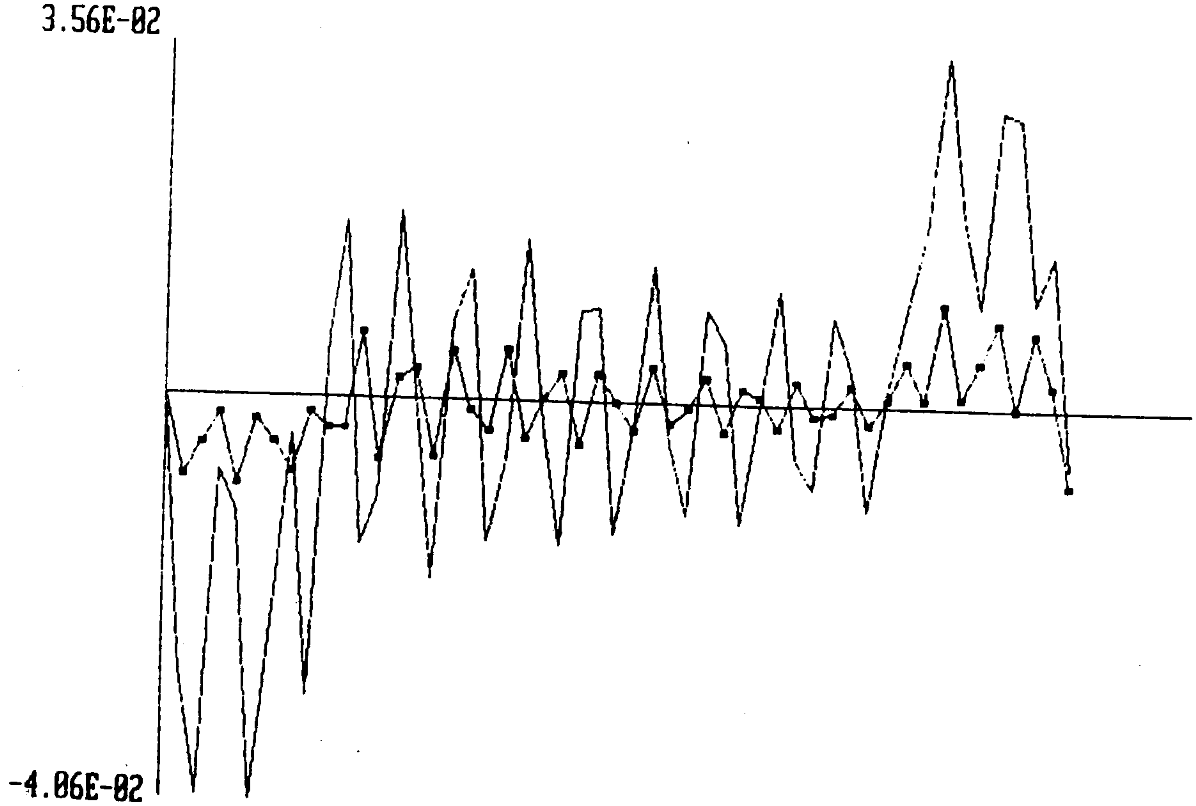
ETA5 RUN TIME = 4.892 pf0000.6na

LCOPY



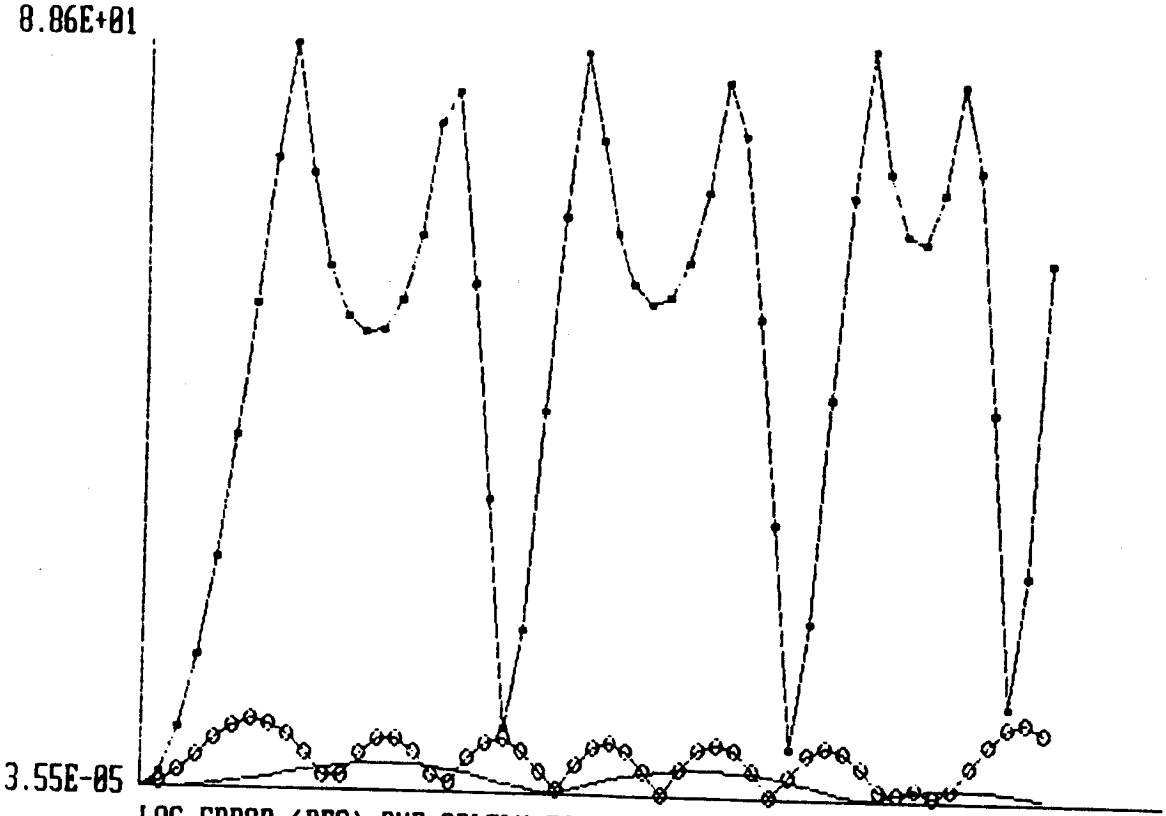
ETA8 RUN TIME = 4.892 pf0000.6na

LCOPY



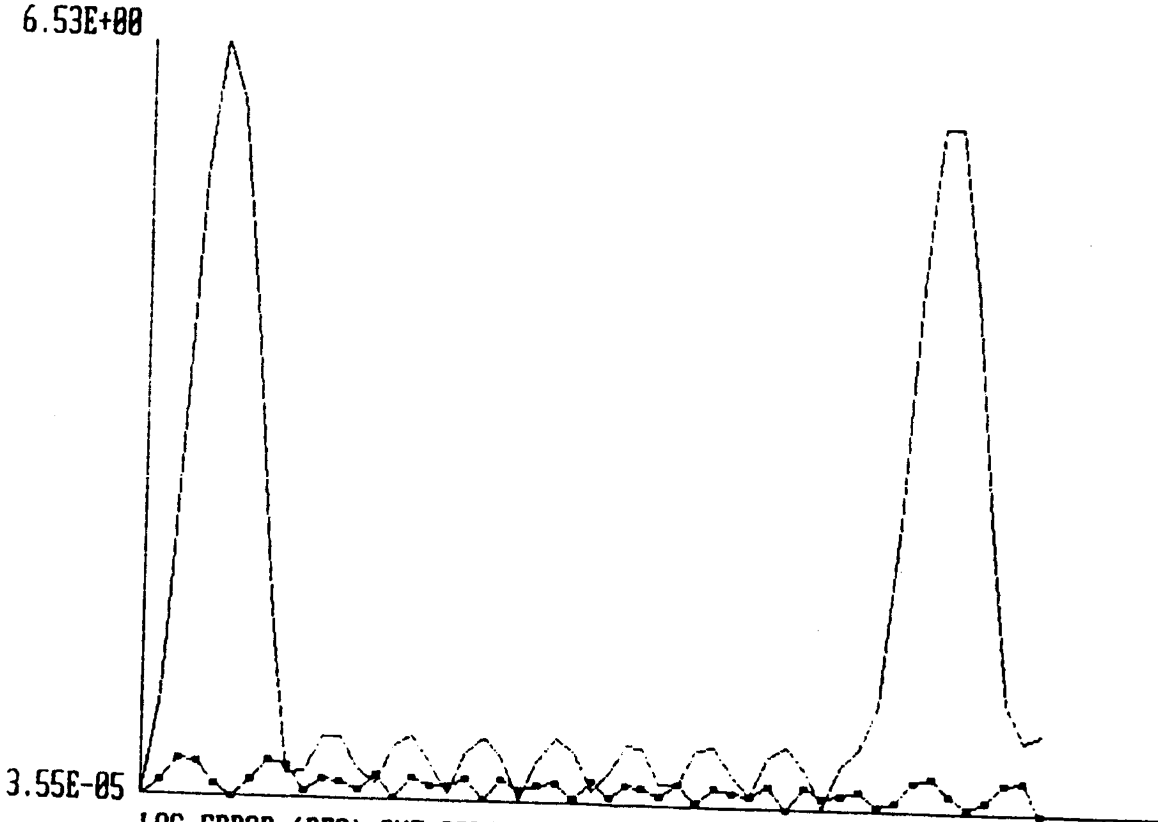
ETA10 RUN TIME = 4.892 pf0000.6na

LCOPY



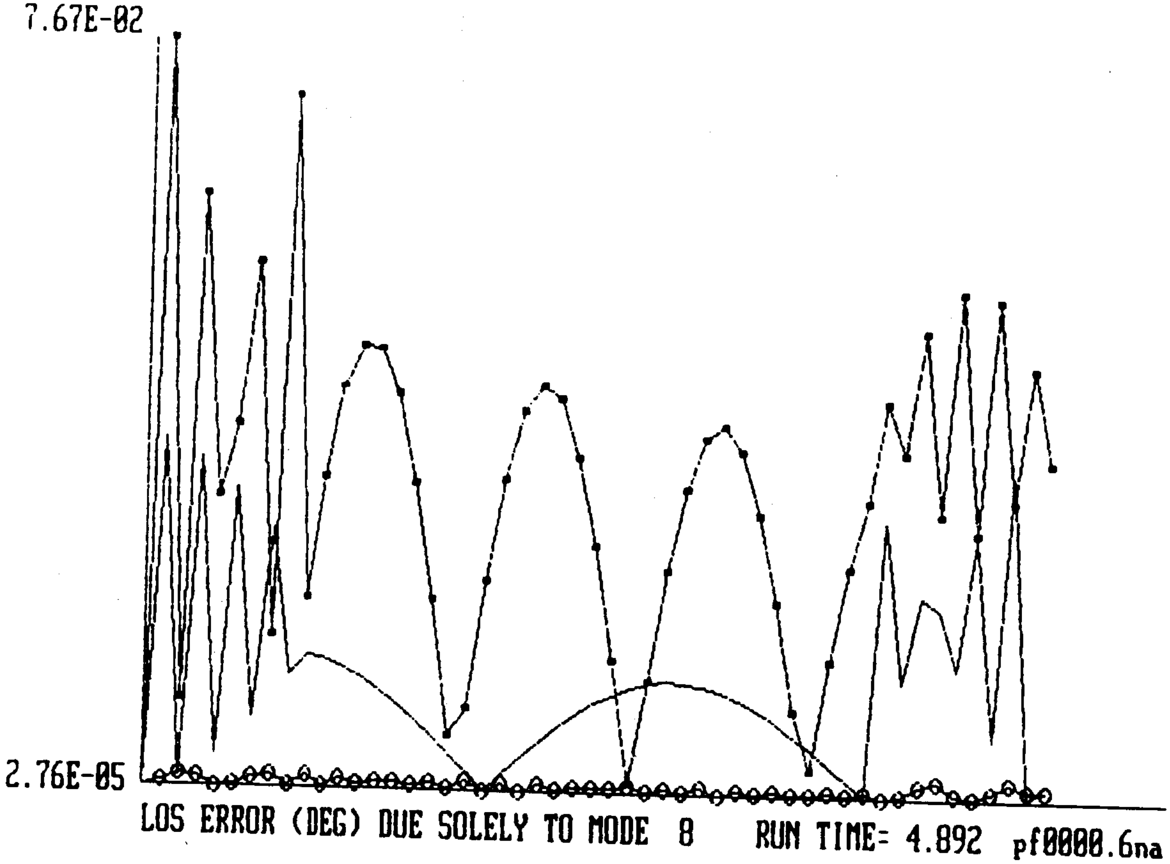
LOS ERROR (DEG) DUE SOLELY TO MODE 3 RUN TIME= 4.892 pf0000.6na

LCOPY

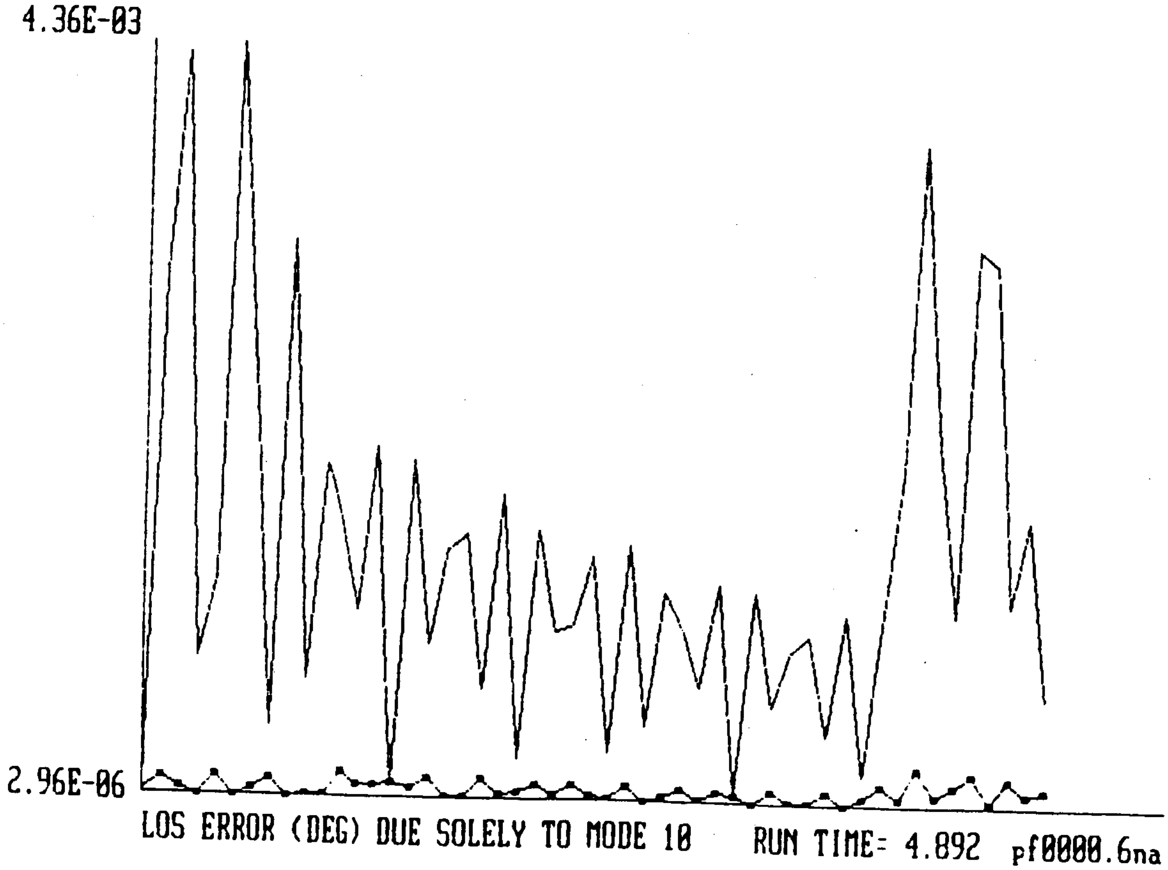


LOS ERROR (DEG) DUE SOLELY TO MODE 5 RUN TIME= 4.892 pf0000.6na

LCOPY


7.67E-02
2.76E-05
LOS ERROR (DEG) DUE SOLELY TO MODE 8 RUN TIME= 4.892 pf0000.6na

LCOPY


4.36E-03
2.96E-06
LOS ERROR (DEG) DUE SOLELY TO MODE 10 RUN TIME= 4.892 pf0000.6na

LCOPY

Actuator/Sensor Influence on First 10 Modes

Mode	Act. 1 - 3	Mode	Act. 4 - 6	Mode	Act. 7 - 8	Mode	Act. 9 - 12
2	0.30019961E-02	5	0.36487188E-01	2	0.14311218E+01	2	0.10711402E+00
4	0.41220308E-03	4	0.25172627E-01	1	0.14061384E+01	1	0.10338868E+00
1	0.40146321E-03	3	0.15999462E-01	3	0.81986851E+00	3	0.10171293E+00
3	0.19184369E-03	2	0.15595800E-01	4	0.39743480E+00	4	0.69439910E-01
5	0.11186474E-03	7	0.14711439E-01	7	0.30395976E+00	9	0.68373762E-01
6	0.69881789E-04	1	0.13037169E-01	9	0.25503686E+00	8	0.67025743E-01
7	0.36829457E-04	9	0.57048416E-02	6	0.21852742E+00	5	0.63191518E-01
8	0.26261532E-04	6	0.34139471E-02	8	0.14623879E+00	10	0.46103600E-01
9	0.15072107E-04	8	0.12352261E-02	10	0.10801539E+00	6	0.39935779E-01
10	0.13497747E-04	10	0.63637015E-03	5	0.74399590E-01	7	0.32263912E-01

Mode	Sen. 1 - 3	Mode	Sen. 4 - 6	Mode	Sen. 7 - 8	Mode	Sen. 9 - 12
2	0.28690067E-03	5	0.34890966E-02	2	0.13466856E+00	2	0.10711402E+00
4	0.39390128E-04	3	0.32387748E-02	1	0.12736945E+00	1	0.10338868E+00
1	0.39113598E-04	4	0.24055073E-02	3	0.12407852E+00	3	0.10171293E+00
3	0.18940789E-04	2	0.15346858E-02	4	0.38158901E-01	4	0.69439910E-01
5	0.10689848E-04	7	0.14879148E-02	7	0.36793593E-01	9	0.68373762E-01
6	0.66779044E-05	1	0.13531352E-02	9	0.30879460E-01	8	0.67025743E-01
7	0.35194691E-05	9	0.67911280E-03	6	0.20832075E-01	5	0.63191518E-01
8	0.25095521E-05	6	0.32624099E-03	8	0.14005536E-01	10	0.46103600E-01
9	0.14402938E-05	8	0.11804001E-03	10	0.10299906E-01	6	0.39935779E-01
10	0.12898448E-05	10	0.60812166E-04	5	0.90737212E-02	7	0.32263912E-01

MODAL-DASHPOT **MD.1**

PART 1: LINEAR VELOCITY FEEDBACK GAIN G_{LVR}

2 FORCE ACTUATOR ON REFLECTORS

--> U_7 (X AXIS); U_8 (Y AXIS)

2 LINEAR VELOCITY SENSORS AT REFLECTOR END

--> Y_{15} (X AXIS); Y_{16} (Y AXIS)

2 "MODELED MODES" FOR DAMPING AUGMENTATION

MODE 1: $\delta_1^* = 2 \times 60\ \%\ \omega_1 = 2.0964$

--> TIME CONSTANT= 0.95 SEC

MODE 2: $\delta_2^* = 2 \times 67\%\ \omega_2 = 2.6389$

--> TIME CONSTANT= 0.76 SEC

PART 2: ANGULAR VELOCITY FEEDBACK GAIN G_{AVR}

3 TORQUE ACTUATORS ON REFLECTOR

--> U_4 (X AXIS); U_5 (Y AXIS); U_6 (Z AXIS)

3 ANGULAR VELOCITY SENSORS AT REFLECTOR END

--> Y_{10} (X AXIS); Y_{11} (Y AXIS); Y_{12} (Z AXIS)

3 "MODELED MODES" FOR DAMPING AUGMENTATION

MODE 3: $\delta_3^* = 2 \times 3\ \%\ \omega_3 = 0.3065$

--> TIME CONSTANT= 6.53 SEC

MODE 4: $\delta_4^* = 2 \times 3\%\ \omega_4 = 0.4470$

--> TIME CONSTANT= 4.47 SEC

MODE 5: $\delta_5^* = 2 \times 3\%\ \omega_5 = 0.7742$

--> TIME CONSTANT= 2.58 SEC

DYNAMICS: $M \frac{d^2 x}{dt^2} + D \frac{dx}{dt} + K x = f$

FORCE (TORQUE) ACTUATORS AND DISPLACEMENT SENSORS:

$$f = B_F u \qquad y = C_D \frac{dx}{dt}$$

CONTROL LAW FOR DISPLACEMENT-OUTPUT FEEDBACK:

$$u = - G_D y$$

FULL-ORDER CLOSED-LOOP SYSTEM EQUATION:

$$\frac{d^2 \eta}{dt^2} + \Delta \frac{d\eta}{dt} + (\Omega^2 + \Phi^T B_F G C_D \Phi) \eta = 0$$

MODAL-SPRING APPROACH

DESIGN TO AUGMENT STIFFNESS TO EACH MODE OF A REDUCED-ORDER MODEL

LET $\omega_{i\,NEW}$ BE DESIRED FREQUENCY FOR MODELED MODE i

SET $\Phi_M^T B_F G C_V \Phi_M = DIAG\left[\omega_{i\,NEW}^2 - \omega_i^2\right]$

$$= DIAG\left[\sigma_i\right]$$

THEN SOLVE FOR FEEDBACK GAIN MATRIX G,

$$G = (\Phi_M^T B_F)^{\dagger} \; DIAG\left[\sigma_i\right] \; (C_D \Phi_M)^{\dagger}$$

USING THE PSEUDO-INVERSES $(\;)^{\dagger}$ DEFINED AS FOLLOWS

$$(\Phi_M^T B_F)^{\dagger} = (\Phi_M^T B_F)^T \left[(\Phi_M^T B_F)(\Phi_M^T B_F)^T\right]^{-1}$$

$$(C_D \Phi_M)^{\dagger} = \left[(C_D \Phi_M)^T (C_D \Phi_M)\right]^{-1} (C_D \Phi_M)^T$$

PRE-DESIGN ANALYSES -- MODAL SPRINGS

PLACEMENT OF 2-AXIS PROOF-MASS ACTUATORS

1 AT REFLECTOR END
-- PEAK OF MODES 1, 2, 3

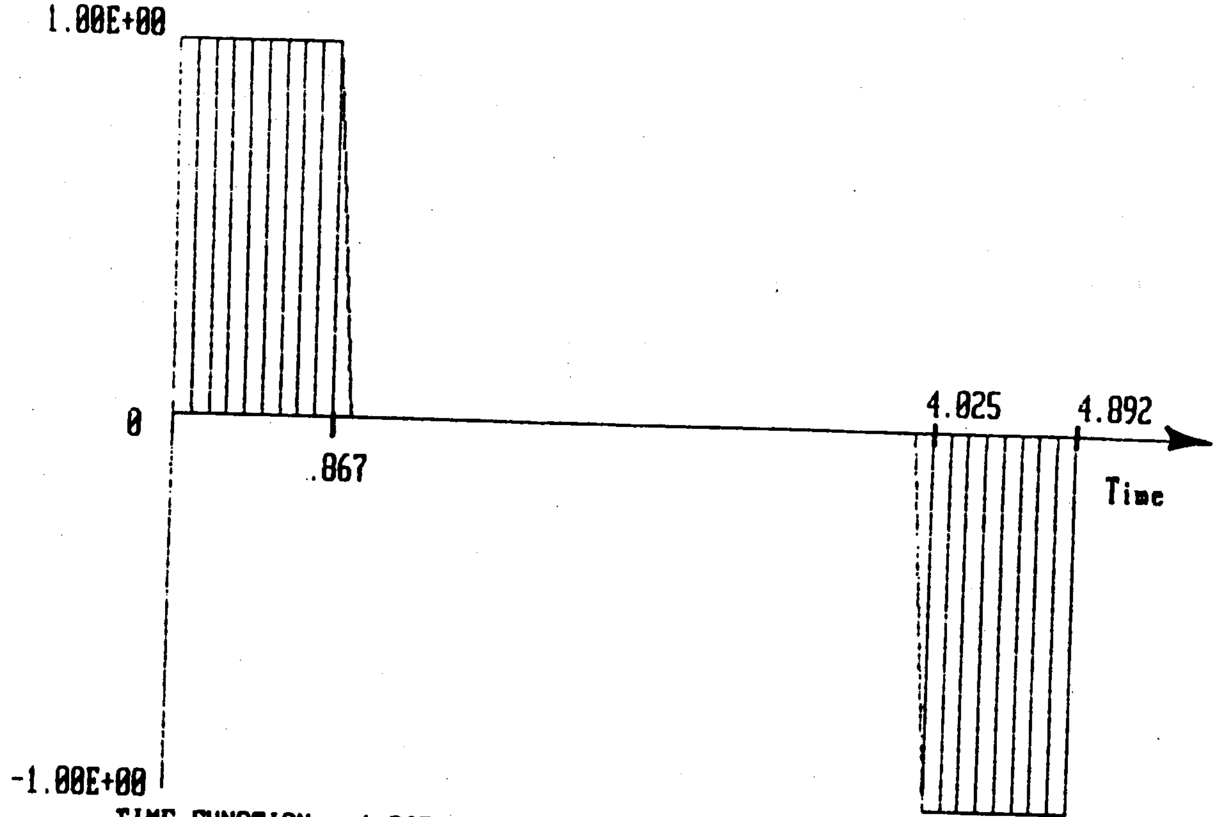
1 AT 92FT FROM SHUTTLE (70.77% LENGTH)
-- PEAK OF MODE 4

FFT ANALYSIS OF BPB SLEW DISTURBANCE

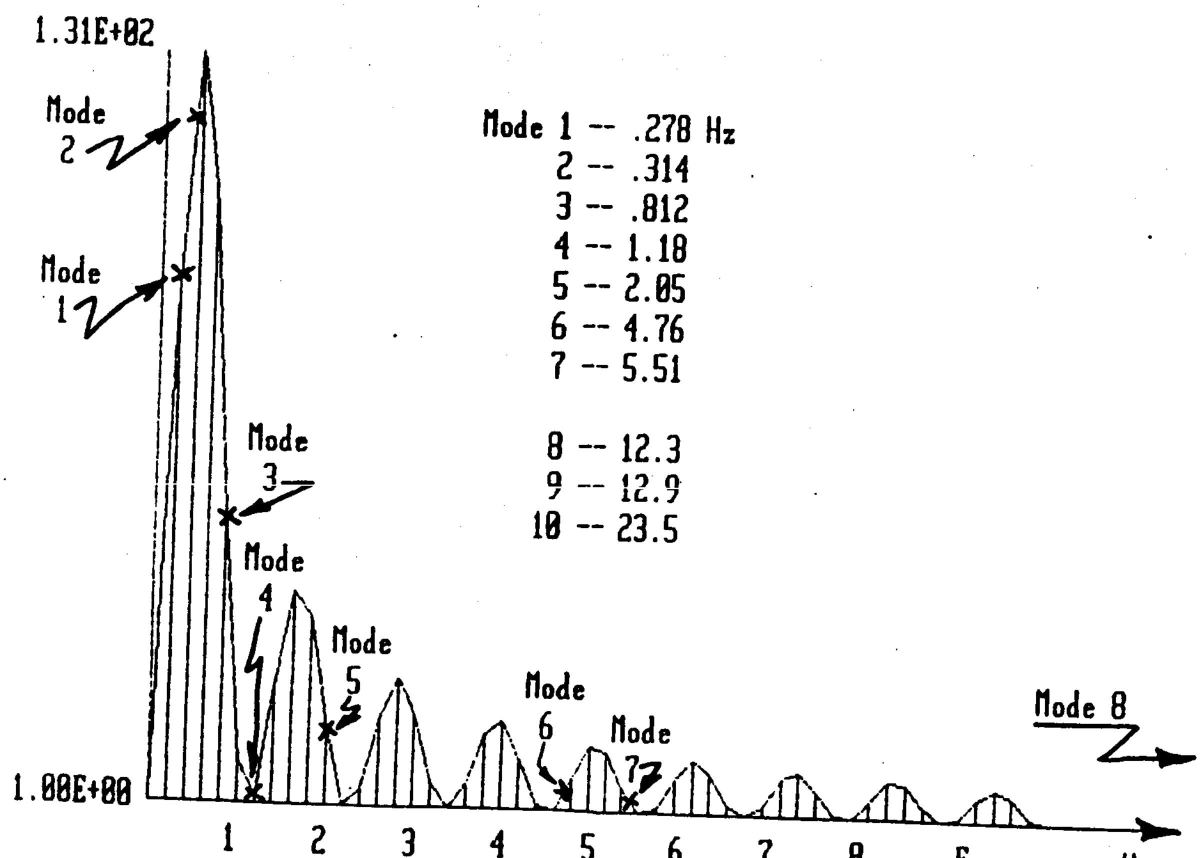
==> SHFIT MODES 2 & 3 UP AND AWAY !!!

AVOID CONTROL SPILLOVER TO MODE 1 !

IGNORE MODE 4



TIME FUNCTION (.867,4.025,4.892,4.892,512,51) FFTrs.11



MAGNITUDE SPECTRUM (.20 HZ) FFTrs.11

MODAL-SPRING **MS.1**

LINEAR DISPLACEMENT FEEDBACK GAIN G_{LDM}

2 2-AXIS PROOF-MASS ACTUATORS ON MAST:

1 AT REFLECTOR END

--> U_9 (X AXIS); U_{10} (Y AXIS)

1 AT 92 FT FROM SHUTTLE (70.77% LENGTH)

--> U_{11} (X AXIS); U_{12} (Y AXIS)

4 LINEAR DISPLACEMENT SENSORS ON MAST:

CO-LOCATED WITH PROOF-MASS ACTUATORS

--> Y_{13}, Y_{17} (X AXIS);

Y_{14}, Y_{18} (Y AXIS)

3 "MODELED MODES" FOR STIFFNESS AUGMENTATION

<u>MODE 1</u>: $\sigma_1^* = 0$

<u>MODE 2</u>: $\sigma_2^* = (2\pi \times 0.7)^2 - (2\pi \times 0.3136)^2$

$= 15.4627$

<u>MODE 3</u>: $\delta_3^* = (2\pi \times 0.85)^2 - (2\pi \times 0.812)^2$

$= 2.4290$

MODAL-DASHPOT **MD.2**

LINEAR VELOCITY FEEDBACK GAIN G_{LVM}

2 2-AXIS PROOF-MASS ACTUATORS ON MAST:

1 AT REFLECTOR END

--> U_9 (X AXIS); U_{10} (Y AXIS)

1 AT 92 FT FROM SHUTTLE (70.77% LENGTH)

--> U_{11} (X AXIS); U_{12} (Y AXIS)

4 LINEAR VELOCITY SENSORS ON MAST:

CO-LOCATED WITH PROOF-MASS ACTUATORS

--> Y_{15}, Y_{19} (X AXIS);

Y_{16}, Y_{20} (Y AXIS)

3 "MODELED MODES" FOR DAMPING AUGMENTATION

<u>MODE 1</u>: $\delta_1^* = 2 \times 2.7\ \%\ \omega_1 = 0.0943$

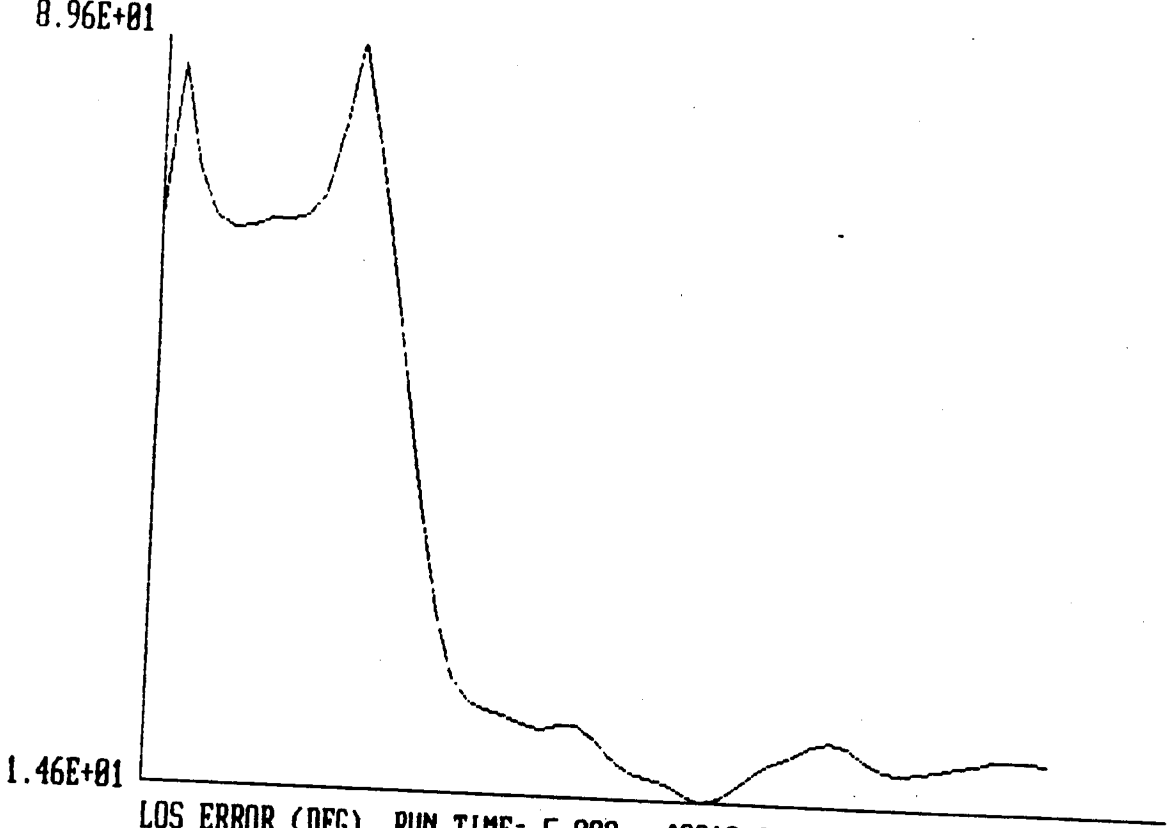
<u>MODE 2</u>: $\delta_2^* = 2\times\ 2.7\%\ \omega_2(\text{NEW}) = 0.2375$

<u>MODE 3</u>: $\delta_3^* = 2 \times 2.7\ \%\ \omega_3 = 0.2758$

MODAL-DASHPOT **MD.3**

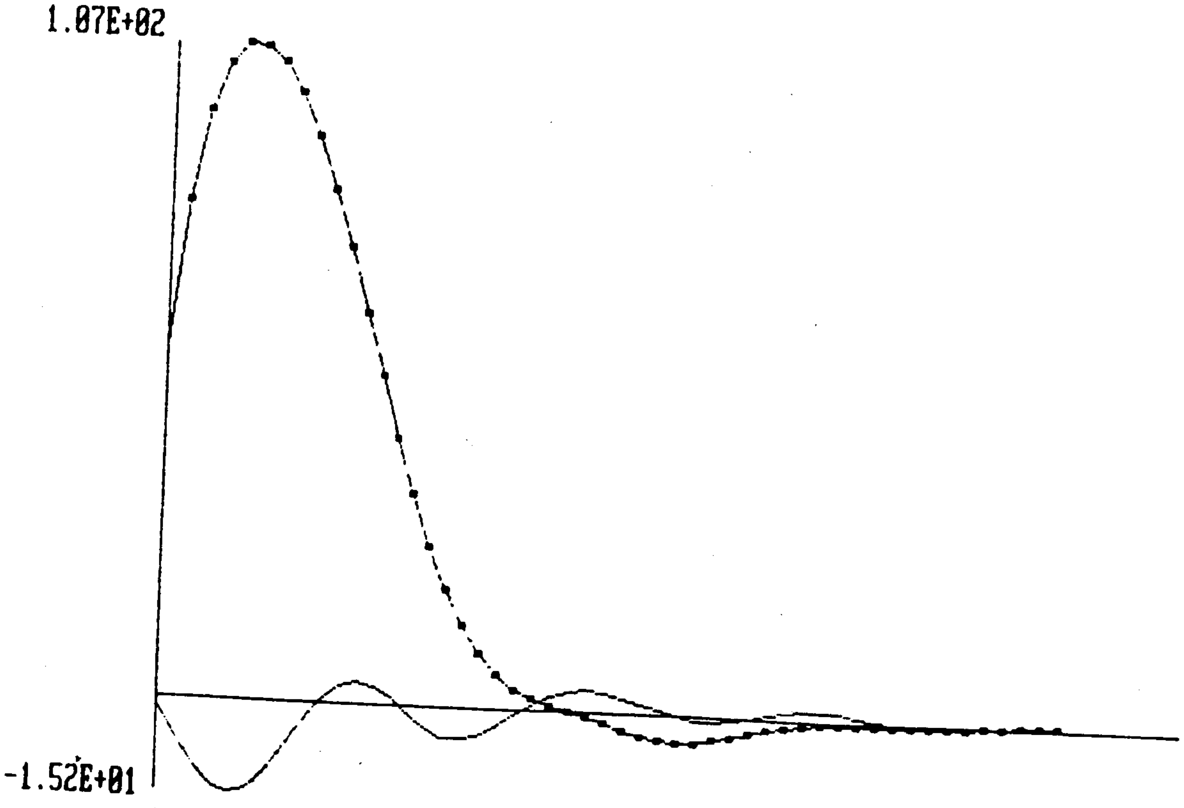
PART 1: LINEAR VELOCITY FEEDBACK GAIN G_{LVM}

PART 2: ANGULAR VELOCITY FEEDBACK GAIN G_{AVR}



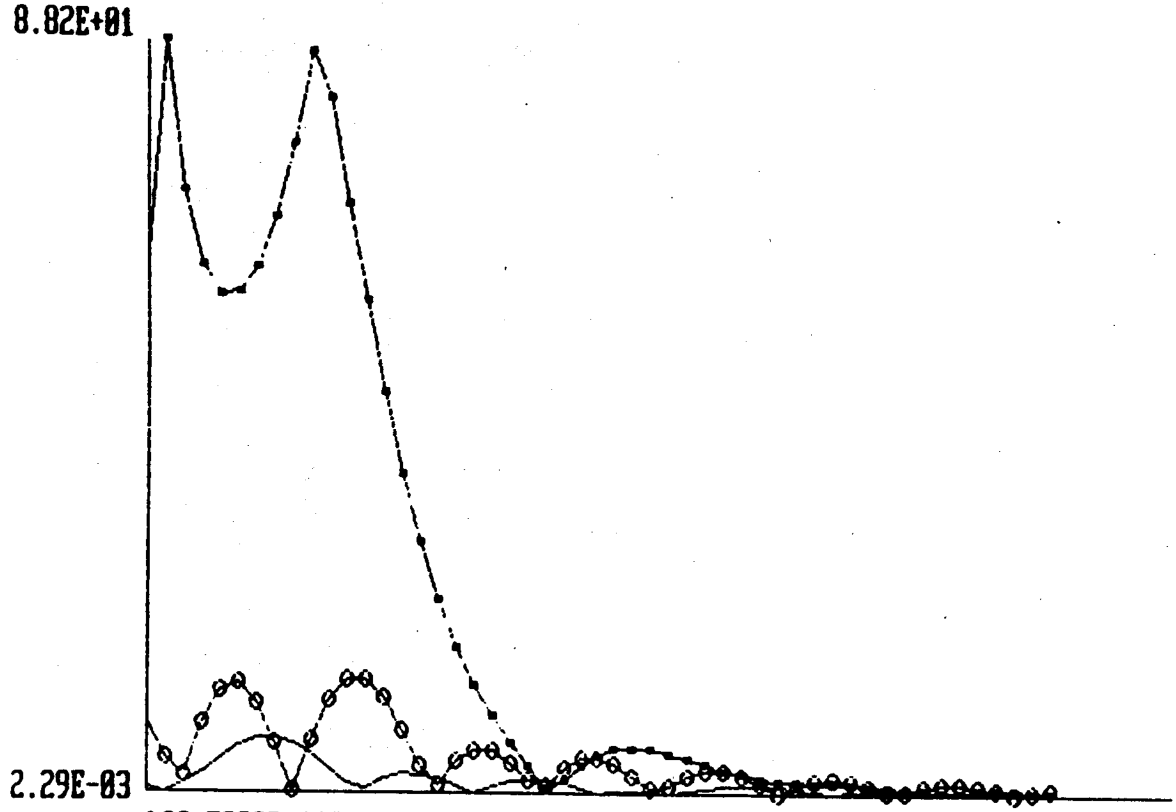
LOS ERROR (DEG) RUN TIME= 5.000 pf0010.6na

LCOPY



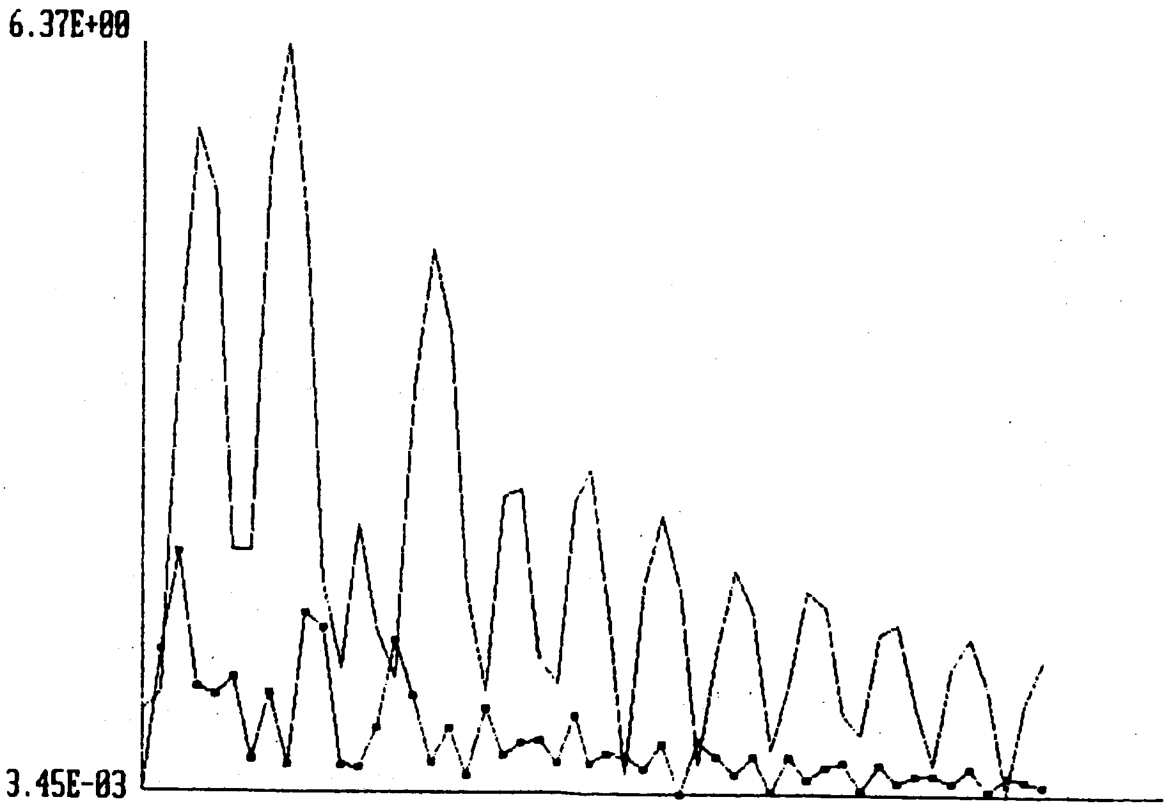
Y14 RUN TIME = 5.000 pf0010.6na

LCOPY



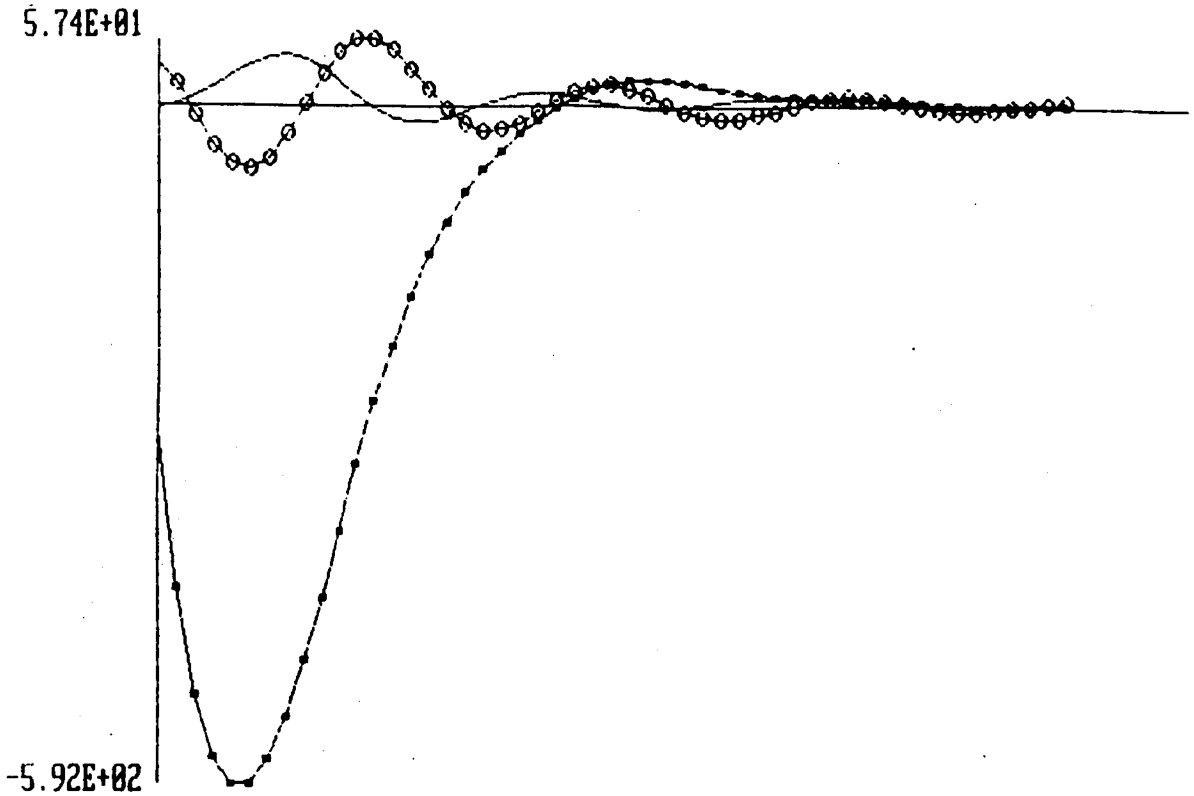
LOS ERROR (DEG) DUE SOLELY TO MODE 3 RUN TIME= 5.000 pf0010.6na

LCOPY



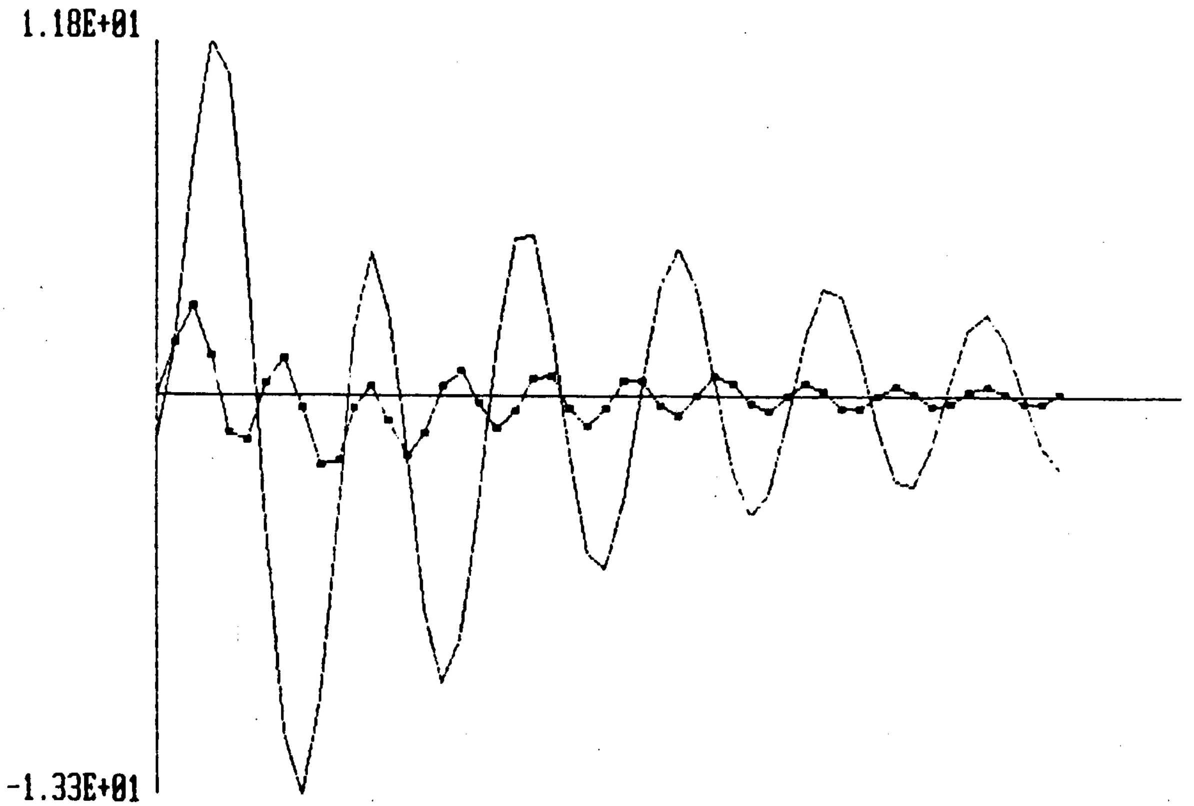
LOS ERROR (DEG) DUE SOLELY TO MODE 5 RUN TIME= 5.000 pf0010.6na

LCOPY



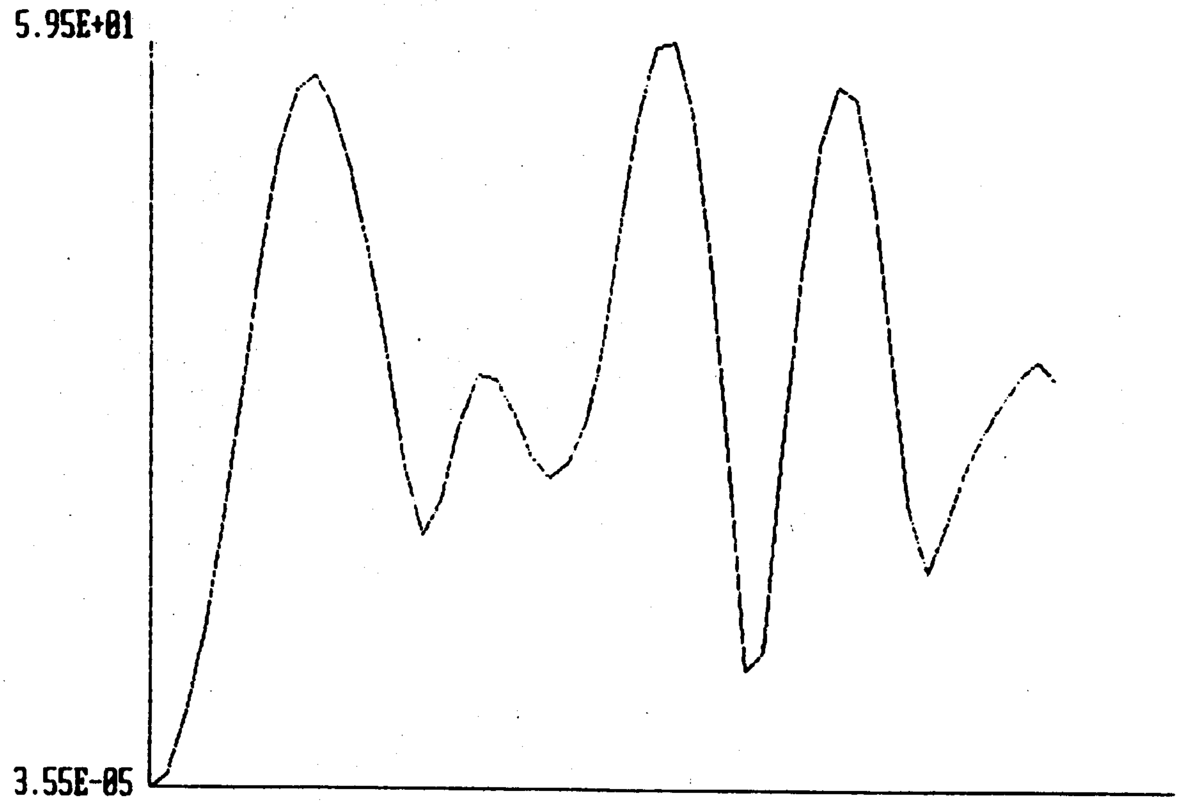
ETA3 RUN TIME = 5.000 pf0010.6na

LCOPY



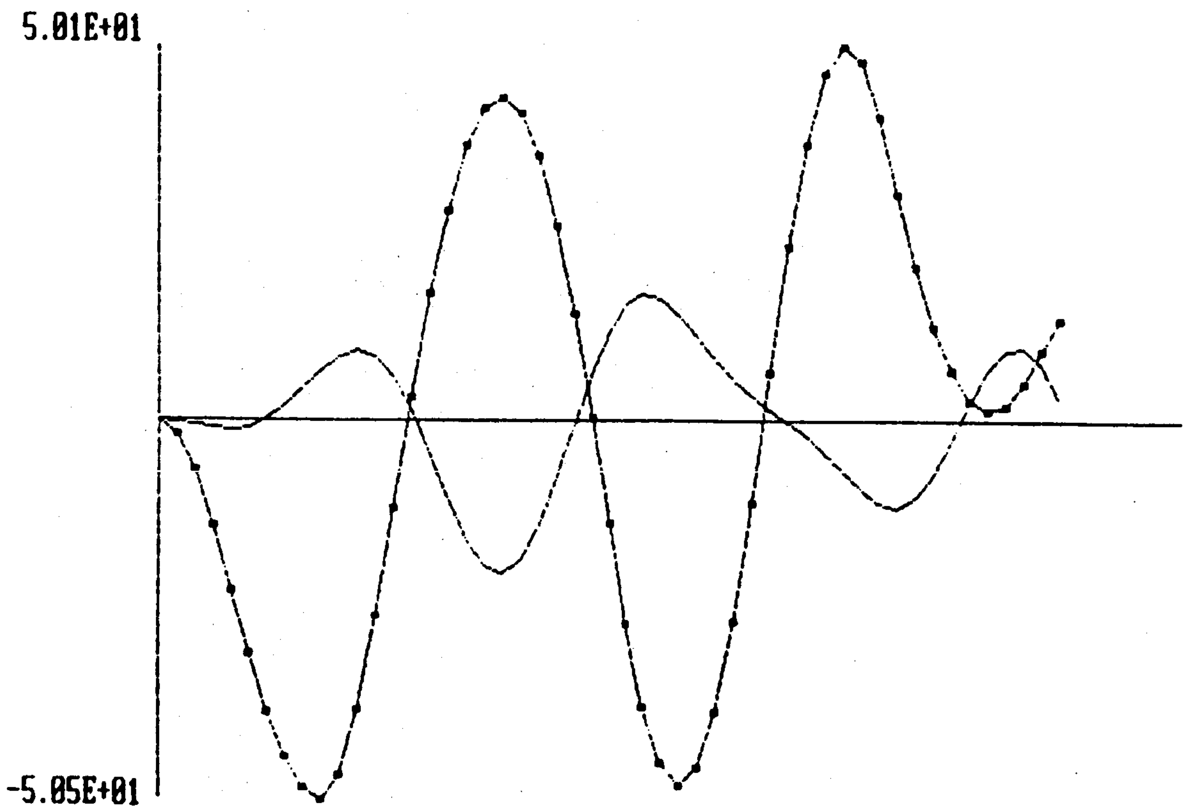
ETA5 RUN TIME = 5.000 pf0010.6na

LCOPY



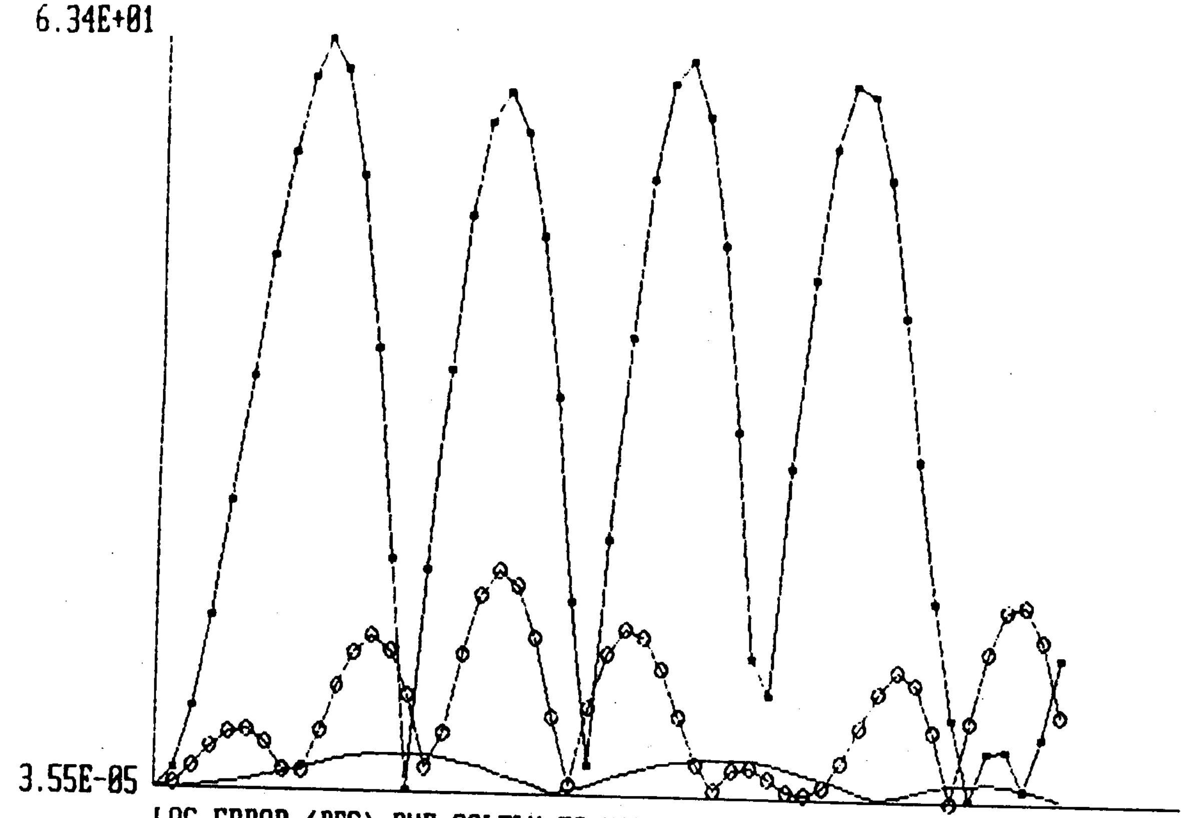
LOS ERROR (DEG) RUN TIME= 4.892 pf0100.6na

LCOPY



Y14 RUN TIME = 4.892 pf0100.6na

LCOPY



LOS ERROR (DEG) DUE SOLELY TO MODE 3 RUN TIME= 4.892 pf0100.6na

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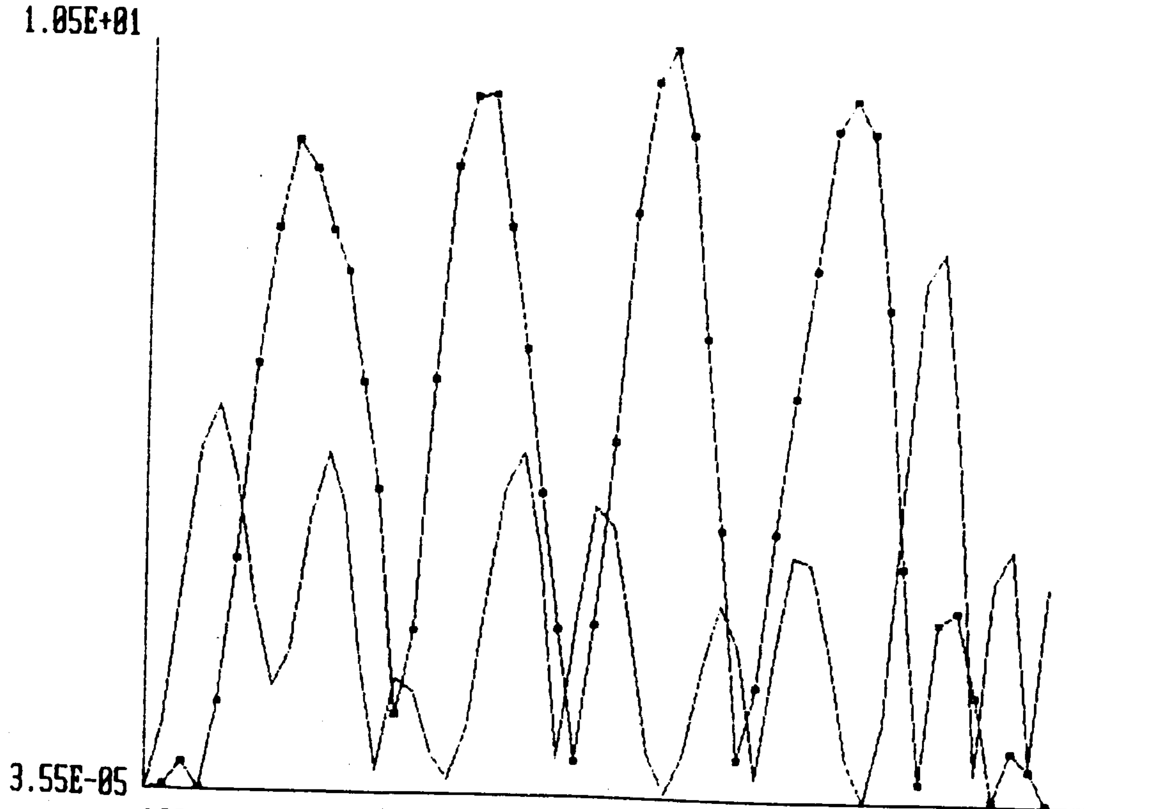
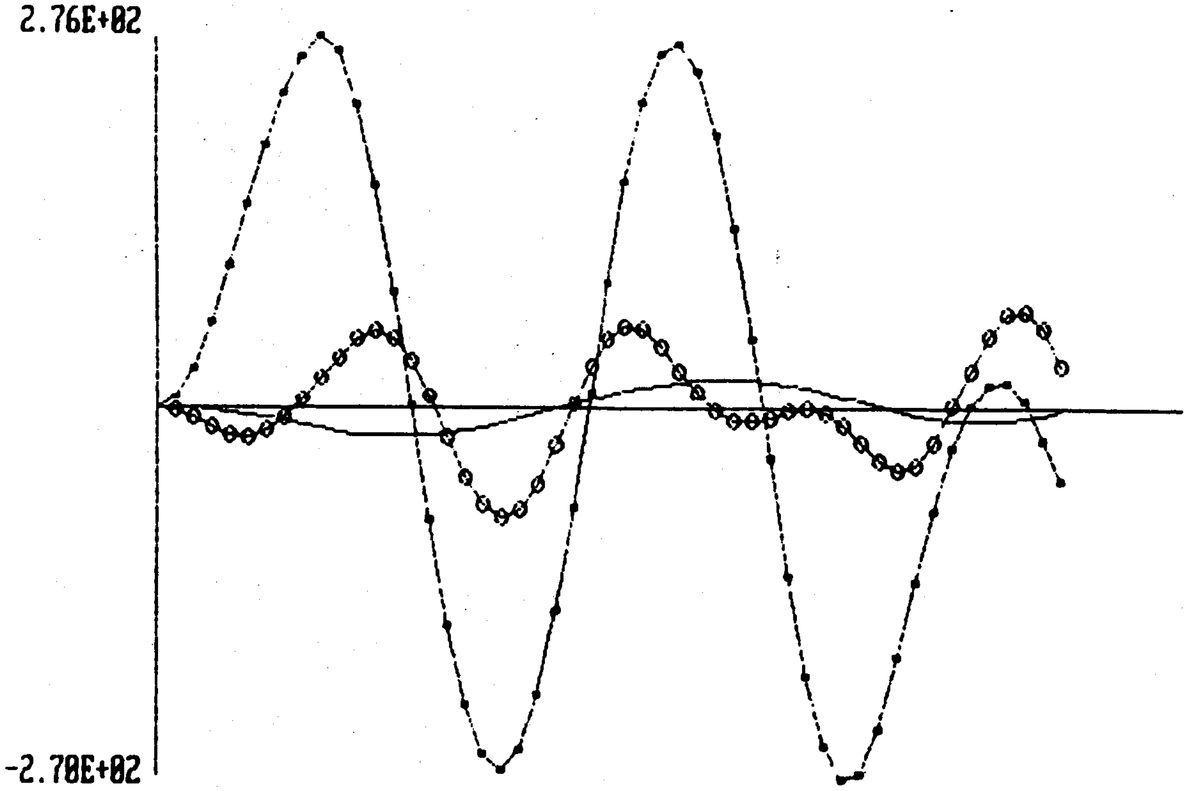


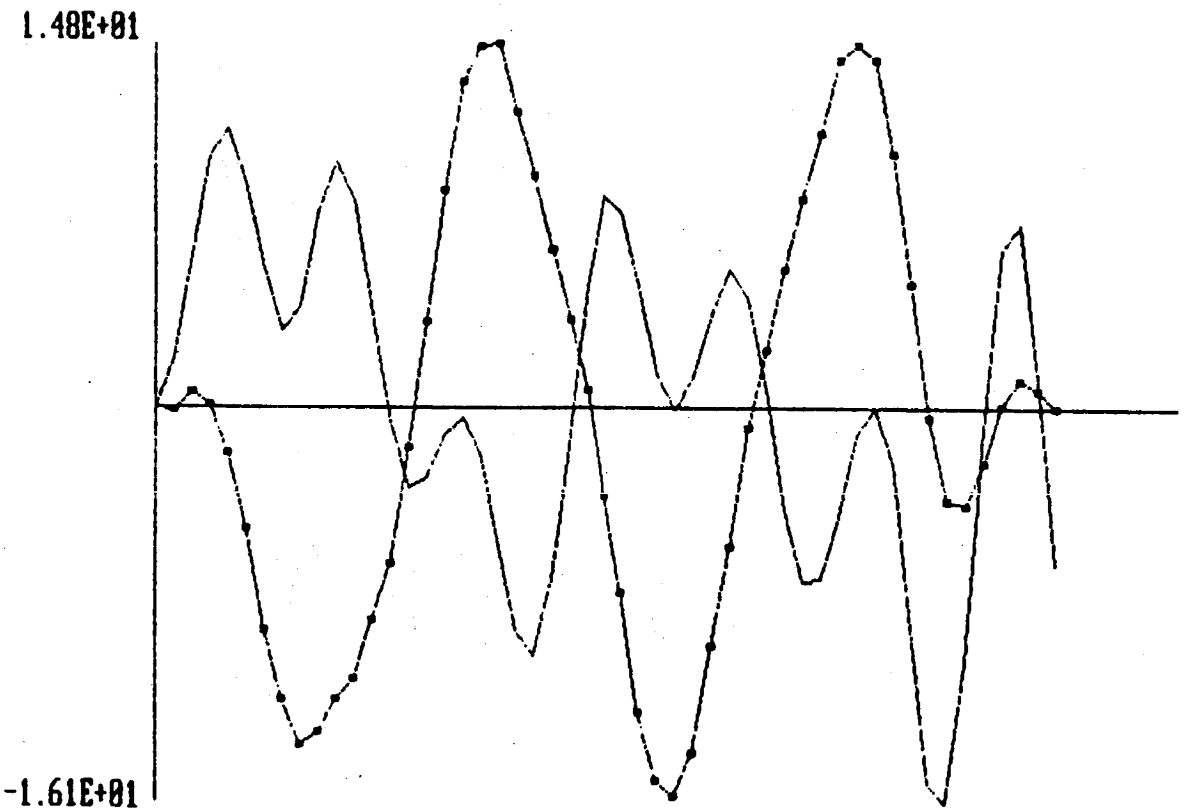
LOS ERROR (DEG) DUE SOLELY TO MODE 5 RUN TIME= 4.892 pf0100.6na

LCOPY



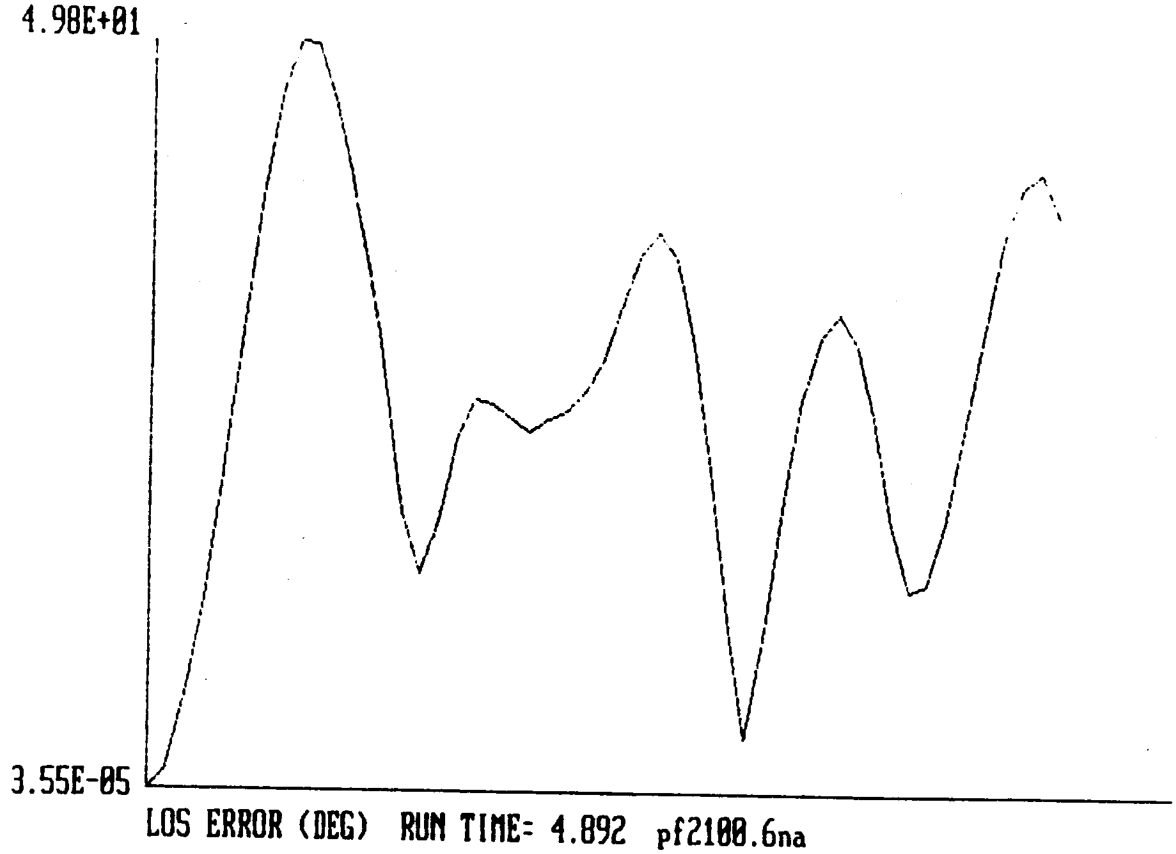
ETA3 RUN TIME = 4.892 pf0100.6na

LCOPY



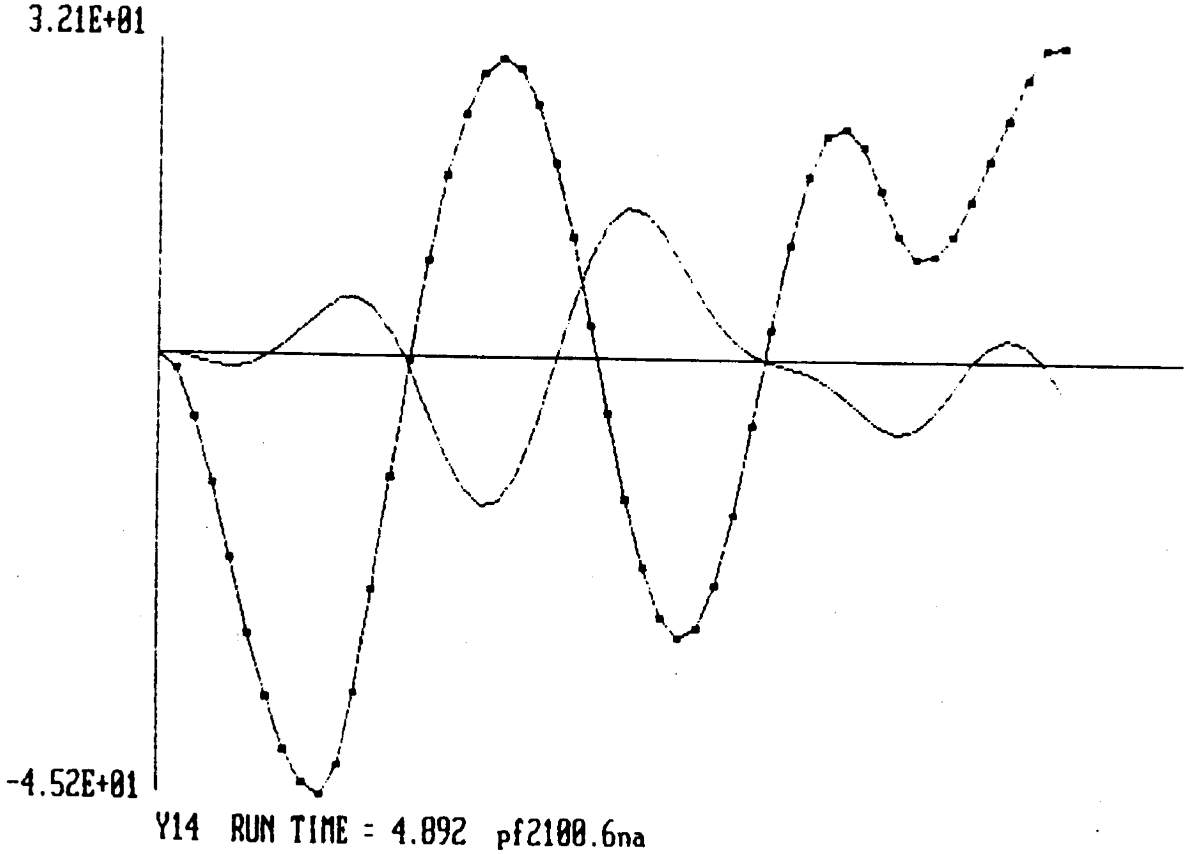
ETA5 RUN TIME = 4.892 pf0100.6na

LCOPY



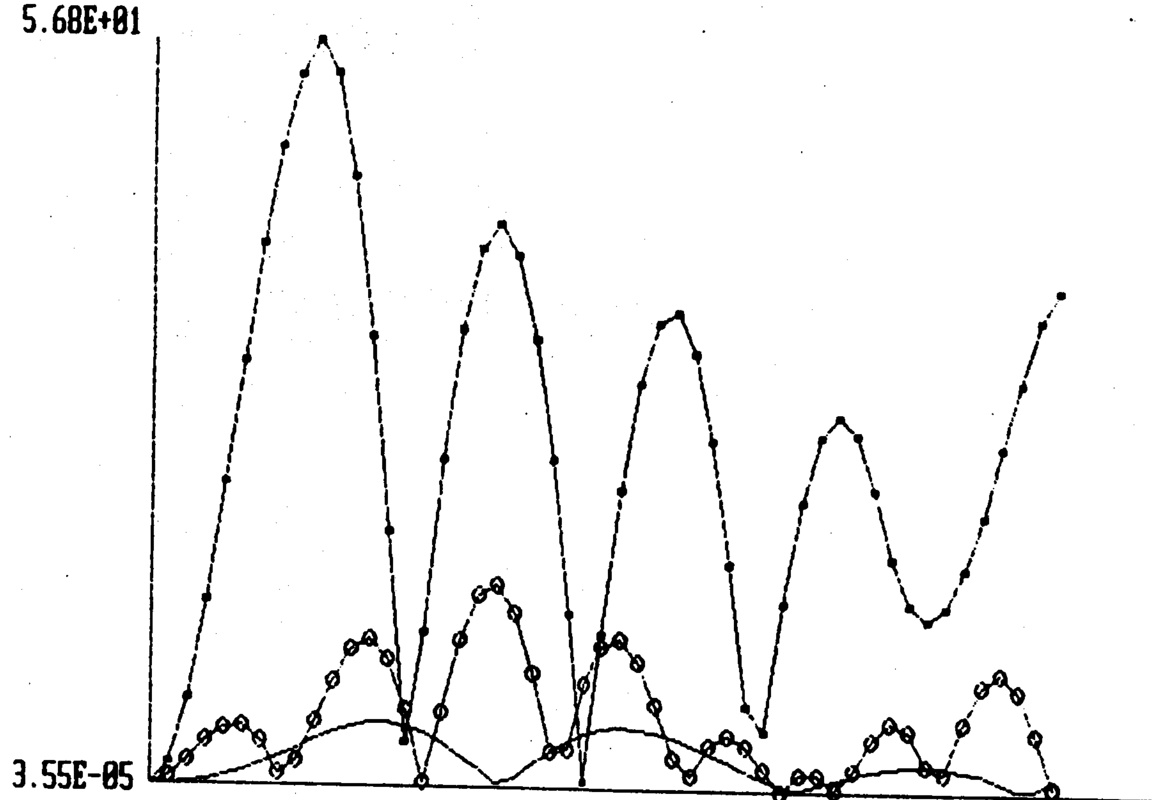
4.98E+01
3.55E-05
LOS ERROR (DEG) RUN TIME= 4.892 pf2100.6na

LCOPY



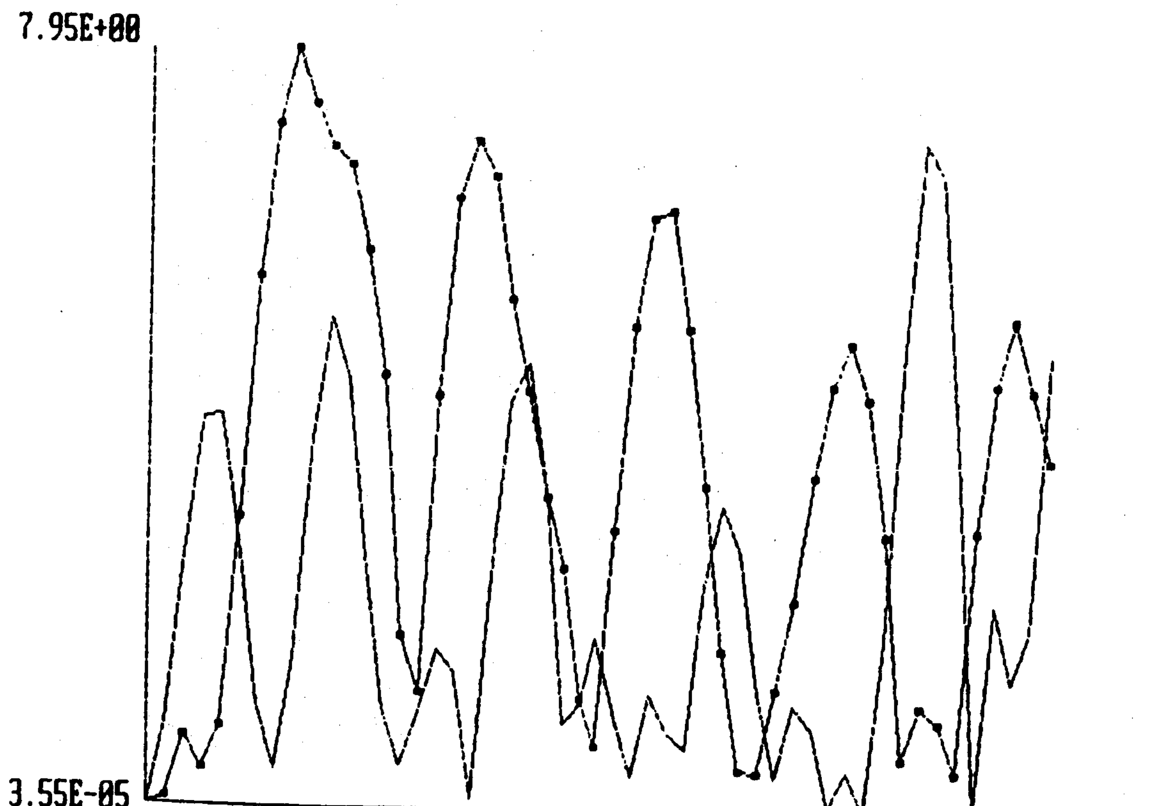
3.21E+01
-4.52E+01
Y14 RUN TIME = 4.892 pf2100.6na

LCOPY



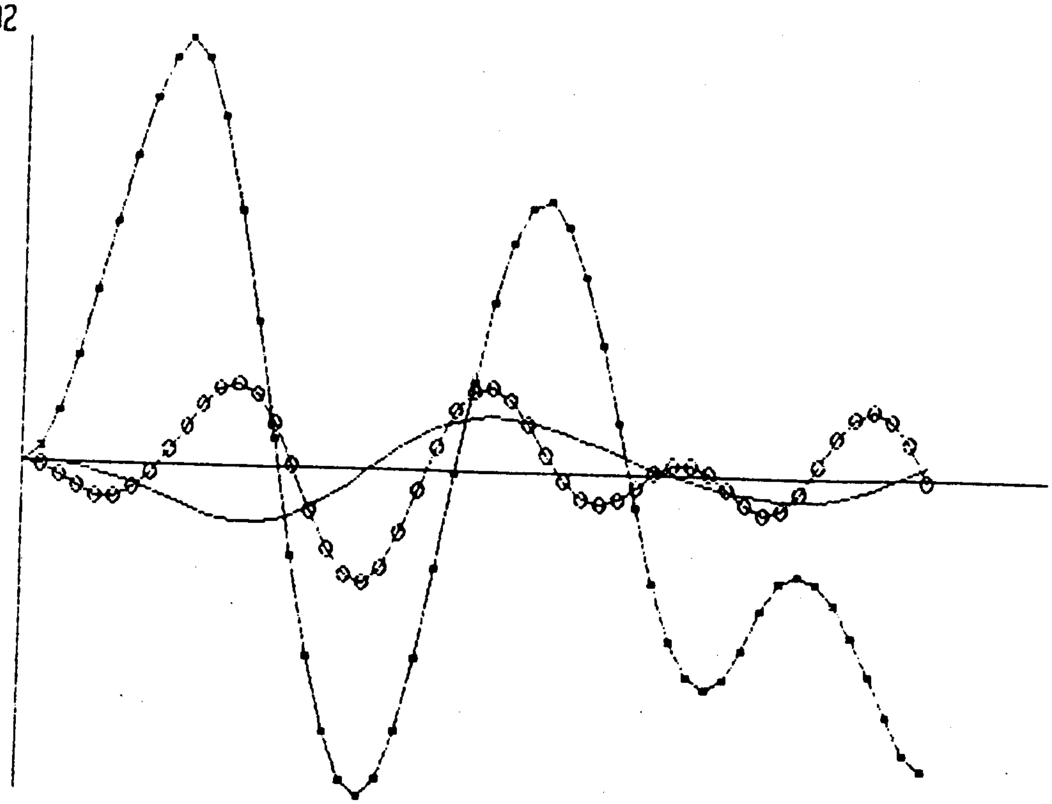
LOS ERROR (DEG) DUE SOLELY TO MODE 3 RUN TIME= 4.892 pf2100.6na

LCOPY



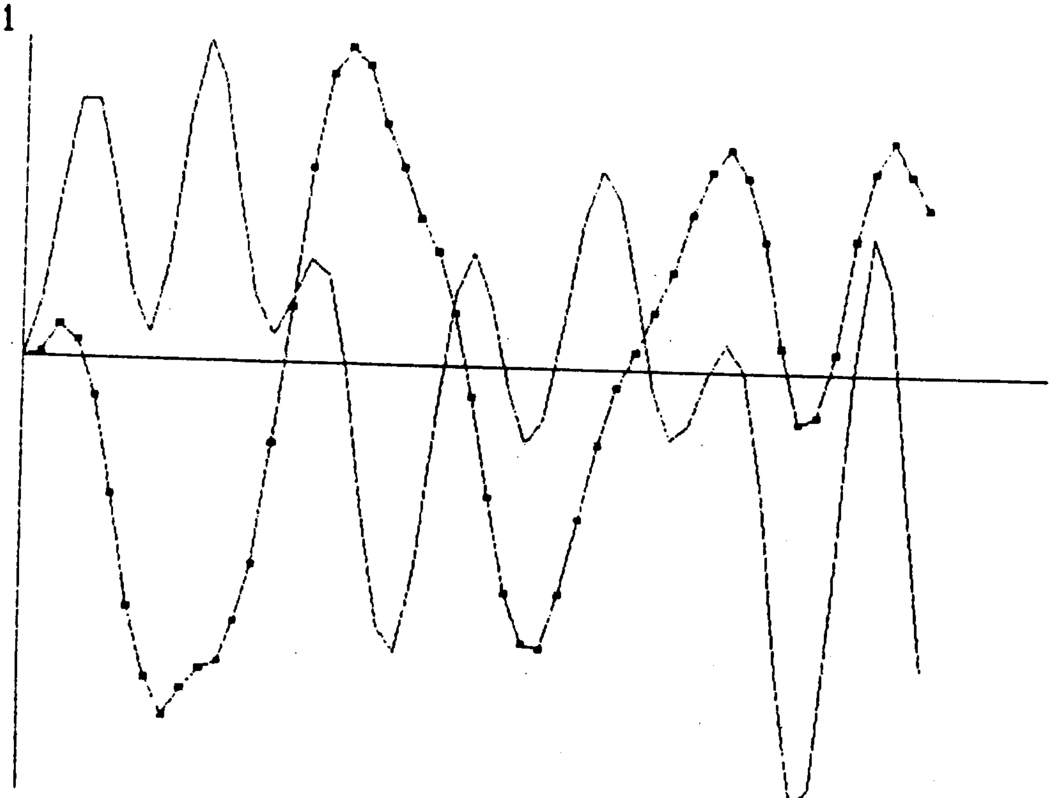
LOS ERROR (DEG) DUE SOLELY TO MODE 5 RUN TIME= 4.892 pf2100.6na

LCOPY



ETA3 RUN TIME = 4.892 pf2100.6na

LCOPY



ETA5 RUN TIME = 4.892 pf2100.6na

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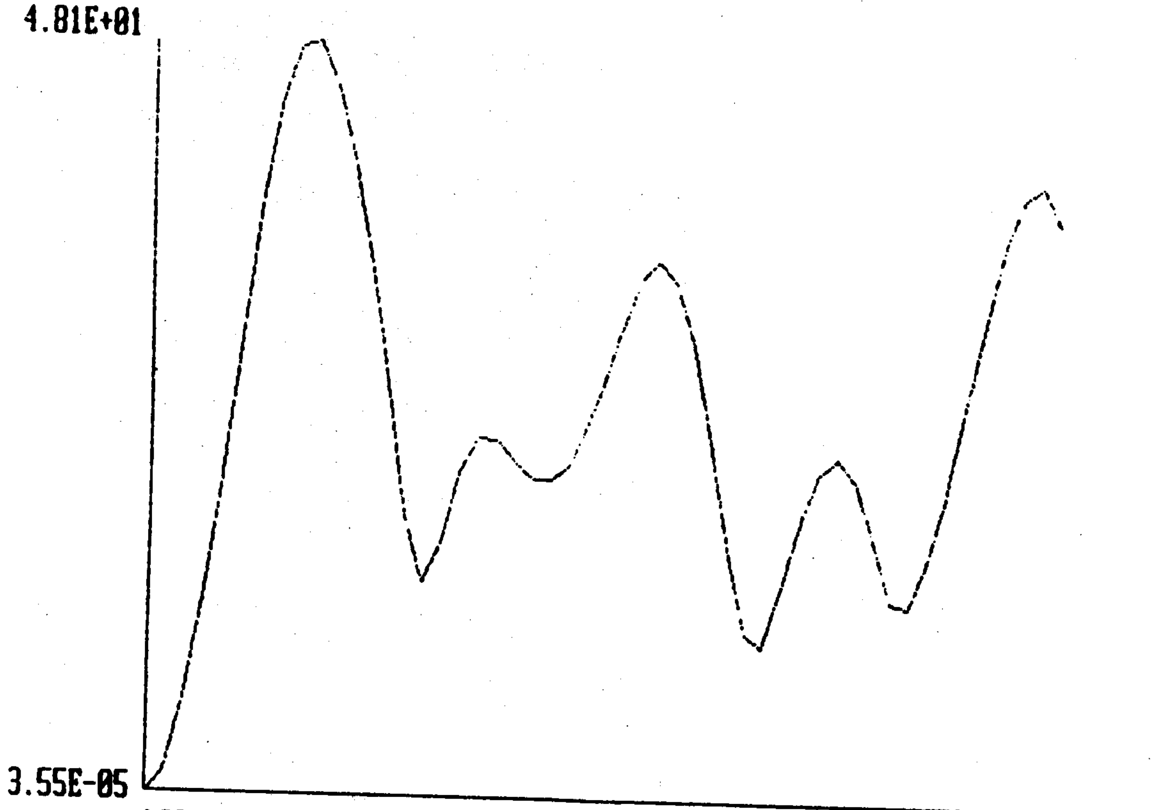

LOS ERROR (DEG) RUN TIME= 4.892 pf3100.6na

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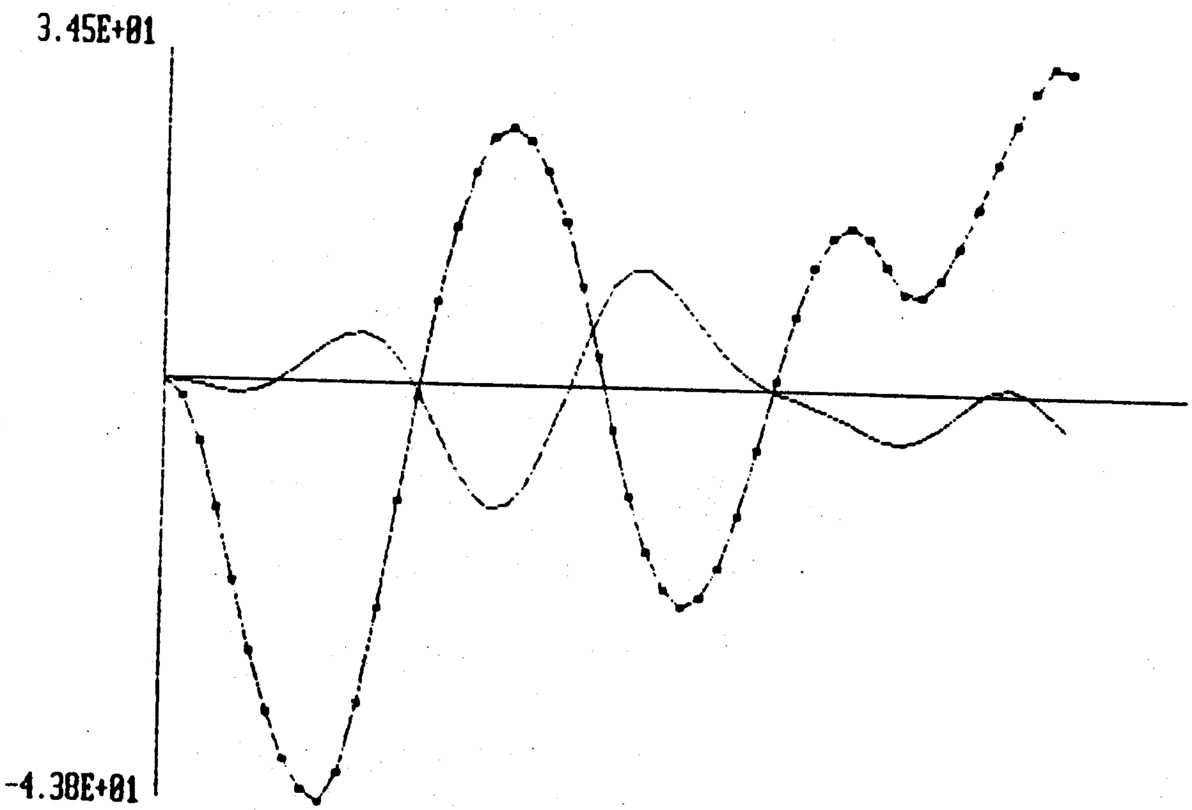
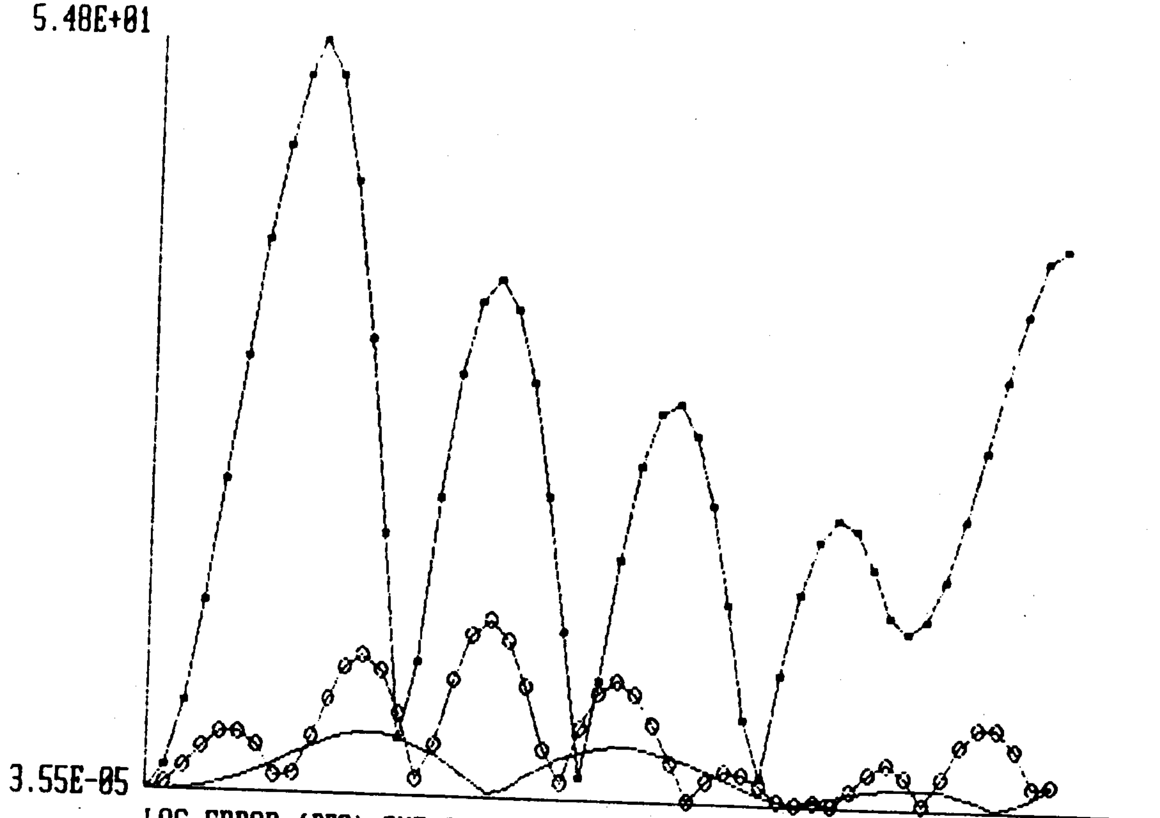


Y14 RUN TIME = 4.892 pf3100.6na

LCOPY



LOS ERROR (DEG) DUE SOLELY TO MODE 3 RUN TIME= 4.892 pf3100.6na

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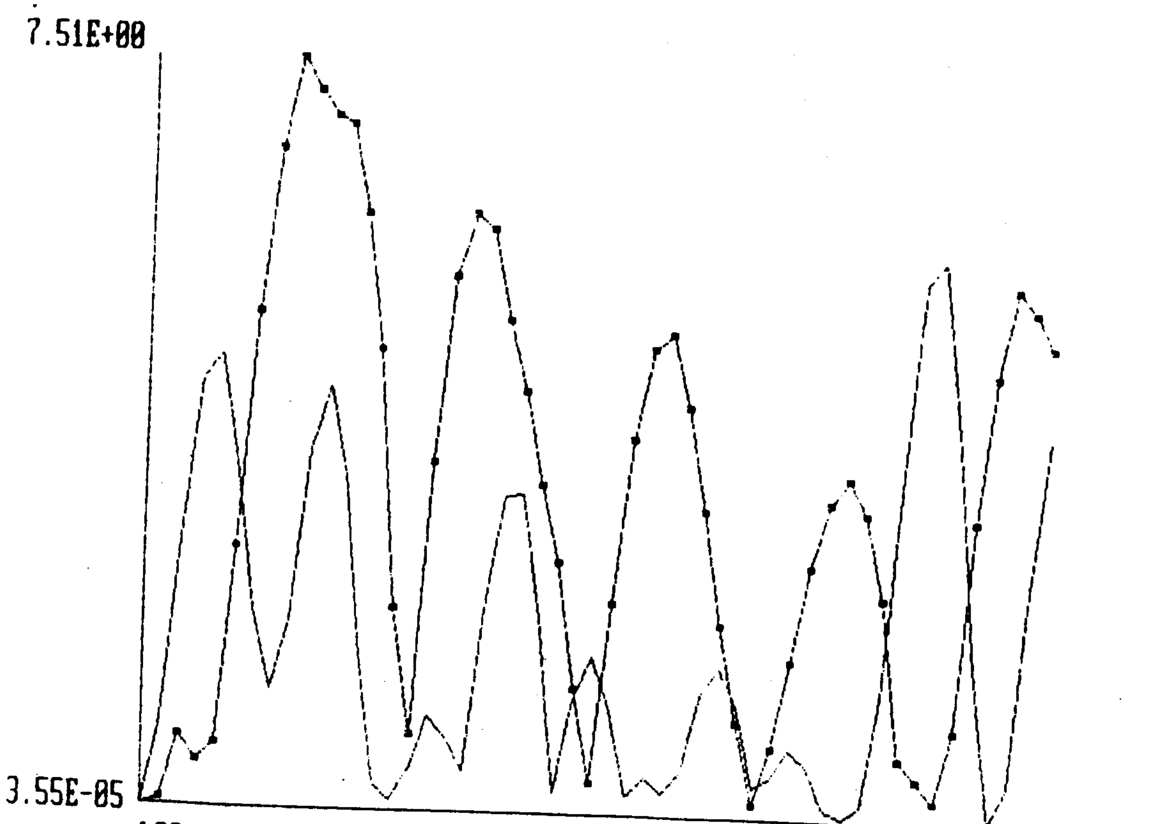

LOS ERROR (DEG) DUE SOLELY TO MODE 5 RUN TIME= 4.892 pf3100.6na

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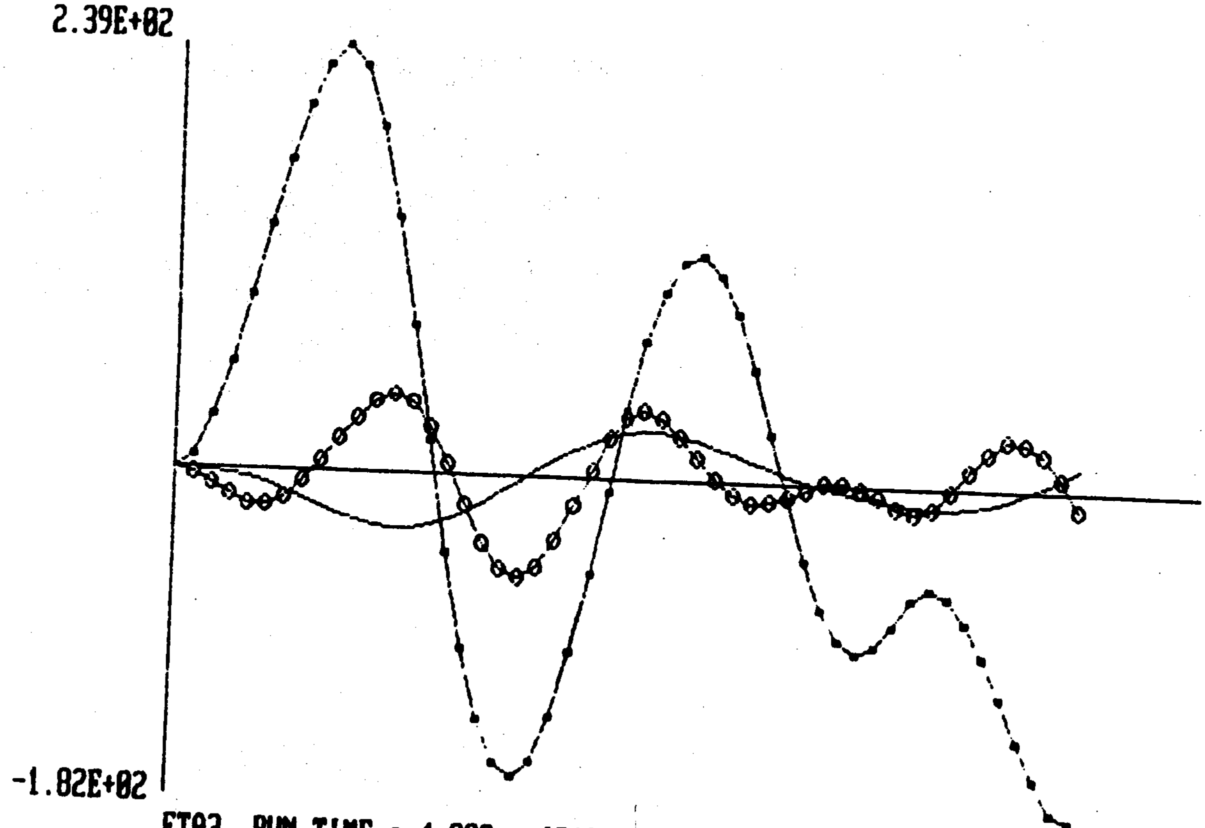

ETA3 RUN TIME = 4.892 pf3100.6na

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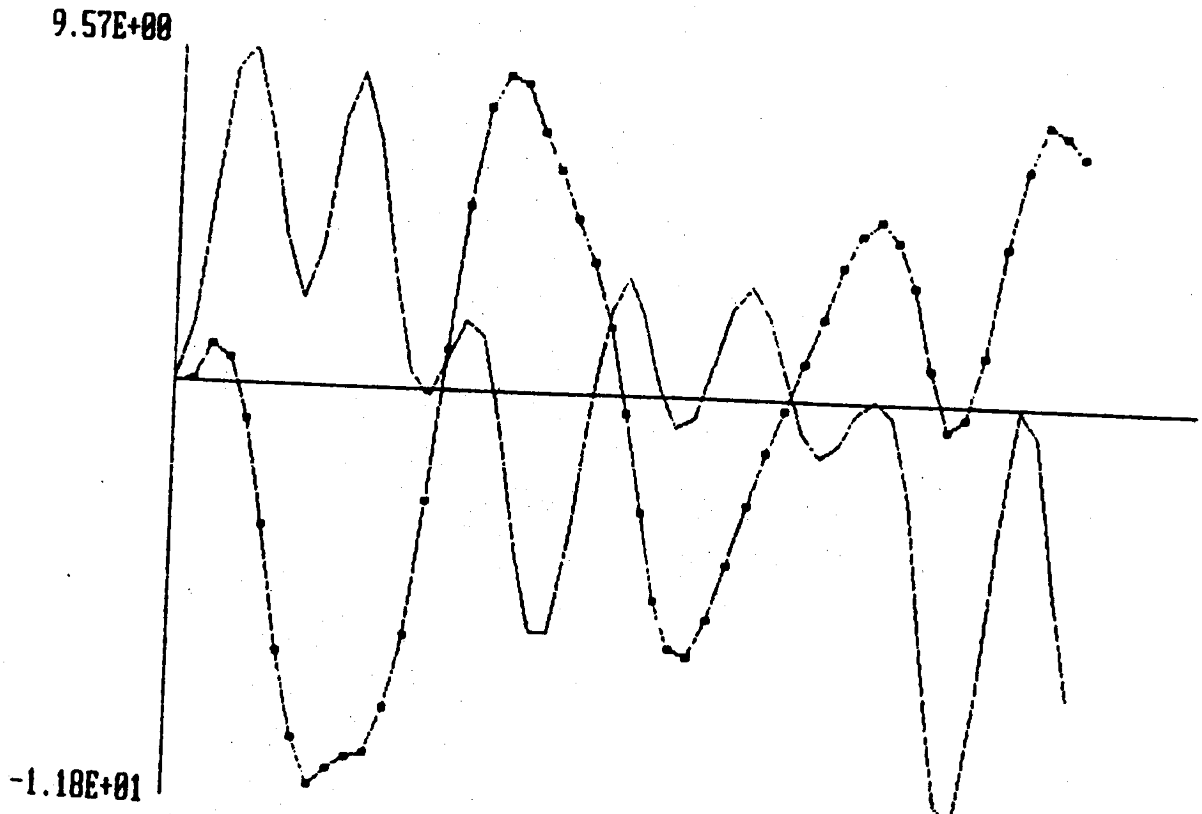

ETA5 RUN TIME = 4.892 pf3100.6na

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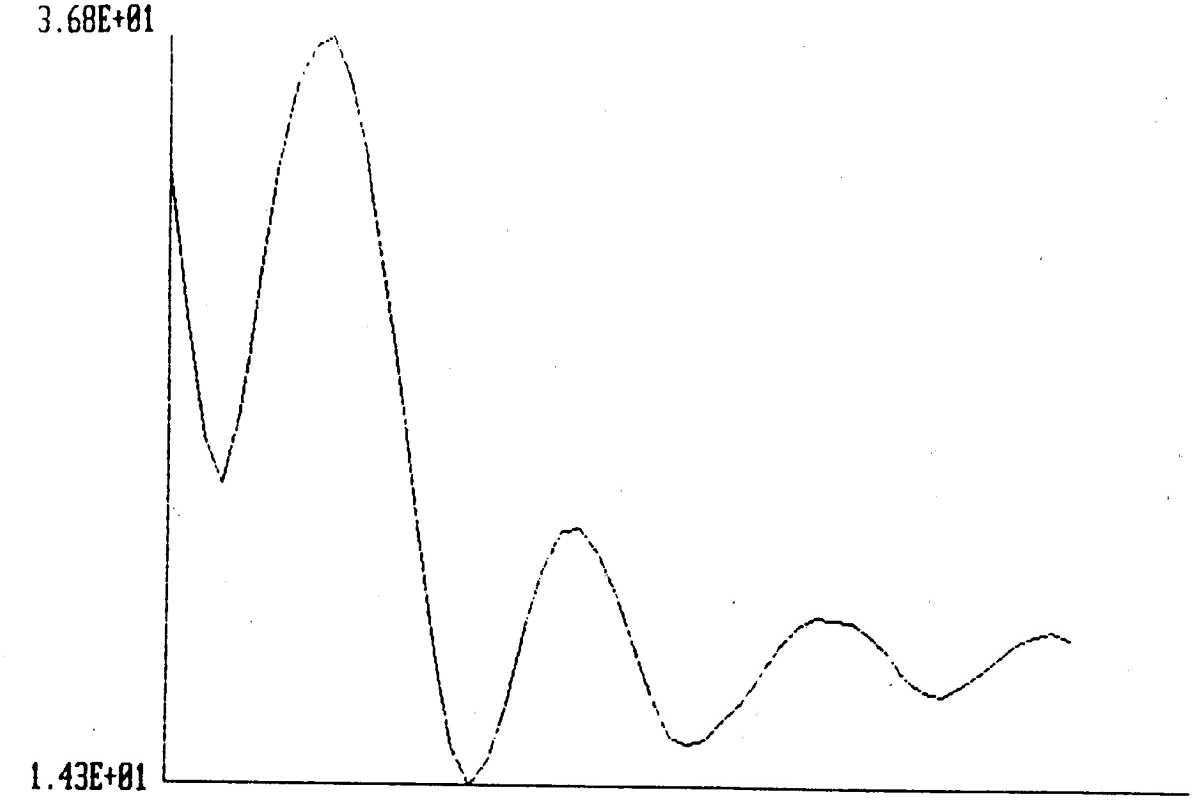

LOS ERROR (DEG) RUN TIME= 5.000 pf0110.6na

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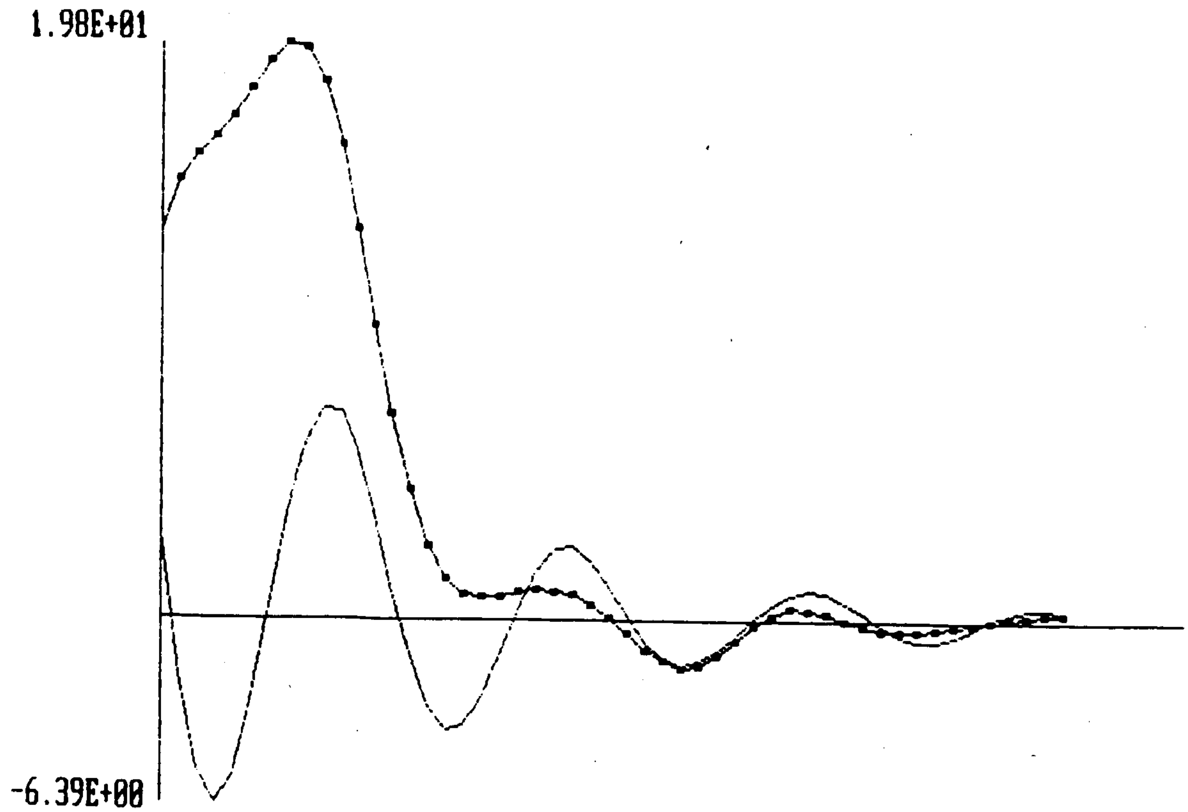
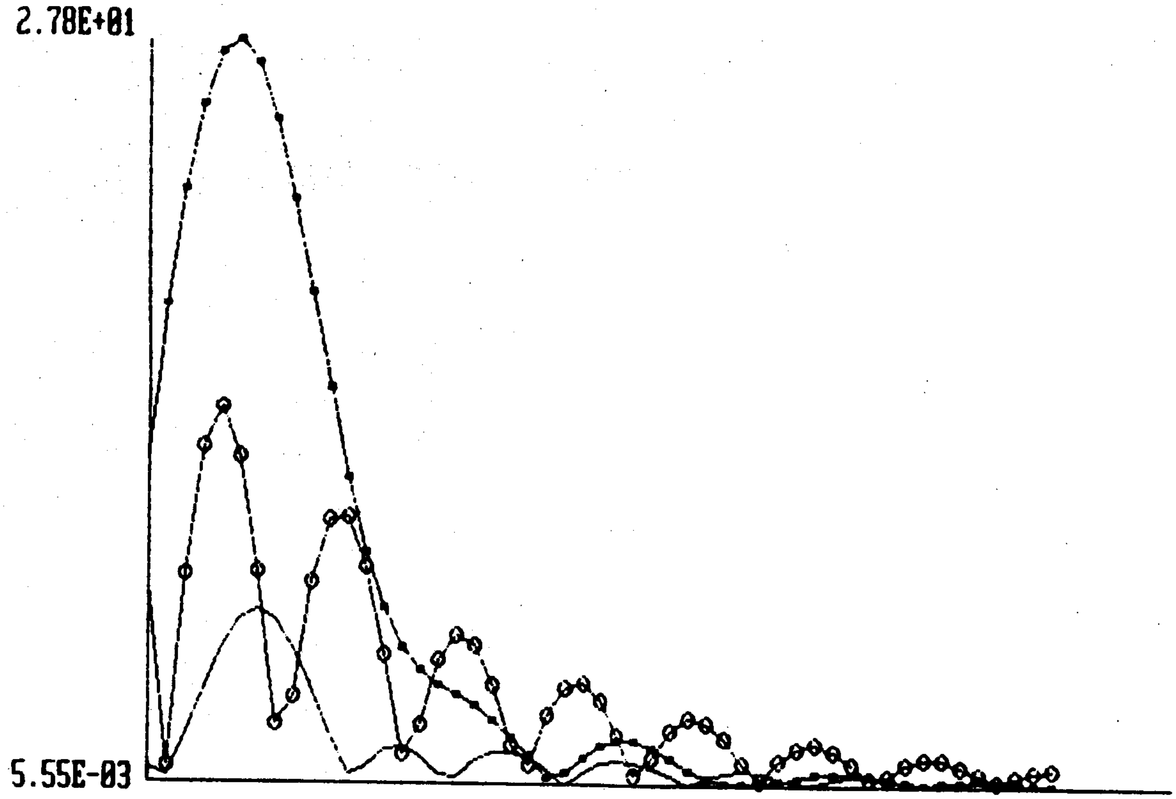


Y14 RUN TIME = 5.000 pf0110.6na

LCOPY



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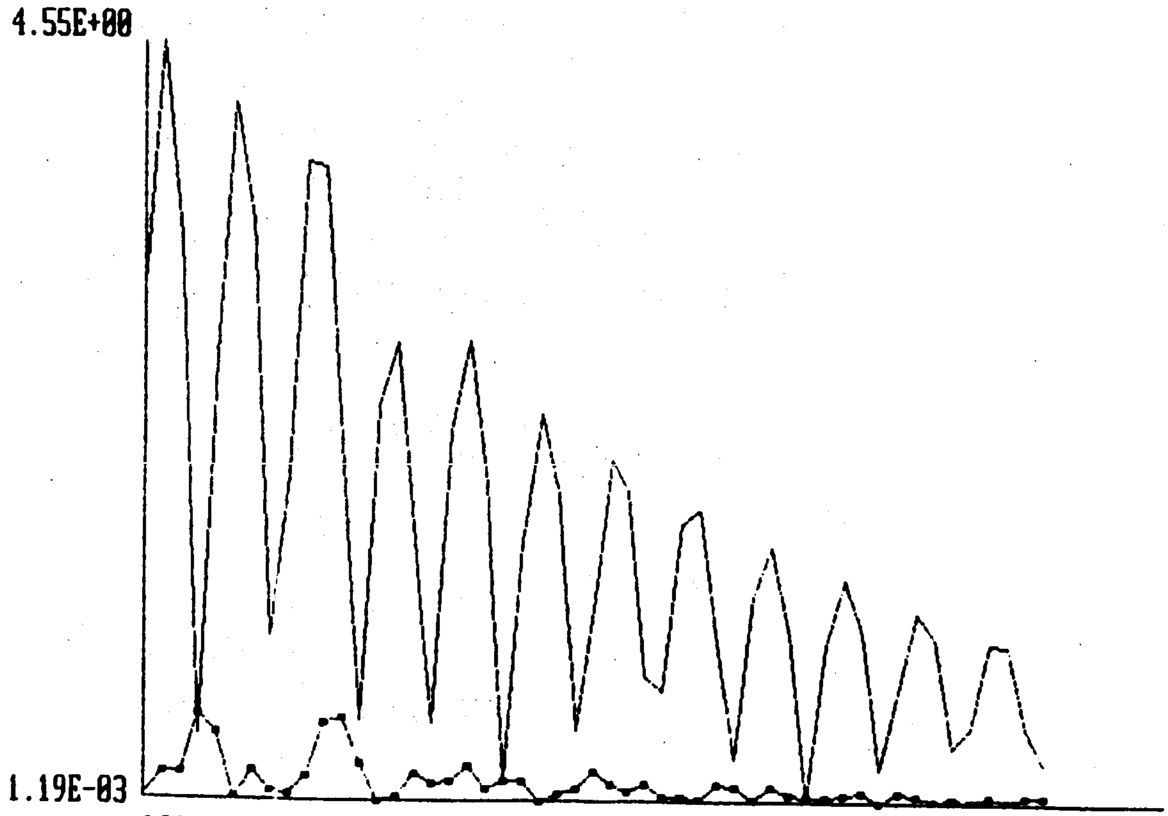

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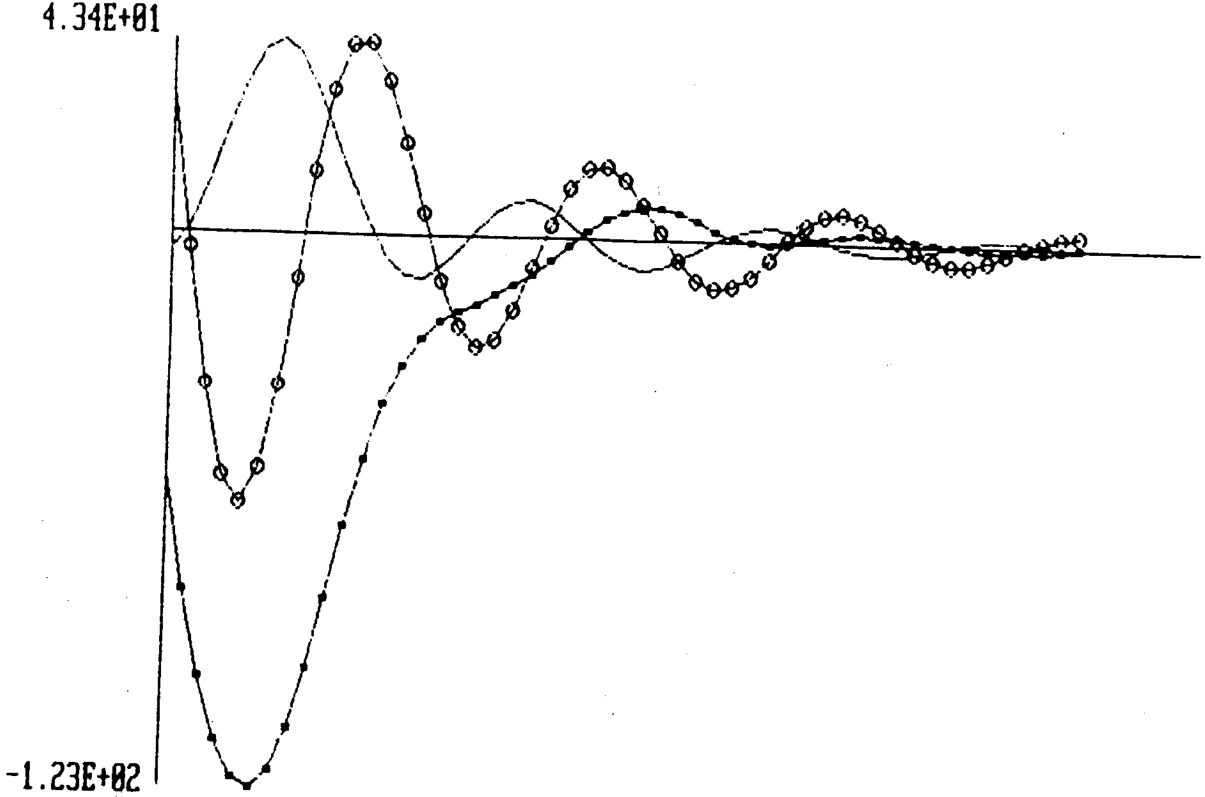

ETA3 RUN TIME = 5.000 pf0110.6na

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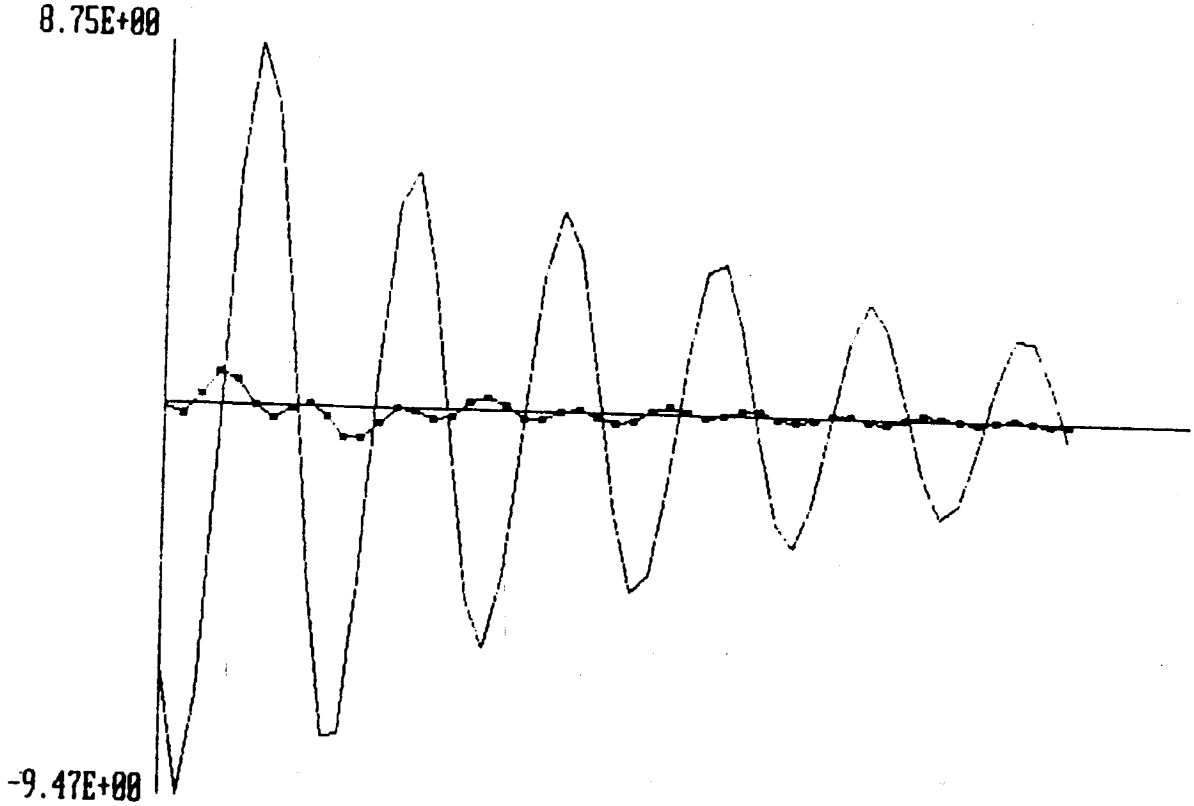

ETA5 RUN TIME = 5.000 pf0110.6na

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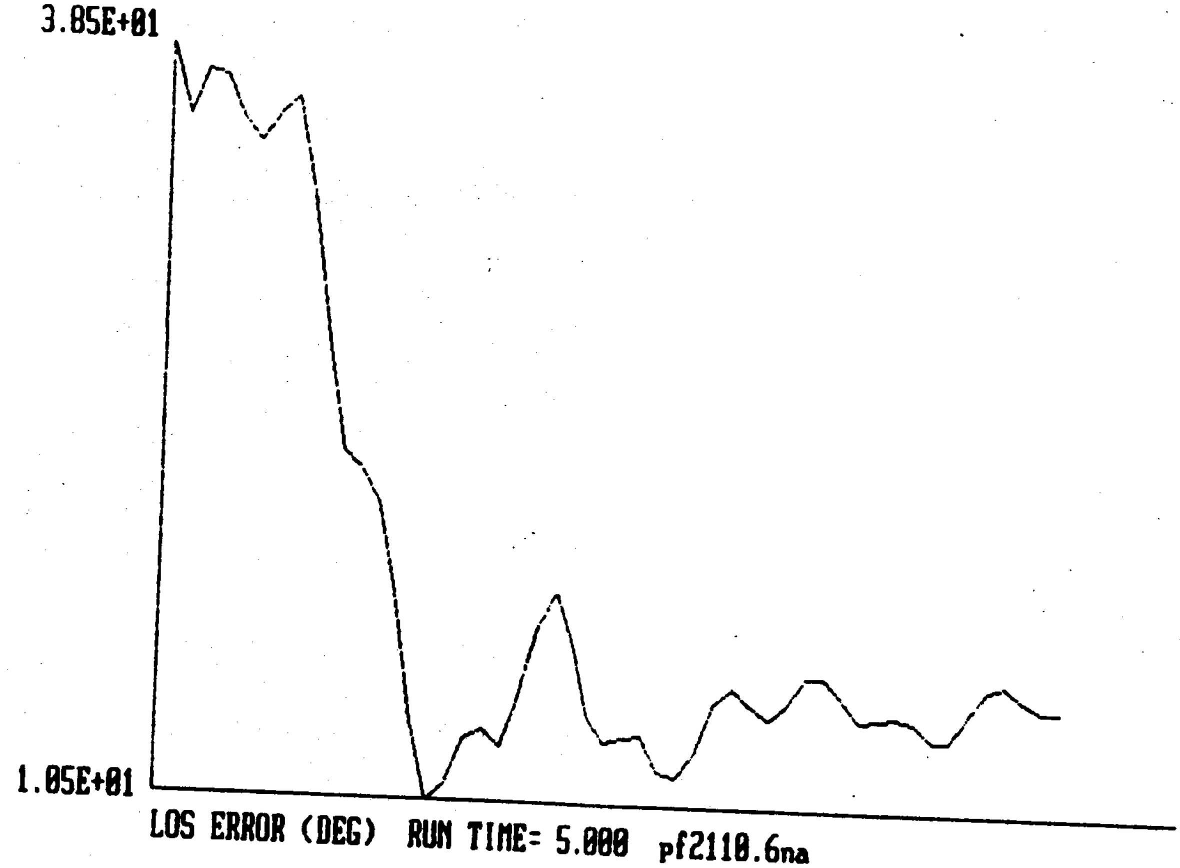
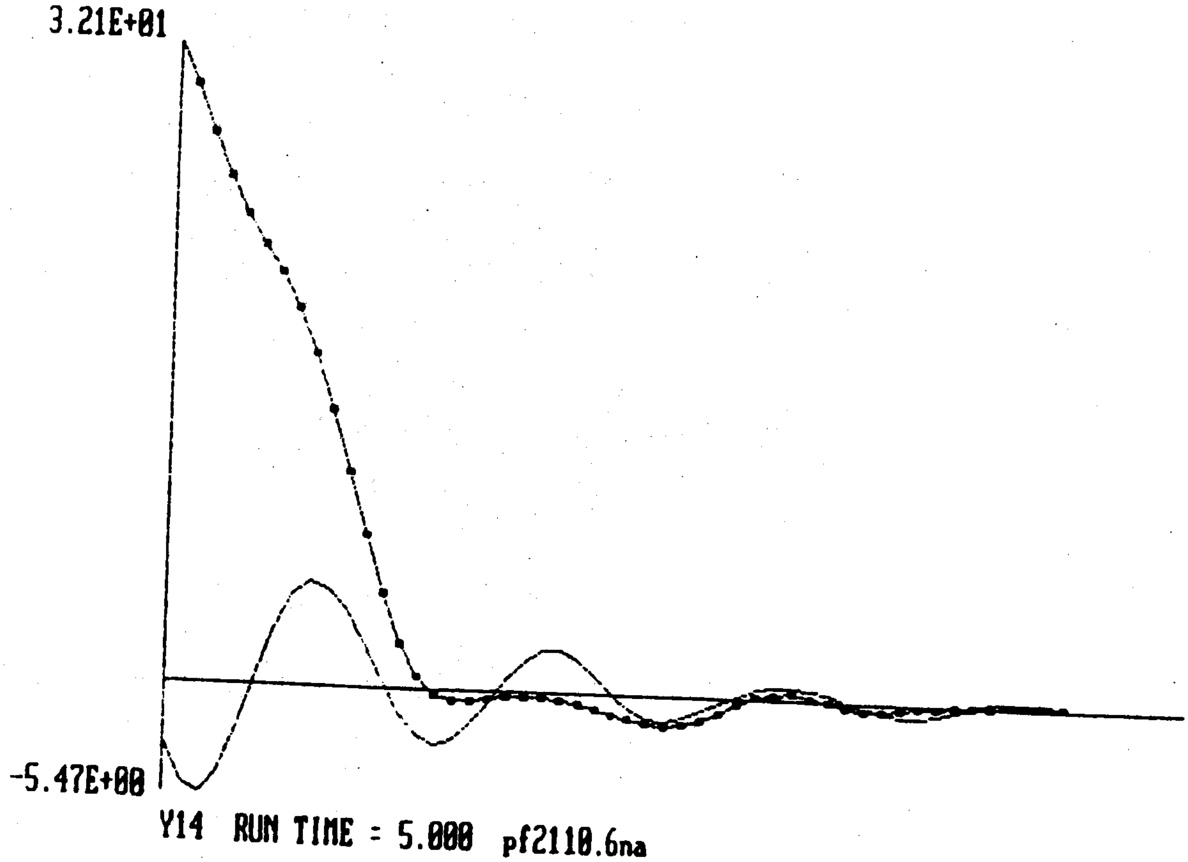
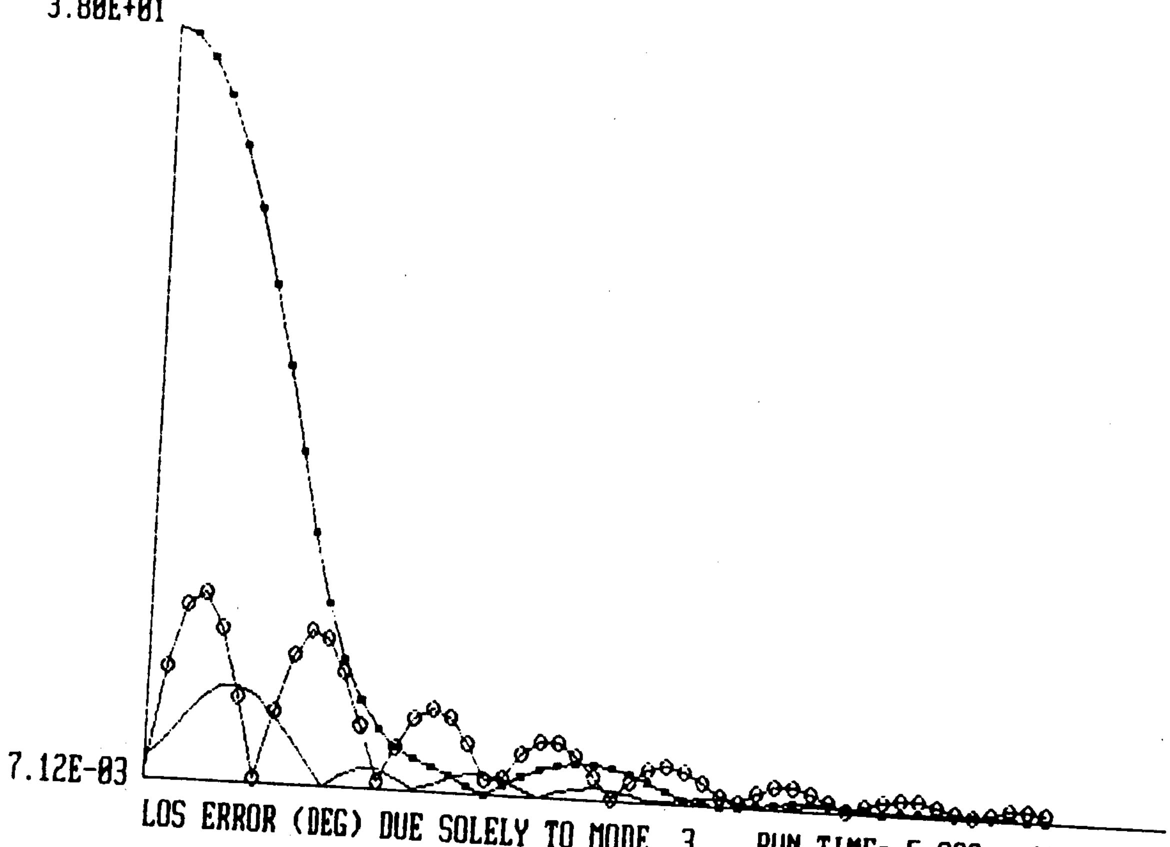

3.85E+01
1.05E+01
LOS ERROR (DEG) RUN TIME= 5.000 pf2110.6na

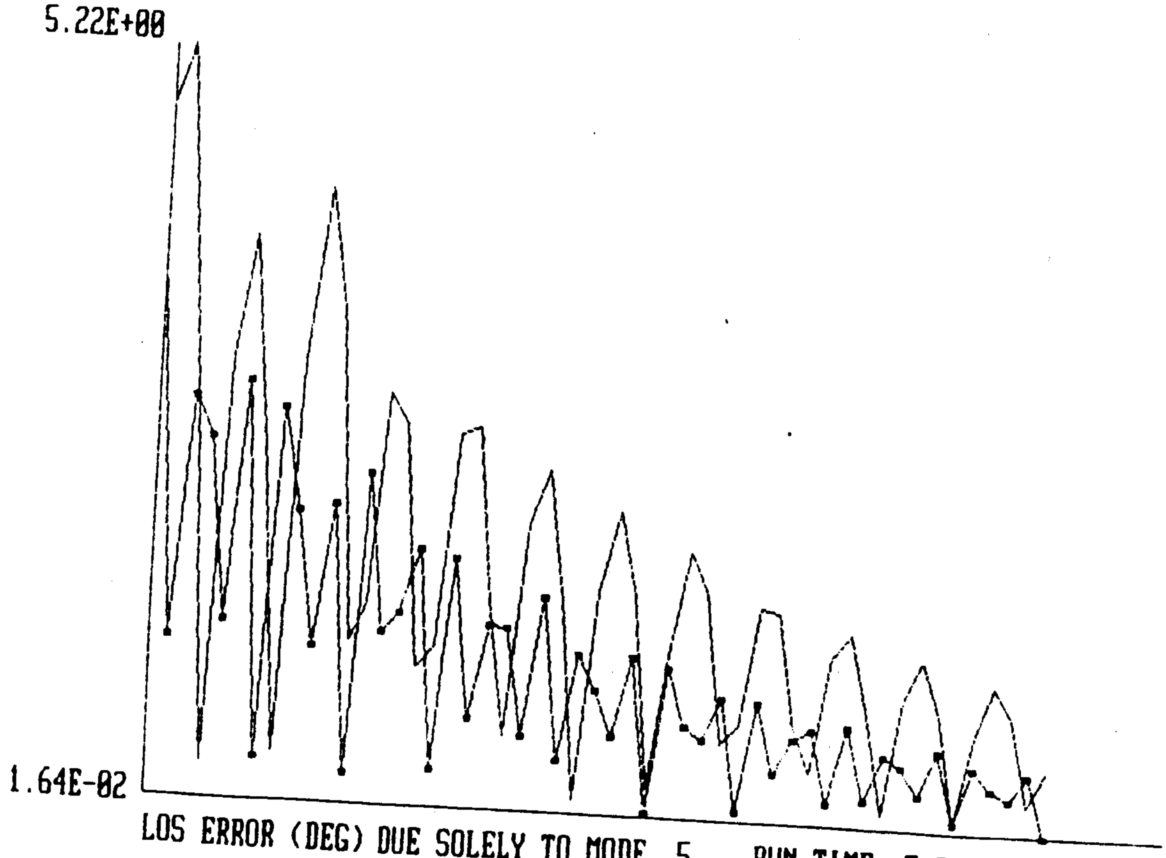
LCOPY


3.21E+01
-5.47E+00
Y14 RUN TIME = 5.000 pf2110.6na

LCOPY


3.80E+01
7.12E-03
LOS ERROR (DEG) DUE SOLELY TO MODE 3 RUN TIME= 5.000 pf2110.6na

LCOPY


5.22E+00
1.64E-02
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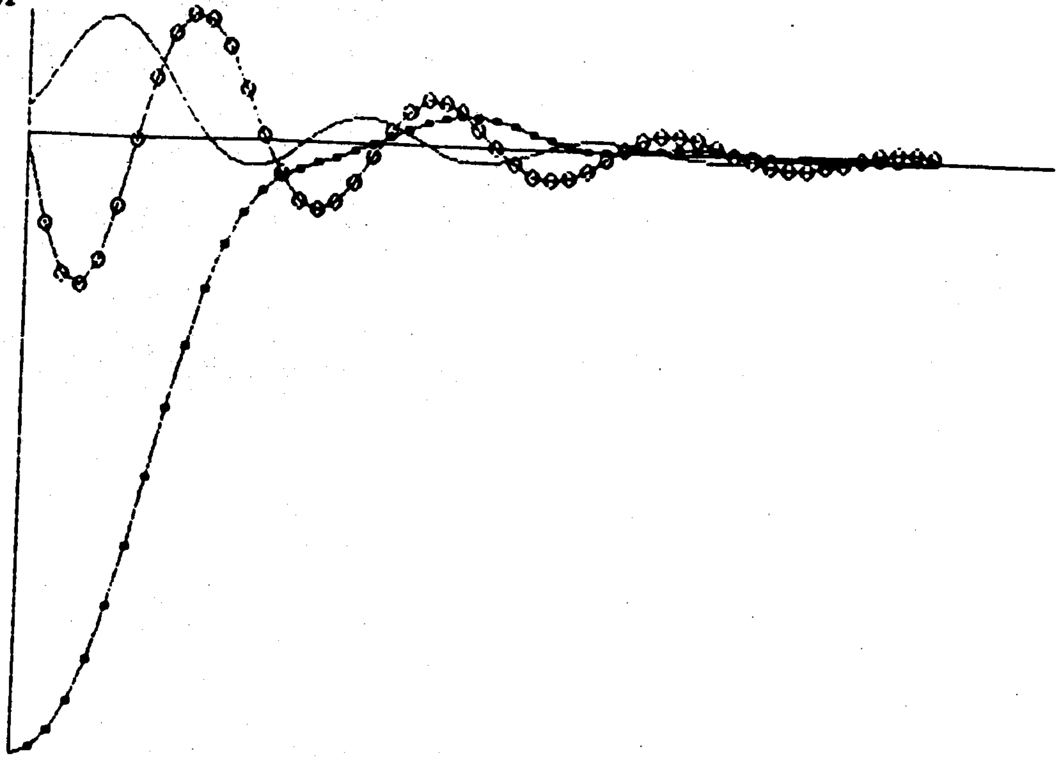
LCOPY



ETA3 RUN TIME = 5.000 pf2110.6na

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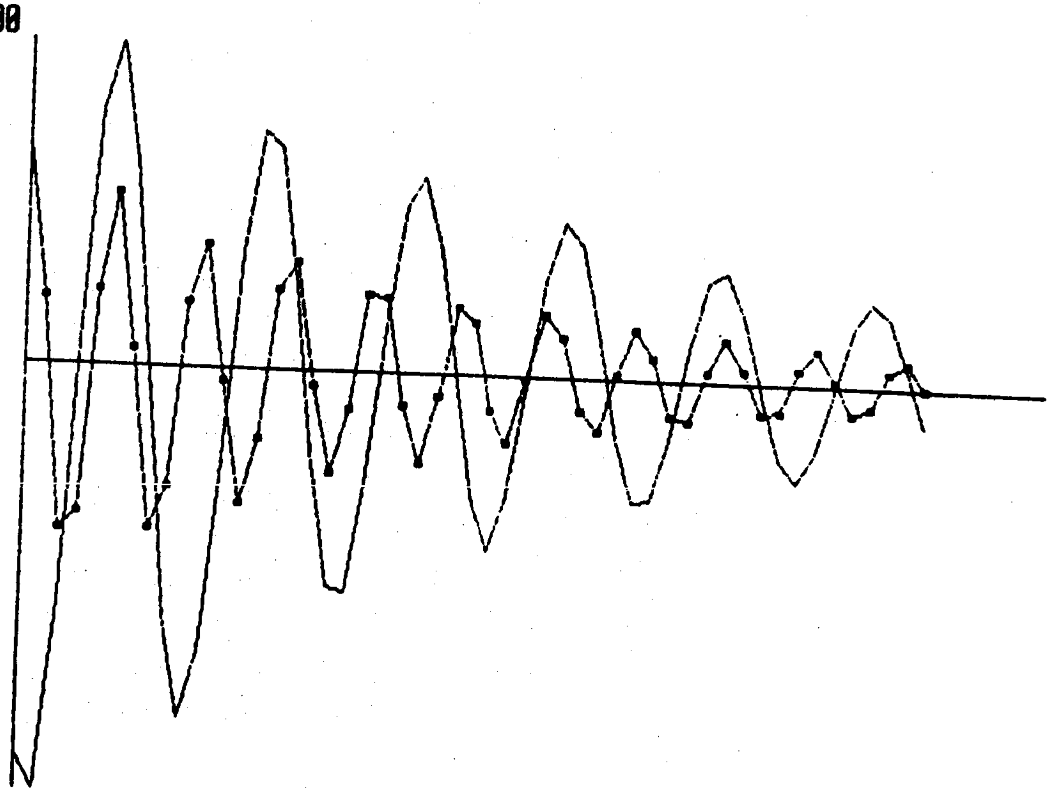
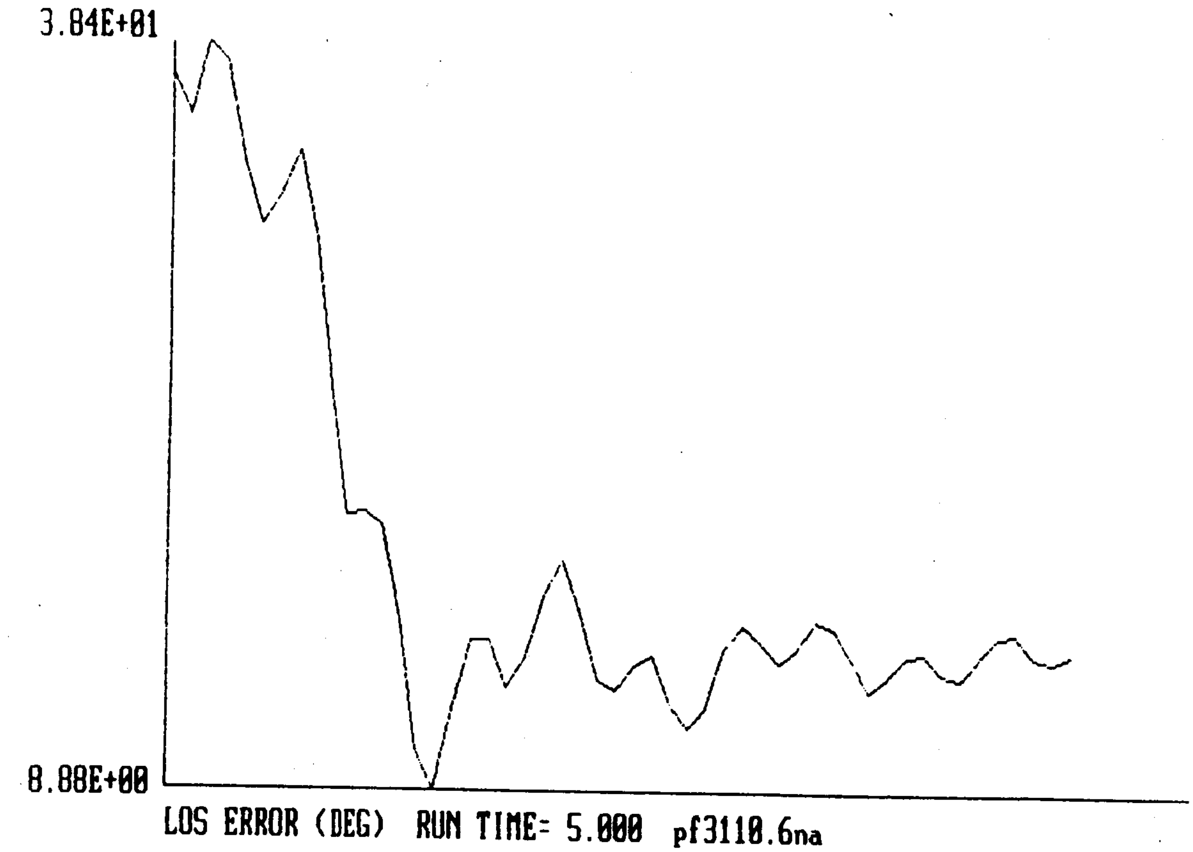
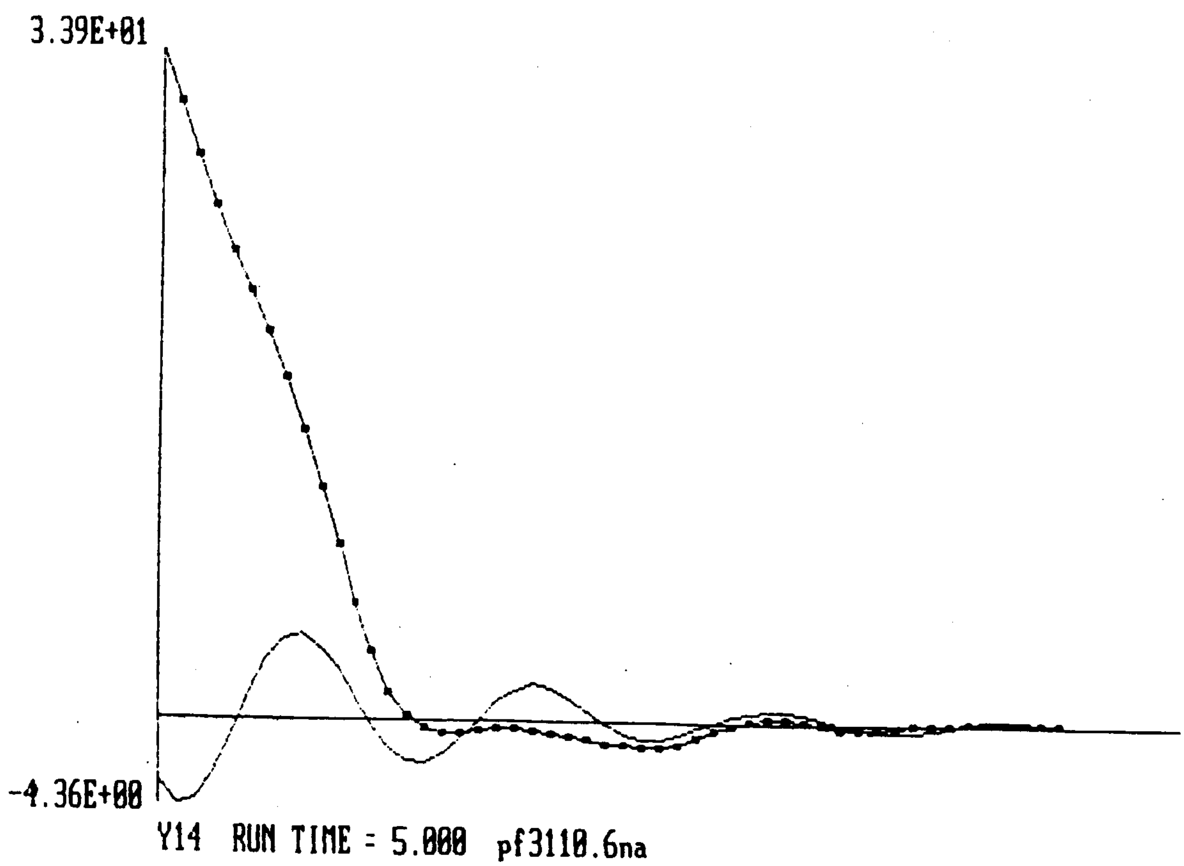


ETA5 RUN TIME = 5.000 pf2110.6na

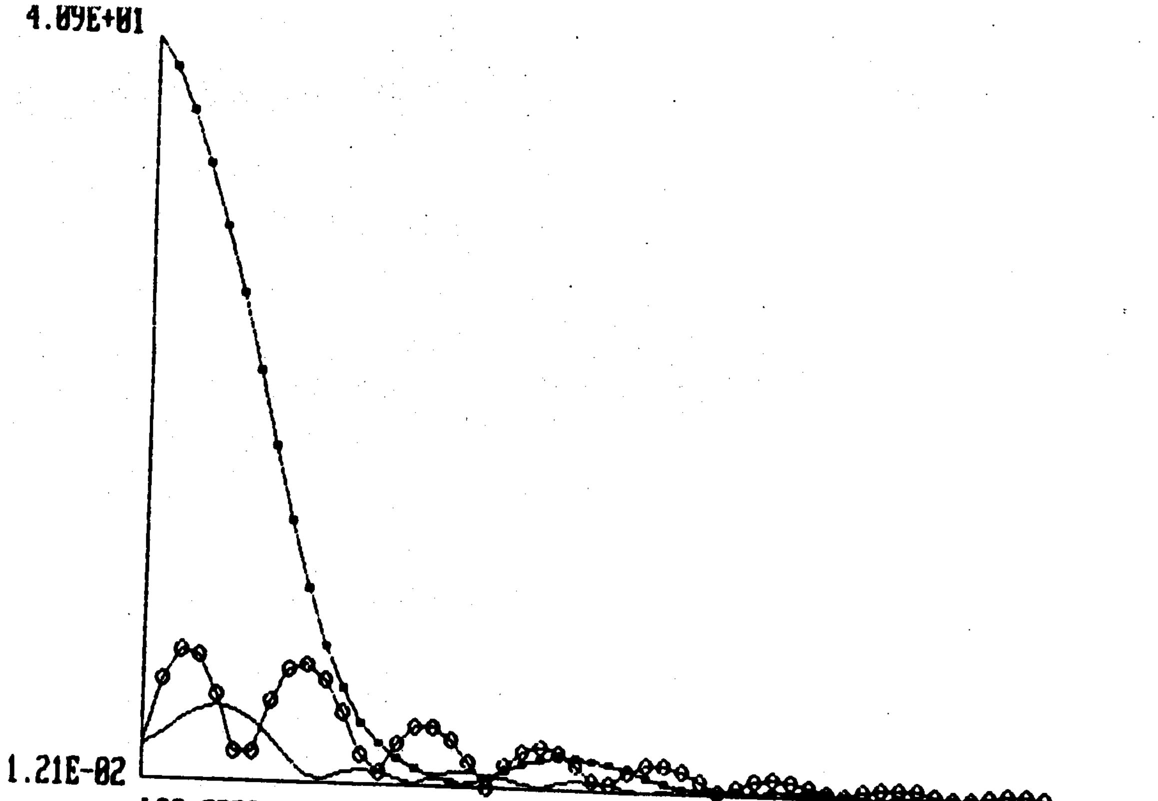
LCOPY


3.84E+01
0.00E+00
LOS ERROR (DEG) RUN TIME= 5.000 pf3110.6na

LCOPY

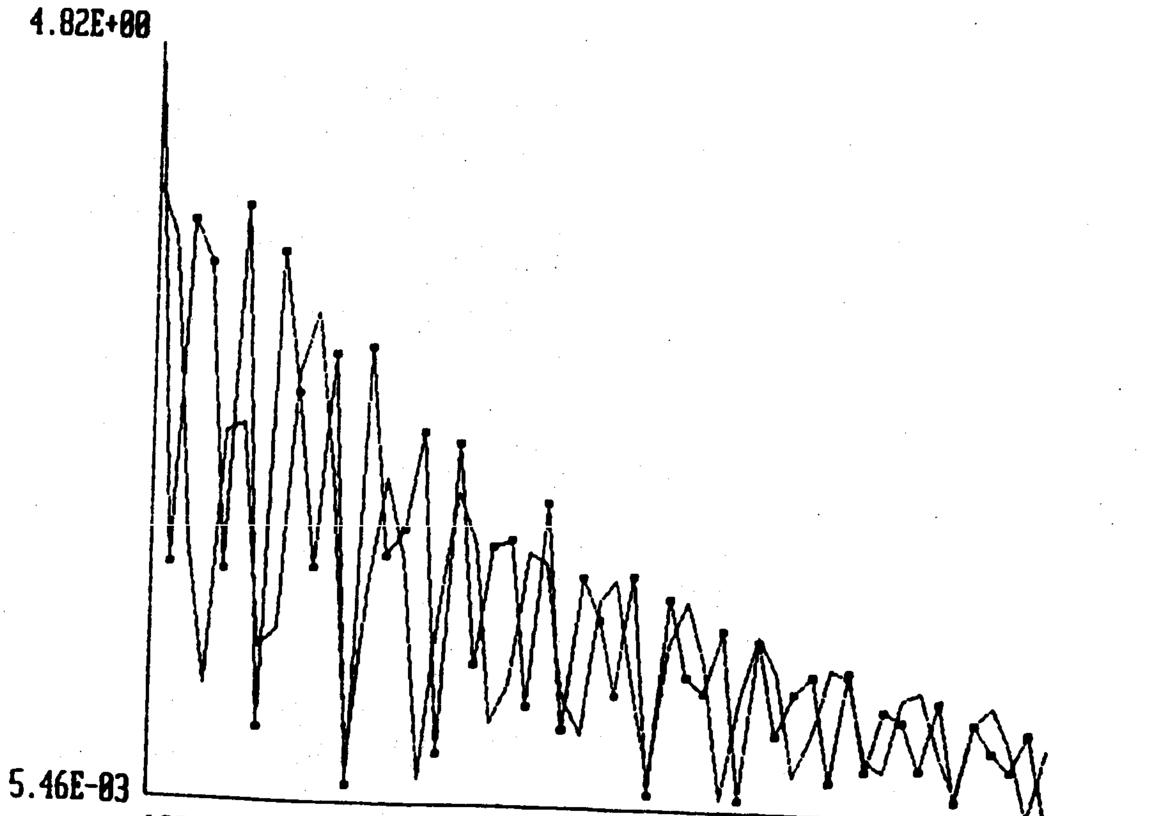

3.39E+01
-4.36E+00
Y14 RUN TIME = 5.000 pf3110.6na

LCOPY



LOS ERROR (DEG) DUE SOLELY TO MODE 3 RUN TIME= 5.000 pf3110.6na

LCOPY



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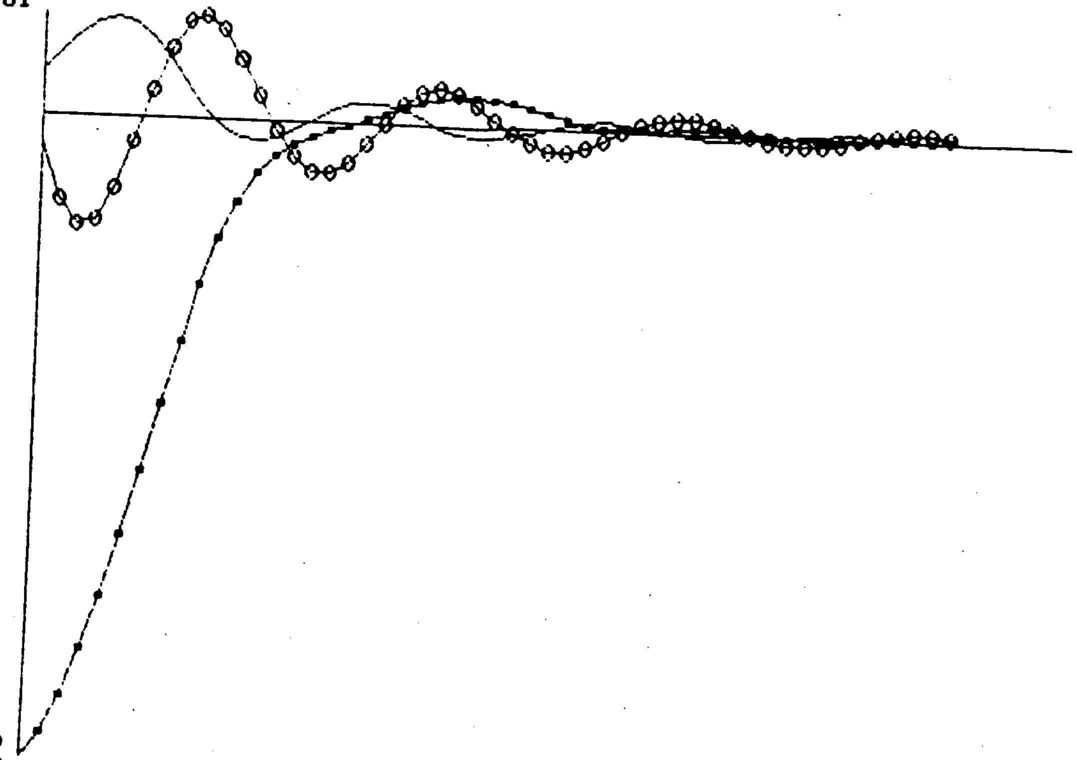
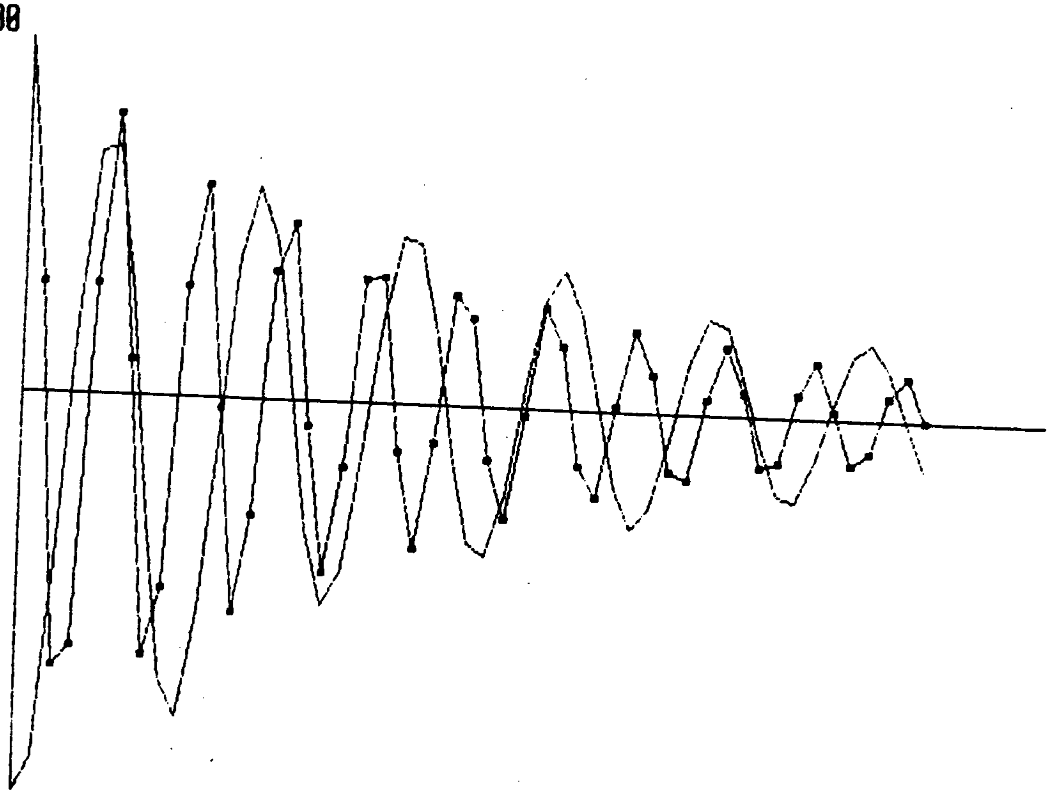
LCOPY



ETA3 RUN TIME = 5.000 pf3110.6na

LCOPY



ETA5 RUN TIME = 5.000 pf3110.6na

LCOPY

CONCLUSIONS

GENERAL:

- MODAL-DASHPOT AND MODAL-SPRING CONTROLLERS PROVIDE QUICK AND EFFECTIVE VIBRATION CONTROL
  -- EVEN EXCITED BY MOST VIOLENT, BANG-BANG TYPE
- HIGH-GAIN PROBLEMS CAN BE AVOIDED BY PROPER SELECTION OF "MODELED MODES" AND PROPER LEVEL OF AUGMENTATION
- MODAL DASHPOTS AND MODAL SPRINGS MOST EFFECTIVE DUDRING THE INITIAL PERIOD OF LARGE VIBRATIONS
  -- NEED LQG/LTR HIGH-PERFORMANCE CONTROLLERS FOR PRECISION POINTING/STABILIZATION LATER
- LOS ERROR DUE SOLELY TO EACH MODE EXCITED BY THE DISTURBANCE PROVIDES A SOUND MEASURE OF IMPORTANCE OF INDIVIDUAL MODES
  -- CORRECT SELECTION OF MODES TO CONTROL

SPECIFIC ON THE NUMERICAL SIMULATIONS:

- USING MODAL DASHPOTS AFTER EXCITATION GREATLY REDUCED EXCESSIVE LOS JITTER AND MAST BENDING (F0010 VS F0000)
  - -- MAY REQUIRE LARGE CONTROL FORCES AND MOMENTS AND NOT BE VERY PRECISE
  - -- BUT ARE FAST AND EFFECTIVE

- USING MODAL SPRINGS DURING EXCITATION PREVENTED EXCESSIVE LOS JITTER AND MAST BENDING (F0100 VS F0000)

- USING MODAL DASHPOTS WITH MODAL SPRINGS DURING EXCITATION FURTHER REDUCED JITTER AND BENDING (F2100 & F3100 VS F0100)

- APPROPRIATE USE OF MODAL DASHPOTS AND SPRINGS BOTH DURING AND AFTER EXCITATION SUPPRESSED LOS JITTER AND MAST BENDING EFFECTIVELY AND QUICKLY (F0110, F2110 & F3110 VS F0000)

- MORE ACTIVE DAMPING SURING EXCITATION MAY NOT BE BETTER, HOWEVER (F3110 VS F2110)
  - -- MAY REQUIRE MORE CONTROL FORCES AND MOMENTS, SUPPRESS LESS LOS JITTER, LESS MAST BENDING

ISSUES NEEDED TO BE ADDRESSED:

- COUPLING OF RIGID-BODY DYNAMICS
- INTEGRATED DESIGN WITH LQG/LTR FOR HIGH PRECISION
  - -- MODAL DASHPOTS AND SPRINGS AS INNER LOOP TO ENHANCE STABILITY AND ROBUSTNESS
  - -- LQG/LTR AS OUTER LOOP TO ENHANCE PRECISION
- TOTAL TIME FOR THE REQUIRED ACCURACY IN LOS POINTING AND STABILIZATION
- EVULUATION ON THE LABORATORY APPARATUS