FLEXIBLE ROBOT CONTROL: MODELING AND EXPERIMENTS

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ABSTRACT

A dynamic model fills several roles in the development of flexible manipulators and their control structures. A proper dynamic model permits identification of the proper state variables for control, completes the mathematical model used in design studies and in simulation, and provides the forward transform needed in model-based control. While there exist many proven analytical approaches, and although numerous models have been constructed and tested, there remains a need for *simple* models which capture all the important behavior while otherwise suppressing modeling complexities and computational demands. Such simple models are necessary for online applications because of their computational compactness, and are advantageous for design and simulation studies because of their accessibility by users. For manipulator control applications, an *ideal* (simple) model might contain independent variables no greater in number than the state variables required for acceptable control. This paper describes such a model and its use in experimental studies of flexible manipulators.

The analytical model developed in this research uses the equivalent of Rayleigh's method to approximate the displaced shape of a flexible link as the static elastic displacement which would occur under end rotations as applied at the joints. The generalized coordinates are thereby expressly compatible with joint motions and rotations in serial link manipulators, because the amplitude variables are simply the end rotations between the flexible link and the chord connecting the end points. The equations for the system dynamics are quite simple and can readily be formulated for the multi-link, three-dimensional case. When the flexible links possess mass and (polar moment of) inertia which are small compared to the concentrated mass and inertia at the joints, the analytical model is exact and displays the additional advantage of reduction in system dimension for the governing equations.

Four series of pilot tests have been completed. Studies on a planar single-link system were conducted at Carnegie-Mellon University, and tests conducted at Toshiba Corporation on a planar two-link system were then incorporated into the study. A single link system under three-dimensional motion, displaying biaxial flexure, was then tested at Carnegie-Mellon. The most recent tests, also conducted at Carnegie-Mellon, studied a three-dimensional system in which coupled (biaxial) flexural-torsional vibrations were present. In every test series effective control of the flexible system was accomplished; performance of the proposed model was studied and confirmed.

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FLEXIBLE ROBOT CONTROL:
MODELLING AND EXPERIMENTS

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Describing a simple dynamic model:
- Useful for rapid prototyping and control system development

- Useful during manipulator design

- Applicable for real-time computation

Describing experimental results:
- Single-link 2-D

- Single-link 3-D

- Two-link 2-D

- Two-link 3-D

Modelling Link Flexibility Effects

Problems:

- Manipulators are non-linear by their configuration

- All models for flexible dynamics must approximate the solutions to PDE's

- Generalized co-ordinates (mode shapes) are often utilized

- Truncated mode shape models: OK, but not fully consistent with manipulator control

Demands:

- Generalizable to M-DOF manipulators

- Simple to formulate and use in simulation

- Computable in real-time

Intended Users

Laboratory research in flexible manipulator control

These restrictions are common:
- Single-link distributed mass systems
- Direct drive motors
- Planar systems
- Modelling based on truncated mode shapes

Our experimental target:
- General multi-link, 3-D system
- Mechanical actuation, with friction, backlash, etc.
- Possibly joint-dominated in mass

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Experimental Apparatus at Carnegie-Mellon

Reconfigurable manipulator; modular design, up to 6DOF
- **Mechanical**
    - Each joint: DC-motor/harmonic drive/ potentiometer
    - Reconfiguration and link changeout using tubing and NPT hardware
- **Computational:**
    - Motorola VMEbus System 1000: 68010, VersaDOS, Pascal
    - Smalltalk-80 (One concurrent implementation under VersaDOS, a second Unix implementation on Sun-3)
- **Sensing:**
    - Position (rotation) sensing on joints
    - Strain sensing on links
    - Vision end-point sensing (not used for control)
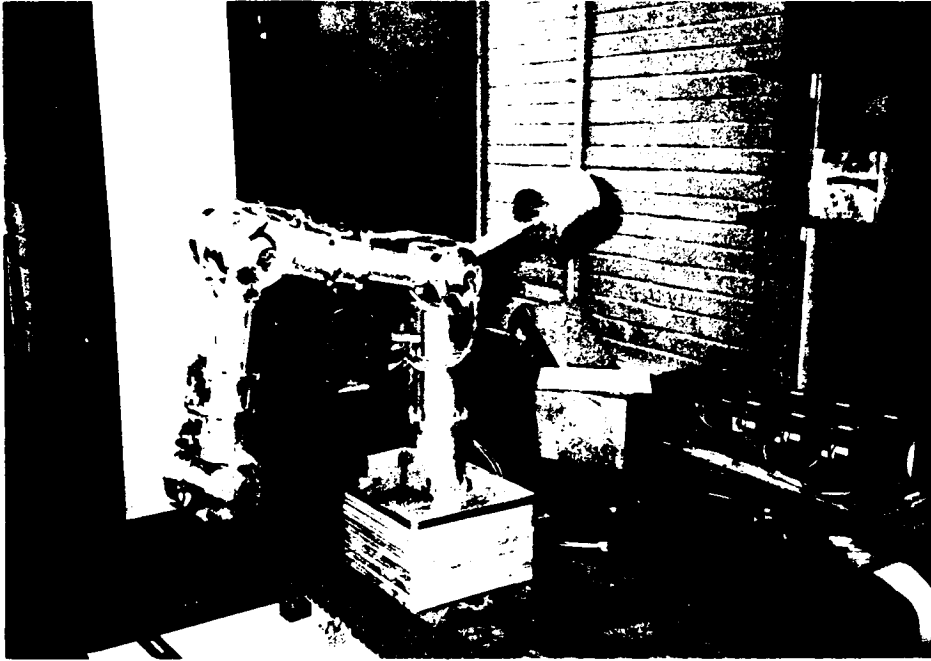
MANIPULATOR IN A 6-DOF TWO LINK CONFIGURATION (BOTH LINKS RIGID)

MANIPULATOR IN A 3-DOF TWO LINK CONFIGURATION (ONE RIGID, ONE FLEXIBLE)

554
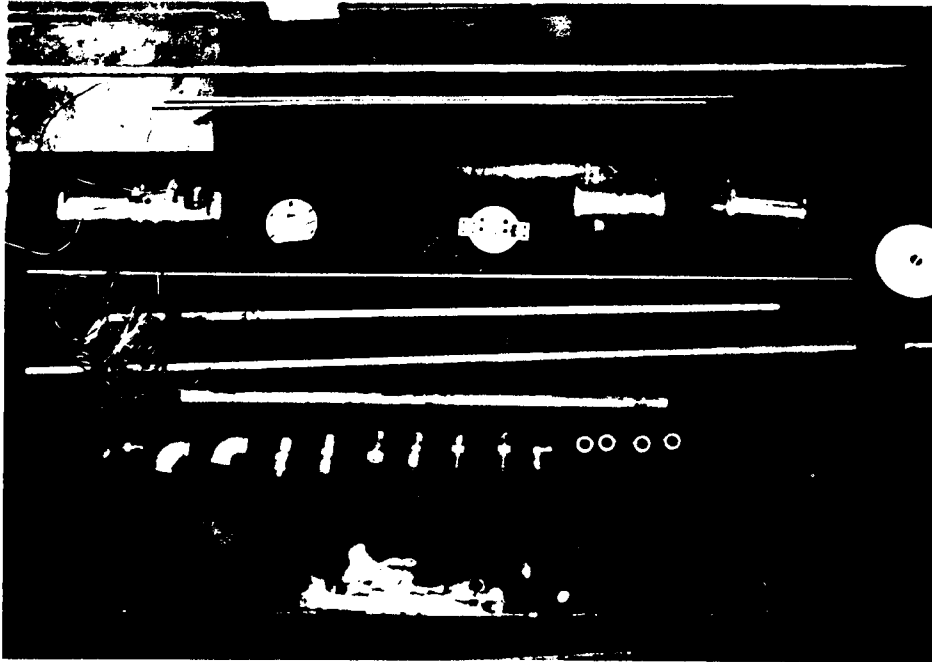
HARDWARE FOR TUBING (SWAGELOK), NPT, AND LINK CHANGEOUT
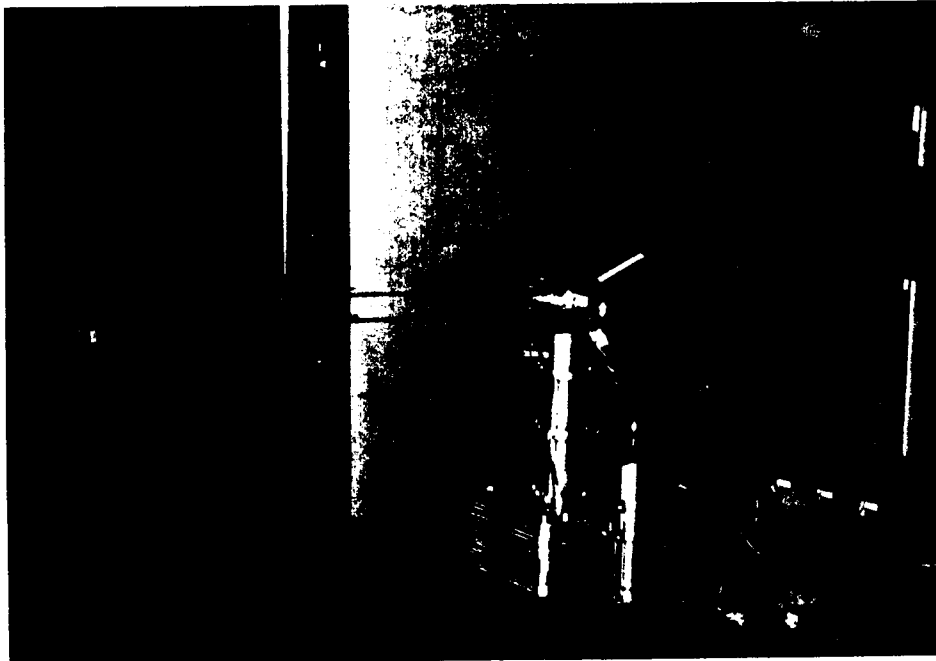
MANIPULATOR IN A SINGLE LINK 3-D CONFIGURATION

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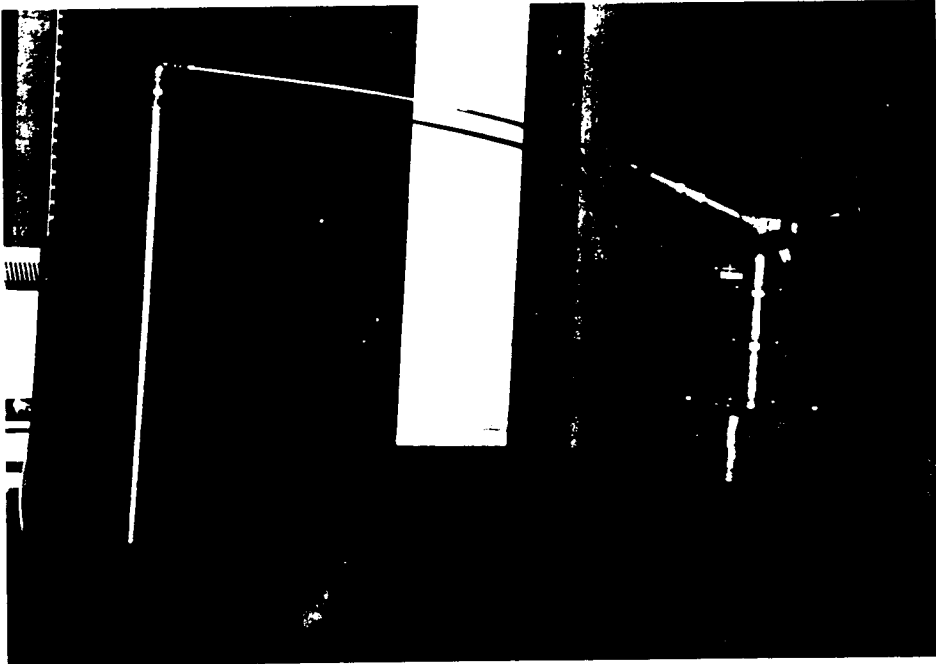
MANIPULATOR IN A 3-DOF TWO LINK CONFIGURATION

MANIPULATOR IN A 4-DOF TWO LINK CONFIGURATION FOR FORCE COGNITIVE EXCAVATION

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A Simple Model for a General Flexible Link

Starting points to consider:

- Link motion results from concatenation to other links; the non-linear configuration problem, present in rigid manipulators as well.

- The link itself deforms as a result of the end-forces and the inertial forces acting on it.

- Which quantities can be observed or sensed?

- Which quantities can be controlled?

- How is the (approximate) solution to the PDE for link deformation to be contained within the dynamics equation? (What are the amplitude variables for the generalized co-ordinates chosen?)

First step in the approach: View first the motion of the *chord* connecting the end points, and then refer the (elastic) deformations to that chord.

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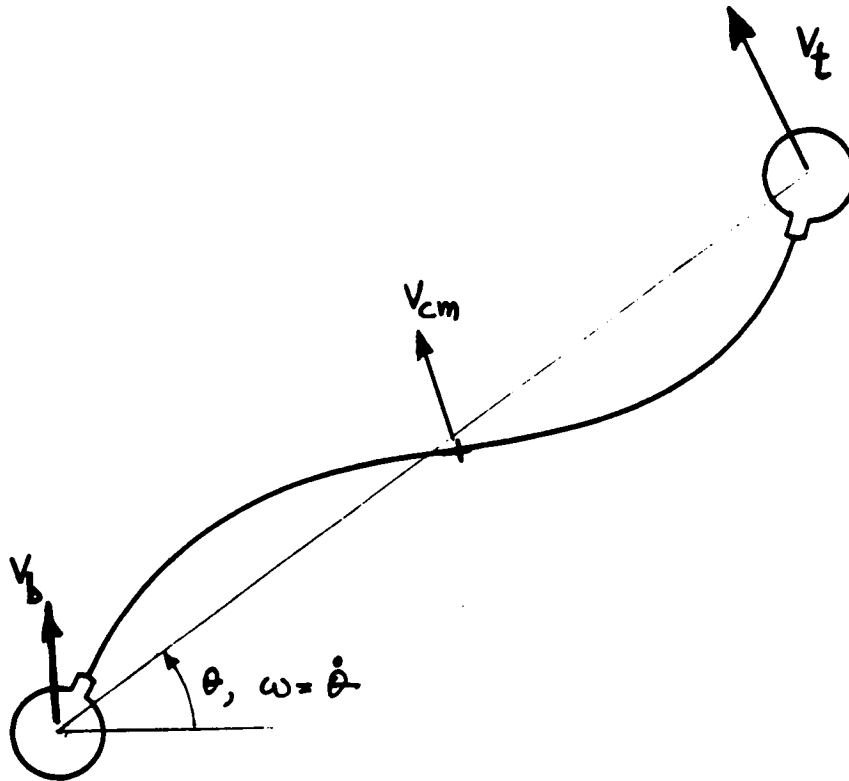
A FLEXIBLE LINK (SHOW IN 2-D) IN MOTION

NOTE "CHORD" ACTS AS A "RIGID BODY"
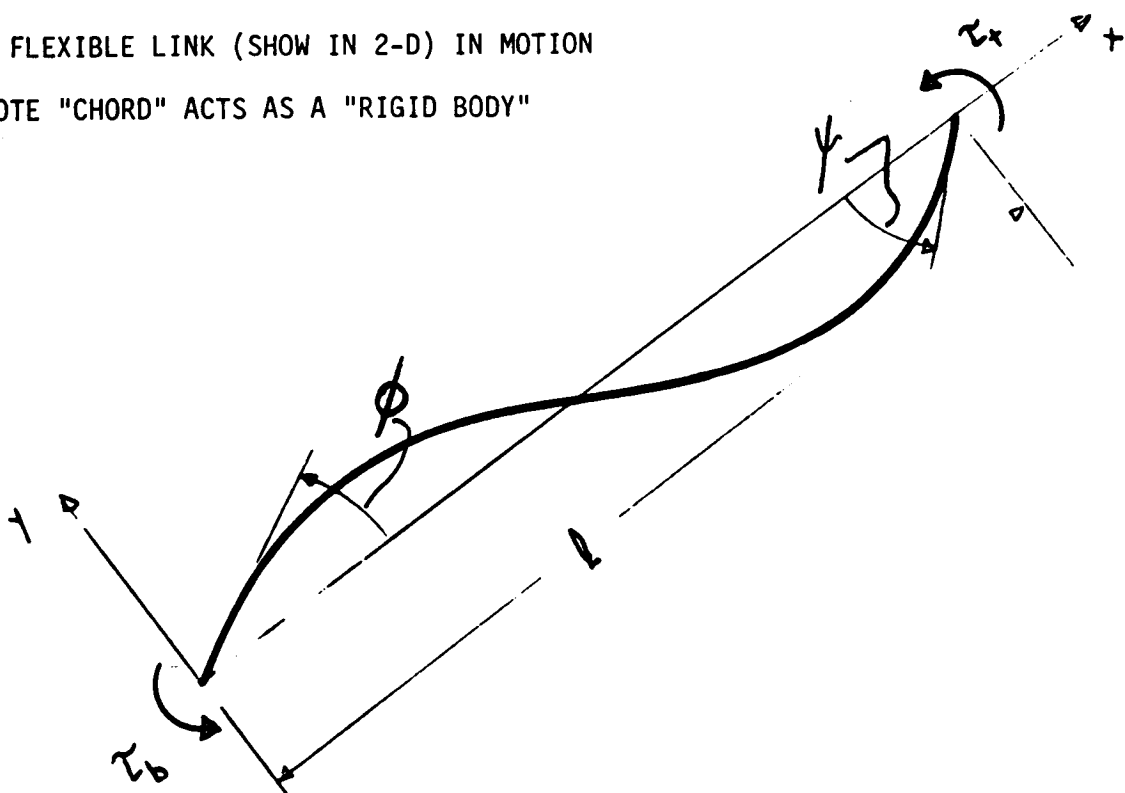
ELASTIC DEFORMATIONS REFERENCED TO THE CHORD

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Kinematics/Mechanics of the Simple Model

Chord motion:

- Denote rotation by θ, equivalent to a rigid-link formulation.

- Include dynamic effects of concentrated masses and inertias at joints.

- *Assume* that inertial effects of the link are modelled (from θ and ω) by the translation and rotation of the (c.m. of) the chord.

Deformations (displacements) of the flexible link:

- Displacements $y(x)$ are referenced to the chord.

- *Assume* that the displacements equal those resulting from static application of end-rotations ϕ and ψ.

- Displacement and potential energy:

$$y(x) = x(x-\ell)[(\phi+\psi)x - \phi\ell]/\ell^2$$

$$U = 2EI[\phi^2 + 2\phi\psi + \psi^2]/\ell$$
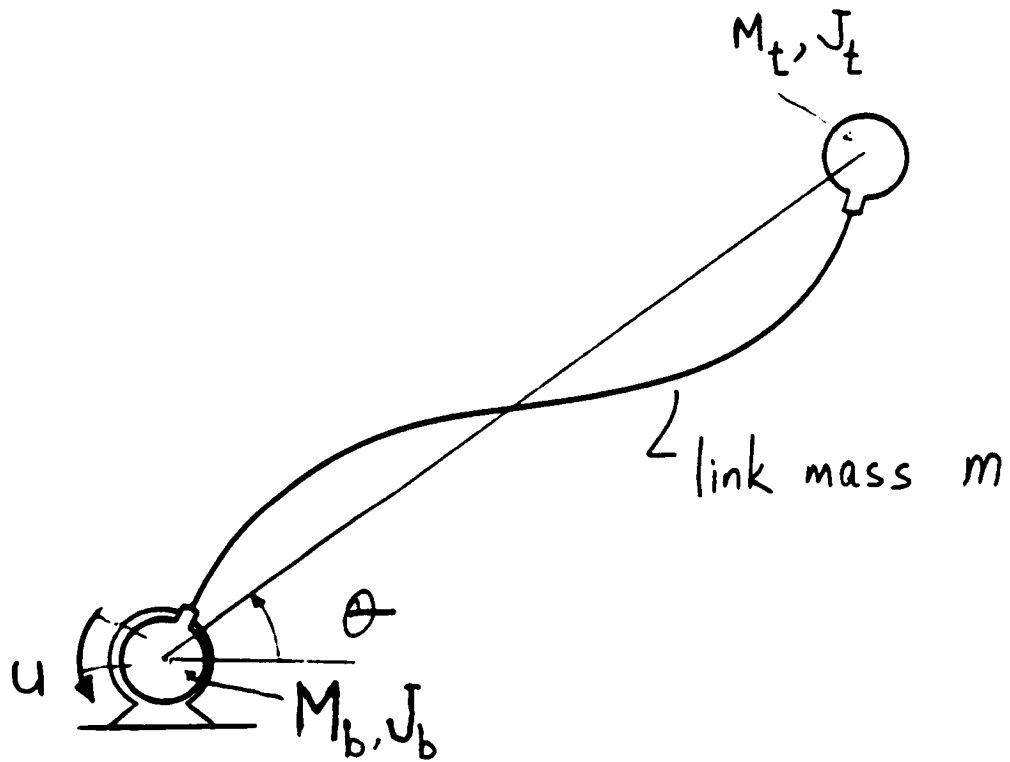
$$\begin{bmatrix} (J_b + J_t + \frac{1}{3}m\ell^2 + M_t\ell^2) & J_b & J_t \\ J_b & J_b & 0 \\ J_t & 0 & J_t \end{bmatrix} \begin{Bmatrix} \ddot{\theta} \\ \ddot{\phi} \\ \ddot{\gamma} \end{Bmatrix} + \frac{EI}{\ell} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 4 & 2 \\ 0 & 2 & 4 \end{bmatrix} \begin{Bmatrix} \theta \\ \phi \\ \gamma \end{Bmatrix} = \begin{Bmatrix} u \\ u \\ 0 \end{Bmatrix}$$

A SINGLE LINK SYSTEM; EQUATIONS OF MOTION FROM APPLICATION OF THE SIMPLE MODEL

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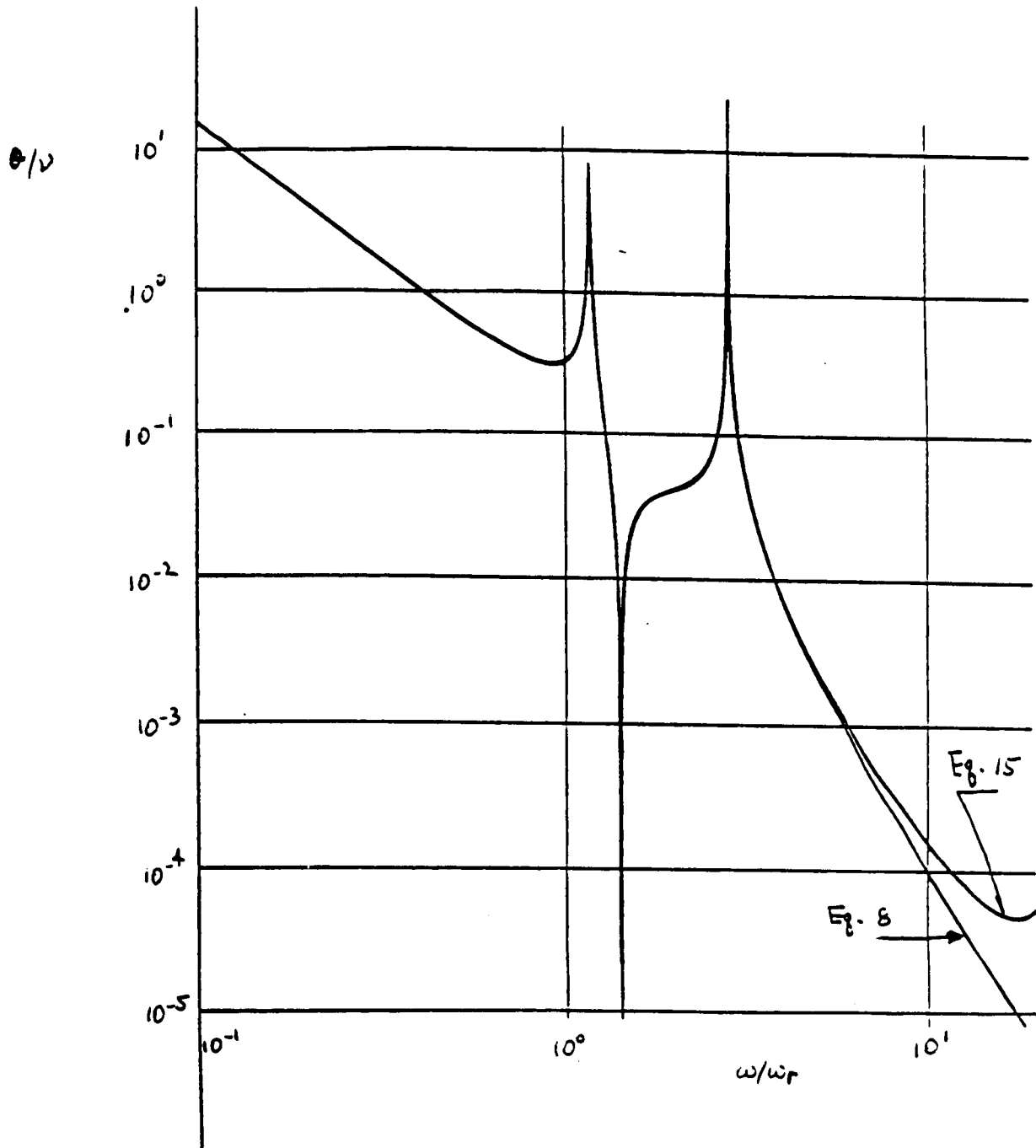
COMPARISON OF TRANSFER FUNCTIONS, SIMPLE MODEL VS. EXACT MODEL

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Properties of the Simple Model

The model is equivalent to Rayleigh's method, using an assumed shape with two *amplitude variables*, ϕ and ψ.

- Inertial effects of the joints are properly modelled, and are consistent with the mathematical formulation. (Functions in θ)

- The model is also a lumped mass assumption of *m* acting on the *chord*. (If this is the dominant link inertial effect, then the error is small.)

- The assumed shape has only 2 "dof," and can only approximate the real shape.

- Some higher order effects are plainly "missed," as they would be for a truncated mode solution.

- The formulation would be useful for control, because the variables θ, ϕ and ψ can be measured and actuated.

- For joint-dominant systems the model should be very accurate, and if joint inertias are small the equations reduce in order.

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Applications to Manipulator Control

Equations of motion can be used as follows:

- To confirm the number and the identity of *state variables* for control.

- To perform simulation studies.

- To set gains from classical control theory. (In principle)

- To compute variable gains for a non-linear system. (In principle)

- To accomplish model-based (shaped) control.

- To accomplish model-based feedforward control; requires real-time performance.

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Single Link Systems

1. Planar (2-D) motion
    - Actuator was a direct drive DC motor.

    - The simple model produces 3x3 equations of motion.

    - Tip has mass but low inertia; system order reduces to 2; state variables are identified as θ and ϕ.

    - Sensing of rotation $(\theta+\phi)$ and strain $(\sim\phi)$.

    - Perform experiments; set gains by trial and error.

    - Discussion of friction effects.

2. Spherical (3-D) motion
    - Actuation using two joints of the modular manipulator.

    - See videotaped results.

    - Controllable despite friction and backlash.
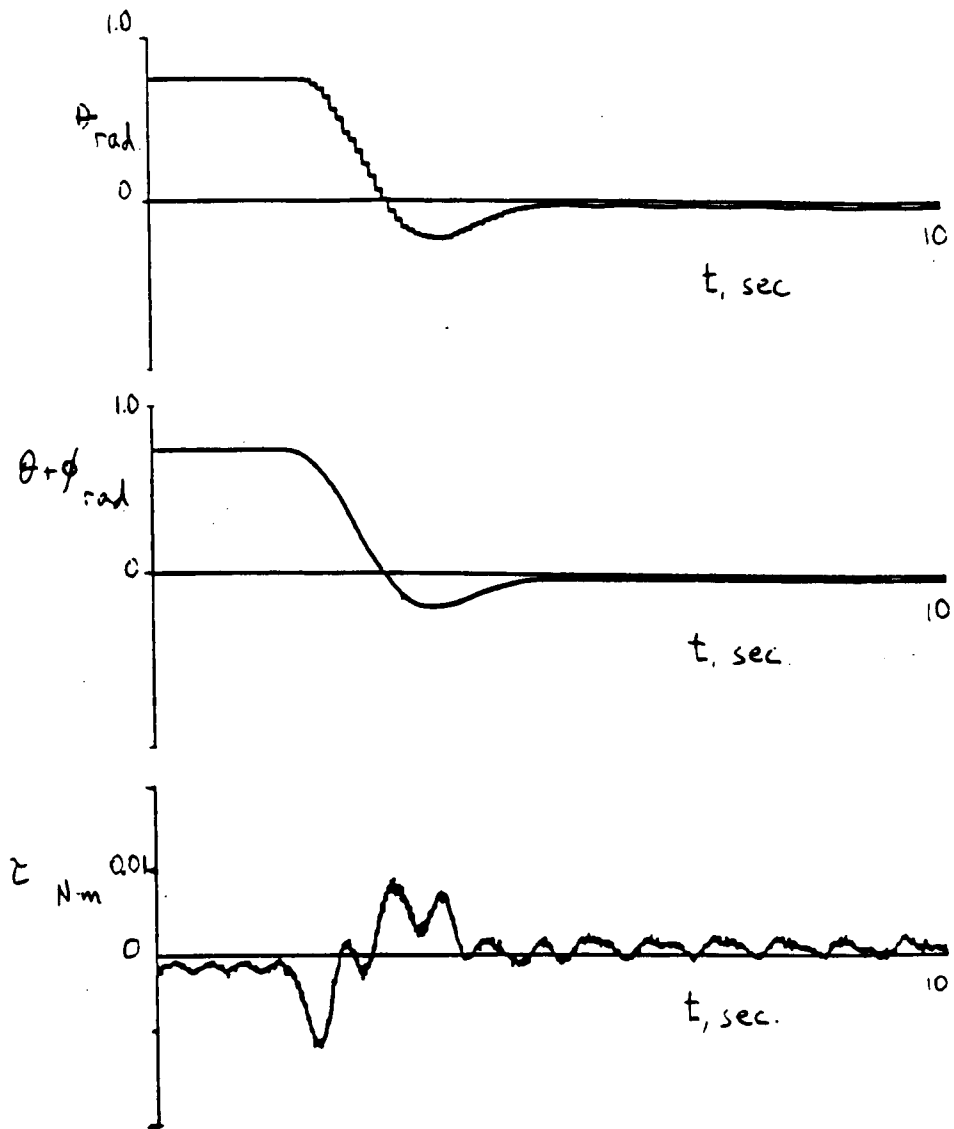
EXPERIMENTAL RESULTS, PLANAR SINGLE LINK SYSTEM

565
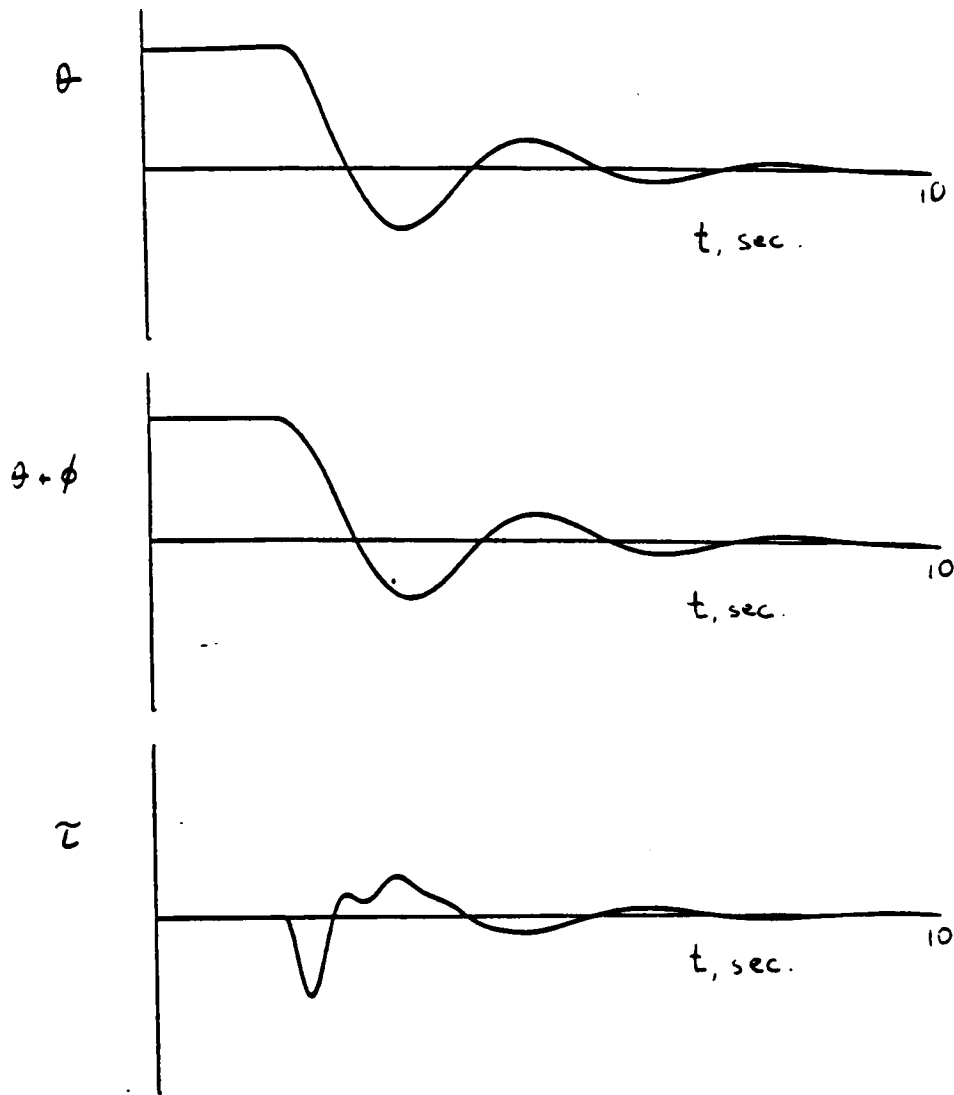
SIMULATION RESULTS, PLANAR SINGLE LINK SYSTEM
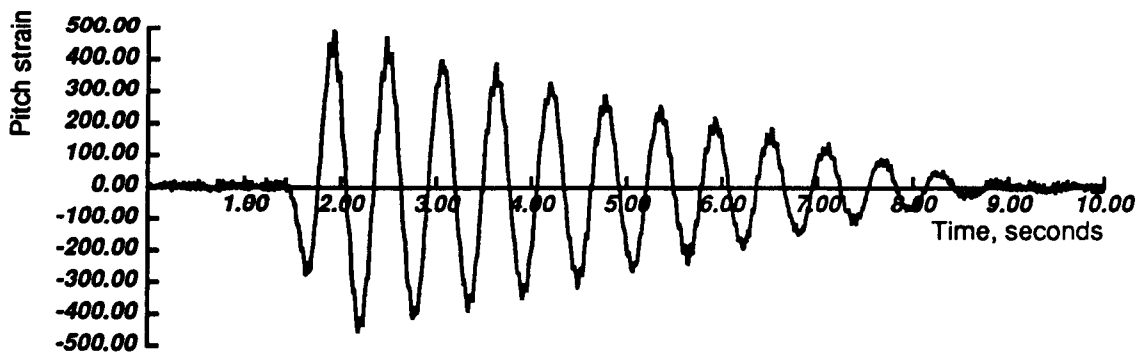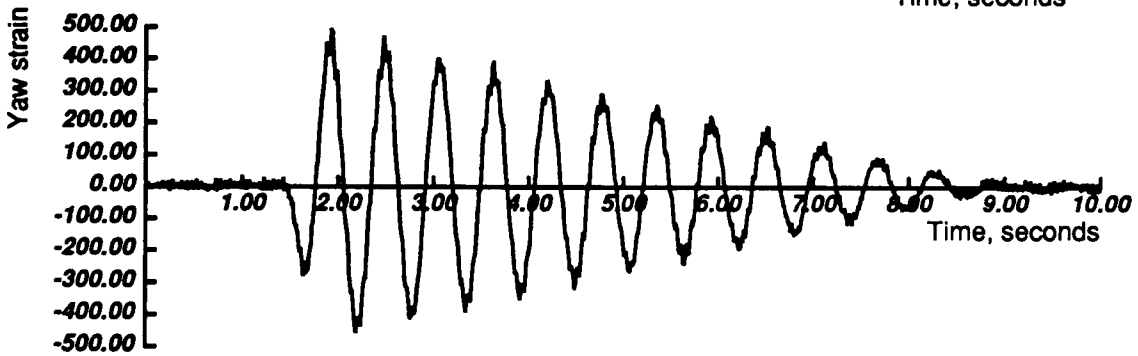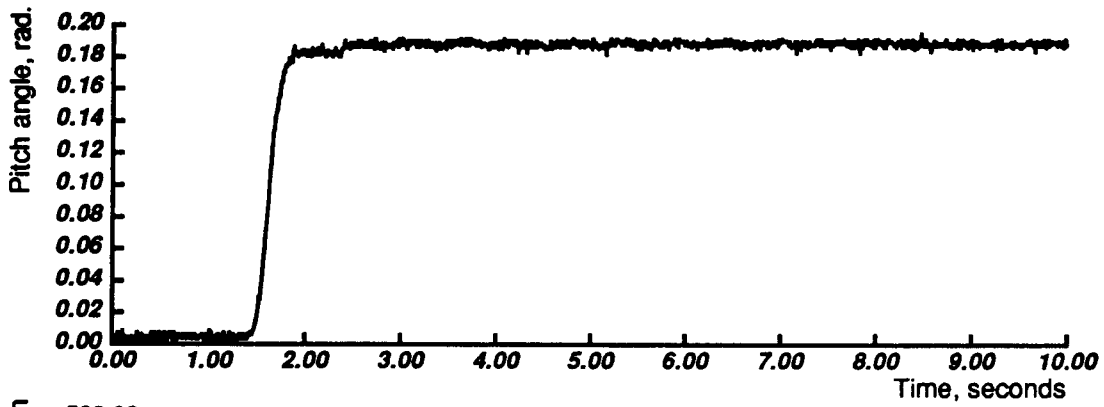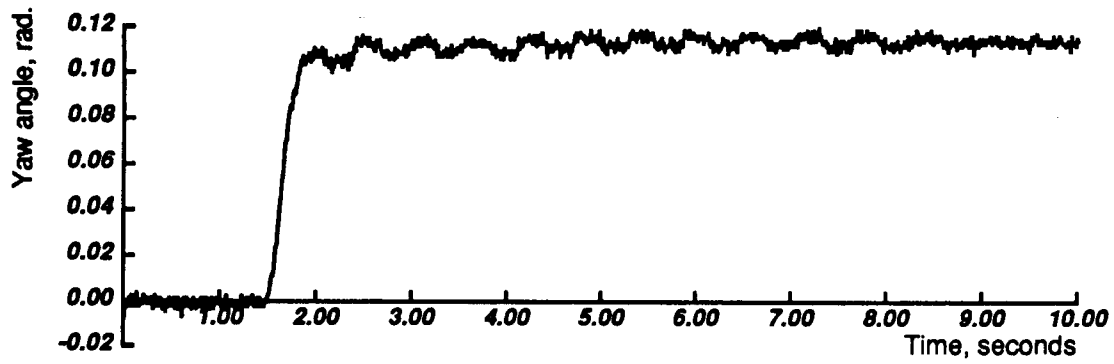
Figure 1: Feedback on Position (Rotation) Only

SINGLE LINK SYSTEM, 3-D (SPHERICAL) MOTION

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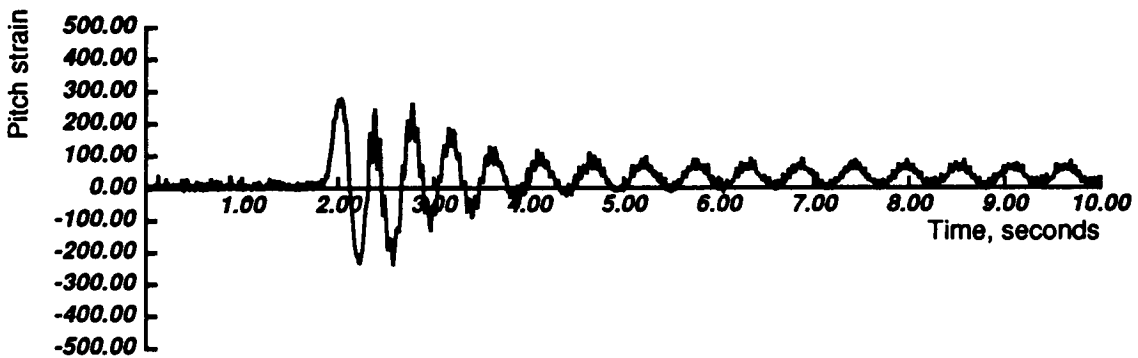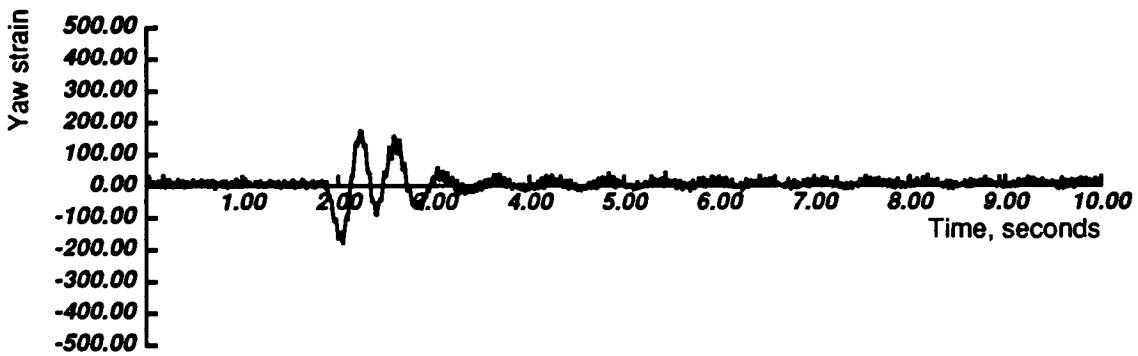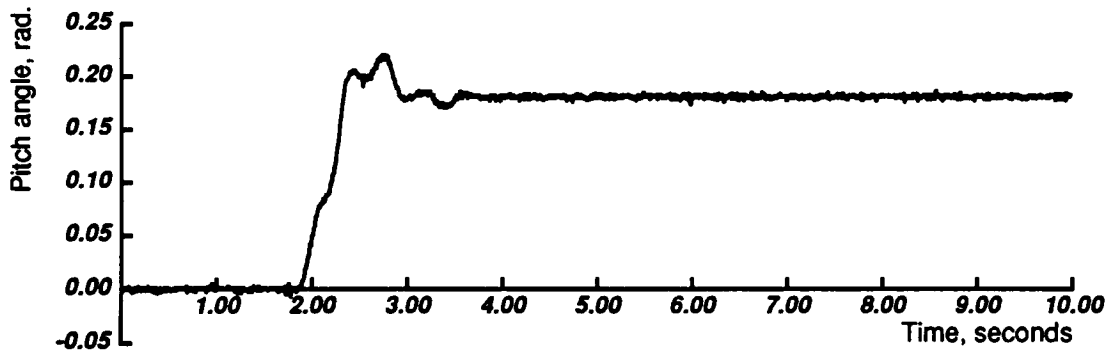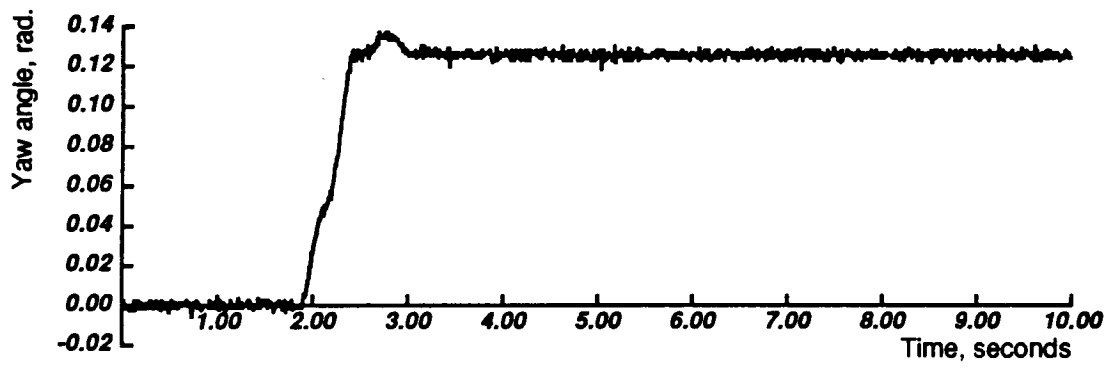
Figure 1: Feedback on Position (Rotations) and Strains

SINGLE LINK SYSTEM, 3-D (SPHERICAL) MOTION

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Planar Two Link System

- Experiments performed at Toshiba.

- Air table, 2-D manipulator.

- Four state variables: θ's and ϕ's.

- Compare experimental and simulation results.

- Friction in actuators causes vibration.

- Feedforward control is attempted, inclusive of friction effects.

- Model based feedforward control limits vibration.
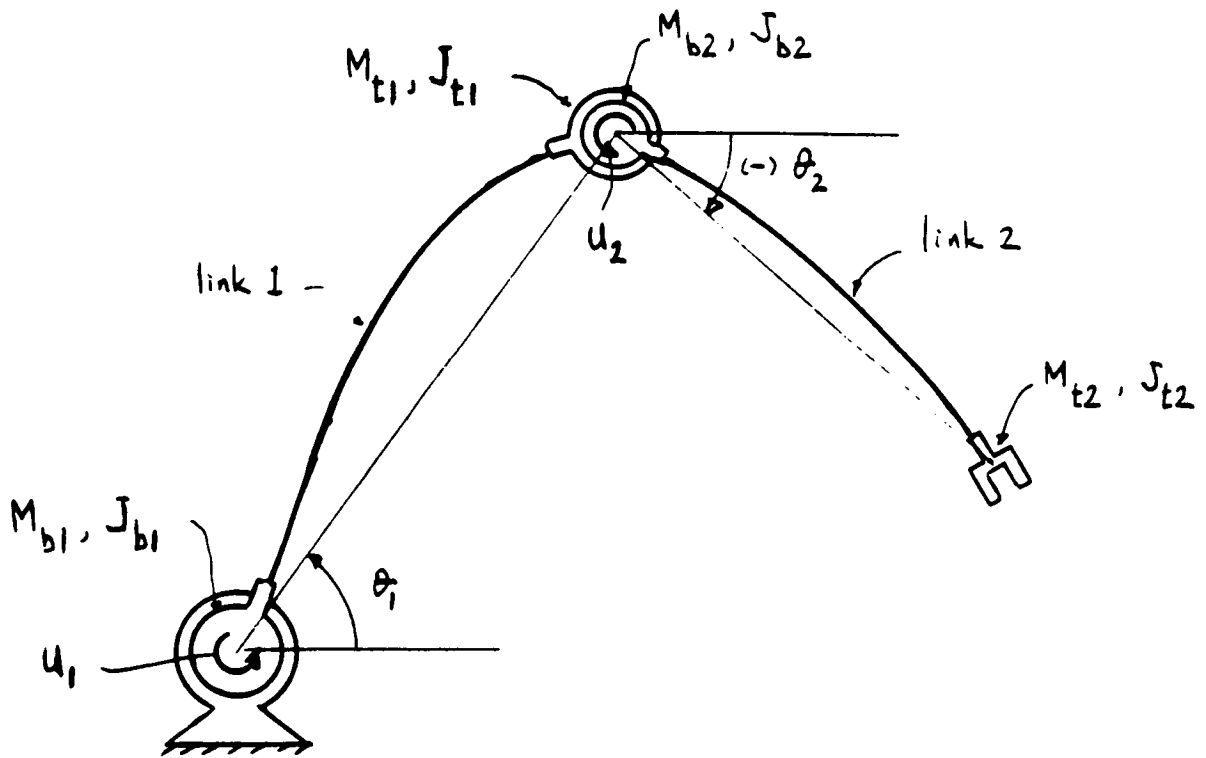
2-DOF TWO LINK PLANAR SYSTEM (AIR TABLE, HORIZONTAL PLANE)
(EXPERIMENTS CONDUCTED AT TOSHIBA)

570
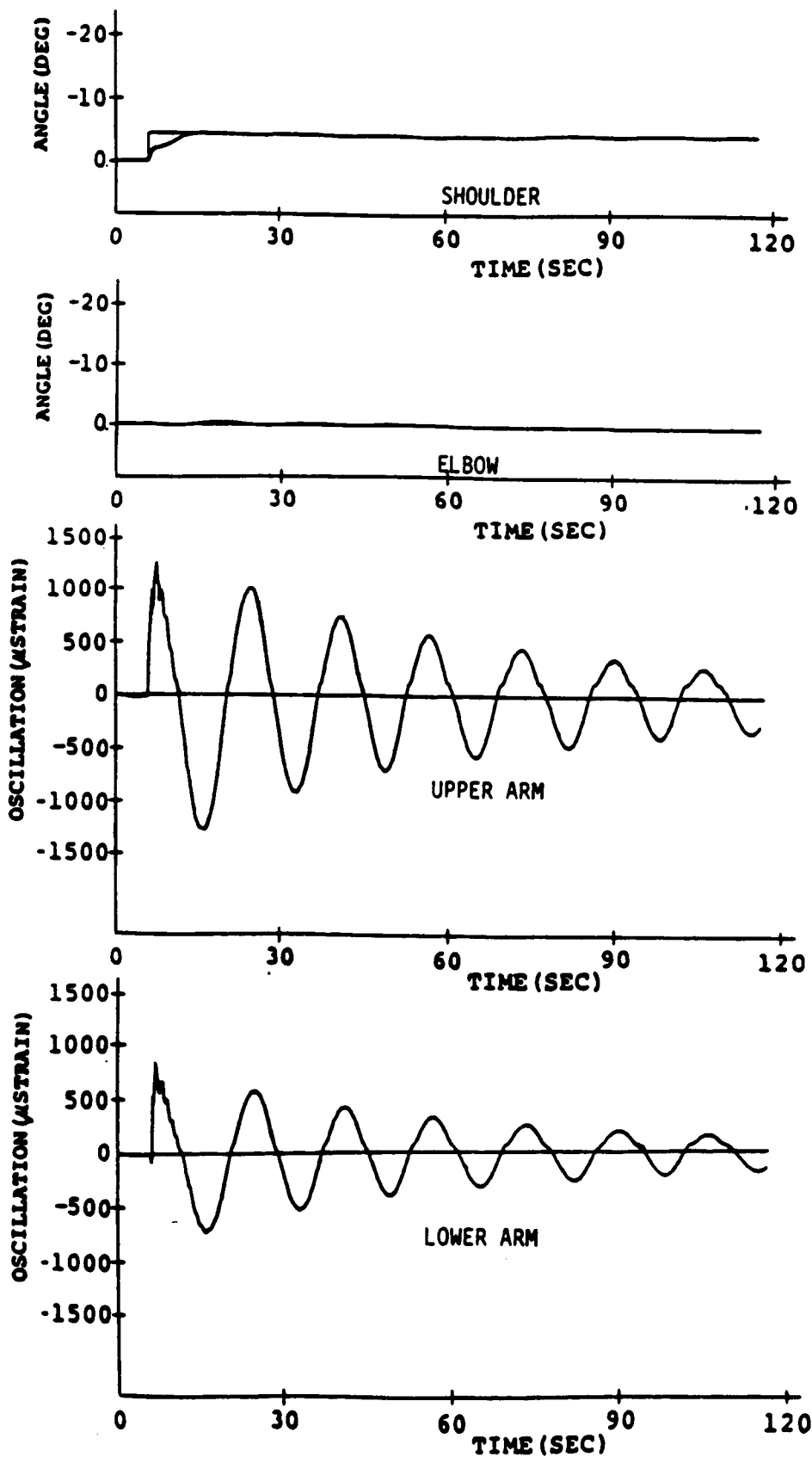
PLANAR TWO-LINK MANIPULATOR: EXPERIMENTAL RESULTS

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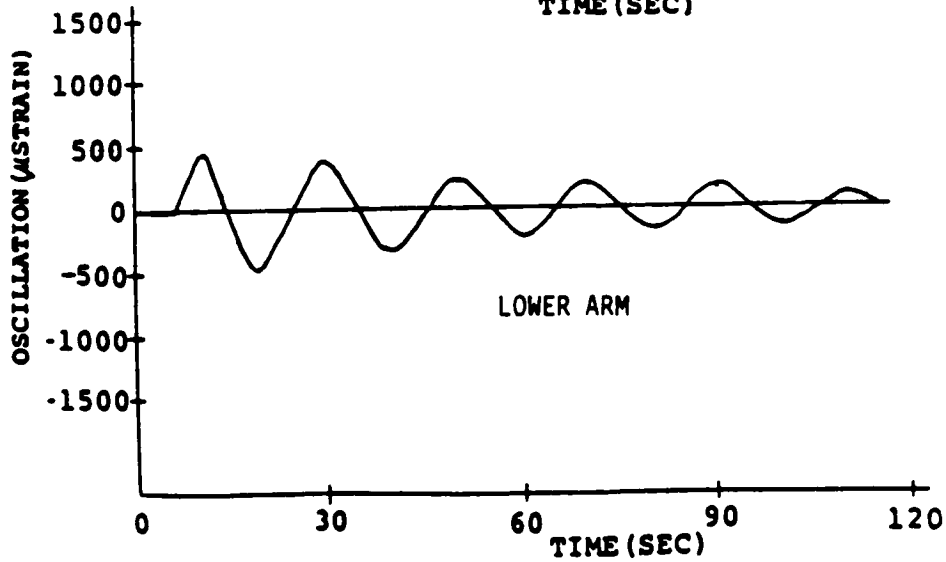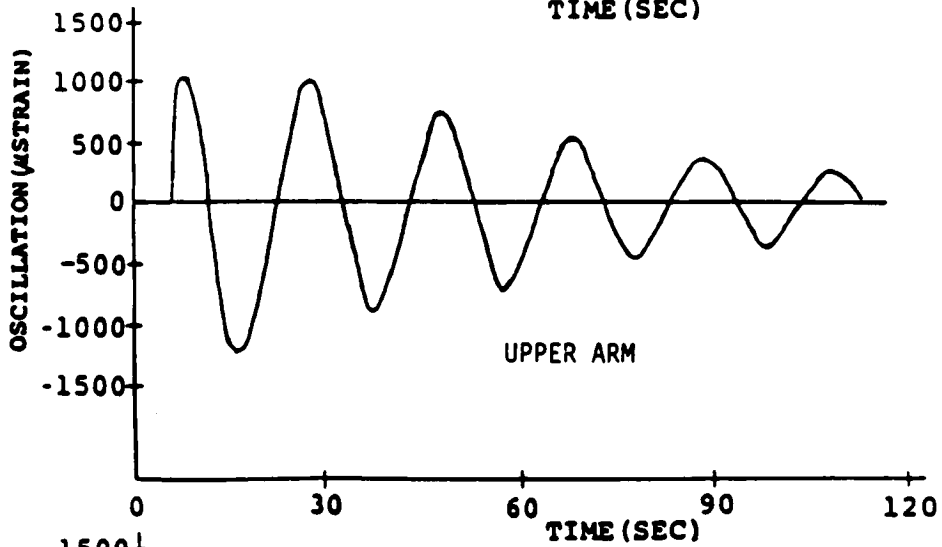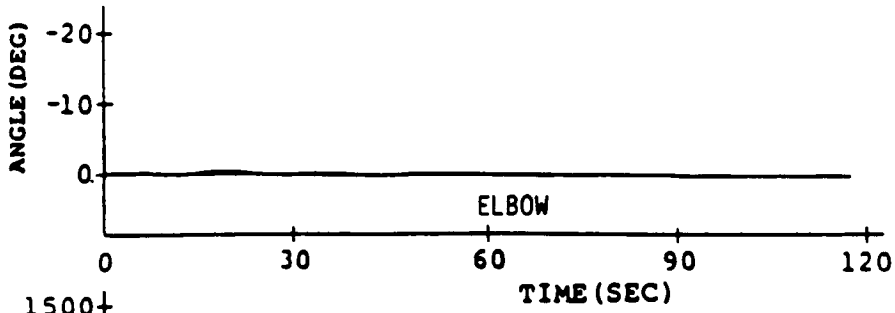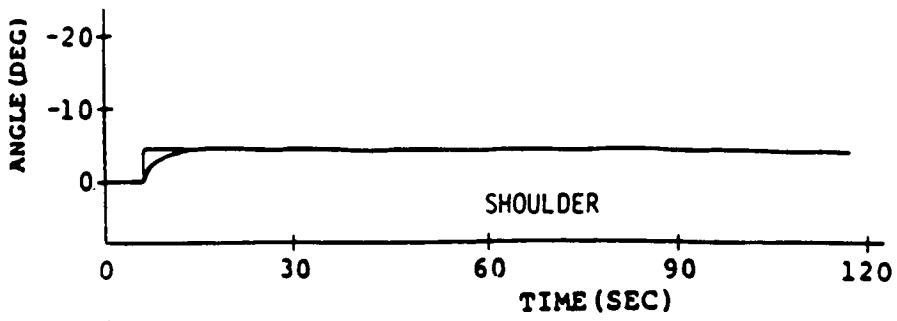
PLANAR TWO-LINK MANIPULATOR: SIMULATION RESULTS

Fig. 6a

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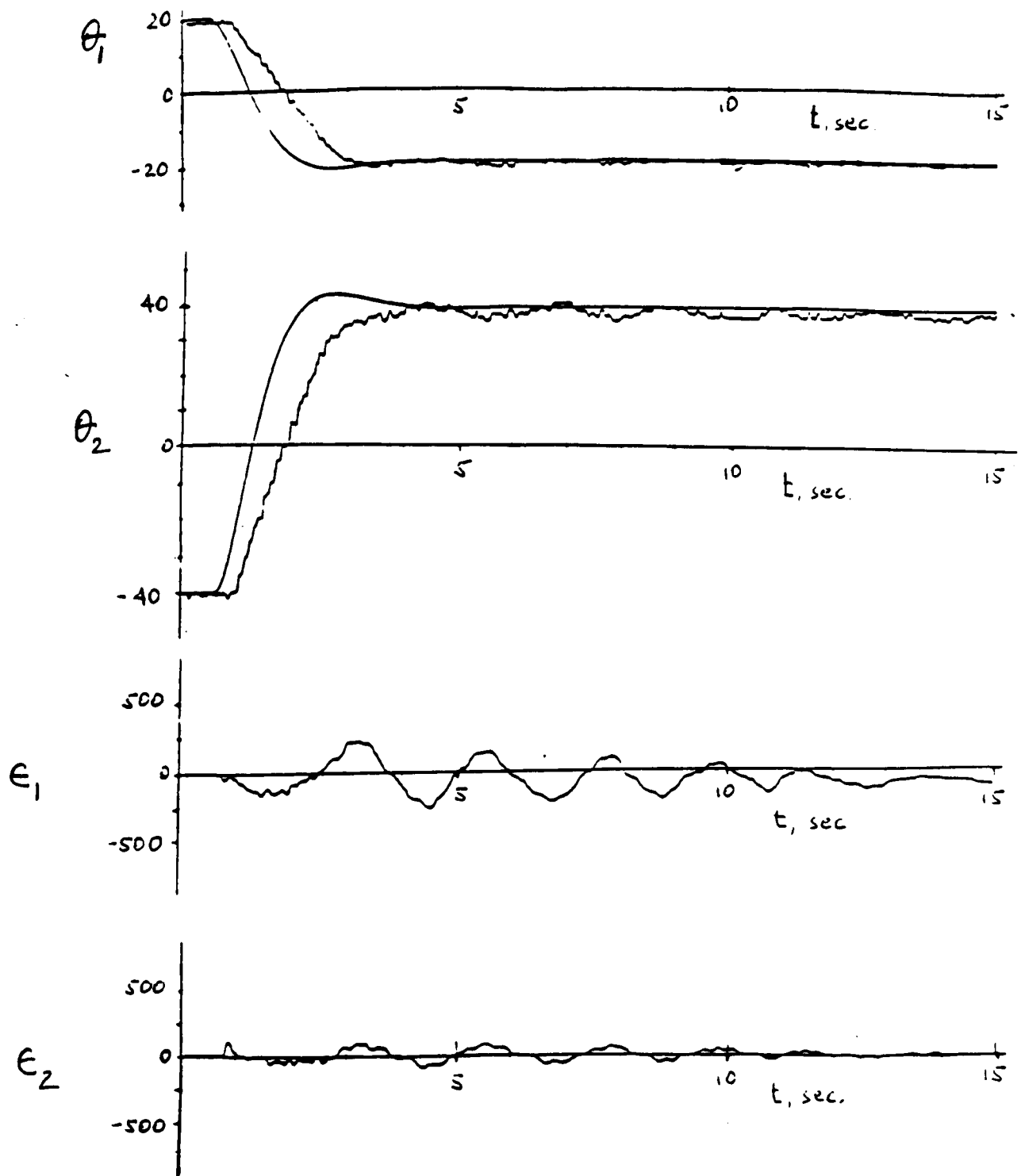
EXPERIMENTAL RESULTS, FEEDBACK CONTROL: NOTE VIBRATION EFFECT, FROM FRICTION

573
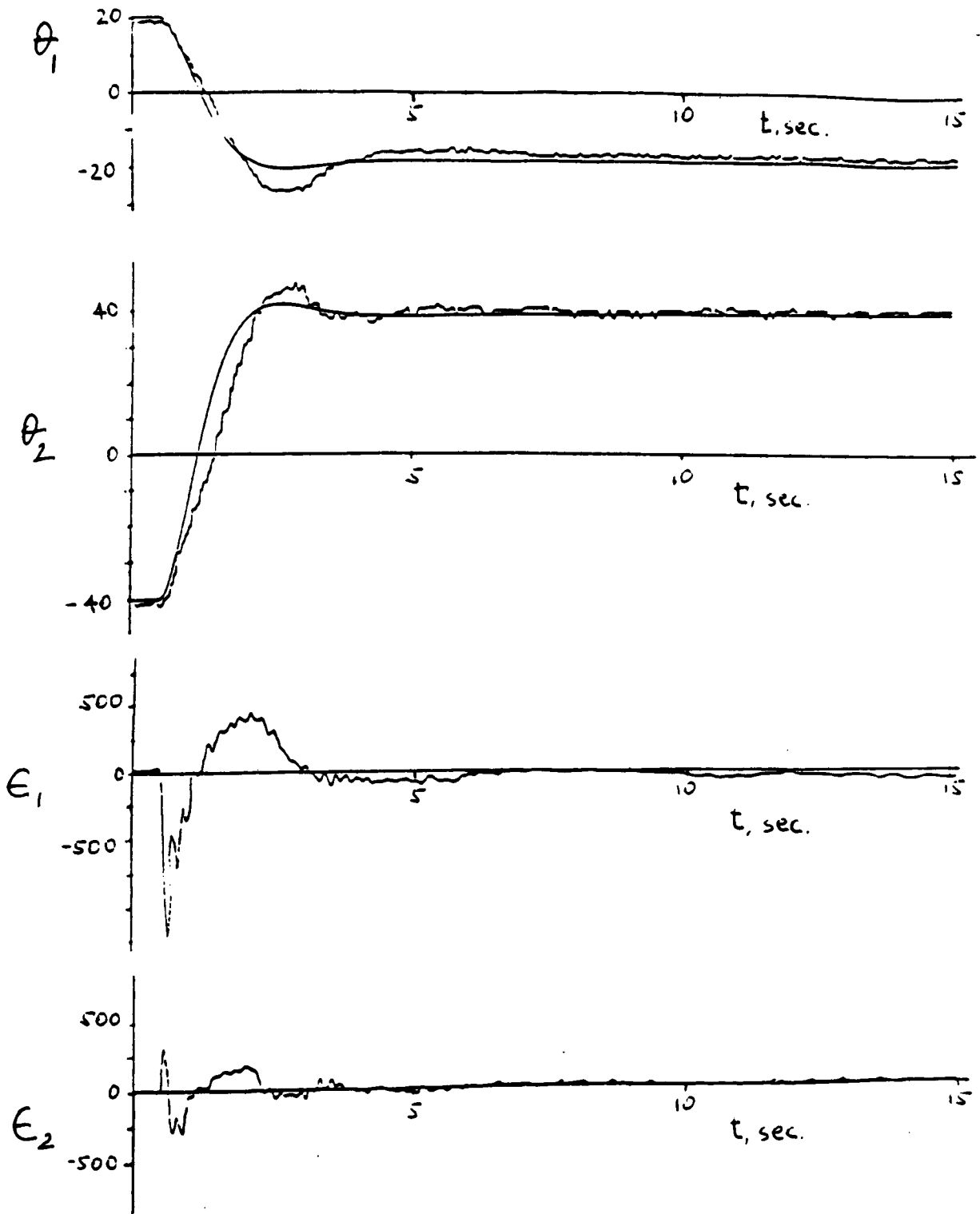
EXPERIMENTAL RESULTS, FEEDFORWARD CONTROL: NOTE ELIMINATION OF VIBRATION

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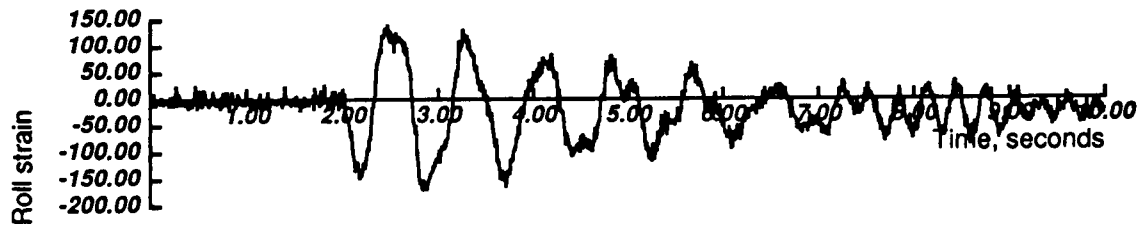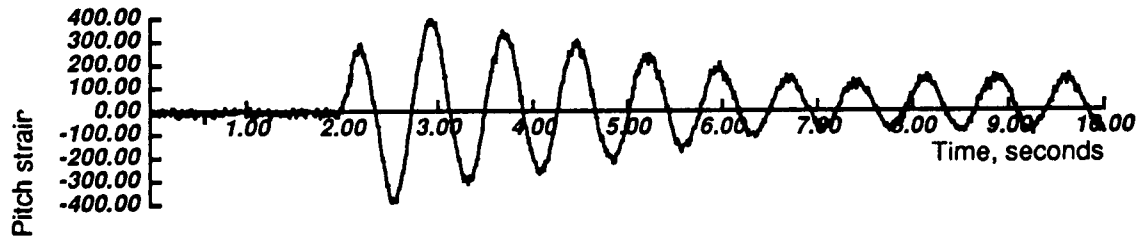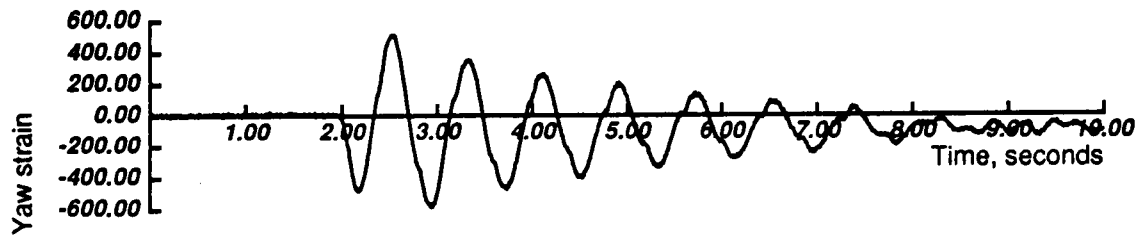# Combined Flexural-Torsional (3-D) Motion

Experiments performed April 1988:

- Three actuated DOF (yaw, pitch, roll).

- Two links; one flexible, one rigid.

- Linear feedback control; gains by trial and error.

- Coupled flexural and torsional vibrations.

- See videotape; see experimental results.

- Actuator properties by system identification (in process).

- Analtyical model used in simulation studies (in process).

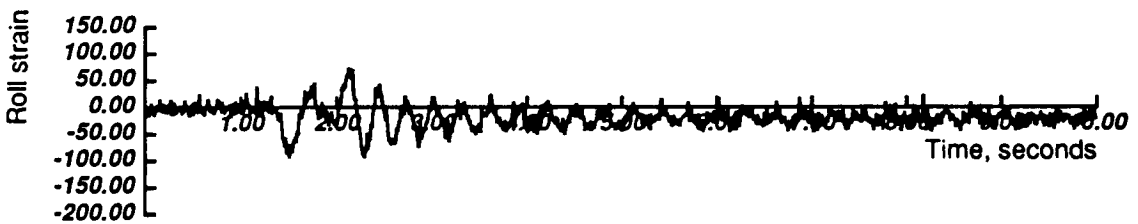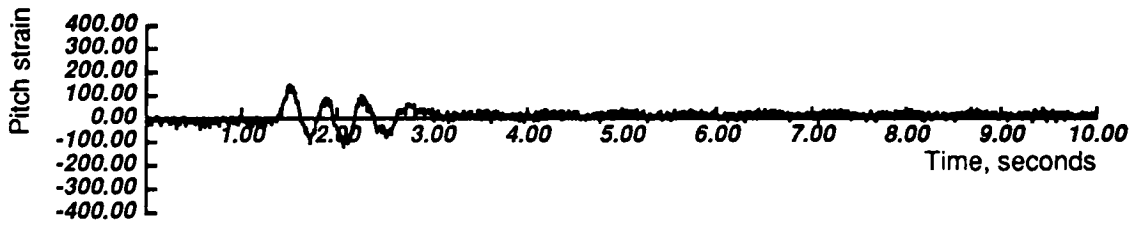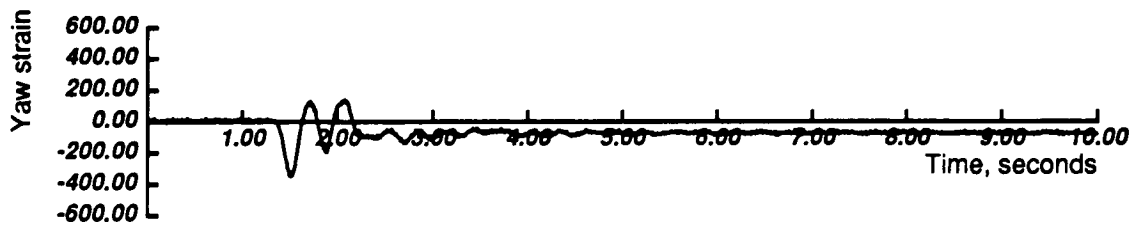- Next phase: distal link made flexible, 4 (or 5) actuated DOF.

575
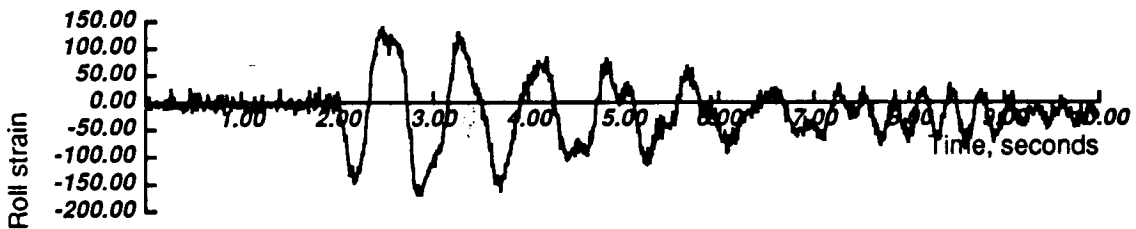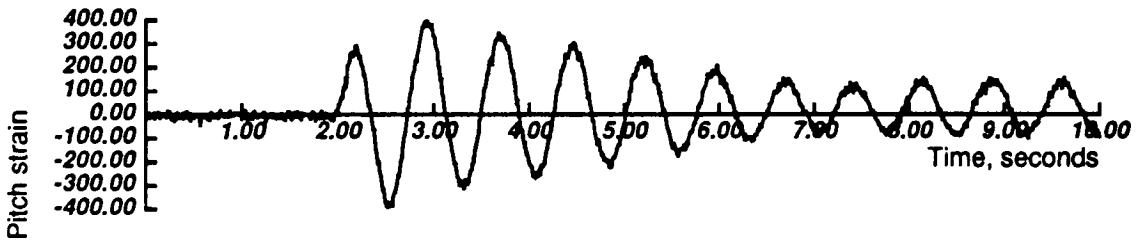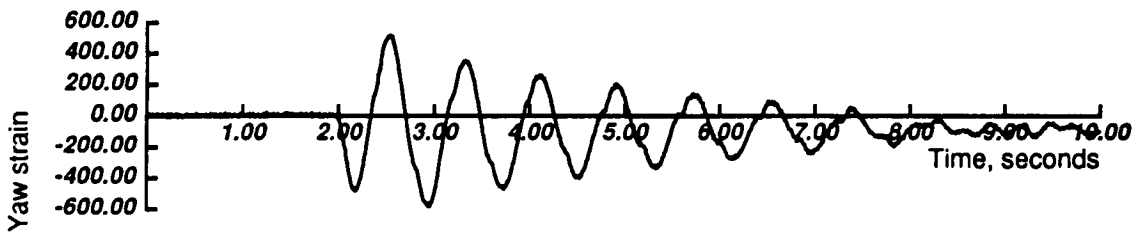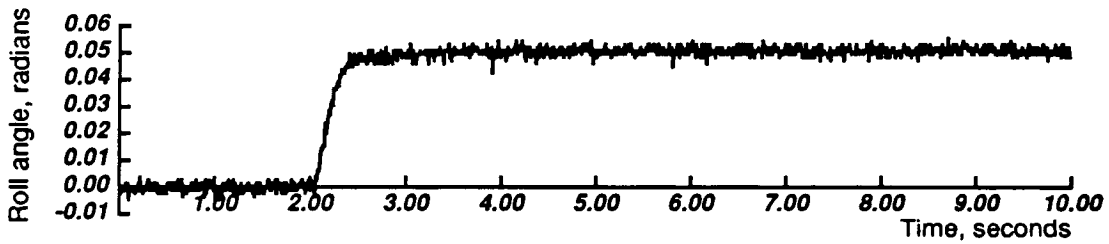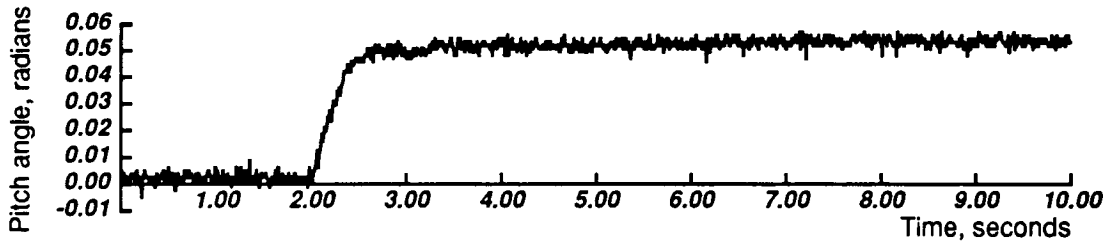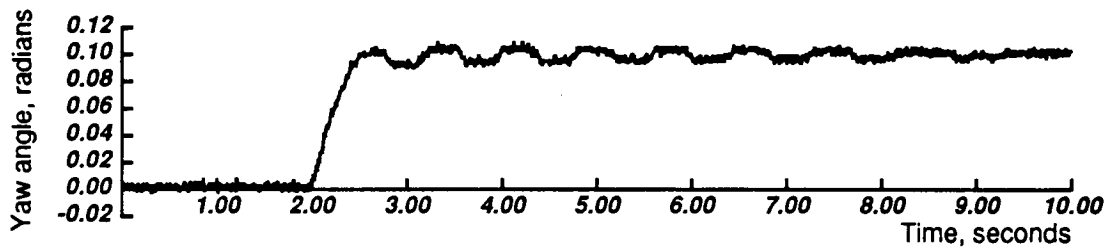
COUPLED FLEXURAL-TORSIONAL MOTIONS ROTATIONS AND STRAINS

FEEDBACK CONTROL ON POSITION; NO FEEDBACK ON STRAIN

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COUPLED FLEXURAL-TORSIONAL MOTION: STRAINS

FEEDBACK CONTROL ON POSITION; NO FEEDBACK ON STRAIN

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COUPLED FLEXURAL-TORSIONAL MOTION: STRAINS

FEEDBACK CONTROL ON POSITION AND ON STRAIN

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Discussion and Conclusions

- The model may be well suited for serial link manipulators, including joint-dominated systems.

- Accuracy for MDOF systems, non-linear in configuration, remains to be examined.

- Control experiments must be extended beyond linearized regions.

- The major application is model-based control, still to be studied in depth.

- Effects of friction, backlash, deadband should be included.

- Friction or torque ripple can excite higher modes.

- Frequencies of unmodelled (higher) modes can be adjusted by inserting "redundant" actuators.