Control Design Approaches for LaRC Experiments

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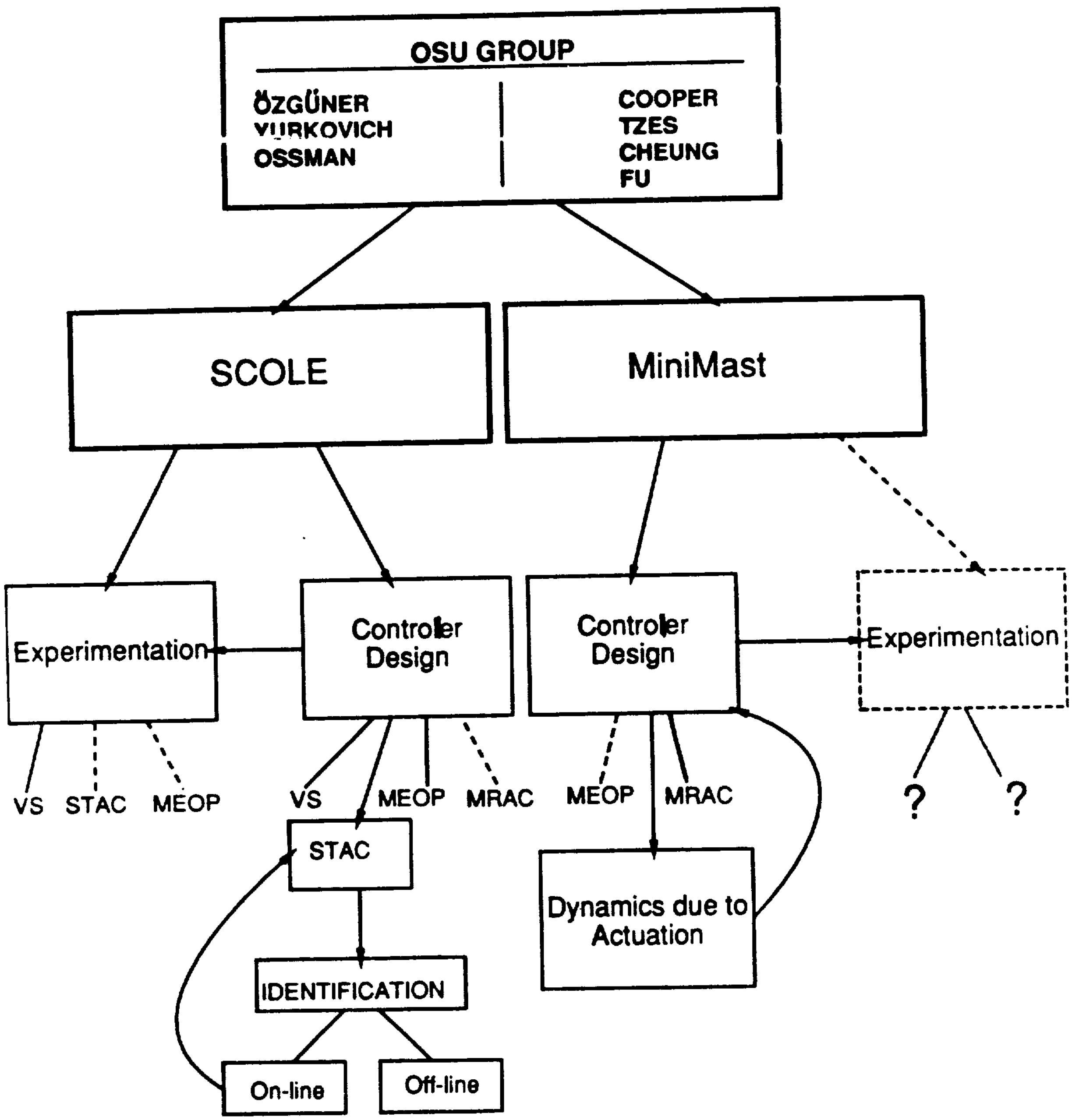
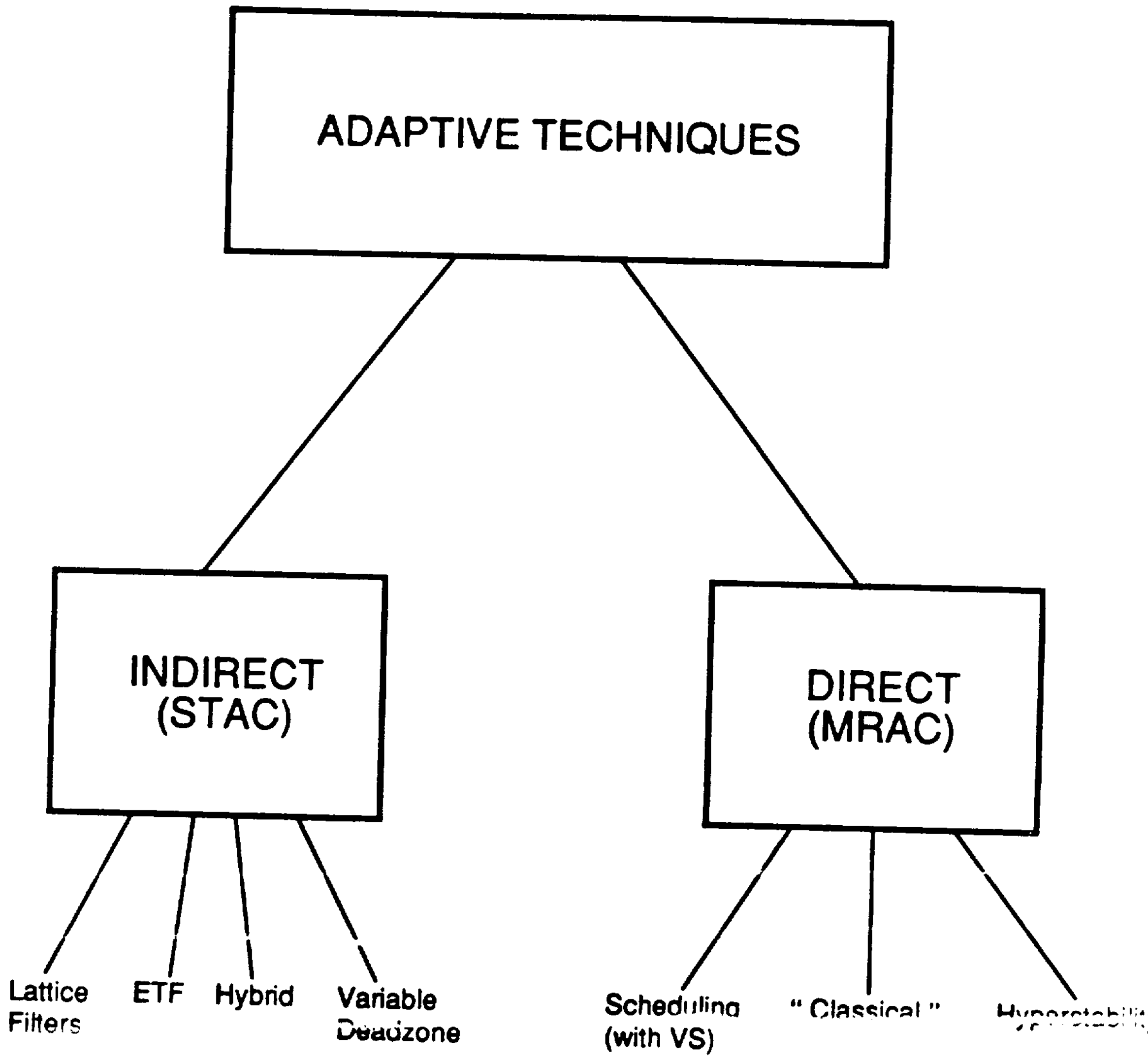
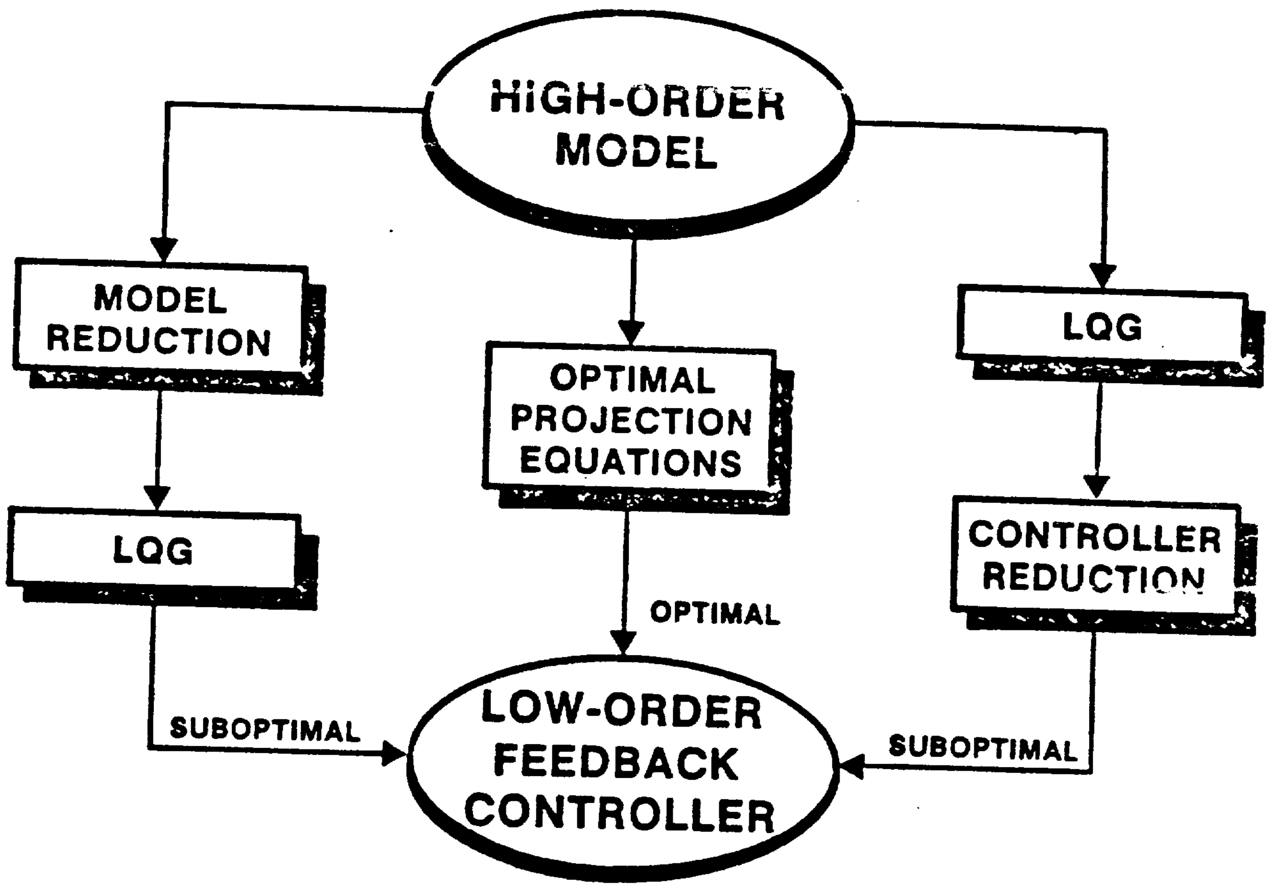

OSU GROUP
ÖZGÜNER
YURKOVICH
OSSMAN
COOPER
TZES
CHEUNG
FU
SCOLE
MiniMast
Experimentation
Controller Design
Controller Design
Experimentation
VS
STAC
MEOP
VS
MEOP
MRAC
MEOP
MRAC
?
?
STAC
IDENTIFICATION
On-line
Off-line
Dynamics due to Actuation


ADAPTIVE TECHNIQUES
INDIRECT (STAC)
DIRECT (MRAC)
Lattice Filters
ETF
Hybrid
Variable Deadzone
Scheduling (with VS)
" Classical "

Direct Fixed–Order Compensator Design



Given ...

$$\begin{aligned} \dot{x} &= Ax + Bu + w_1 \\ y &= Cx + w_2 \quad , \end{aligned}$$

... design an n_c^{th} order *robust*, zero set-point compensator

$$\begin{aligned} \dot{x}_c &= A_c x + F y \\ u &= -K x_c \end{aligned}$$

to minimize

$$J = \lim_{\tau \to \infty} \frac{1}{\tau} \int_0^{\tau} (x^T(t) R_1 x(t) + u^T(t) R_2 u(t)) dt \quad ,$$

LQG Solution

$$
\begin{aligned}
K &= R_2^{-1} B^T P \quad , \\
F &= Q C^T V_2^{-1} \quad , \\
A_c &= A - BK - FC \quad ,
\end{aligned}
$$

P and Q positive definite solutions to

$$
\begin{aligned}
PA + A^T P + R_1 - PBR_2^{-1} B^T P &= 0 \quad , \\
QA^T + AQ + V_1 - QC^T V_2^{-1} CQ &= 0 \quad .
\end{aligned}
$$

$$
\begin{aligned}
0 &= PA_s + A_s^T P + \sum_{i=1}^{\mu} A_i^T P A_i - P_s^T R_{2s}^{-1} P_s + R_1 \\
&\quad + \sum_{i=1}^{\mu} (A_i - Q_s V_{2s}^{-1} C_i)^T \hat{P} (A_i - Q_s V_{2s}^{-1} C_i) + \tau_\perp^T P B R_2^{-1} B^T P \tau_\perp \\
0 &= A_s Q + Q A_s^T + \sum_{i=1}^{\mu} A_i Q A_i^T - Q_s V_{2s}^{-1} Q_S^T + V_1 \\
&\quad + \sum_{i=1}^{\mu} (A_i - B_i R_{2s}^{-1} P_s) \hat{Q} (A_i - B_i R_{2s}^{-1} P_s)^T + \tau_\perp Q C^T V_2^{-1} C Q \tau_\perp^T \\
0 &= \hat{P} A_{QS} + A_{QS}^T \hat{P} + P_s^T R_{2s}^{-1} P_s - \tau_\perp^T P B R_2^{-1} B^T P \tau_\perp \\
0 &= A_{PS} \hat{Q} + \hat{Q} A_{PS}^T + Q_s V_{2s}^{-1} Q_s^T - \tau_\perp Q C^T V_2^{-1} C Q \tau_\perp^T
\end{aligned}
$$

Application to SCOLE

- Reflector Panel
- Objective: Vibration Damping
- 3 inputs (reaction wheels at hub)
- 5 outputs (gyros at hub, accelerometers at reflector center)
- 10 modes

MEOP procedure

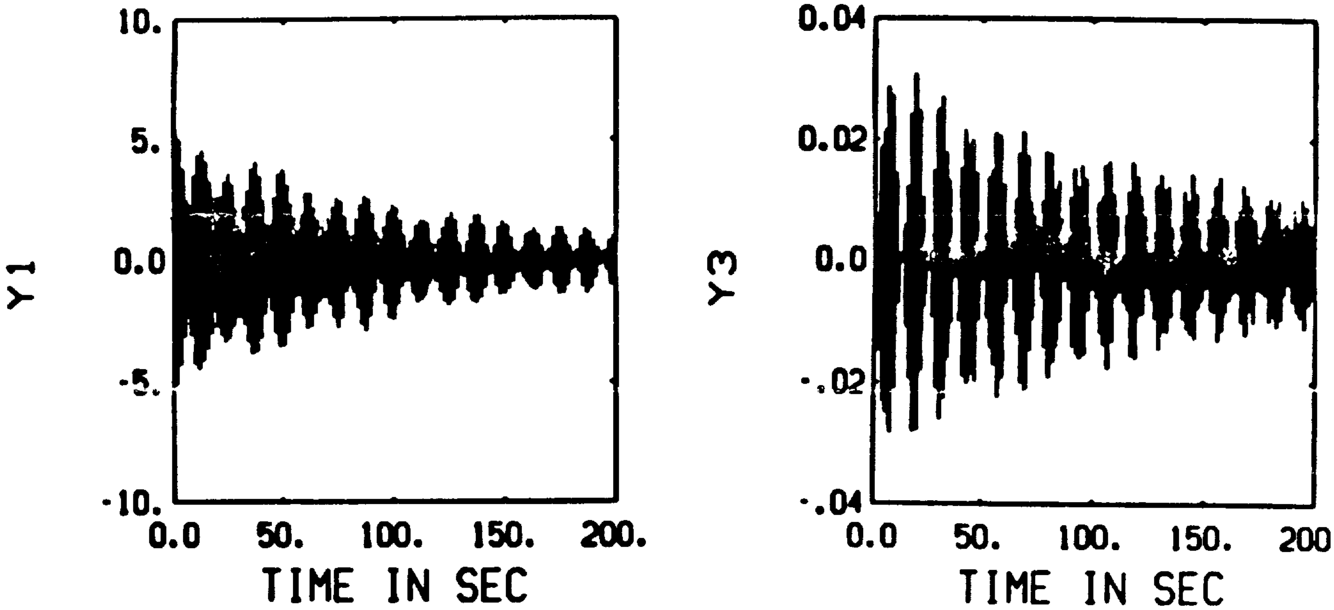
- Robustification with respect to modal frequencies
- Robustness measure: ϵ
- Results:

Order	$\lvert\epsilon\rvert$	$\frac{d\omega}{\omega}$ (%)	Cost
20	0.0138	-20 to +4	0.229
12	0.0141	-30 to +20	0.231
10	0.0153	-45 to +30	0.231
8	0.0140	-9 to +30	0.235

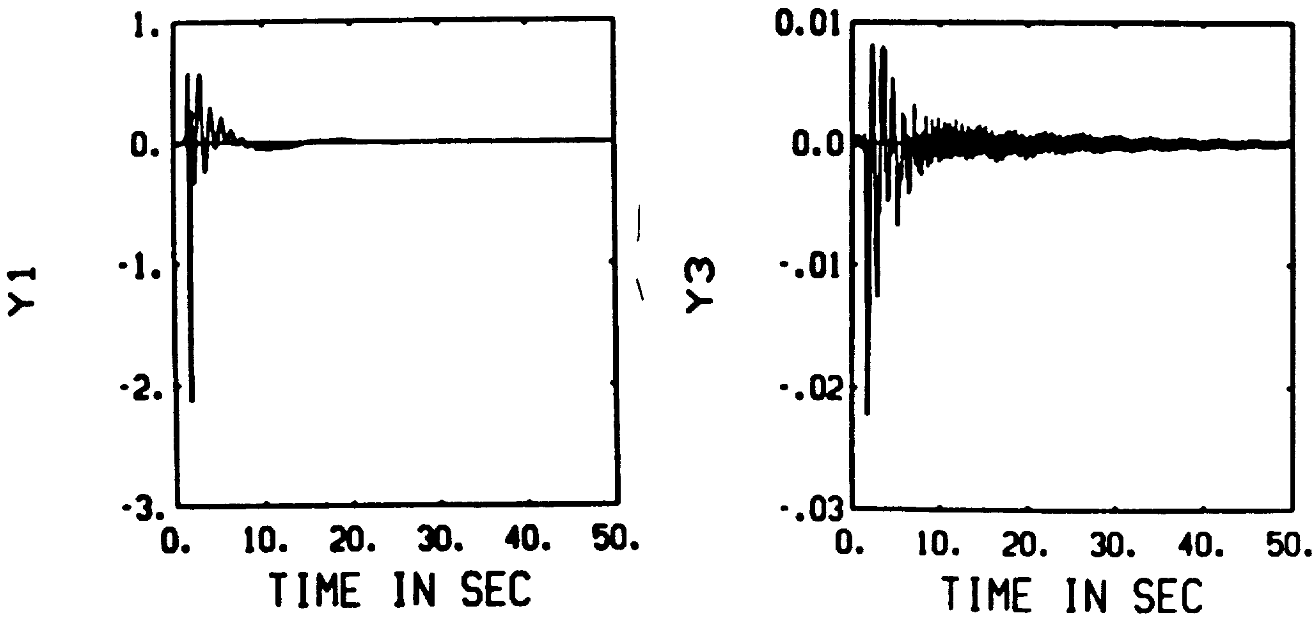
Optimal Projection Design

Order	$\lvert\epsilon\rvert$	$\frac{d\omega}{\omega}$ (%)	Cost
20	0.0148	-25 to +40	0.407
12	0.0156	-50 to +50	0.311
10	0.0154	-50 to +50	0.319
8	0.0154	-40 to +40	0.322

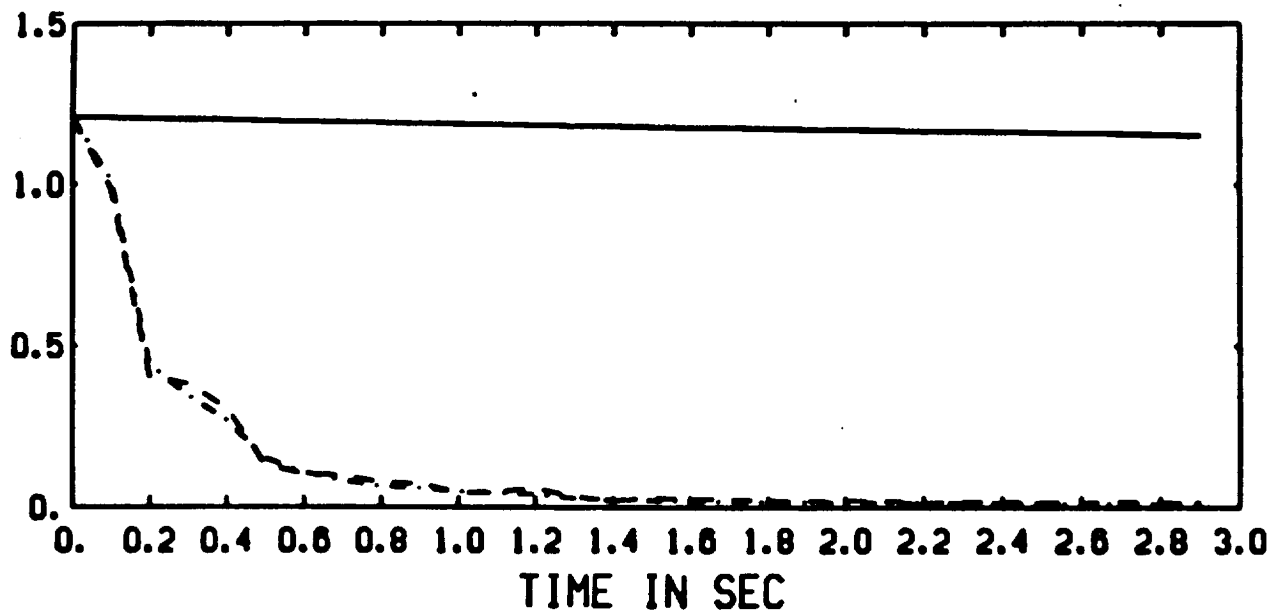
MEOP Designs



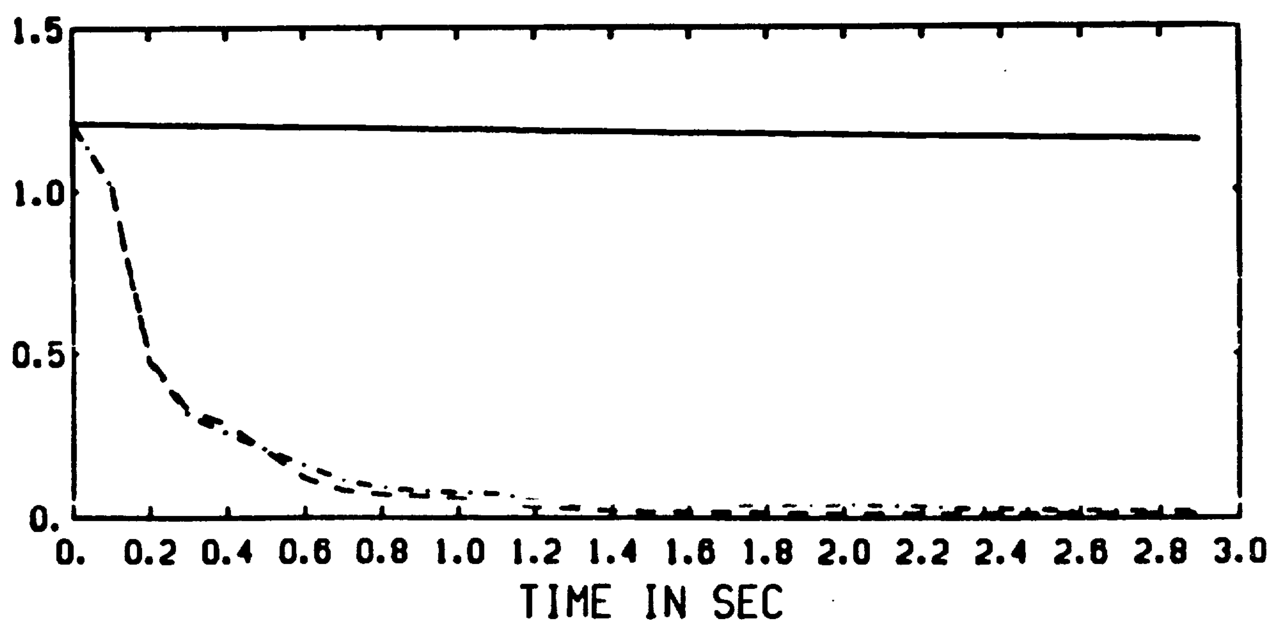
Open loop outputs.



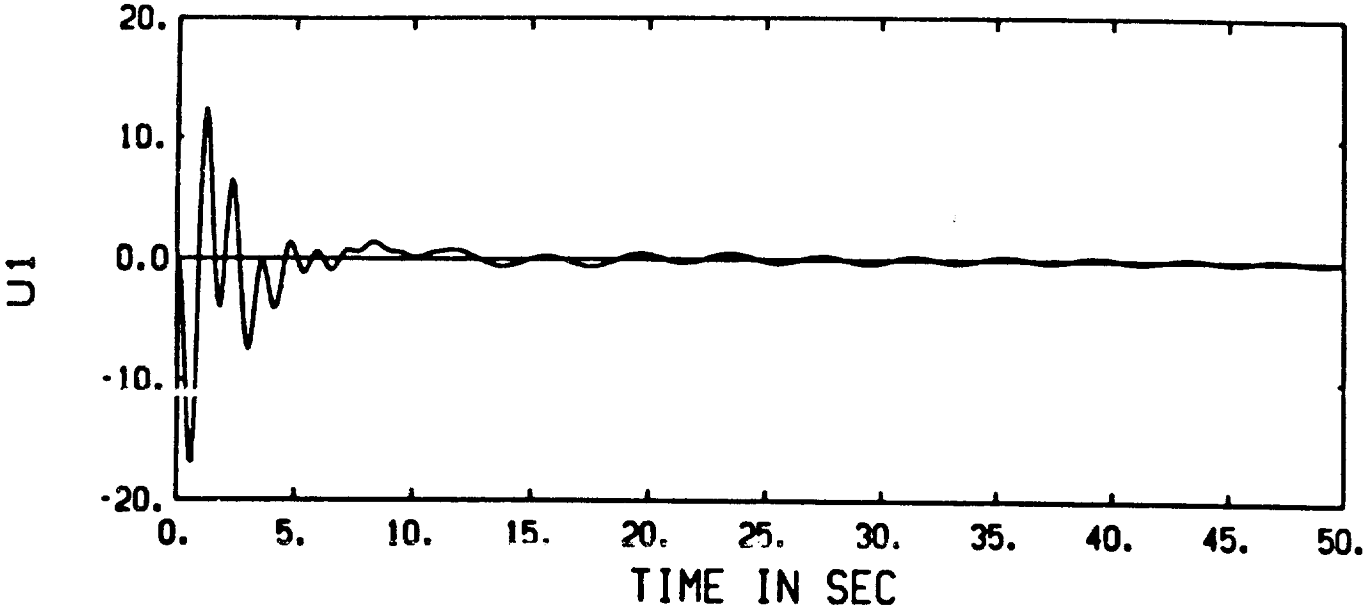
Closed loop outputs.



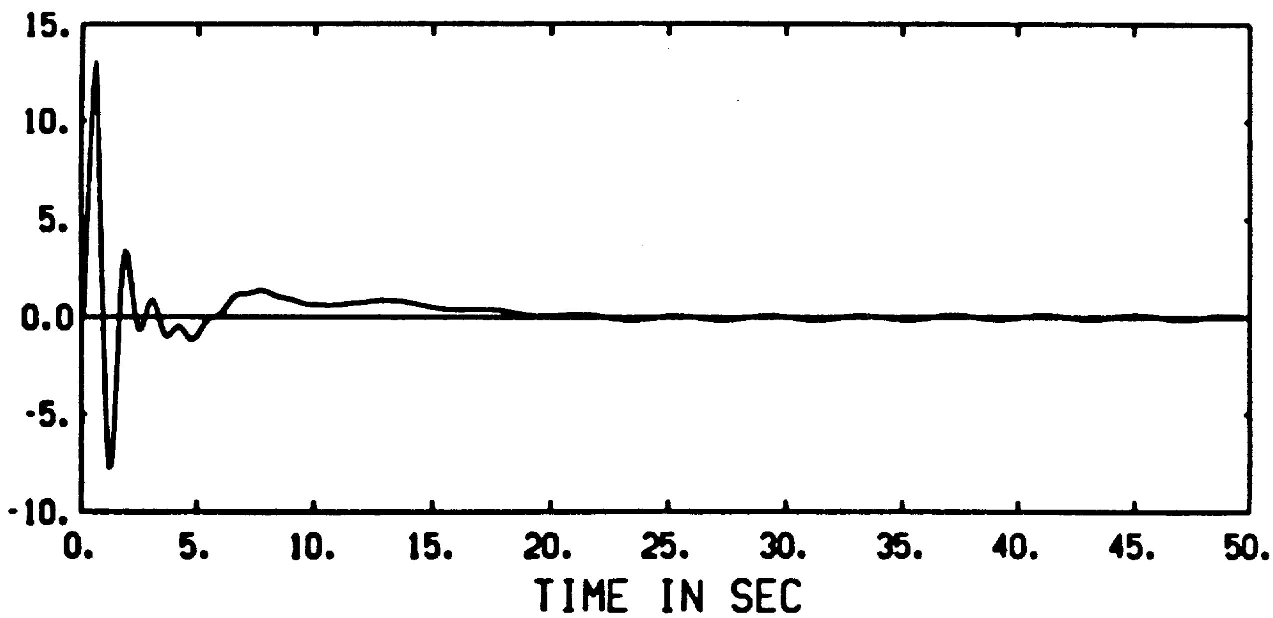
Vibrational energy profile
(full order designs)



Vibrational energy profile
(reduced-order designs)



Torque input on x-axis at the hub.



Torque input on y-axis at the hub.

Model Reference Adaptive Control (MRAC)

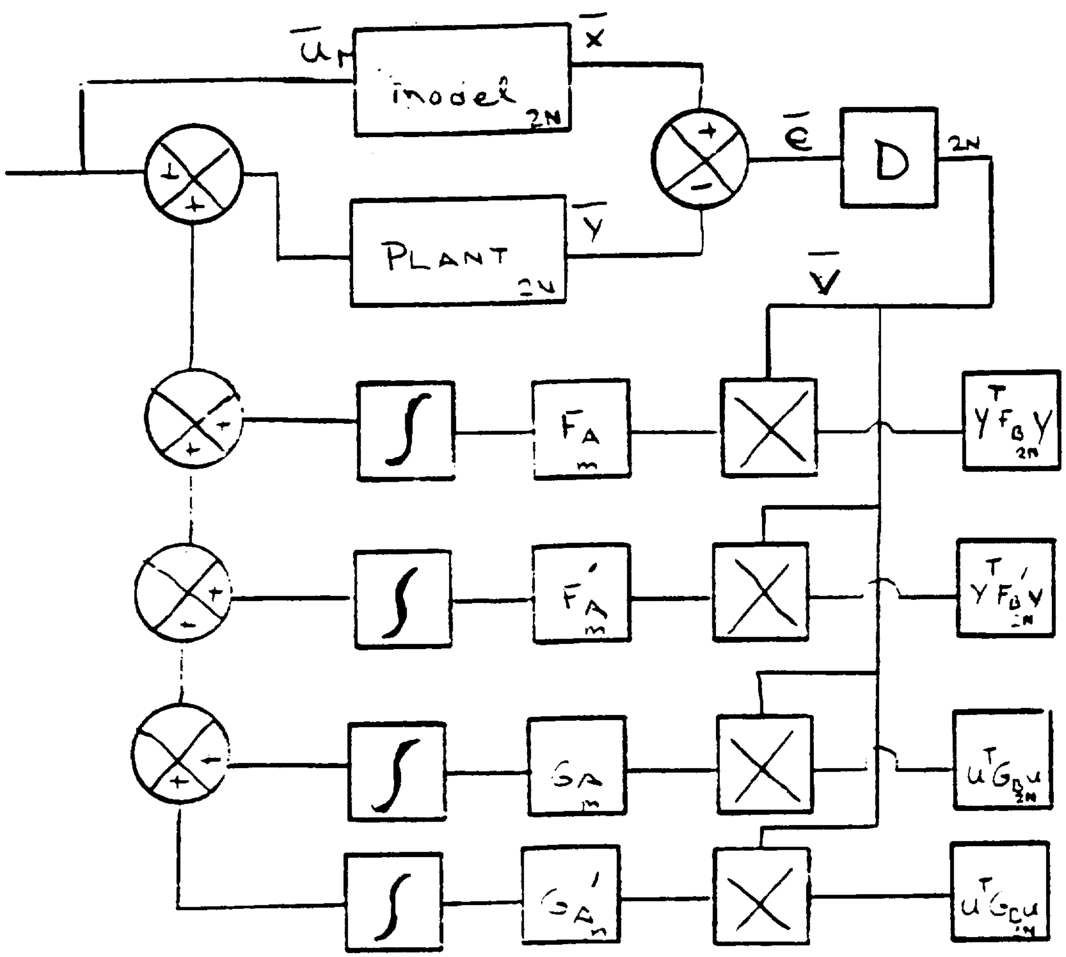
Procedure:

Find largest possible family of adaptation laws assuring stability, select specific adaptation law for particular application.

Methods:

Hyperstability and Positivity Concepts

Control Approach



PI Adaptive Model Following Feedback

Control Objectives

- Control designed for first five modes

- 2–10% damping required

mode number	Frequency Hertz	Desired Damping
1	.964	10%
2	.964	10%
3	7.17	2%
4	7.51	2%
5	9.6	2%

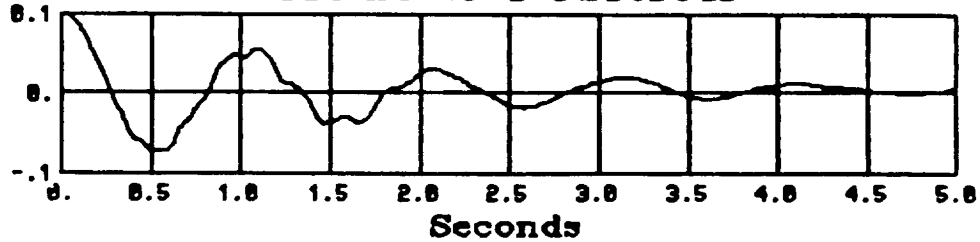
- Effects of actuator dynamics not included

Application to MiniMast

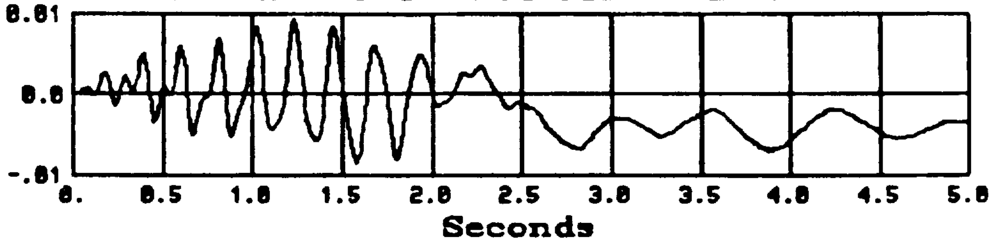
Mini Mast Modal Frequencies		
mode number	Frequency Hertz	Mode Type
1	.964	x - y
2	.964	y - z
3	7.17	plate
4	7.51	torsion
5	9.6	y - z
6	9.8	x - z
7	10.2	y - z
8	12.1	mix
9	16.08	mix
10	16.8	mix

Mini Mast Model Actuators						
number	FEM Point	Actuator Type	Cordinate Frame			Force Limitations
			X	Y	Z	
1	334	Linear Actuator	1	0	0	30 newtons
2	336	Linear Actuator	1	0	0	30 newtons
3	335	Linear Actuator	0	1	0	30 newtons
4	337	Linear Actuator	0	1	0	30 newtons
5	338	Reaction Wheel	0	0	1 Rot	50 Ft. - lb.

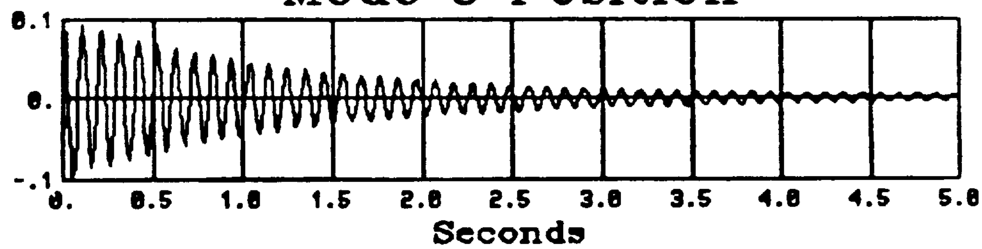
Mode 2 Position



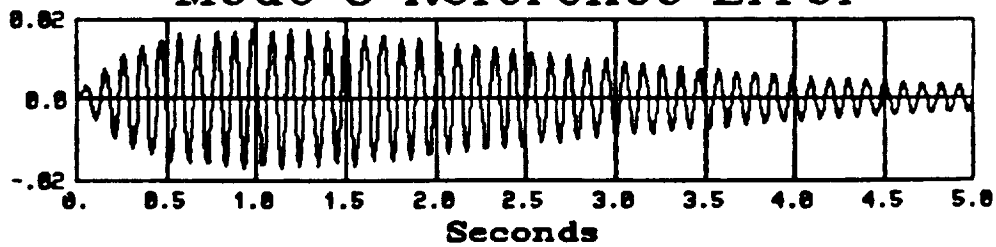
Mode 2 Reference Error



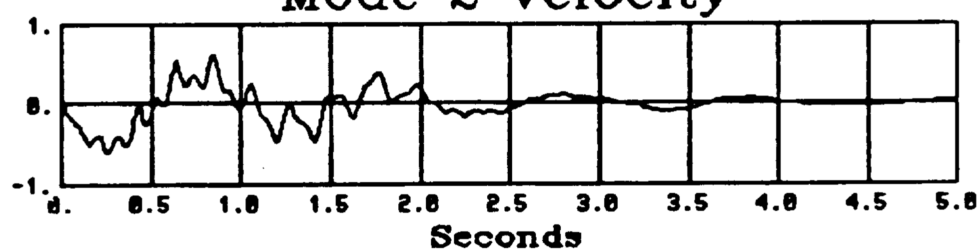
Mode 5 Position



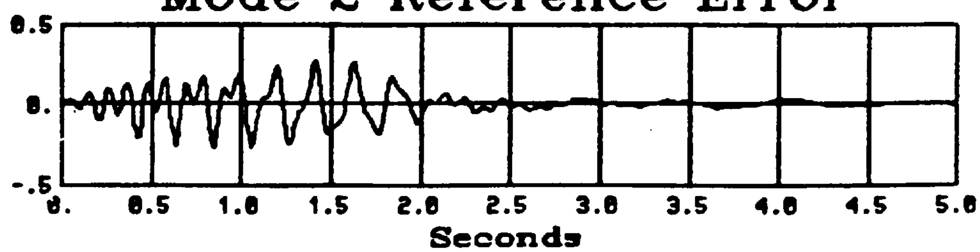
Mode 5 Reference Error



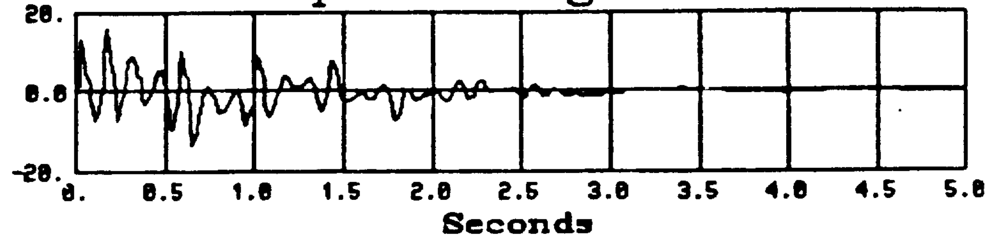
Mode 2 Velocity



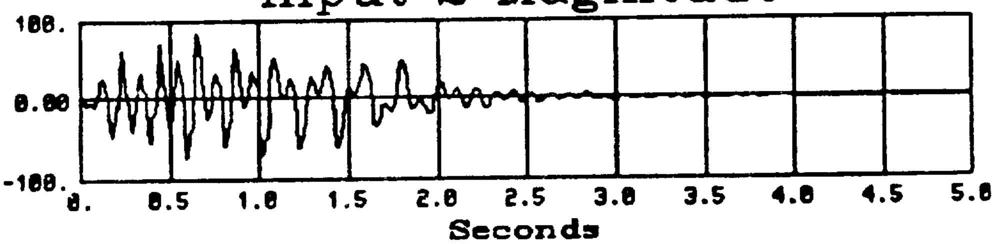
Mode 2 Reference Error



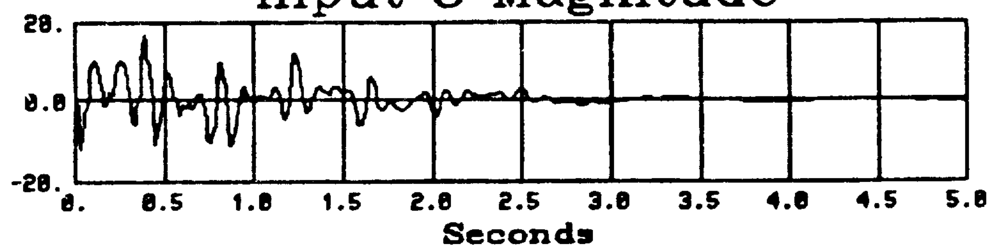
Input 1 Magnitude



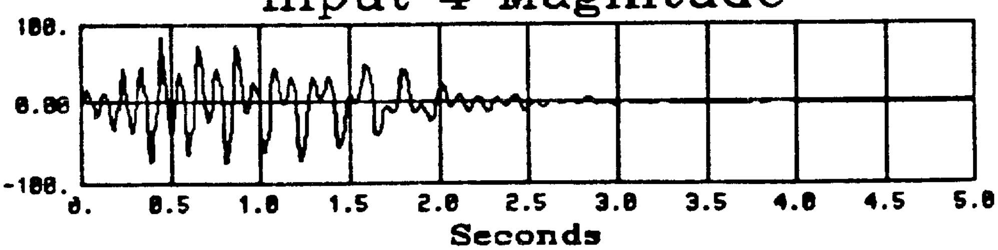
Input 2 Magnitude



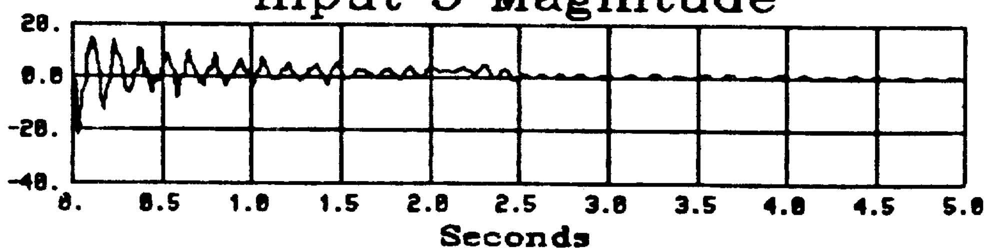
Input 3 Magnitude

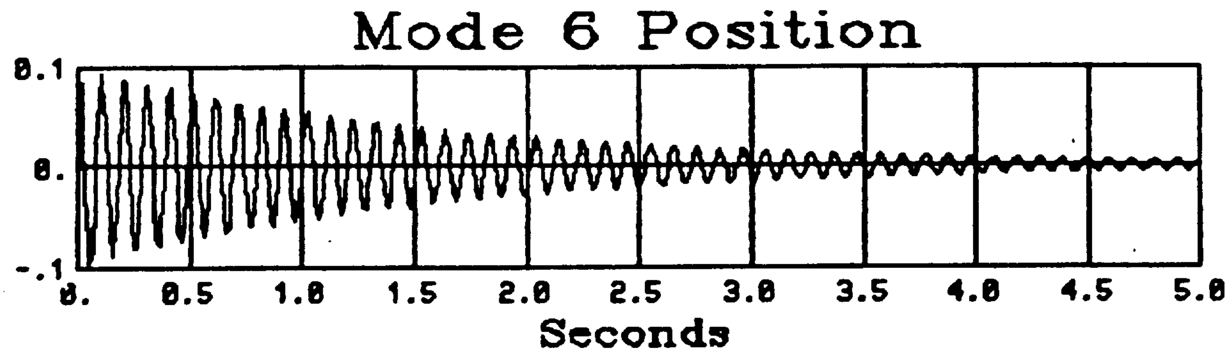


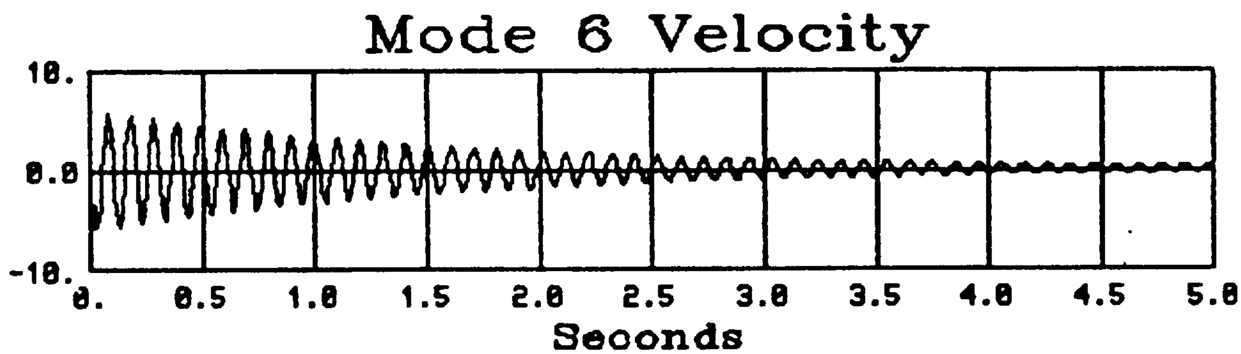
Input 4 Magnitude

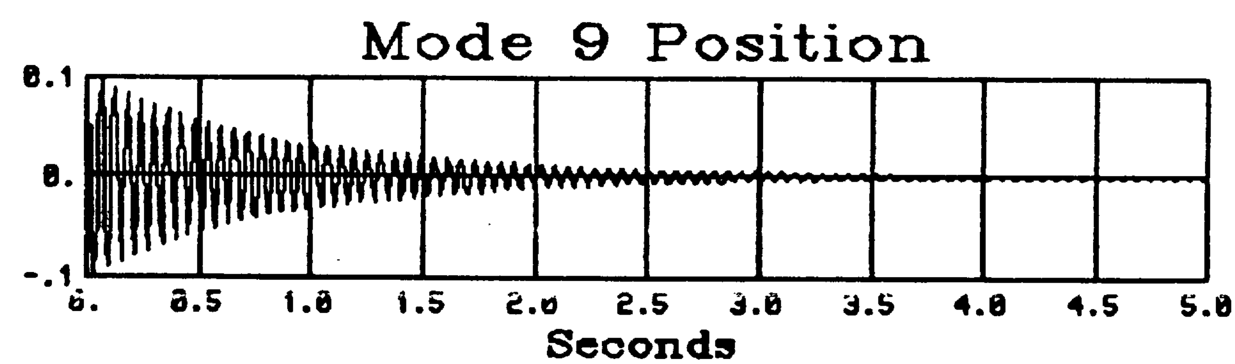


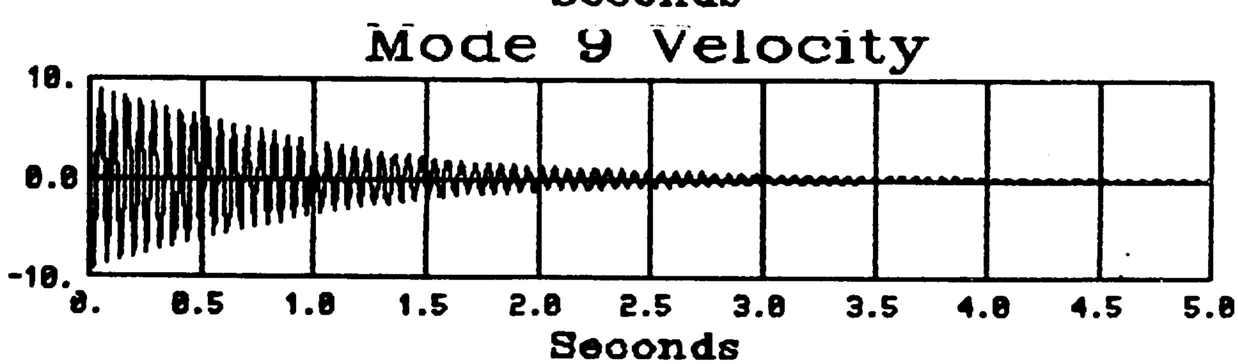
Input 5 Magnitude




Mode 6 Position
0.1
0.
-.1
0.
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Seconds


Mode 6 Velocity
10.
0.0
-10.
0.
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Seconds


Mode 9 Position
0.1
0.
-.1
0.
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Seconds


Mode 9 Velocity
10.
0.0
-10.
0.
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Seconds

Outlook

- Effects of Actuator Dynamics

- Refinement of STAC

- System Identification

- Experimentation