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Proof-Mass Actuator Placement Strategies for Regulation of Flexure During the SCOLE Slew

by

Shalom (Mike) Fisher
Naval Research Lab

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PROOF-MASS ACTUATOR PLACEMENT STRATEGIES FOR REGULATION OF FLEXURE DURING THE SCOLE SLEW MANEUVER

Shalom ("Mike") Fisher
Naval Research Laboratory

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STATEMENT OF THE REGULATOR PROBLEM

HOW DO DIFFERENT ACTUATOR PLACEMENT STRATEGIES AFFECT BEAM FLEXURE DURING LOS SLEW MANEUVER AND SETTLING

OBJECTIVES OF THIS ANALYSIS

- **Immediate**

1. To find the best placement for the actuators.
2. To determine the importance of placement, i.e, what is the sensitivity of beam flexure to actuator placement.

- **Ultimate**

1. To "close the loop" and apply regulation to the experimental test model of SCOLE.
2. To achieve the design challenge goal of .02 degrees LOS pointing error.

PROCEDURES OF THIS ANALYSIS

- NASTRAN finite element model for flexible beam with 21 grid points on beam
  Reflector and shuttle body assumed to be rigid

- Nonlinear DISCOS simulation of 20 degree slew

- Closed-loop linear quadratic regulator (LQR)

- Regulator uses:
  1. Proof mass actuators on beam
     Maximum force is 10 lbs.
     Maximum stroke is 1 foot.
  2. Thruster moments on shuttle body
     Thruster forces on reflector

BRIEF CONCLUSIONS FROM SIMULATION

1. Maximum relative orientation of reflector to shuttle, due to flexure during the simulation, is reduced by a factor of four by the proof-mass actuators.

2. Maximum flexure amplitude is insensitive to changes in actuator locations.

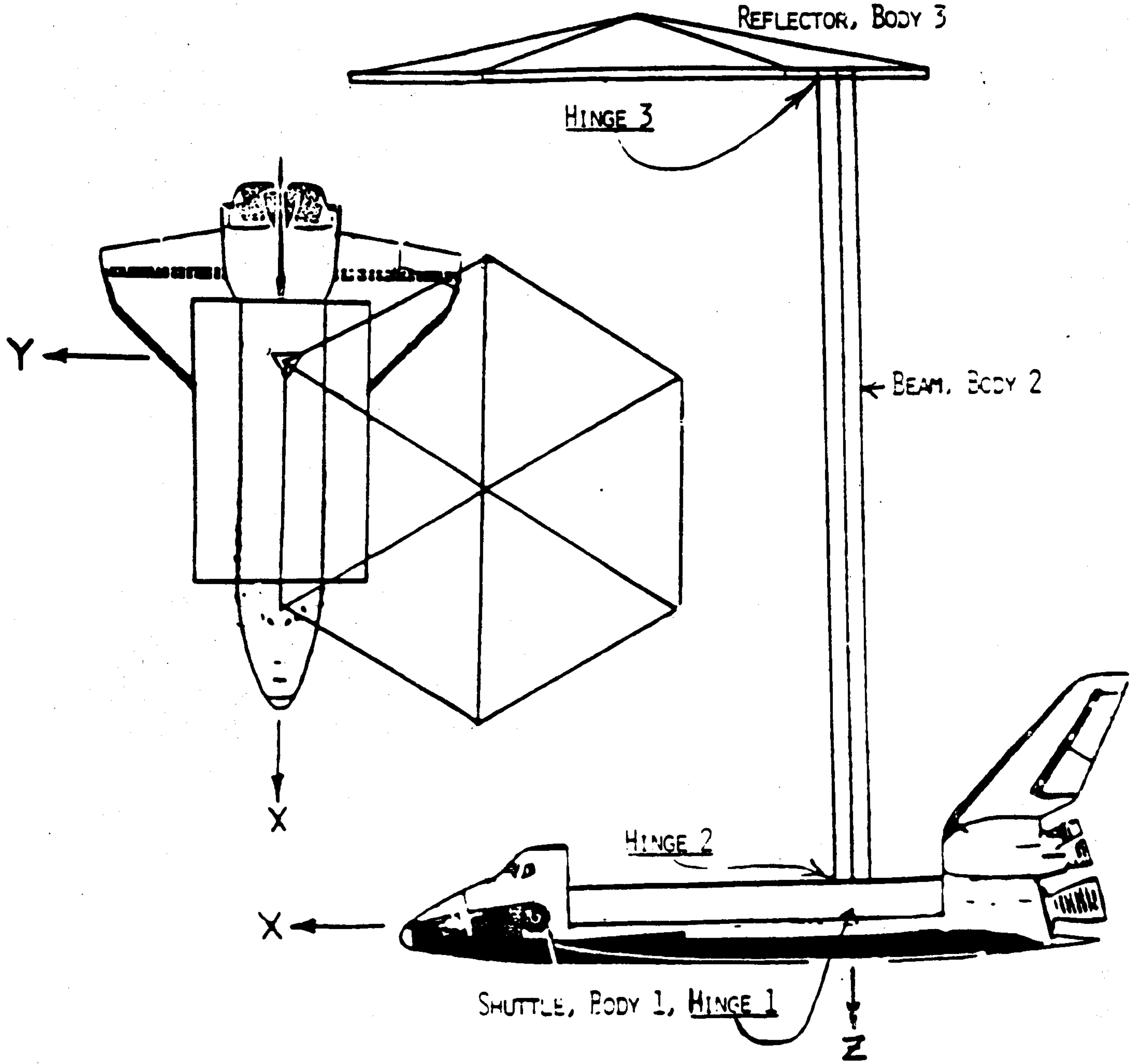
3. Damping of the flexure oscillations is sensitive to changes in actuator placement.

4. Good actuator placements can generate an overdamping in the flexure oscillations.

DISCOS SIMULATION: RIGID BODIES CONNECTED BY HINGES

MASS AND MOMENT OF INERTIA PROVIDED BY USER FOR EACH BODY

LOCATION OF HINGES AND SENSORS



COMPONENTS OF THE ANALYSIS

1. Nastran finite element model of beam, 40 nodes or grid points

   21 on beam itself, including end points.

   12 lowest modes retained for simulation.

2. DISCOS nonlinear simulation

   open loop commanded slew about minimum principal axis

   10,000 ft-lbs torque on shuttle, 22 lbs force on reflector

   Bang-bang control law, slewing time = 11.3 secs.

3. LQ regulator, using ORACLS

   control algebraic Ricatti equation (CARE)

   No noise or time delay in sensors or actuators

LQ REGULATOR FOR FLEXIBLE BEAM

- Purpose: To maintain the flexible beam in a nominally unbent position during the large angle slew

- Method: Linear quadratic regulator (LQR) matrices computed offline via ORACLS.

- Linearized system equation: $\dot{x}(t) = \mathbf{A}x(t) + \mathbf{B}u(t)$

  $x(t)$: components are modal amplitudes and rates
  $\mathbf{A}$: system matrix (from DISCOS)
  $\mathbf{B}$: input matrix, determined by actuator placements
  $u(t)$: input forces, commanded by regulator control

- Cost functional to be minimized:

$$J = \int_0^\infty [x^T(s)Qx(s) + u^T(s)Ru(s)]ds$$

LQ REGULATOR (CONTINUED)

- Objectives in minimizing cost functional:

  1. Maximize regulator performance
  2. 10lb limitation on actuator force

- Solve control algebraic Ricatti equation :

$$0 = Q + A^T P + PA - PBR^{-1}B^T P$$

set $Q = I$ and $R = rI$, with $r = 10^{-5}$ or 10^{-6}

- Input force vector u(t) is given by:

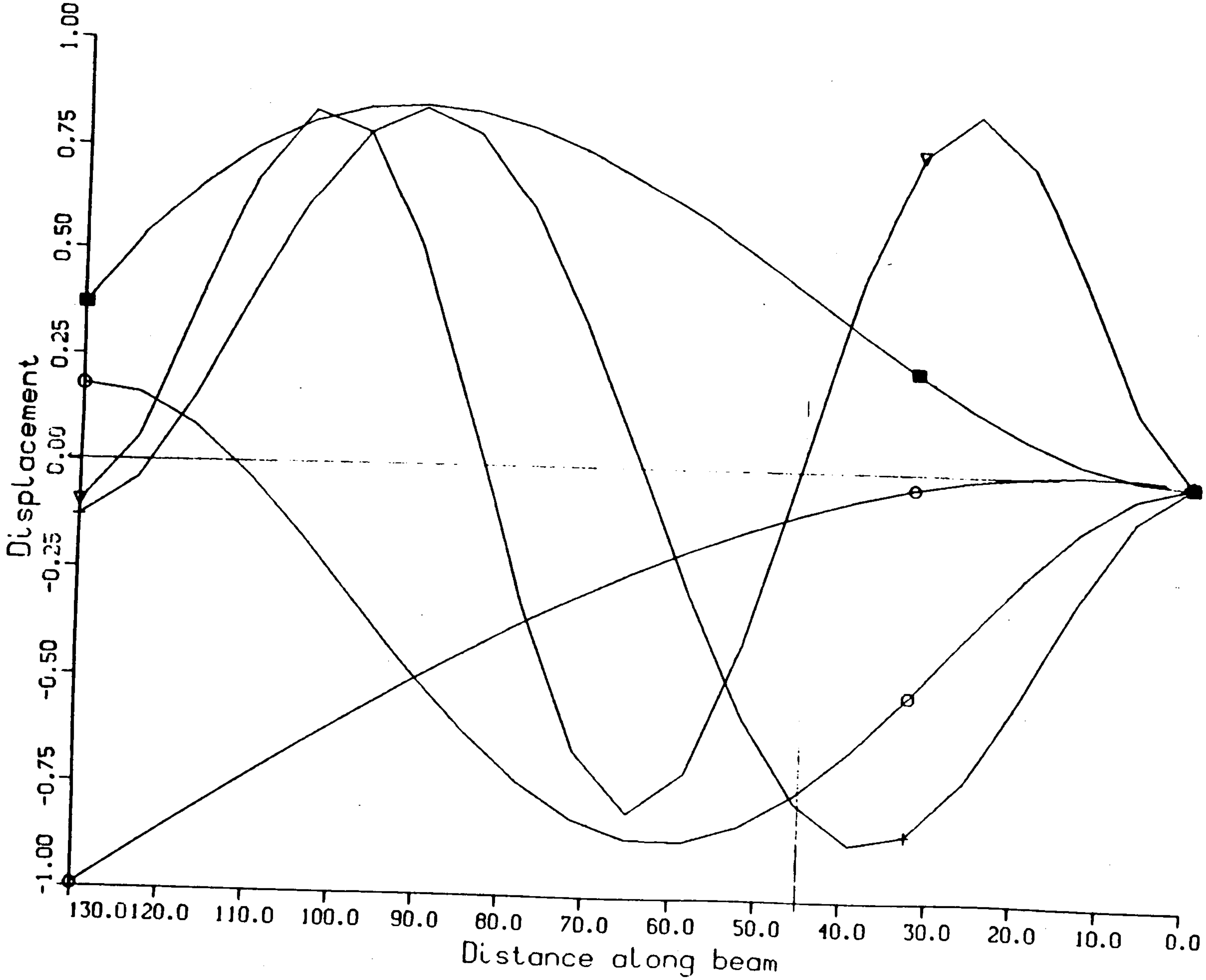
$$u(t) = -R^{-1}B^T P x(t)$$

u(t) is recalculated each time step in DISCOS from current value of x(t) and offline, predetermined values of R, B, and P.

TABLE I: MODES OF THE SYSTEM AS COMPUTED BY NASTRAN

MODE NUMBER	MODE TYPE	ANGULAR FREQ.	FREQ. IN HZ
1	PITCH	1.746	0.278
2	ROLL	1.969	0.313
3	YAW	5.105	0.182
4	ROLL	7.410	1.179
5	PITCH	12.848	2.045
6	ROLL	29.459	4.689
7	PITCH	34.263	5.453
8	ROLL	74.670	11.884
9	PITCH	78.883	12.555
10	COMPRESSION	106.281	16.915
11	ROLL	142.467	22.674
12	PITCH	145.618	23.176

Modal displacement in Y of roll modes



- INPUT MATRIX **B**

  B is of the form : $[\mathbf{B}]_{i,k} = \phi_{i,k}$

  where $\phi_{i,k}$ is input influence coefficient on i_{th} mode from actuator at location k (21 grid points on beam)

  6 degrees of freedom, 3 translational, 3 rotational,

  $$\phi_{i,k} = (\phi_x \quad \phi_y \quad \phi_z \quad \phi_\theta \quad \phi_\phi \quad \phi_\psi)_{i,k}$$

  ϕ_x is x displacement of i_{th} mode at location k

- Degree of controllability, ρ, with 2 actuators at l and n

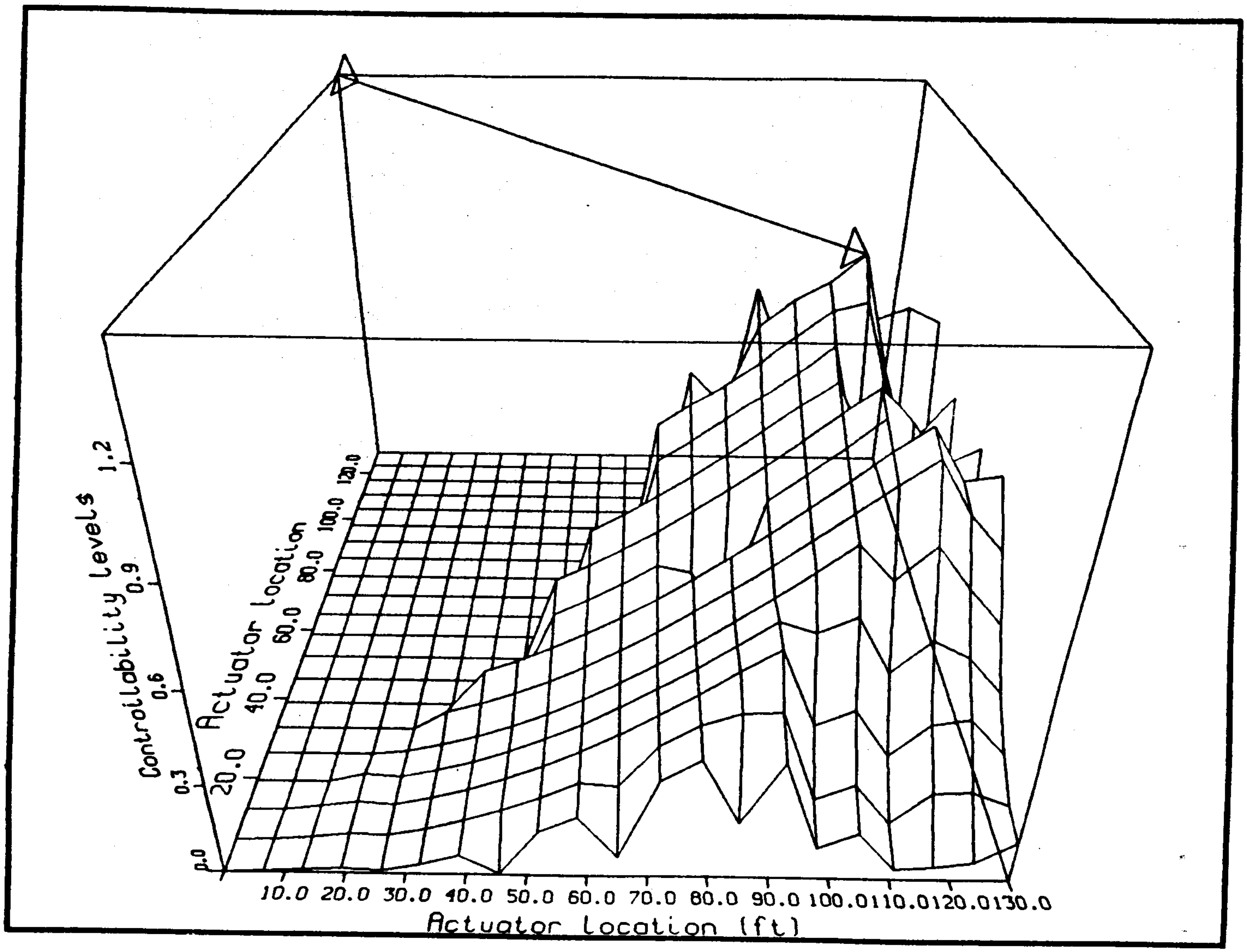
  $$\rho = \min_i [\varepsilon \cdot (|\phi_{i,l}| + |\phi_{i,n}|) + |\phi_{i,1}| + |\phi_{i,21}|]$$

  ε = ratio of actuator influence to thruster influence

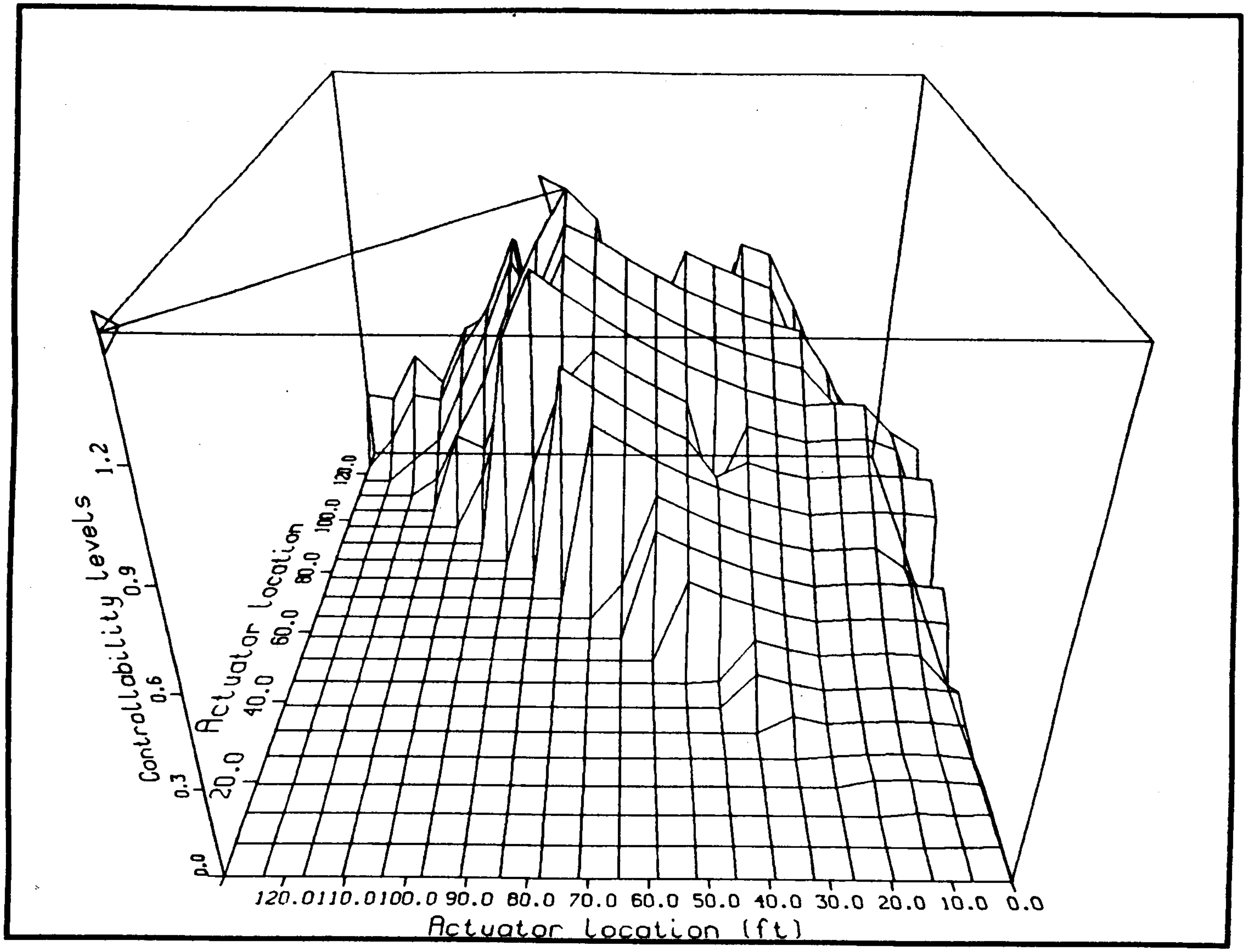
TABLE 2: ACTUATOR LOCATIONS FOR MAXIMUM CONTROLLABILITY

CASE	ACTUATOR 1		ACTUATOR 2	
	Joint #	Location	Joint #	Locatio
No Thrusters	12	104 ft	17	71.5
Actuators/Thrusters = 10	11	110.5	16	78
Actuators/Thrusters = 1	14	91	17	71.5
Actuators/Thrusters = 0.1	13	97.5	17	71.5
Actuators/Thrusters = 0.01	16	78	16	78

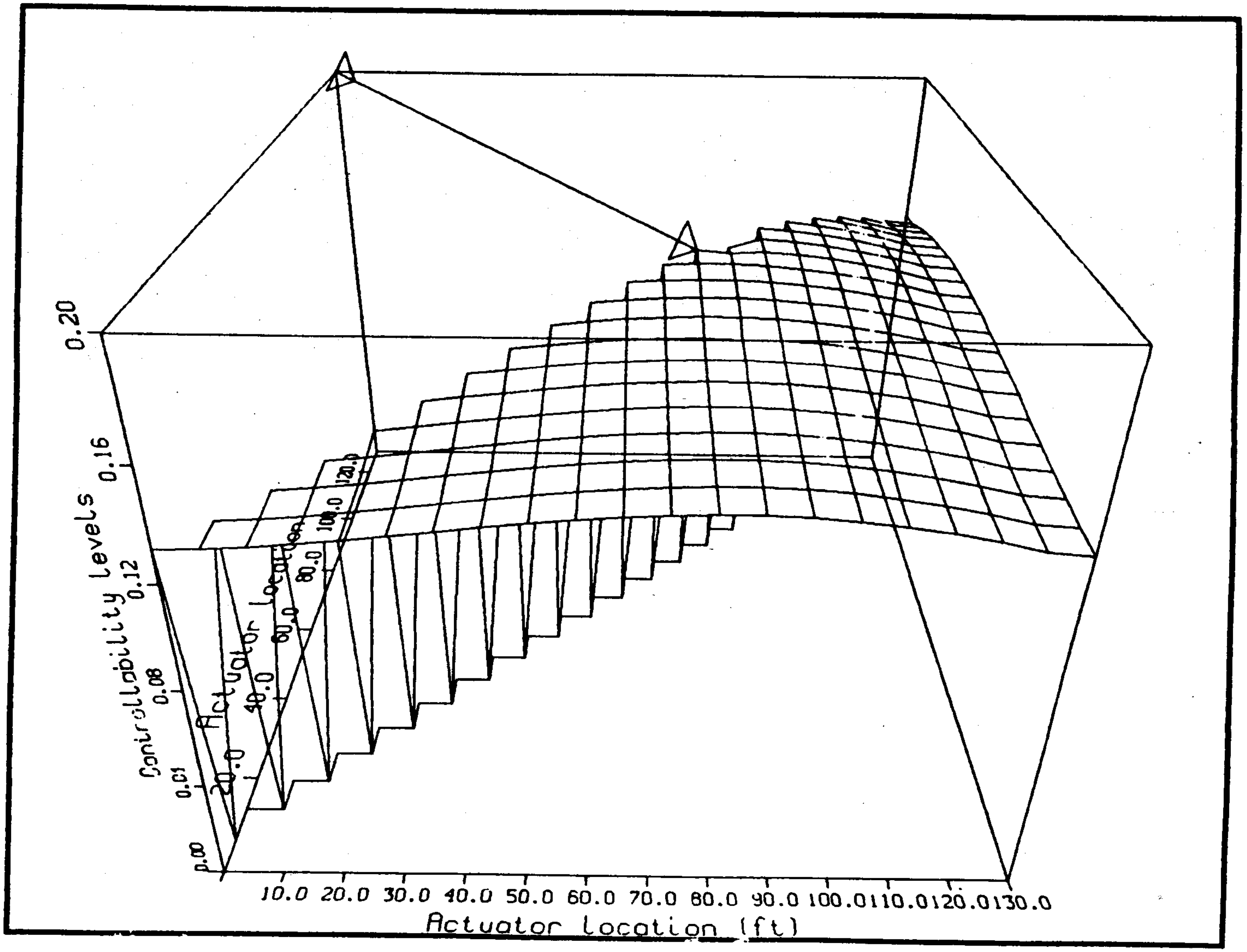
Controllability surface, X view



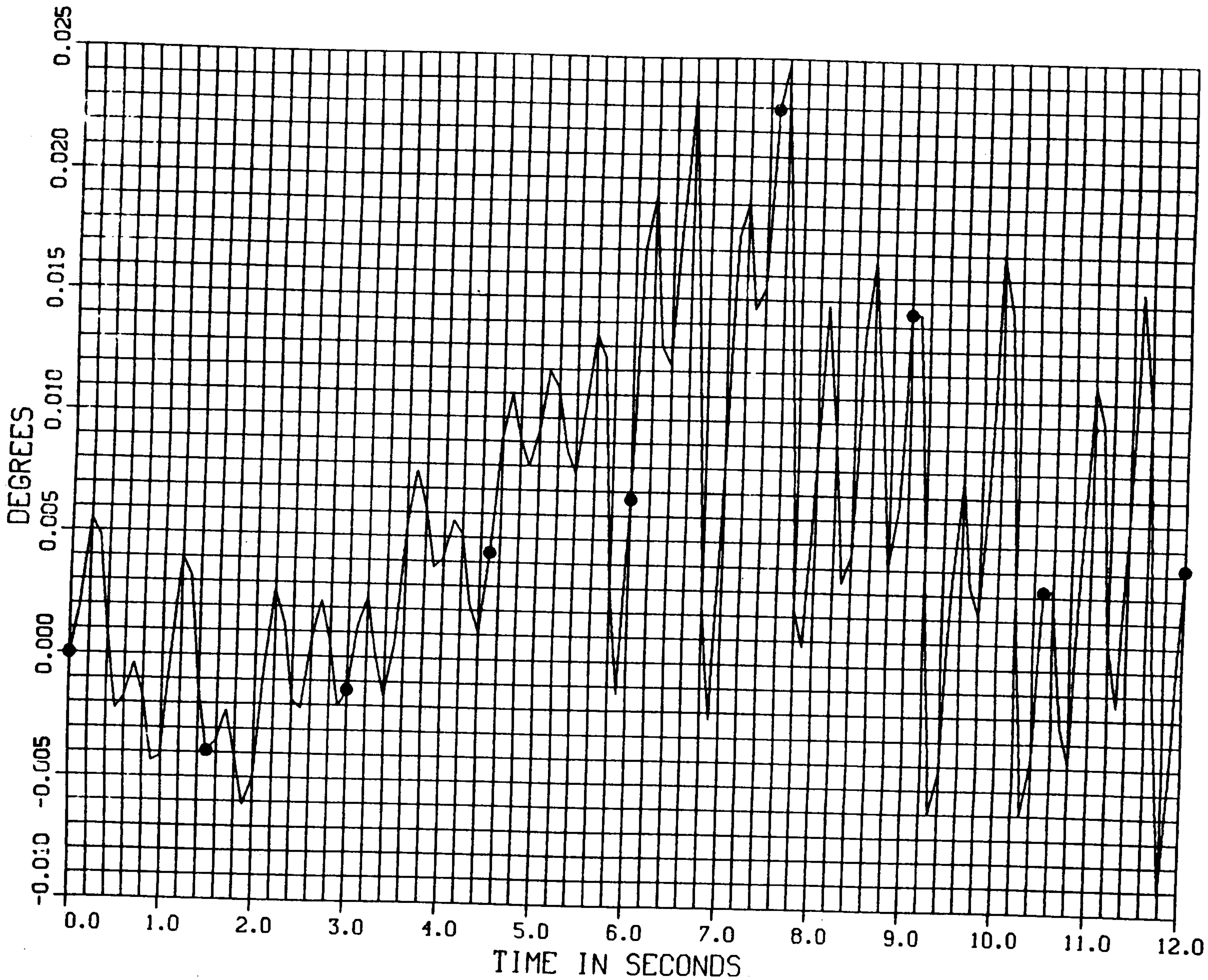
Controllability surface, Y view

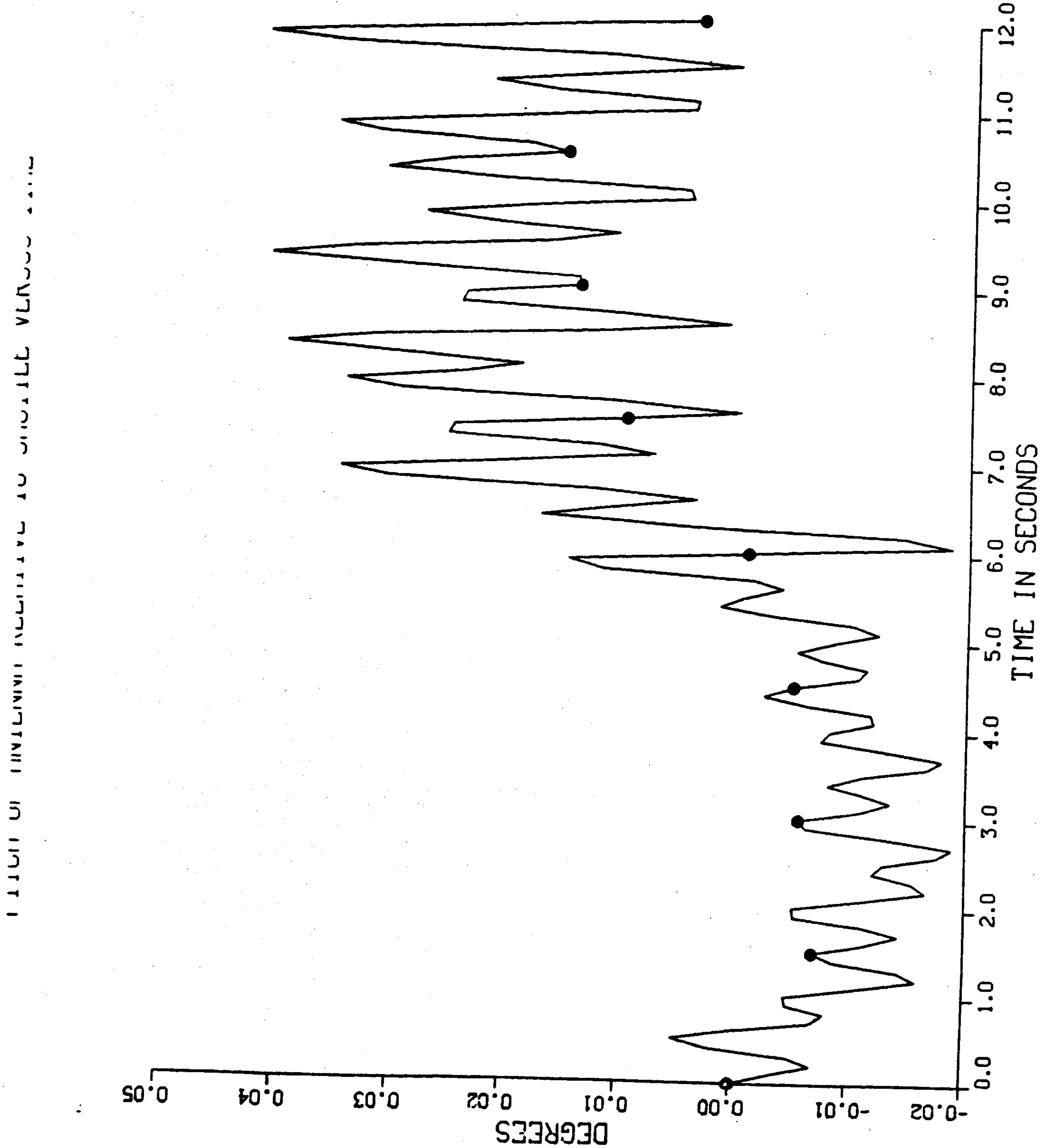


Controllability surface, X view



ROLL OF ANTENNA RELATIVE TO SHUTTLE VERSUS TIME





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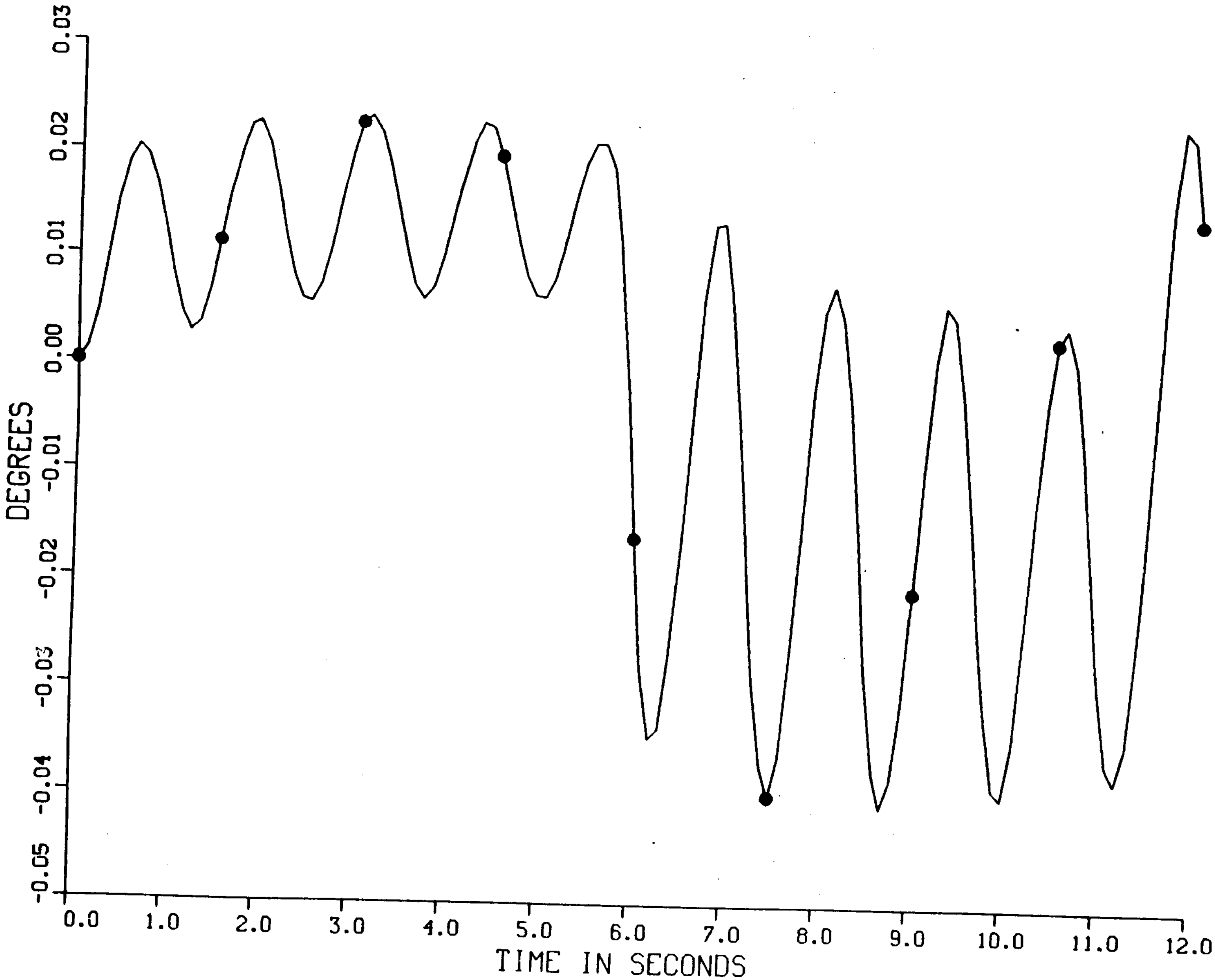
YAW OF ANTENNA RELATIVE TO SHUTTLE VERSUS TIME



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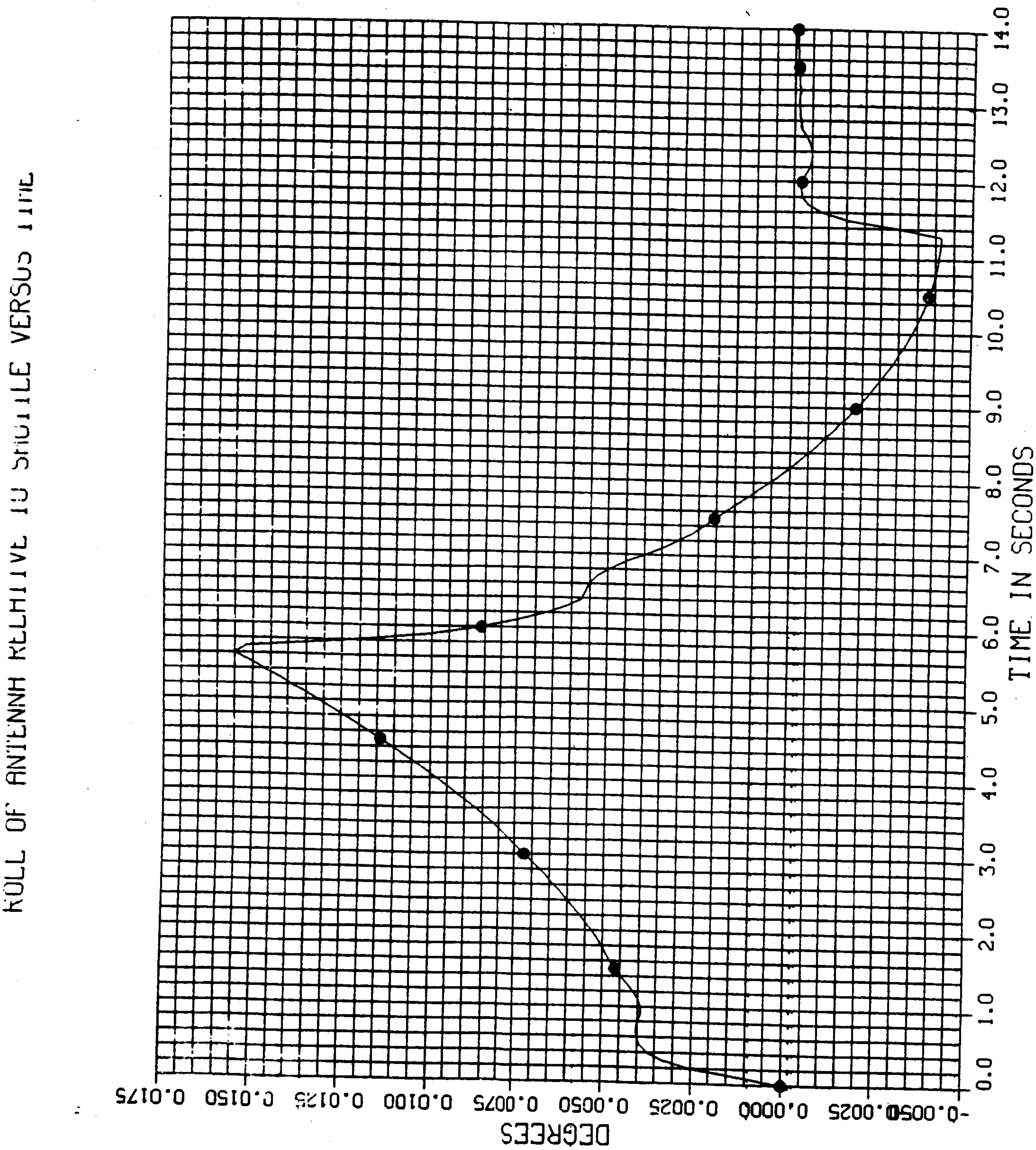
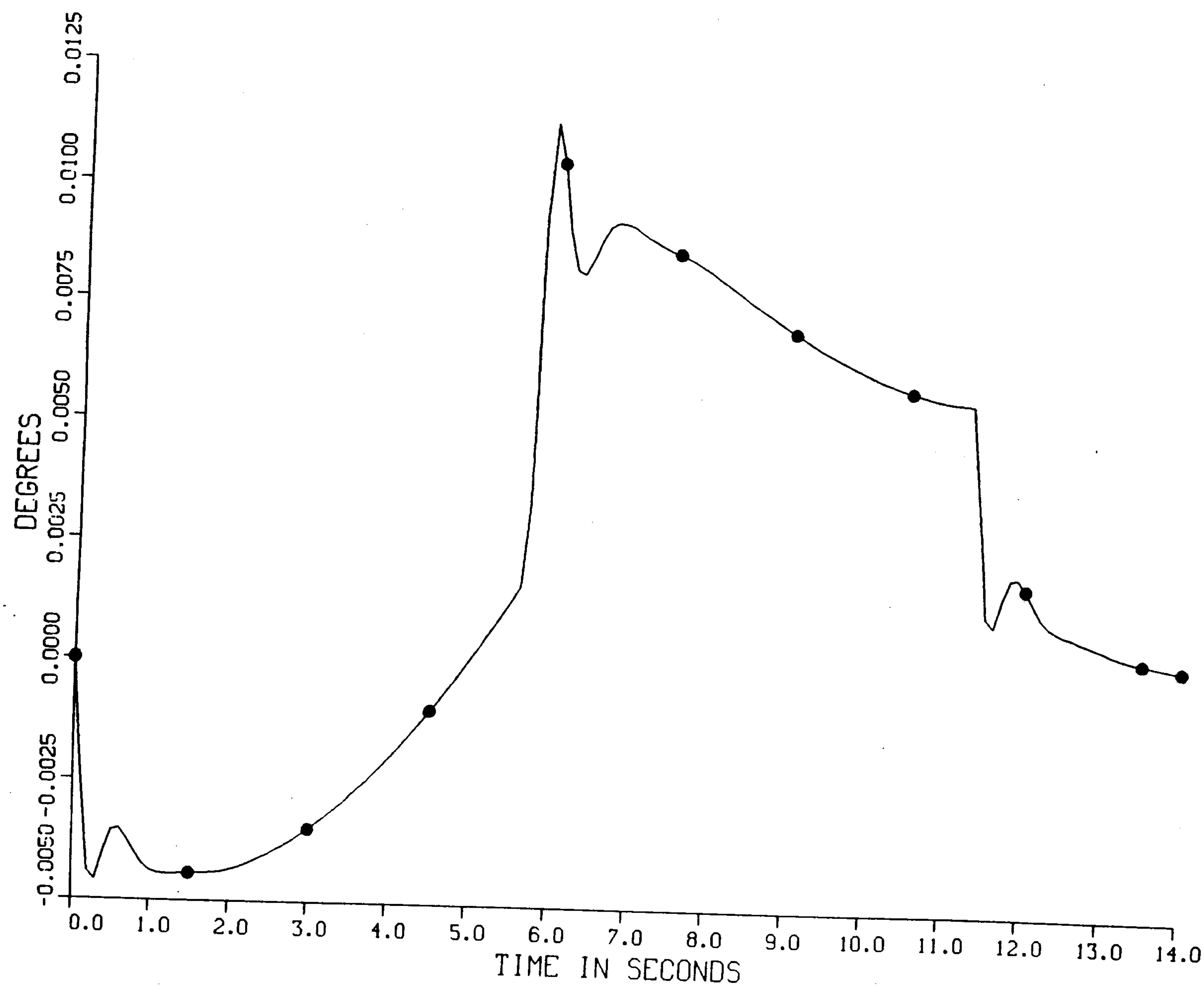
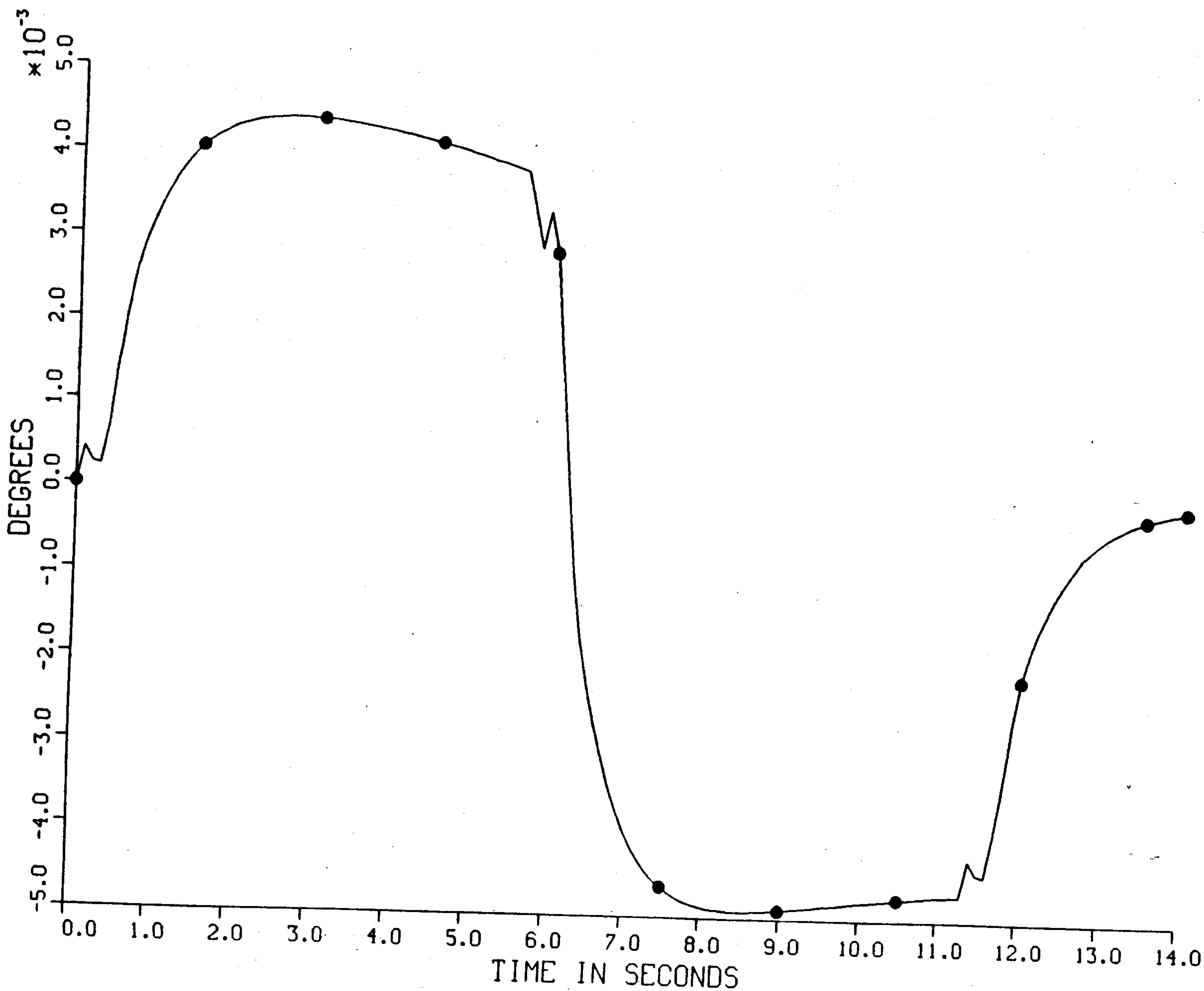

ROLL OF ANTENNA RELATIVE TO SHUTTLE VERSUS TIME
TIME IN SECONDS
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
DEGREES
0.0175
0.0150
0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
-0.0025
-0.0050

PITCH OF ANTENNA RELATIVE TO SHUTTLE VERSUS TIME

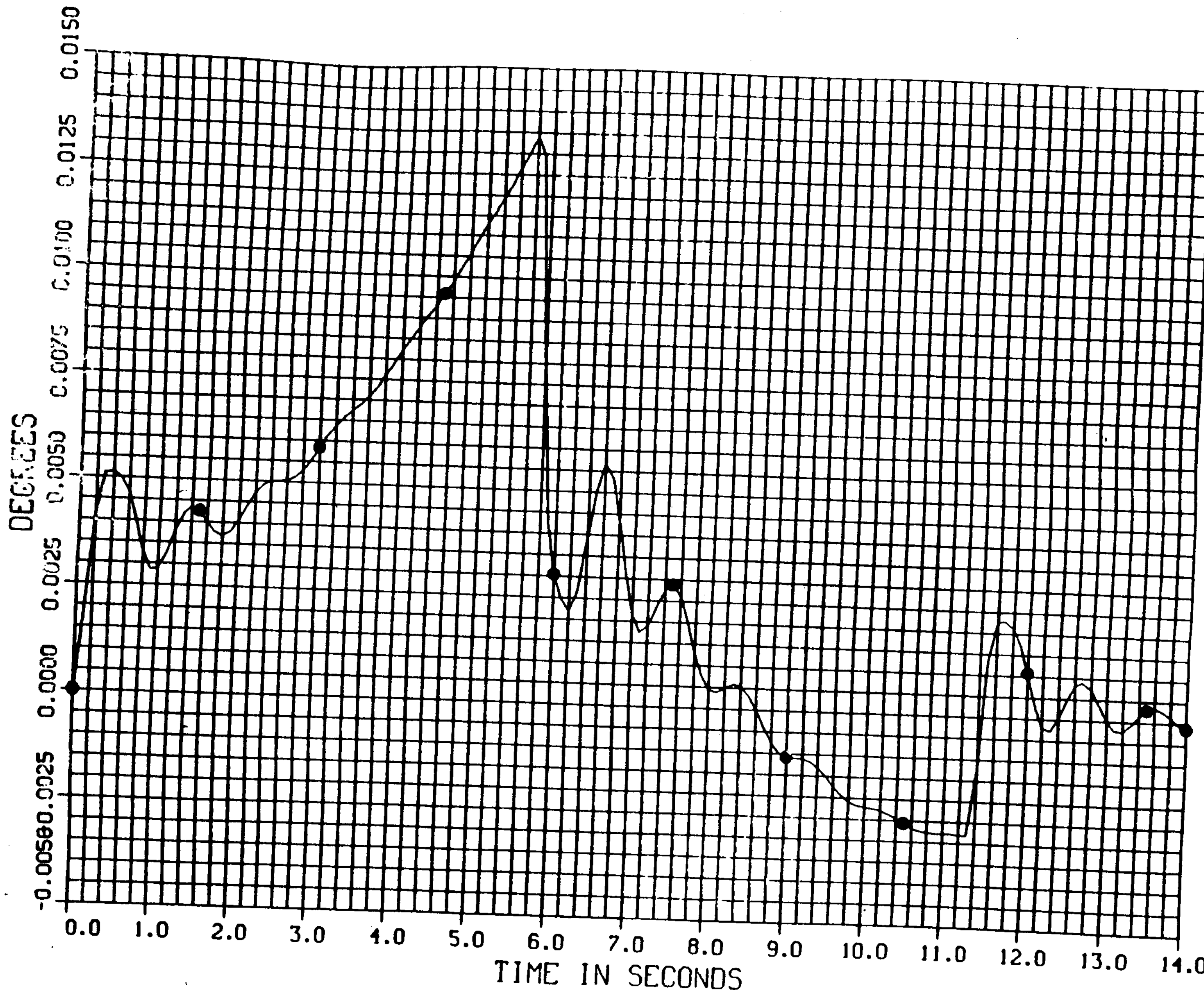


YAW OF ANTENNA RELATIVE TO SHUTTLE VERSUS TIME



ROLL OF ANTENNA RELATIVE TO SHUTTLE VERSUS TIME

Actuators at 37+ 128



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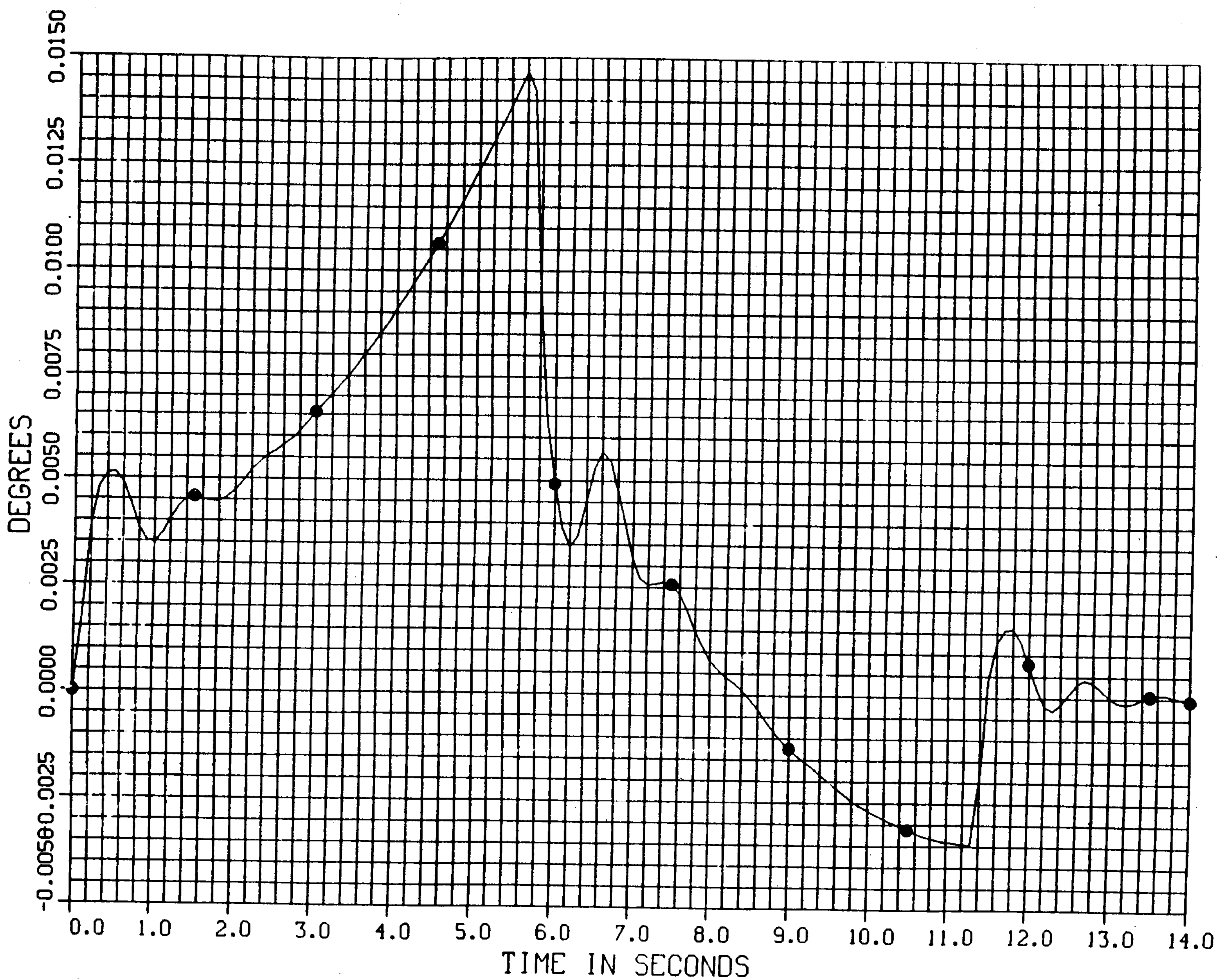
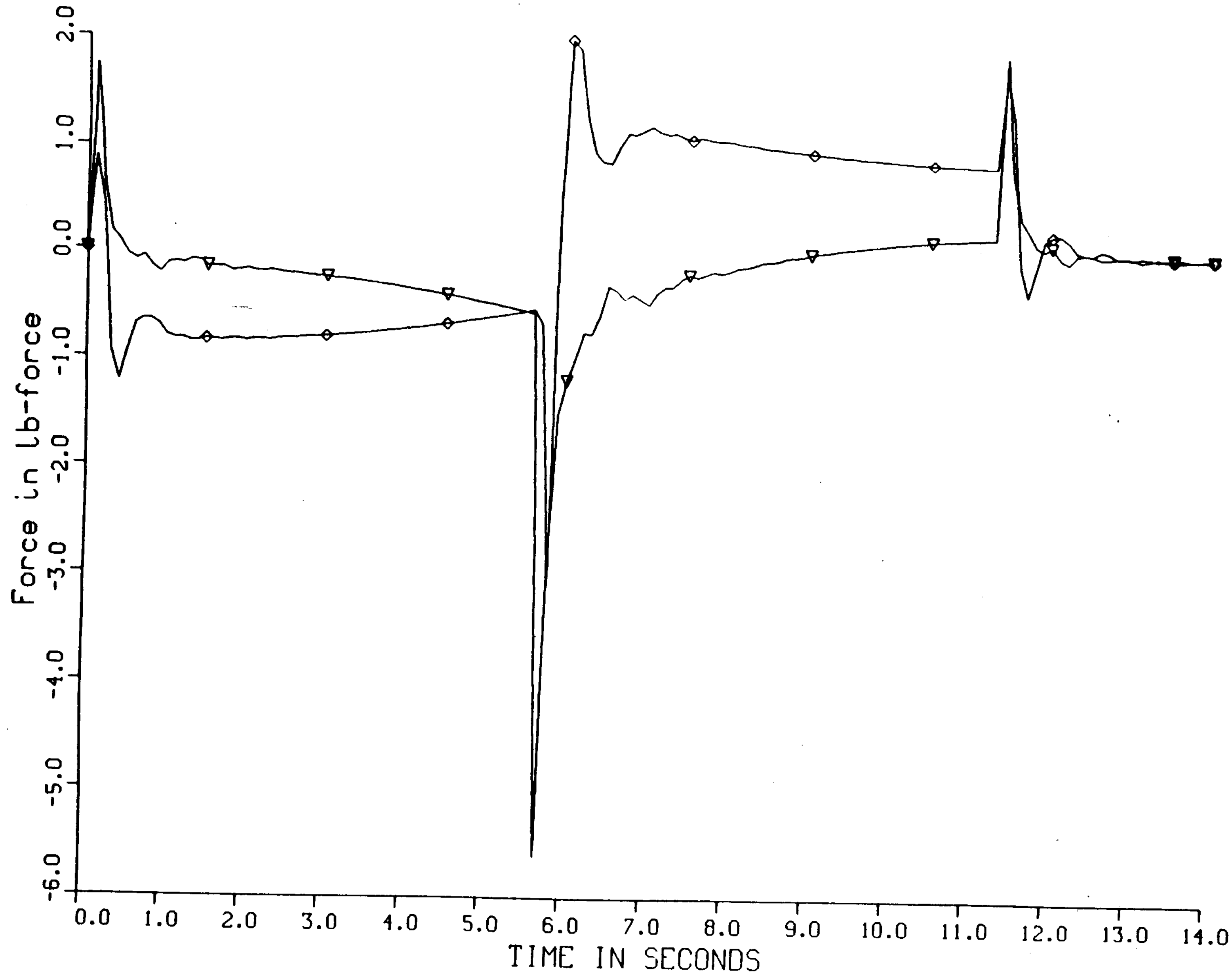
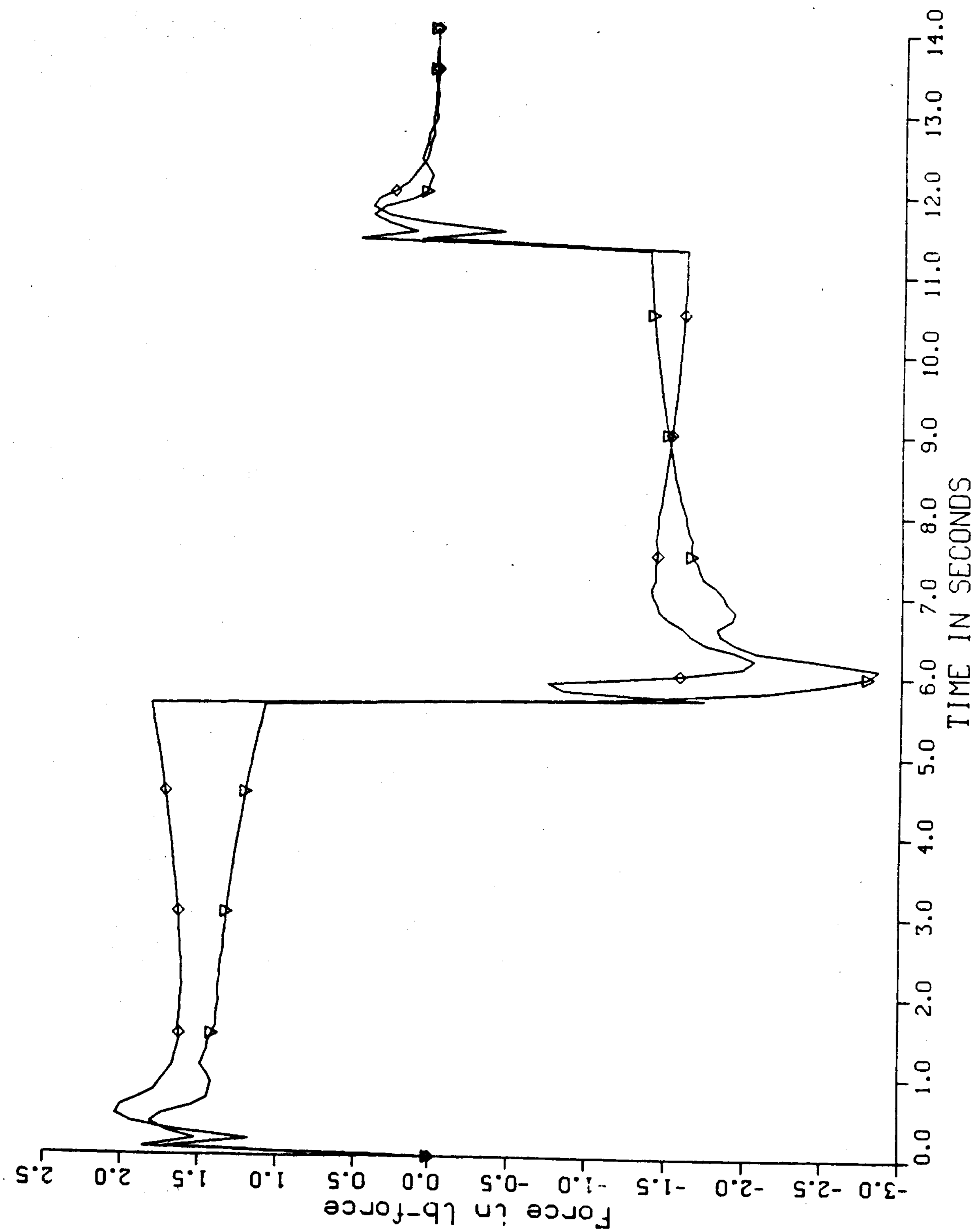
ROLL OF ANTENNA RELATIVE TO SHUTTLE VERSUS TIME   Actuators at 45½+139.5



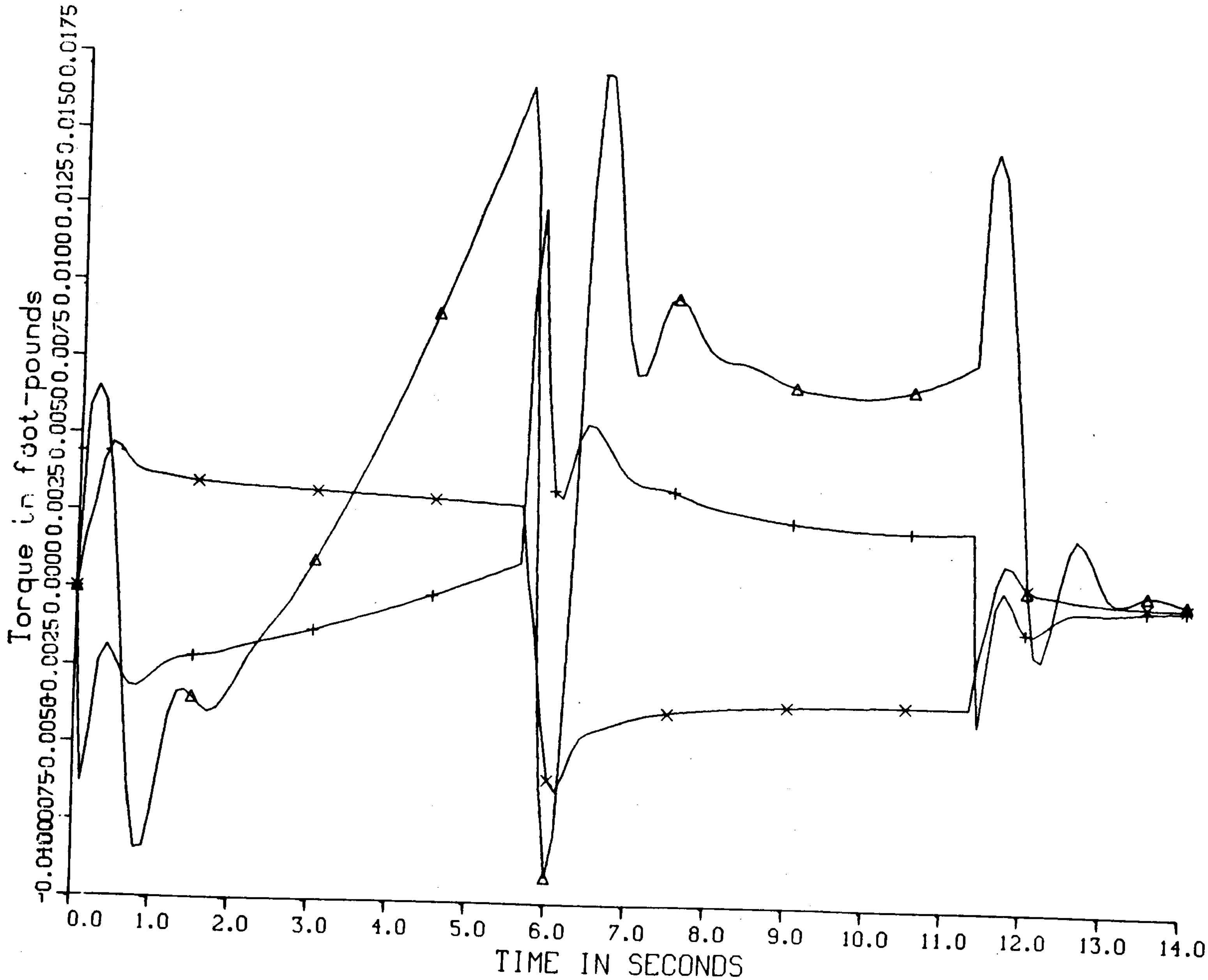
Proof mass forces near base of beam Actuators at 11½ft + 104ft



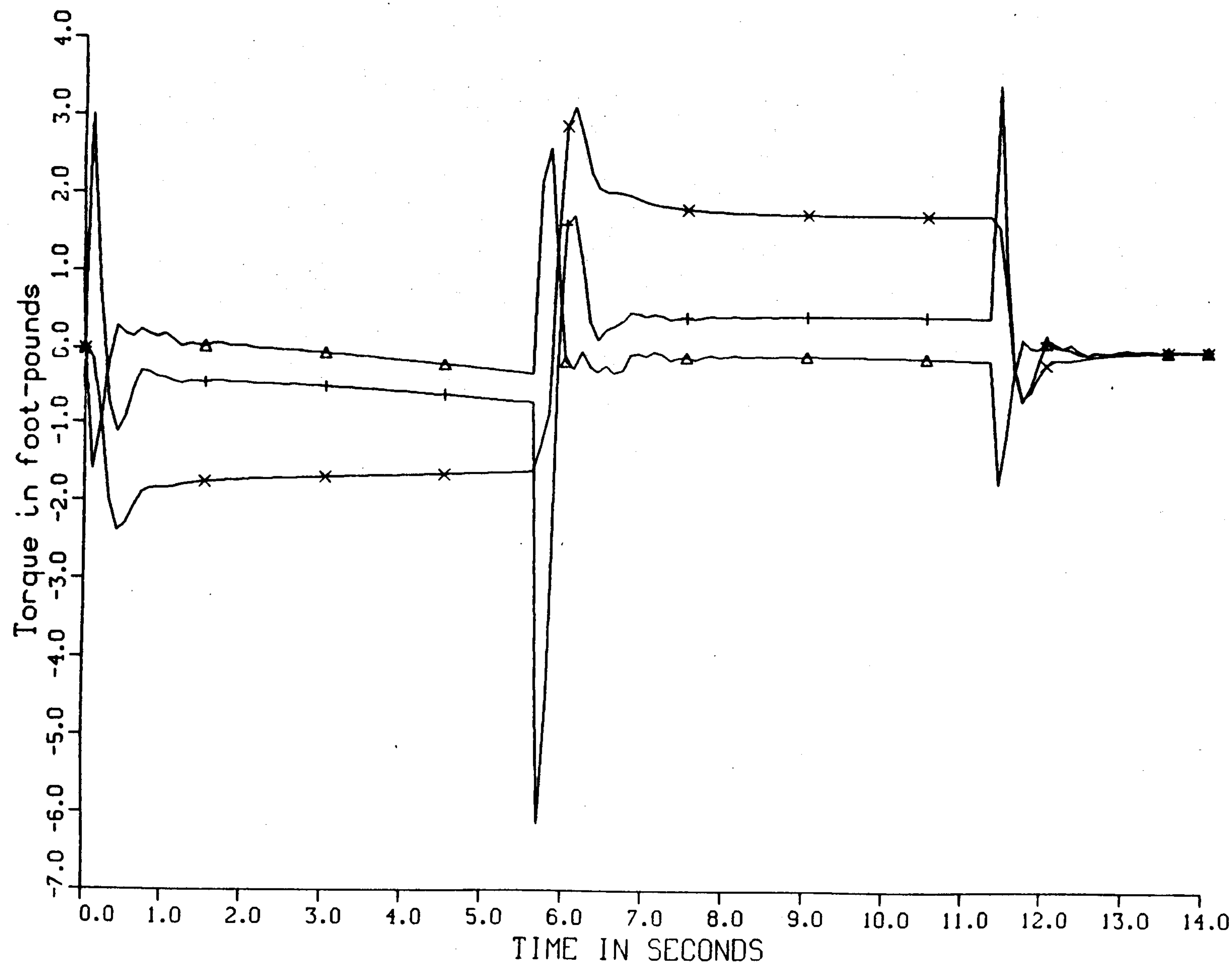
Proof mass forces applied near top of beam   Actuators at 71½ ft + 104 ft.



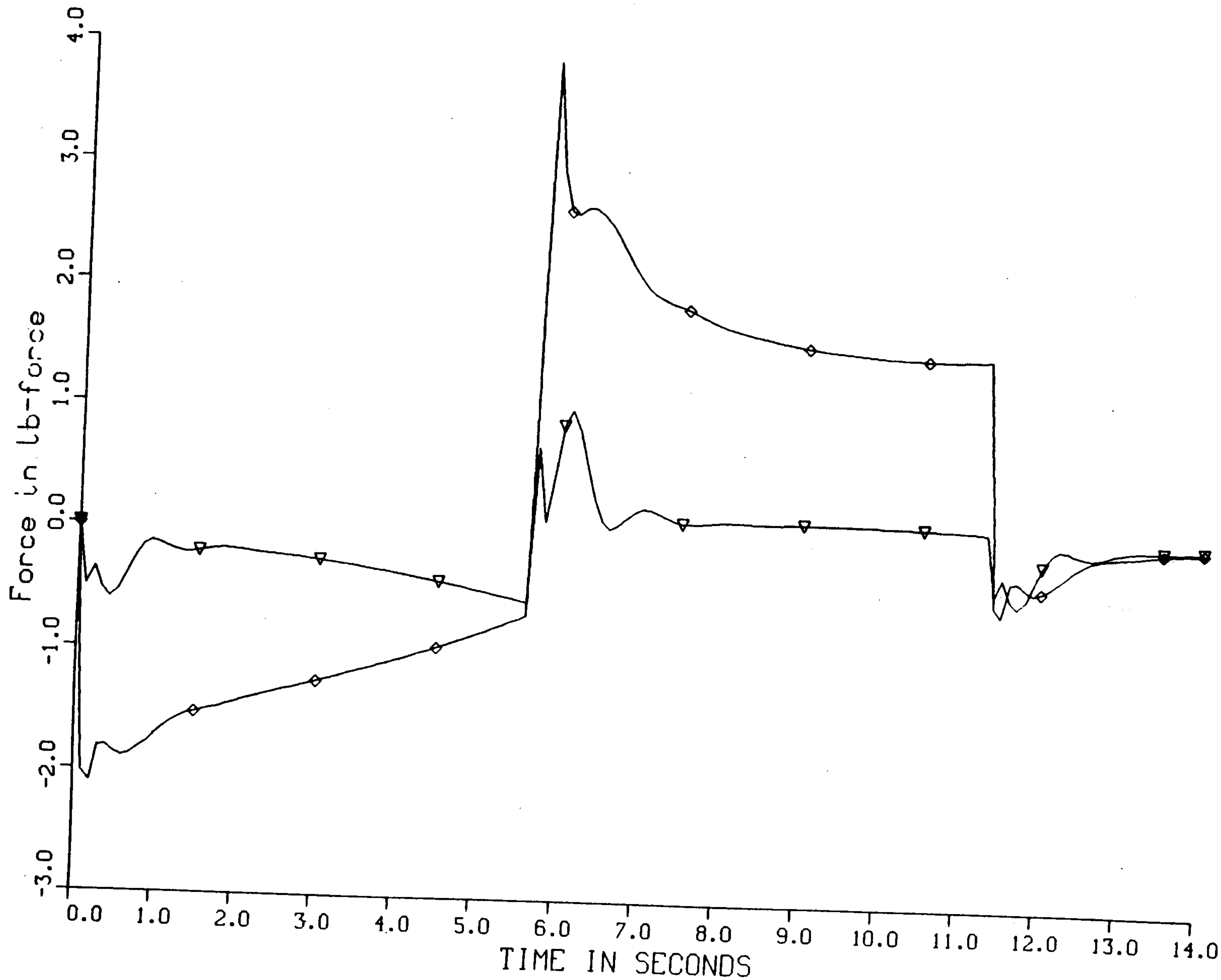
Torques applied at base of beam



Control torques applied at reflector



Forces applied at reflector



CONCLUSIONS

1. PROOF-MASS ACTUATORS CAN REDUCE FLEXURE AMPLITUDE AND DAMP OSCILLATIONS

2. AMPLITUDE OF DEFORMATIONS DURING SLEW IS RELATIVELY INSENSITIVE TO PLACEMENT OF ACTUATORS

3. DAMPING FACTOR OF OSCILLATIONS IS SENSITIVE TO PLACEMENT OF ACTUATORS

4. DEGREE OF CONTROLLABILITY METHOD INDICATES MOST EFFECTIVE PLACEMENT FOR ACTUATORS

FUTURE DIRECTIONS

1. INCLUDE NOISE AND TIME DELAYS IN SENSORS AND ACTUATORS KALMAN FILTER.

2. "CLOSE THE LOOP" BY SIMULATING THE EXPERIMENTAL TEST MODEL OF SCOLE.