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LINEARIZED FLEXIBILITY MODELS IN MULTIBODY DYNAMICS AND CONTROL

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ABSTRACT

~~This presentation discusses~~ simulation of structural response of multi-flexible-body systems by linearized flexible motion combined with nonlinear rigid motion. Advantages and applicability of such an approach for accurate simulation with greatly reduced computational costs and turnaround times are described, restricting attention to the control design environment. Requirements for updating the linearized flexibility model to track large angular motions are discussed. Validation of such an approach by comparison with other existing codes is included. Application to a flexible robot manipulator system is described.

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Linearized Flexibility Models in Multibody Dynamics and Control

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- Some controls requirements of multibody codes
- Introduction to SADACS
- Validation
- Applications
    - Spacecraft
    - Robot manipulators

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Some Controls Requirements

1) General purpose dynamic module

2) Models can be merged in any configuration without creating new structural models

3) Very fast (computationally inexpensive)
   - Short simulation turnover time
     - Time domain analysis with nonlinear controllers
       - Sensitivity studies
       - Stability analysis
   - Control design iteration

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SADACS
Spacecraft Appendage Dynamics and Control Simulation

- Dynamics simulation of multi-flexible-body systems
- Designed for controls engineers/controls environment
- Approximate code to address controls requirements
    - Linearized flexible modal analysis with "configuration update"

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SADACS is designed for controls environment

- Used as general purpose dynamics module in a control simulation environment
- Allows multibody systems to be merged in any desired configuration without creating new structural models
- Very fast (computationally inexpensive) for system design and sensitivity/stability analysis

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- **How fast is SADACS?**
  - **Problem dependent**
  - **Large complex models   100-500 times faster than DISCOS**

- **Why is it fast?**
  - **System modes**
    - **Diagonalized, linear, constant coefficient flexible equations of motion**
    - **Truncation (with residualization) to increase Δt**
    - **Use 'explicit' integration**

- **Propagate linear system until 'update'**

CPU Time Comparisons for 3–Body Problem

CODE	RUN TIMES	REMARKS
DISCOS	> 26 hours	No component modal truncation
DISCOS	5 hours 9 minutes	With component modal truncation
SADACS	10 minutes	With system modal truncation

Other Test Problems :

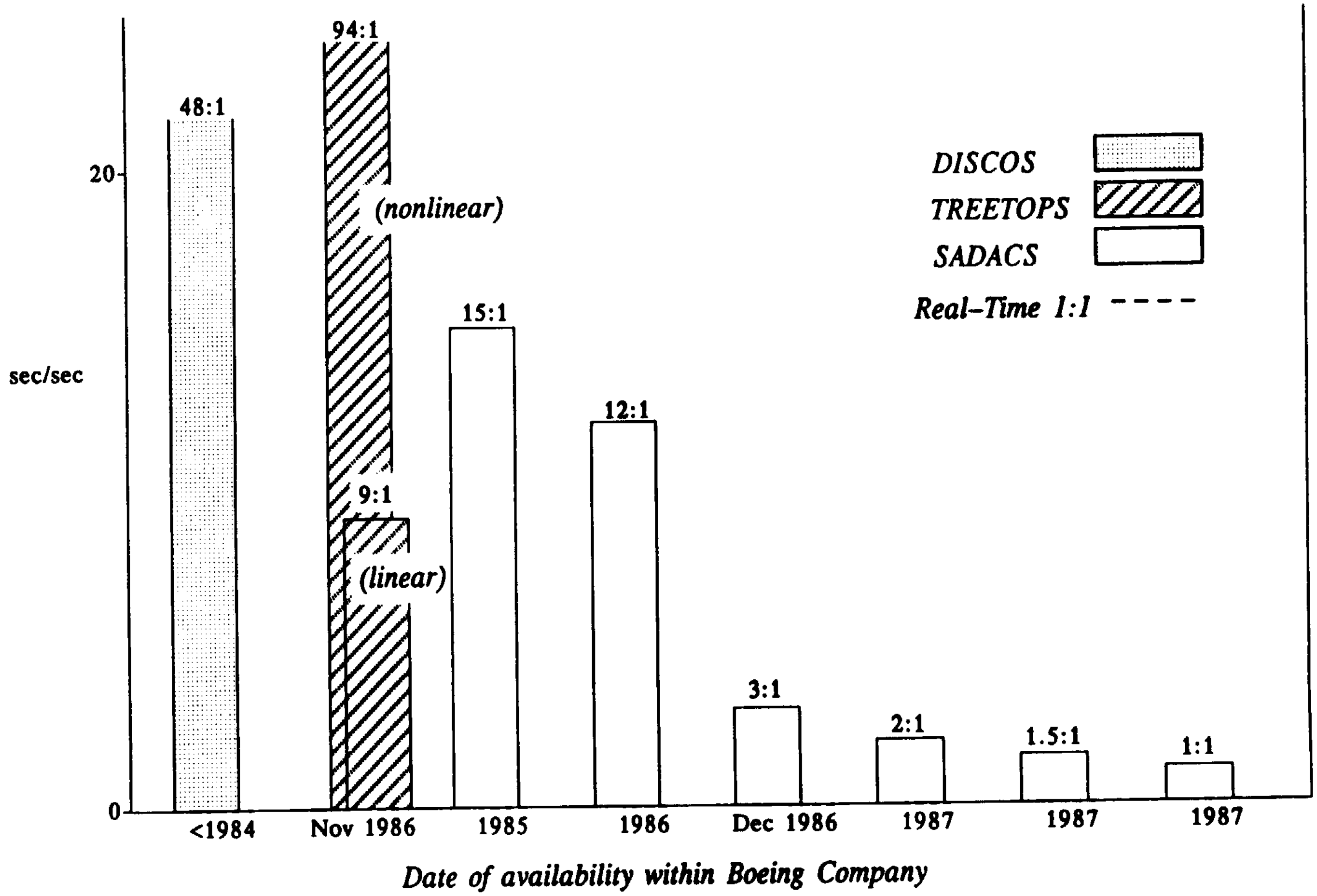
High Speed Simulation of Flexible Mulitbody Dynamics

Presented at MSFC, April 22–24, 1986

CODE	RUN TIMES	REMARKS
DISCOS	$\simeq$ 50 Hours	With component modal truncation
SADACS	$\simeq$ 15 minutes	With system modal truncation

Multi–Flexible–Body Run–Times

3–Body simulation CPU (seconds) / Real–Time (seconds)



SADACS Structure

1) Nonlinear rigid body code
(SD/EXACT, TREETOPS, MBDYN, etc.)

2) Linear flexible dynamics

   - System mode formulation
   - Retain truncated modes quasi-statically

3) System mode update/restart

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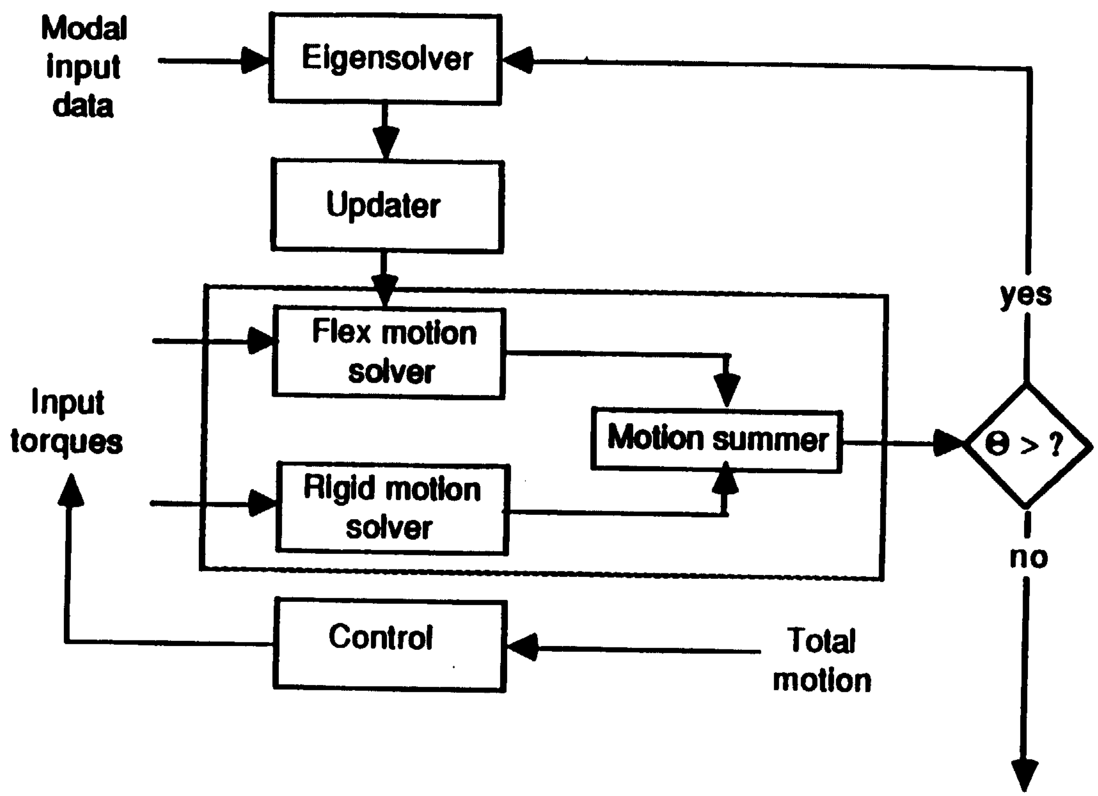
Simplified Diagram of the SADACS Code

Inputs to the system (generalized forces and torques) are applied to both the rigid and flex motion solvers. The rigid motion solver computes the nonlinear rigid body response. The flex motion solver uses a "system mode" formulation to compute the linearized flexible response. The outputs are combined in the motion summer and tested for an "update condition". If an update is not required the outputs are passed out to the simulation. If an update is required, a new eigensolution is performed on the new configuration and the mode shapes, frequencies, and system mode state vector are adjusted.



Simplified Diagram of SADACS Code

The Difficult Technical Problem:

Large angle motions with linear flexibility

- System modes change (shape, frequency) with angular position
- Track changes by 'updating' system modes
  - Update at predetermined angles or time
    - Shape
    - Frequencies
    - Transfer functions
  - Restart dynamic analysis

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Updating Time-Line Overview

A fixed modal set is maintained during a given epoch (time between updates). At the end of the current epoch the pre-update states are known. Following the eigensolution on the new system matrices, the new modes shapes and frequencies are known. The difficult part of the update is then to assign new values to the post-update states.

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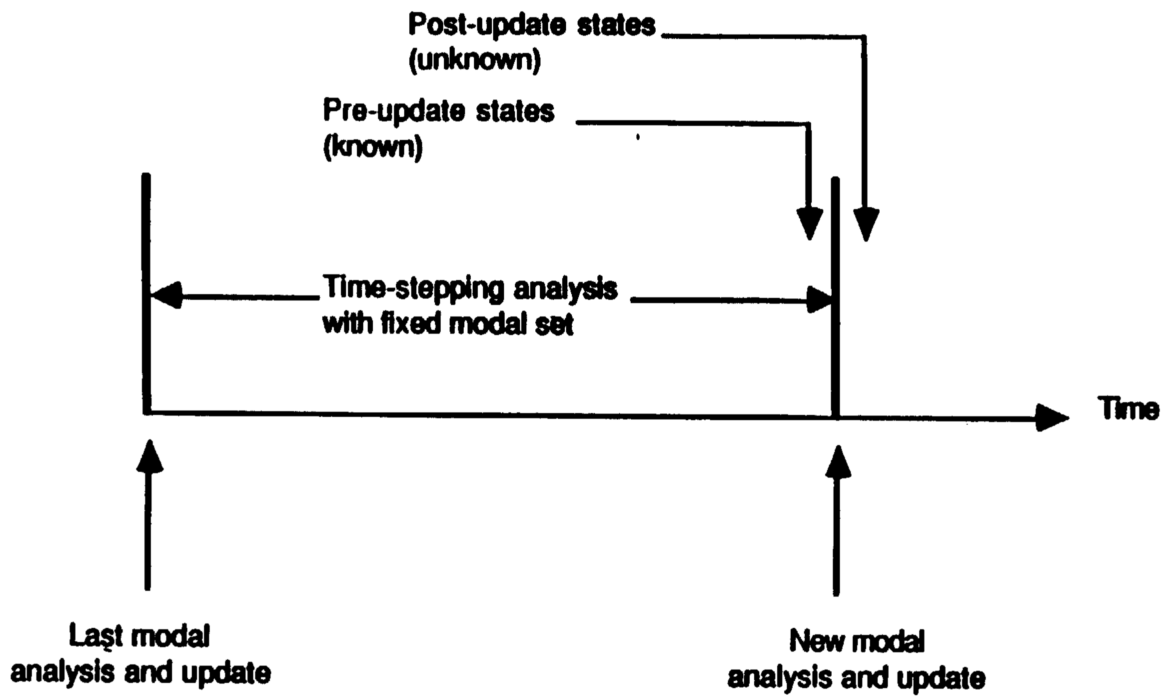

Updating Time-Line Overview

Why is updating a problem?

When gimbal rotations and rates (which include structural deformations) developed in one configuration are imposed on a new configuration, they excite the structure in shapes (modes) that would not have occurred in a 'continuous' solution, and in addition fail to preserve energy.

The problem is nonlinearity-induced trading of excitation, or coupling, between the modes.

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Example problem: chosen to emphasize 'trade' in modal participation

- **Want update that**
  1) **Doesn't ring**
  2) **Maintains energy**
  3) **Tracks frequencies**
  4) **Correct shapes**

- **Coupling of flex into rigid neglected**
  - **SADACS not intended for problems where flex nonlinearities drive rigid motion**

- **Address update entirely with component modal variables**

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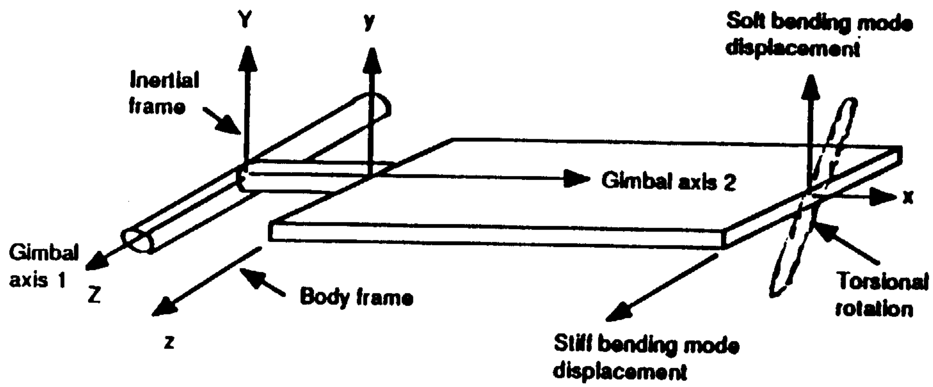
Example Problem

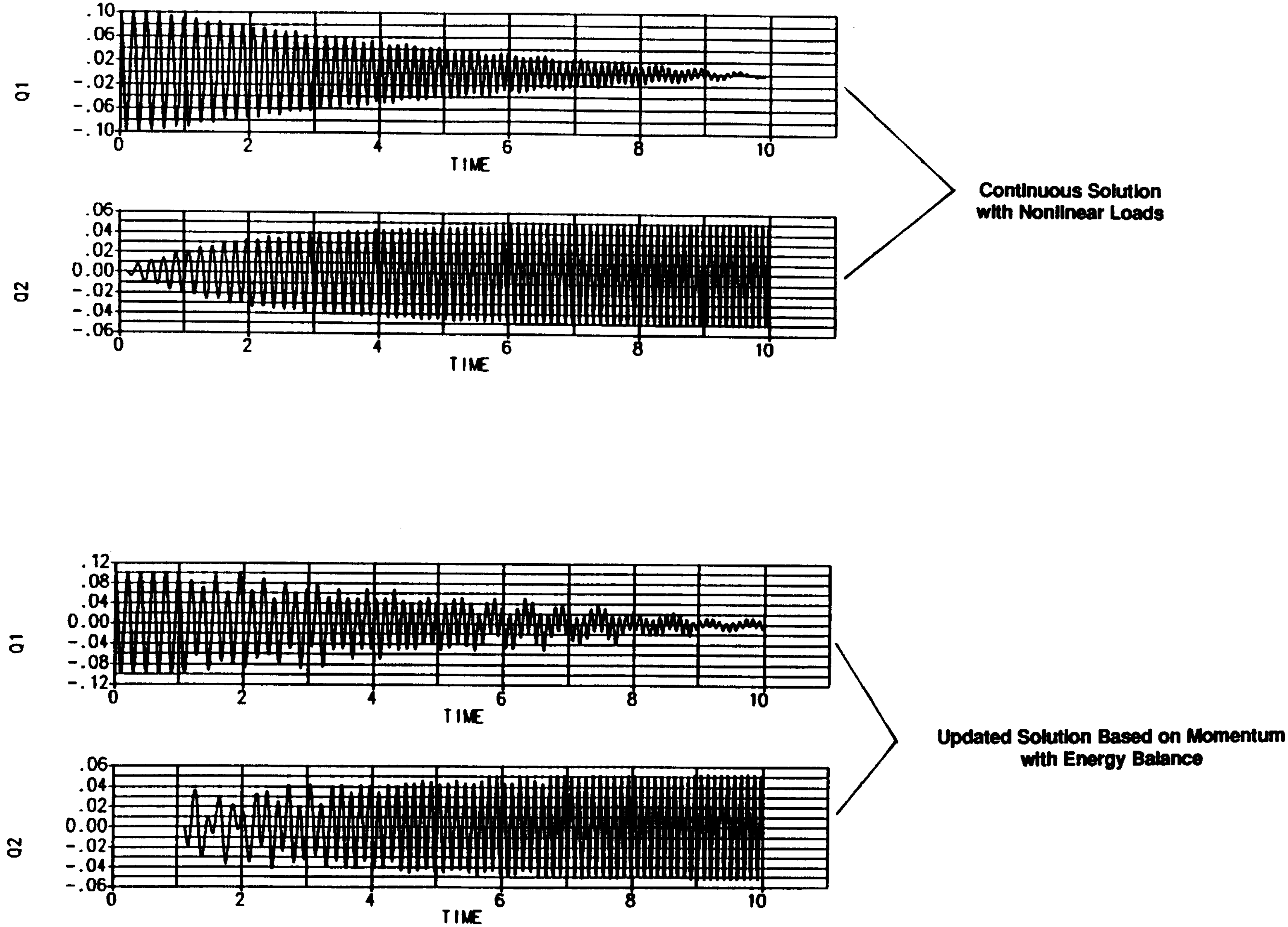
This figure shows the system used to examine the update. The system has two flexible modes with coordinates q_1 (soft mode) and q_2 (stiff mode).



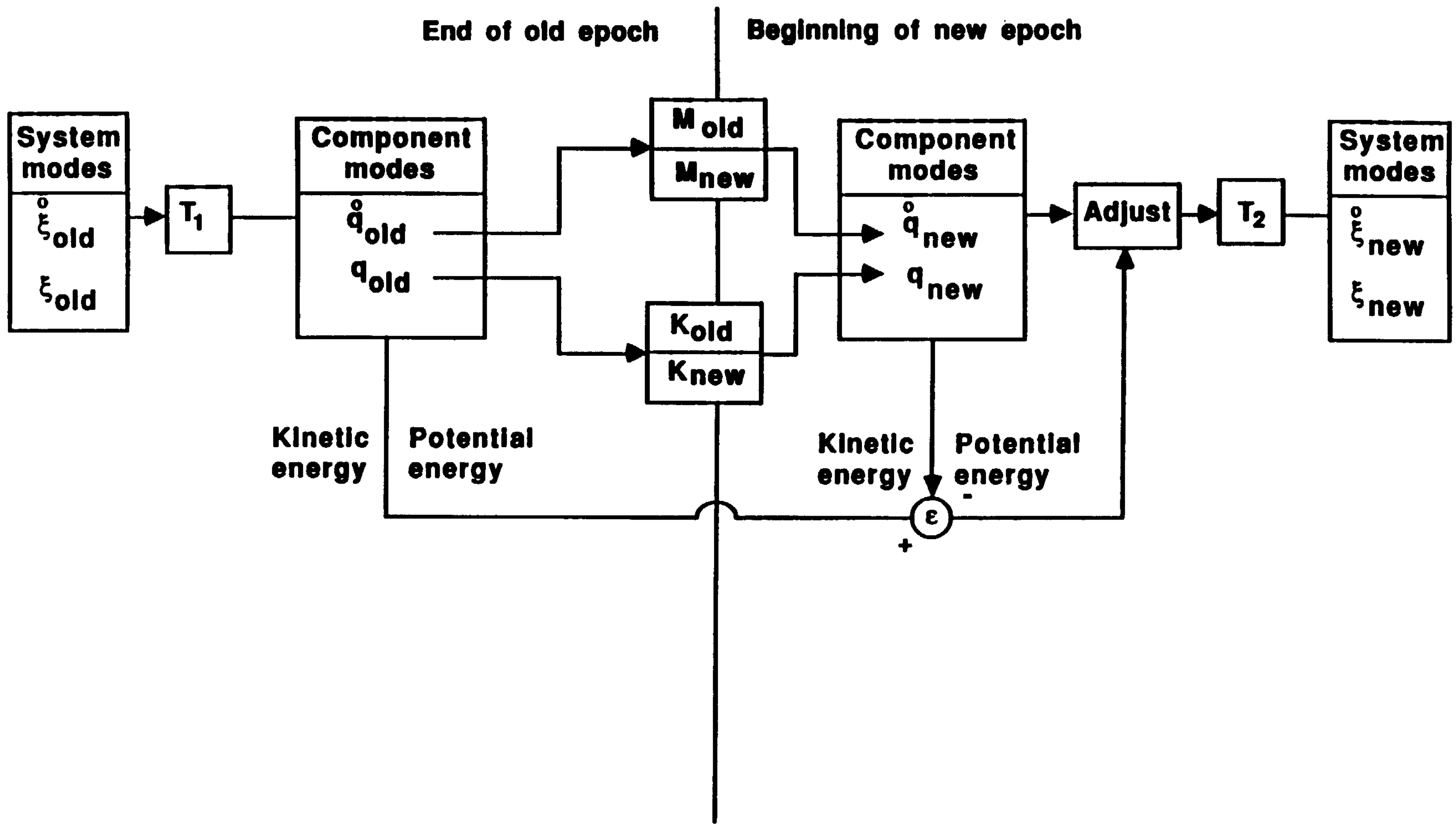
- Rigid coordinates Θ_1, Θ_2
- Flex coordinates q_1, q_2
- Soft mode = 1.59 Hz
- Stiff mode = 3.18 Hz
- $\dot{\Theta}_2$ = 9 deg/sec (constrained)
- Initial conditions:
  Θ_1 = -.03 rad
  q_1 = .1

SADACS vs. Continuous Solution

The top set of plots show the flexible coordinate response when the equations of motion include flex/rigid coupling and are integrated in a continuous manner. The bottom set of plots show the flexible coordinate response using the SADACS approach.


Q1
.10
.06
.02
-.02
-.06
-.10
0
2
4
6
8
10
TIME
Q2
.06
.04
.02
0.00
-.02
-.04
-.06
Continuous Solution
with Nonlinear Loads
.12
.08
.04
-.04
-.08
-.12
Updated Solution Based on Momentum
with Energy Balance

Momentum/Stress Update with Energy Balance



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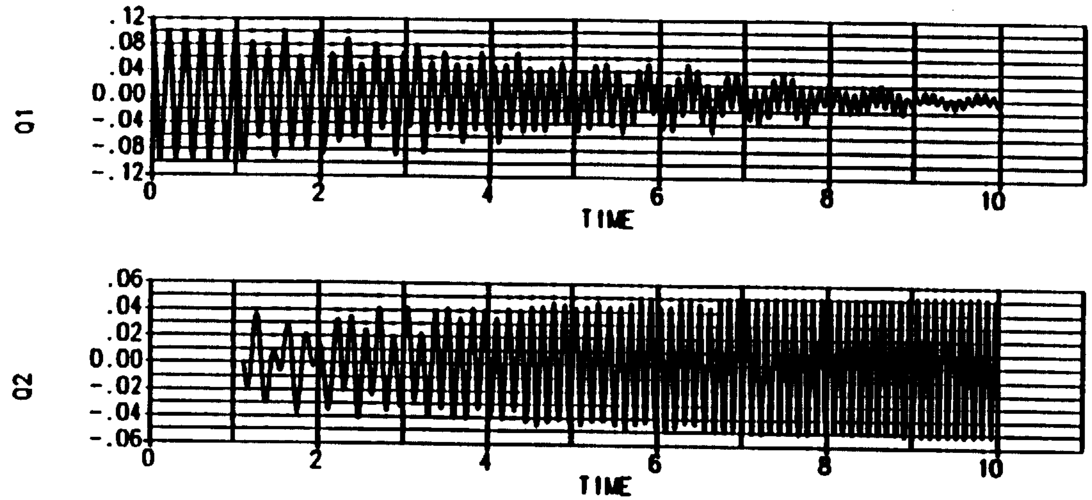
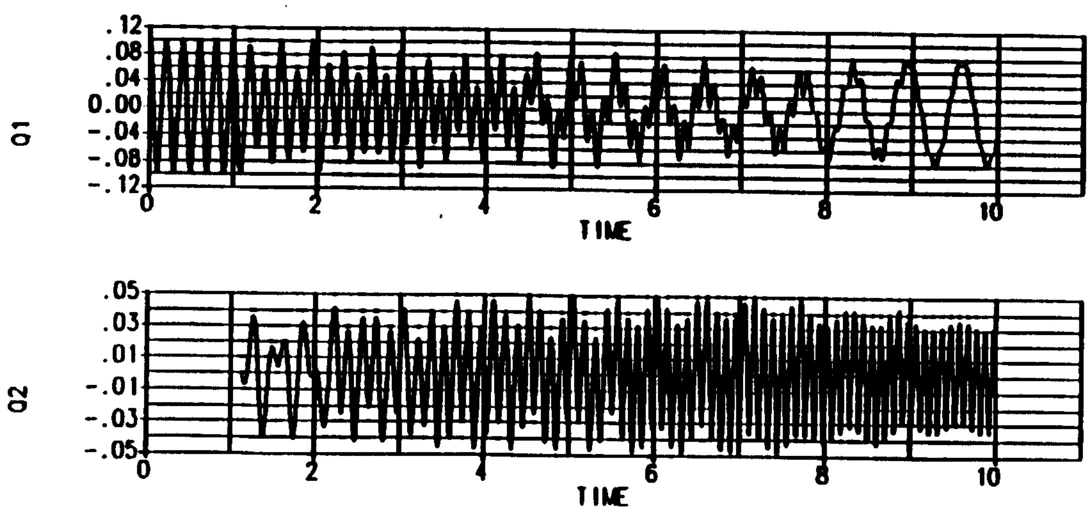
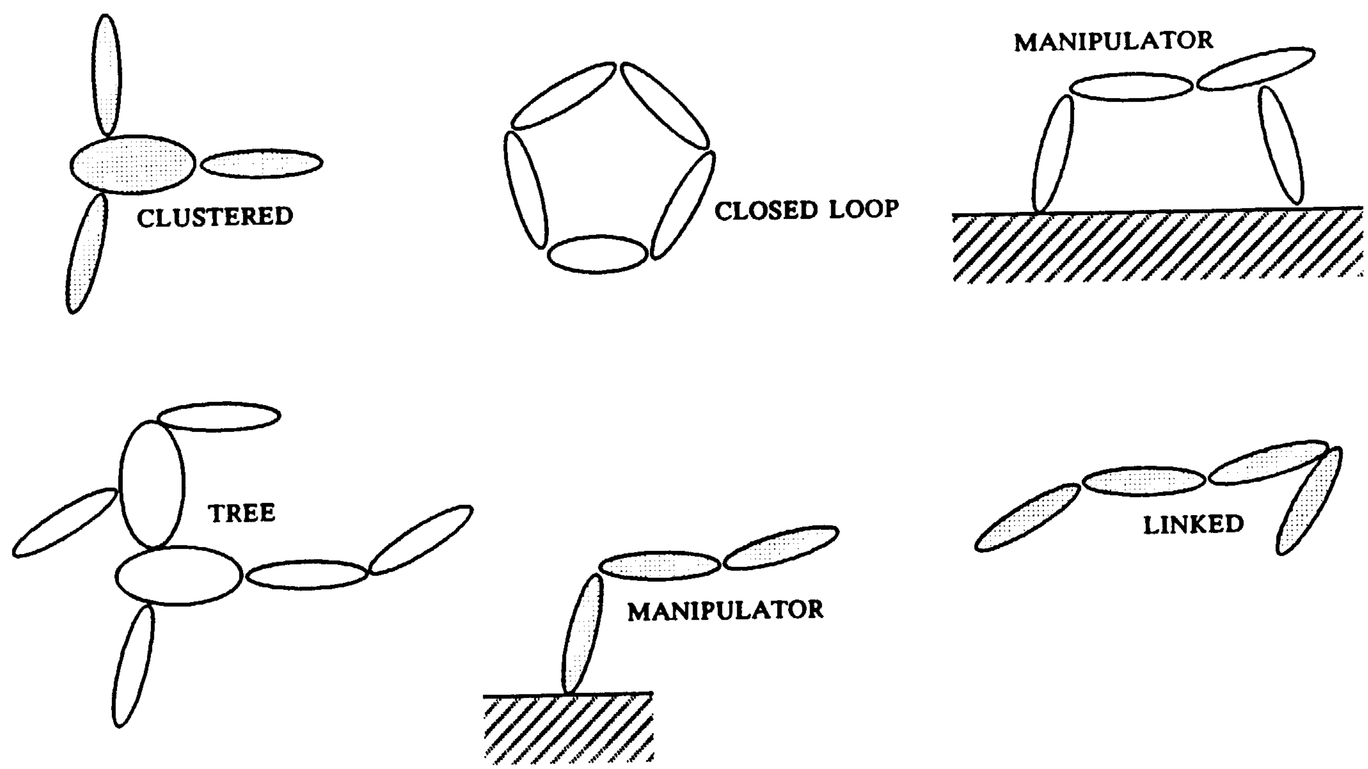


Updated Solution Based on Momentum with Energy Balance



Updated Solution Based on Phase Variables with Energy Balance

FB2 Topology Capabilities

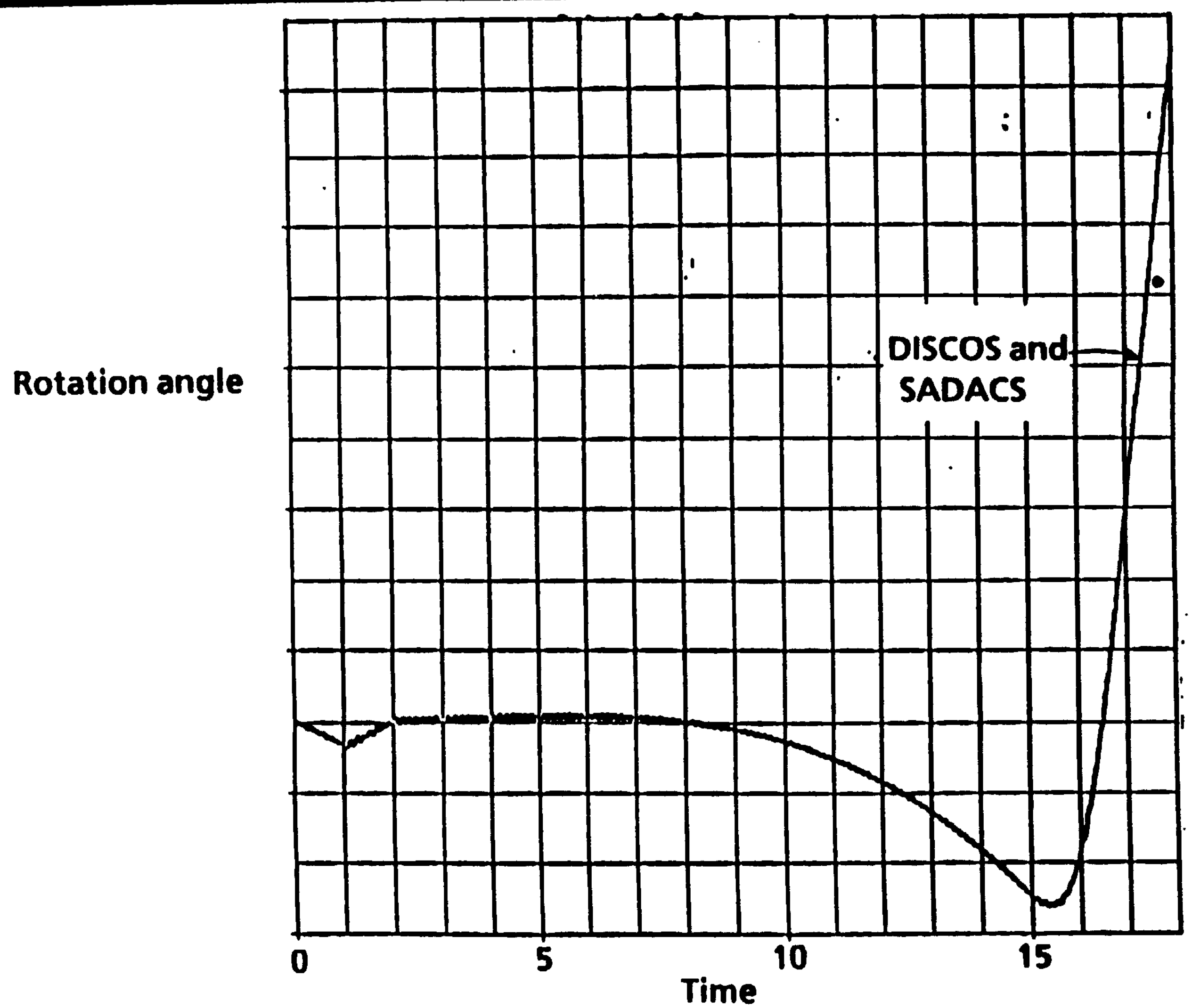


SADACS program capabilities
Summary

- Rigid body analyser
  - based upon the code used (MBDYN, TREETOPS, SD/EXACT etc)
- Flex body analyser (FB2)
  - Number of bodies — no limit
  - Number of flexural modes/body — no limit
  - Number of gimbals — no limit
  - Configurations :
    - cluster
    - linked
    - tree
    - closed loop
    - manipulator
    - multiple closed loop
    - multiply grounded manipulator
  - Degrees of freedom at gimbals — $0 \rightarrow 6$ (totally locked to totally free)

DISCOS-SADACS Comparison:

Main Body Sensor X Rotation Due To Appendage Command



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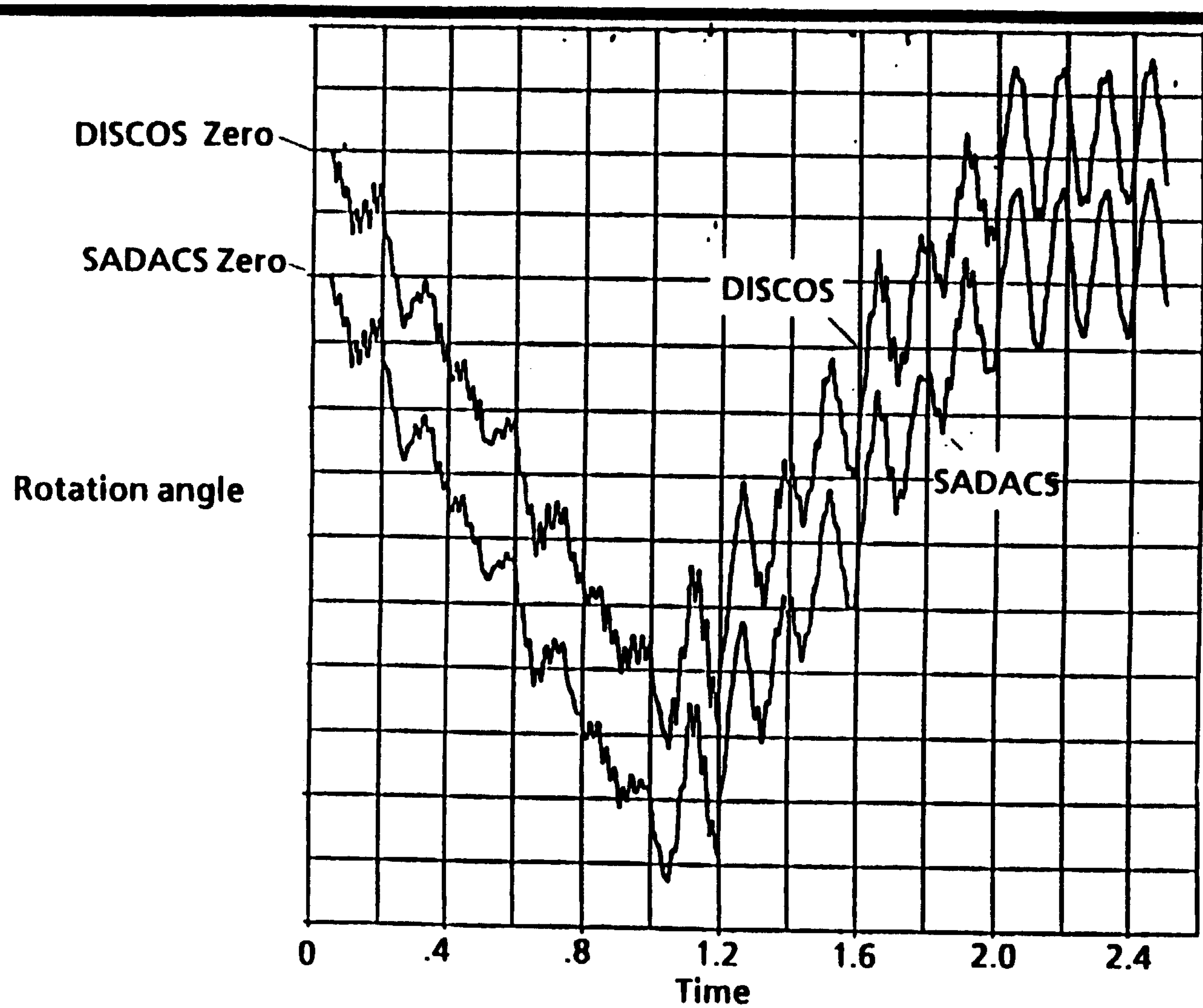
DISCOS-SADACS Comparison:

Main Body Sensor X Rotation Due To Appendage Command



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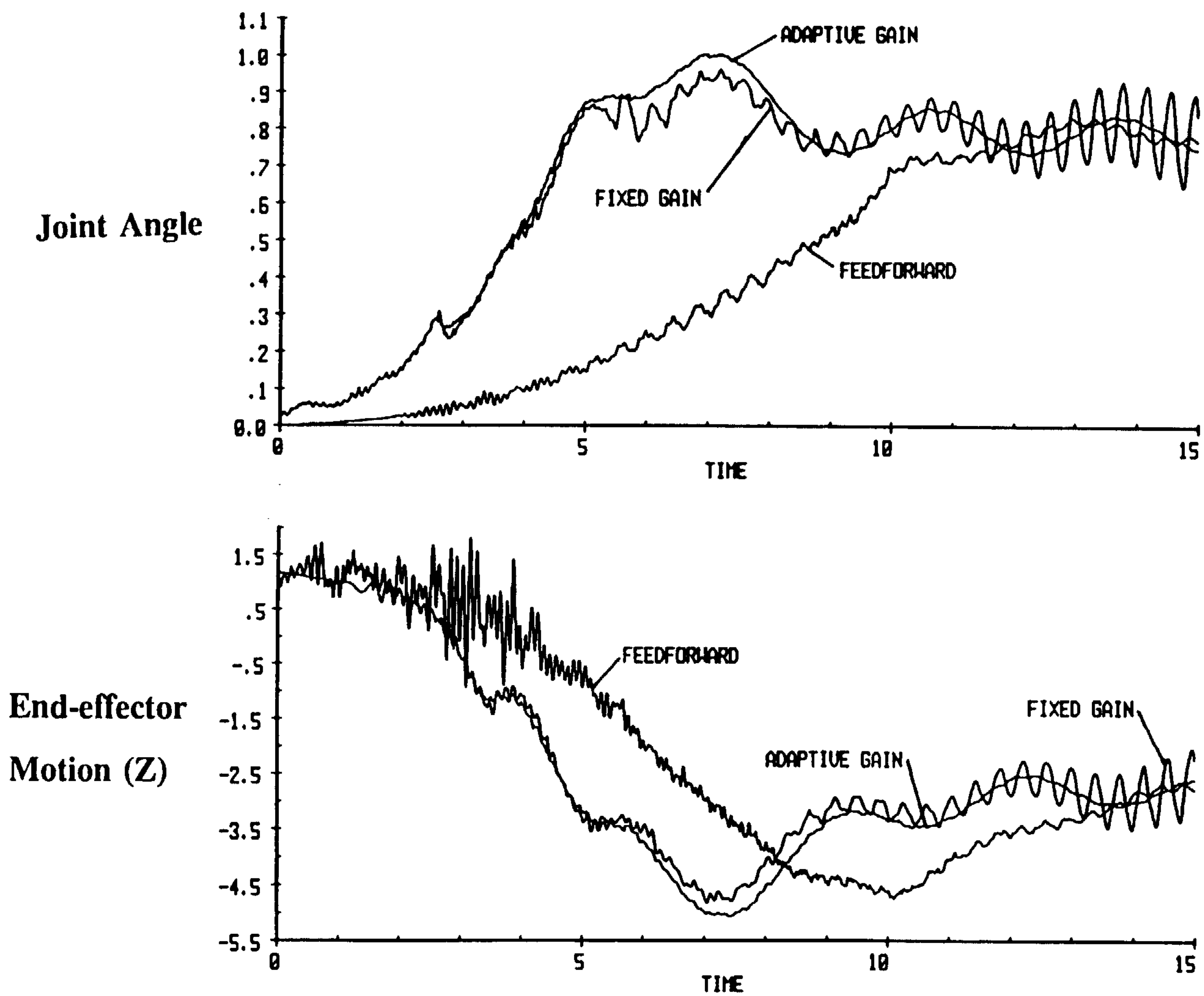
Controller Comparison - Closed Loop

The figure below shows the closed-loop response of a flexible model of the SPAR robot manipulator with three different controllers. The top plot is the first joint angle (waist) and the bottom plot is the z motion of the end-effector (up and down). The three different controllers are feedforward, semi-adaptive gain, and fixed gain.



CONTROLLER COMPARISON - CLOSED LOOP

Applicability

- Large body of common problems
  - Non-spinners
  - Problems not dominated by nonlinear flexible response
- Each new problem should be validated against 'full code' (TREETOPS/DISCOS)

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Conclusions

- SADACS fast, efficient multi-flexible-body simulation code
- Designed for use in controls environment
- New 'update' procedure improves accuracy, efficiency, works better
- Numerical example compared well with 'truth code' solution (DISCOS)

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