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SPACECRAFT DYNAMICS AND CONTROL PROGRAM AT AFRPL

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INTRODUCTION

A number of future DOD and NASA spacecraft such as the space based radar will be not only an order of magnitude larger in dimension than the current spacecraft, but will exhibit extreme structural flexibility with very low structural vibration frequencies. Another class of spacecraft (such as the space defense platforms) will combine large physical size with extremely precise pointing requirement. Such problems require a total departure from the traditional methods of modeling and control system design of spacecraft where structural flexibility is treated as a secondary effect. With these problems in mind, the Air Force Rocket Propulsion Laboratory (AFRPL) initiated research to develop dynamics and control technology so as to enable the future large space structures (LSS).

AFRPL's effort in this area can be subdivided into the following three overlapping areas: (a) Ground Experiments, (b) Spacecraft Modeling and Control, and (c) Sensors and Actuators. This paper summarizes both the in-house and contractual efforts of the AFRPL in LSS. However, only Air Force funded programs are discussed, ongoing Strategic Defense Initiative Office funded efforts are not covered in this paper.

Ground Experiments

* Spacecraft Slew
* Vibration Control
* Shape Determination & Control
* System Identification

Spacecraft Modeling & Control

* Deployment Dynamics
* System Identification
* Modeling & Control

Sensors & Actuators

* Distributed Piezoelectric Actuation
* Distributed Fiber Optic Sensor

Figure 1.

SLEWING AND VIBRATION SUPPRESSION FOR FLEXIBLE STRUCTURES

A number of future DOD and NASA space systems will require rapid slewing (retargeting) of the spacecraft. The large moment of inertia of such spacecraft coupled with rapid retargeting requirement results in slew torque requirement of 10^5 - 10^6 Nm. Currently only ON-OFF reaction control system thrusters can provide the large torque required, however, ON-OFF thrusters by their very nature have the tendency of significantly vibrating the structure. The objective of this project was to develop control laws using thrusters for spacecraft slew which minimize structural vibration and demonstrate the theory on a ground experiment.

The experimental set-up consists of a rigid hub on which four flexible appendages are mounted. The hub is mounted on an air bearing table, thus allowing it to rotate freely about the vertical axis. ½lb control thrusters are mounted in pairs on the ends of two arms. Sensors consist of a hub angle resolver and 4 accelerometers, one on each arm (fig. 2).

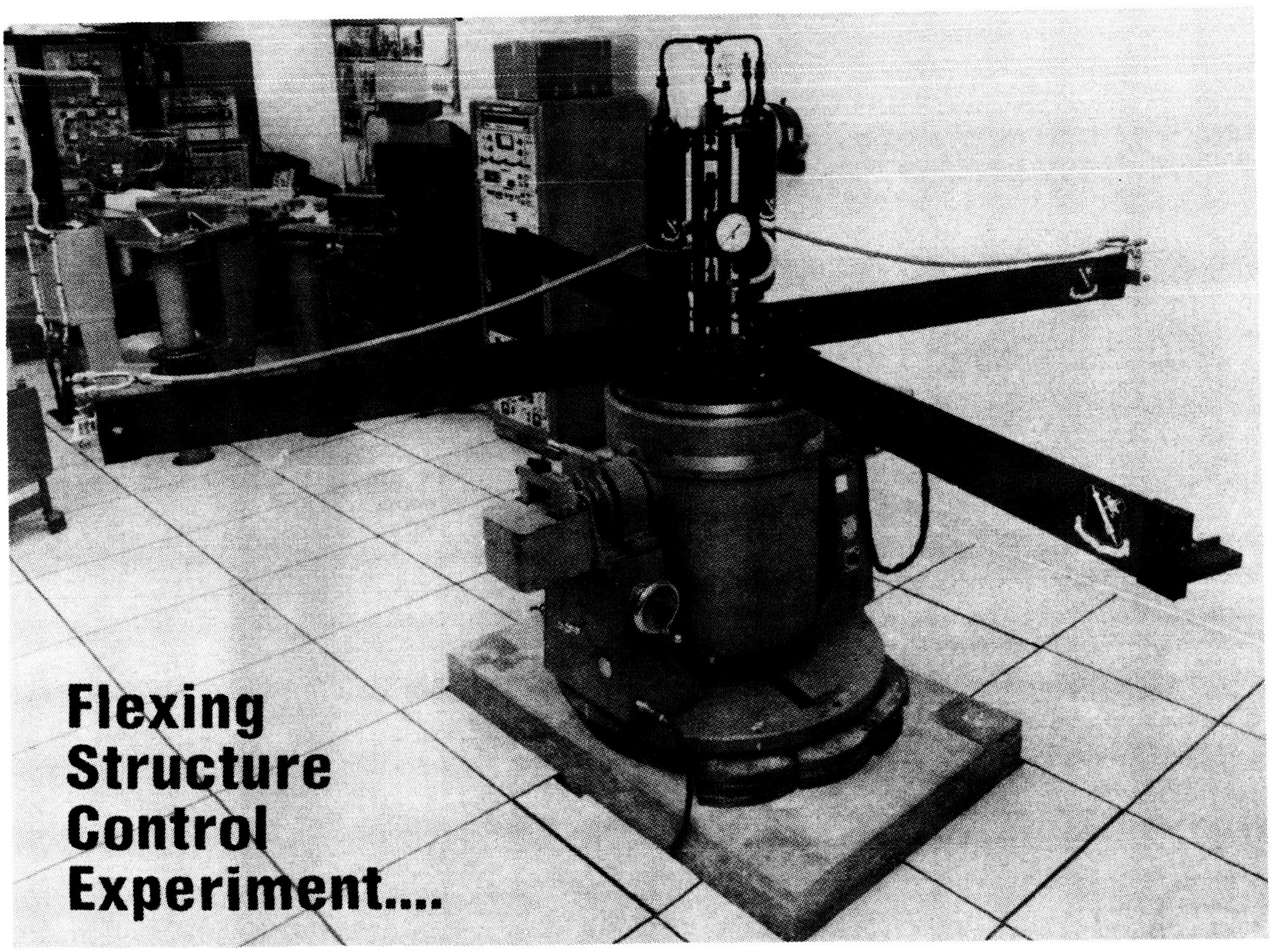
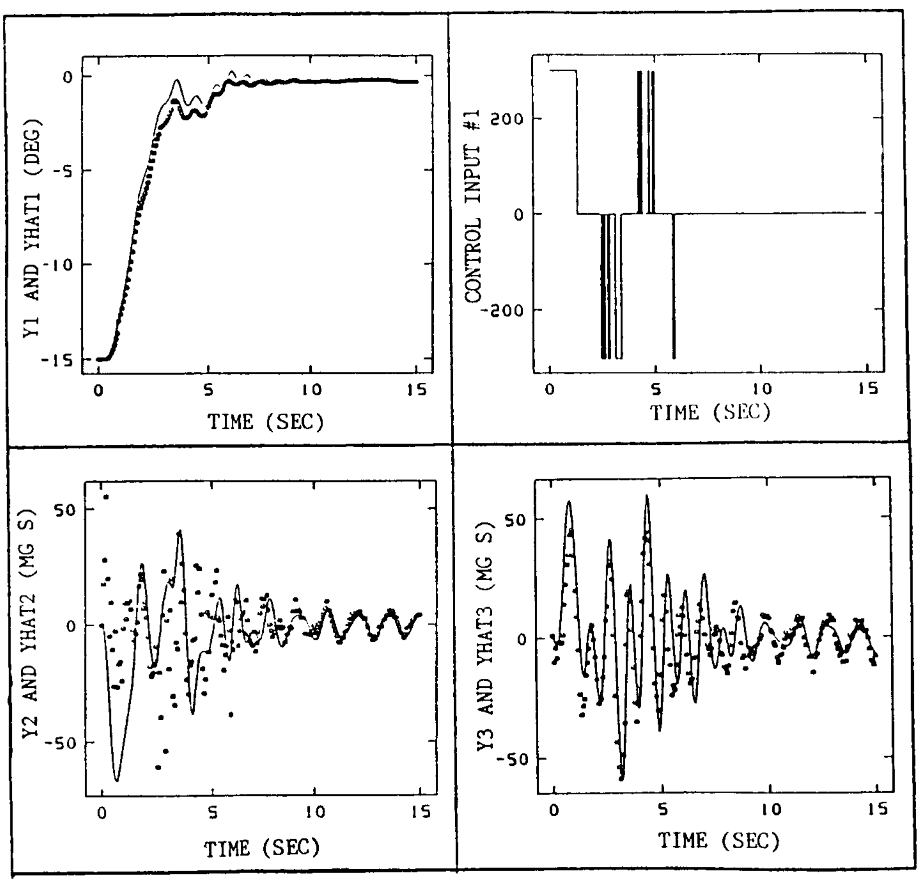


Figure 2.

In the initial set of experiments, the thrusters were used to perform 15-degree slew maneuvers. A computer simulation program was developed to predict the performance of the control system. Fig. 3 shows the performance of the controller for one of the tests (ref. 1). The solid lines correspond to the simulation results whereas the dots are the experimental results. The figure gives the response of the first three modes (Y1 - hub rotation in degrees; Y2, Y3 - amplitude of first and second vibration modes in milli g, respectively).

The experiment demonstrated that ON-OFF thrusters can be used for rapid slew of flexible space structures while minimizing structural vibration. However, the exclusive use of thrusters limits the performance of the control system in the terminal phase of the slew maneuver. This is because of the minimum impulse bit of the thruster system, thus any attempt to dampen structural vibrations below a particular energy level throws the control system into limit cycles. One way of overcoming this problem is to include small linear actuators in the control system. This was confirmed by computer simulations.



TEST #141

- **15° Slew, Rapid Maneuver**
- **R = 9.69 X 10^{-8}**
- **Undershoot Caused by :**
  - **Damping of Rigid Body Mode by Colomb Friction**
  - **2nd Flexible Mode's Substantial Hub Rotation**

Figure 3.

SLEWING AND VIBRATION SUPPRESSION FOR FLEXIBLE STRUCTURES

One of the conclusions of the earlier study was that vibration control of the flexible spacecraft structure during slew can be significantly improved when linear actuation devices are used in combination with thrusters. In the current effort both lumped and distributed linear actuators will be used. Control laws are currently being developed which use, along with ON-OFF thrusters, the hub motor, four bi-directional proof mass actuators (one on the tip of each flexible arm) and piezoelectric film as a distributed vibration suppression actuator on all four arms.

Flexing Structure Slew Control

* Generalized Slew Control
* Verified Controller Design Methods Using the AFRPL/CSDL Experimental Structure
* Suggested Using Linear Actuators Combined with On-Off Thrusters

Linear Torquer Slew Control

* Develop Theory for Combining Linear Actuation Devices Such as Proof-Mass Actuators and CMG's With On-Off Thrusters
* Demonstrate Hybrid Controller Theory Through Analysis and Simulation
* Validate Controller Theory Using AFRPL/CSDL Experimental Structure

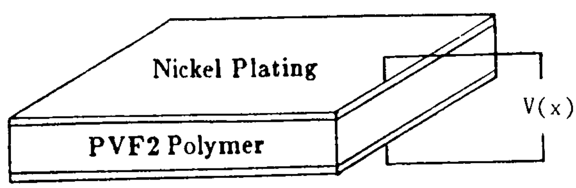
Piezoelectric Distributed Actuator

* Develop Theory for Employing a Piezoelectric Film as a Vibration Controller
* Combine Piezoelectric Film for Vibration Control with On-Off Thrusters, Proof-Mass Actuators and CMG's for Slew Control
* Validate Theory on AFRPL/CSDL Experimental Structure

Figure 4.

One of the most exciting concepts for structural vibration control is the use of a piezoelectric film as a distributed actuator. The concept consists of a thin ($\sim 3\text{x}10^{-2}$mm in thickness) polyvinylidene floride film polarized in one direction. The film elongates or contracts in the polarized direction depending on the magnitude and polarity of the voltage applied across its nickel plated faces (fig. 5). The strain occurs over the entire length of the film, thus making it a truely distributed actuator. This actuator provides the possibility of controlling all the modes of the system, thus avoiding the problem of spillover of the uncontrolled modes (ref. 2).

Preliminary testing of the actuator concept were done on a 15cm long cantilevered steel beam. Fig. 5 compares the performance of two active control logics with the open loop decay of the vibrations. The constant-amplitude controller (a nonlinear controller) provided double the damping of the uncontrolled system for large vibrations. For small vibrations the controller performed extremely well, increasing the damping by a factor of 40 over the uncontrolled system for small vibrations.



PVF_2 Properties

Thickness	$28 \text{ X } 10^{-3}$ mm
Modulus, E	$2.0 \text{ X } 10^{9}$ Nm^2
Density	1800 kgm^{-3}

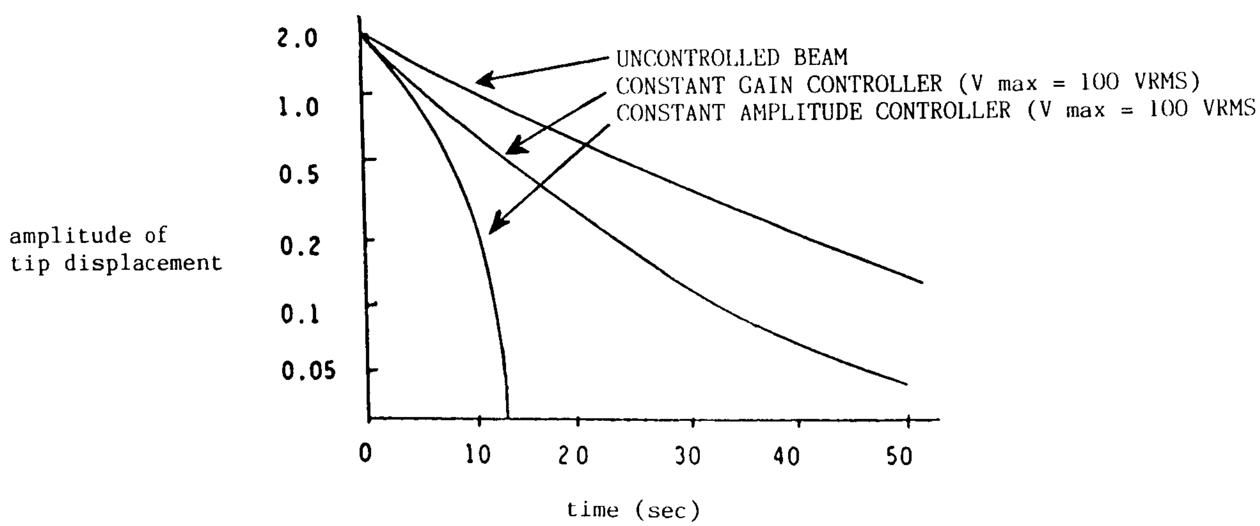
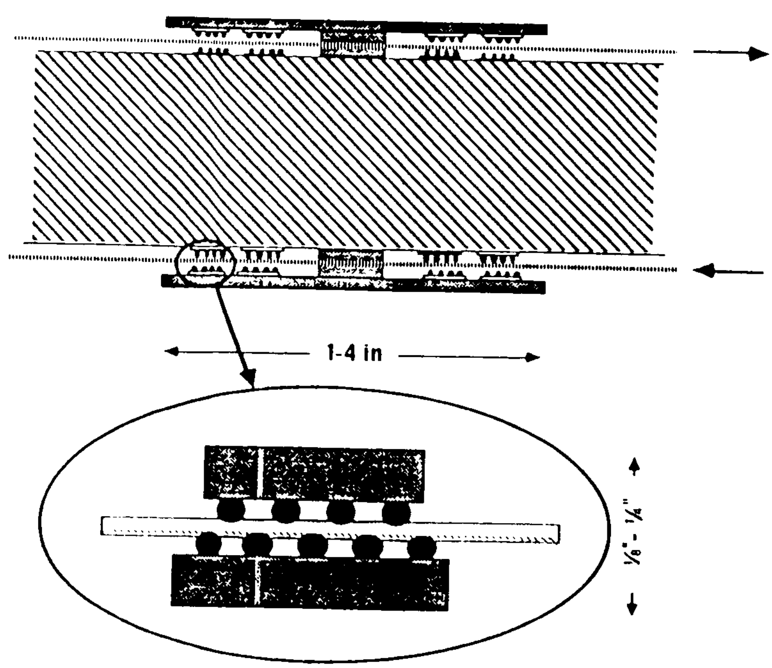


Figure 5.

Another concept which has the potential of high payoff is the possibility of using a fiber optic waveguide as a lightweight distributed sensor. A short and intense pulse of laser light is injected into one end of the fiber. The forward traveling pulse is continuously backscattered towards the source due to Rayleigh scattering. Observation of the Rayleigh backscattered energy is made by placing a beam splitter between the fiber and the source and directing the returned energy at a high speed detector. The fiber is bonded to the structure whose deformation is to be monitored. The fiber is made to pass through a small transducer (see fig. 6) at the locations in the structure where the bending is to be determined. The transducer pinches the fiber thus reducing the return signal from that point. The reduction in the return signal is proportional to the structural bending. Currently the AFRPL is funding a proof of concept demonstration of the lightweight distributed sensor.

- **Demonstrate Feasibility of Distributed Fiber Optic Deflection Sensor**



- **Lightweight Distributed Sensor**

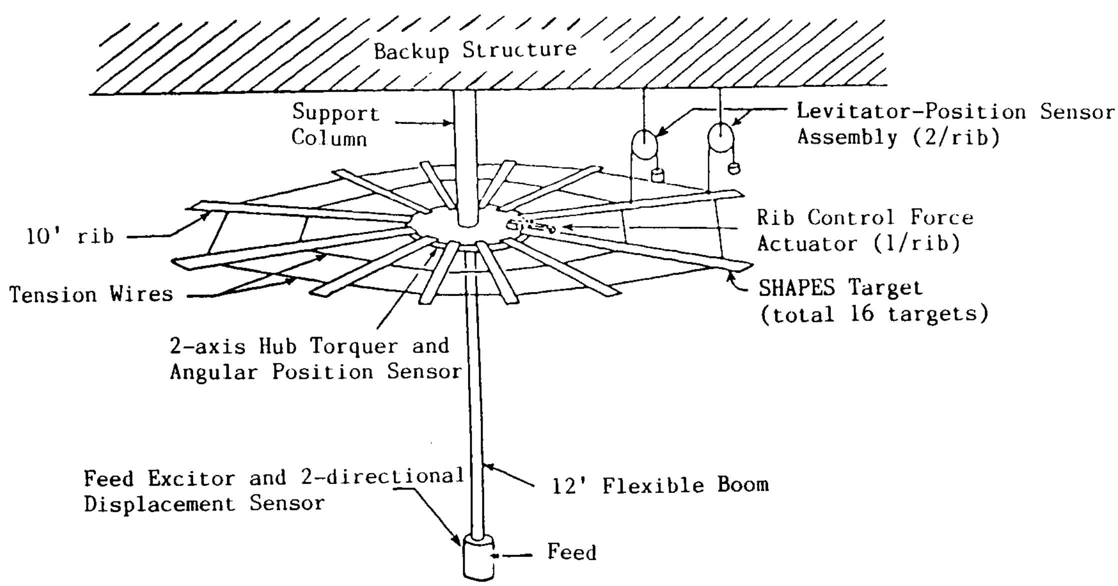
Figure 6.

3-DIMENSIONAL SHAPE CONTROL EXPERIMENT

The objective of this effort is the demonstration of selected shape determination and control technology for future flexible structures using a physical structure in a laboratory environment.

The test article consists of an umbrella-like structure with 10ft long ribs and a 12ft long boom. The neighboring ribs are connected to each other through a pair of tension wires so as to provide coupling. The article is rigidly supported at the center to the backup structure, also each rib is levitated to offset the effects of gravity. The levitation system allows the ribs to freely flex in a vertical plane. An excitor in the feed will be used to introduce noise in the structure. Multiple sensors and actuators such as the SHAPES sensor under development at the Jet Propulsion Laboratory, rib control force actuator, 2-directional displacement sensor on the feed, etc., will be attached to the structure. The experiments to be conducted under this effort include (a) static shape determination, (b) dynamic model identification, (c) transient regulation by distributed control, and (d) parameter error and model truncation compensation using adaptive control techniques.

- **Demonstrate Sensing and Control of a Lightweight Antenna Structure**
- **Establish Standard Test Bed for 3D Structure Control**



- **Reduce Risk for Space-based Radar**

Figure 7.

IN-HOUSE EXPERIMENTS IN CONTROL AND IDENTIFICATION

The objective of the recently initiated in-house experimental effort is to provide the AFRPL with the capability of (a) verifying new parameter identification and control methods being developed and (b) performing a quick feasibility check on new innovative ideas prior to substantial investment in that area. Most importantly, this facility will be made available to university faculty and DOD contractors for conducting experiments. The details of the means through which the facility can be made available are currently being worked on.

The approach involves designing the control system on a control design software package (e.g., MATRIX_X) and then directly implementing it on a desktop real-time controller. In this approach, the control system is down loaded to the controller and implemented in a matter of minutes without the engineer having to program the controller.

In the immediate future, the plan calls for testing the optimal sensor location logic for unique identification (being developed under a separate effort) on a 2-dimensional grid structure. Also work has just begun on a new facility with a test stand which is anchored directly to the bedrock and isolated from the rest of the structure to minimize vibrations. This facility should be available for use in roughly one year. In addition, AFRPL has a number of vacuum chambers of various sizes, the largest one being 30 ft in diameter.

WHY:

* **Provide Feasibility Check on New Ideas**
* **Provide Test Bed for Control & Identification Logic Developed for AFRPL**
* **Provide an Equipped Facility for University Faculty/Students**

HOW:

* **Use Simple 1, 2, & 3-D Structures**
* **Use Design Software Coupled with Real-Time Control/System Identification Hardware for Rapid Turnaround**
* **Up to 30ft Diameter Vacuum Chambers Available**

CURRENT PLAN:

* **Cantilevered Beam & Grid Structure**
* **Use MATRIX_X + Real-Time Controller**
* **Experiments**
    * **System Identification , Vibration Suppression , New Sensor & Actuator , ...**

Figure 8.

A number of future spacecraft such as Space Based Radar (SBR) will be packaged into a compact structurally dense form for launch, and the spacecraft will automatically unfold to the operational state once in orbit. The anticipated large structural size (> 30 meters) coupled with extreme structural flexibility precludes extensive ground testing of the deploying process. An alternate approach to obtain confidence in the spacecraft deployment is to simulate the dynamics on a computer.

None of the currently available computer programs can simulate the deployment of a large class of spacecraft. For deployment studies, DISCOS has proven to be computationally inefficient and requires significant modifications for each application. Since 1982, AFRPL has made significant investments for the development of a general purpose spacecraft deployment prediction code.

State-of-the-Art

- **Analysis**
  - **Dynamic Interactive Simulation of Controls and Structures (DISCOS)**
    - **Requires Significant Modification for Each Application**
    - **Computationally Inefficient**
- **Experiments**
  - **Ground**
    - **Mostly Limited to Simple Structures/Elements (by Size)**
    - **Terrestrial Effects also Limit Utility**
  - **Space Experiments from Shuttle in FY89**

Technology

- **Deployment Simulation of Large Space Systems**

Payoff

- **Reliable and Accurate Computer Simulation of Large Space Systems to Minimize Number of Tests Required on any Given Structure**

Transition Target

- **Space Based Radar**

Figure 9.

LARGE SPACE STRUCTURE DEPLOYMENT DYNAMICS

AFRPL's initial study in the development of a deployment dynamics computer program consisted of two major tasks. In Task 1, a new mathematical formulation for simulating the deploying process was developed and a preliminary design of the software architecture was laid out. In Task 2, a pilot computer program was developed to test the mathematical formulations. The computer program is not a general purpose code and is set up to simulate the deployment of the Grumman bicycle wheel SBR concept only (see ref. 3 for details). In its present form, the code is fairly computer intensive, requiring four hours of CPU time on a VAX 11-750 computer for a 4310 second deployment simulation. The spacecraft was modeled as consisting of eight tubes and eight bridges. The deployed portion of each gore (the radar reflector) was replaced by two cables. Eight stays (four each connected to the upper and lower ends of the hub) provide stiffness to the structure and can stabilize the deployment. In the current version of the code, torsional springs between the bridges and tubes are the source of energy for deployment. An alternate approach is to use motors instead of springs.

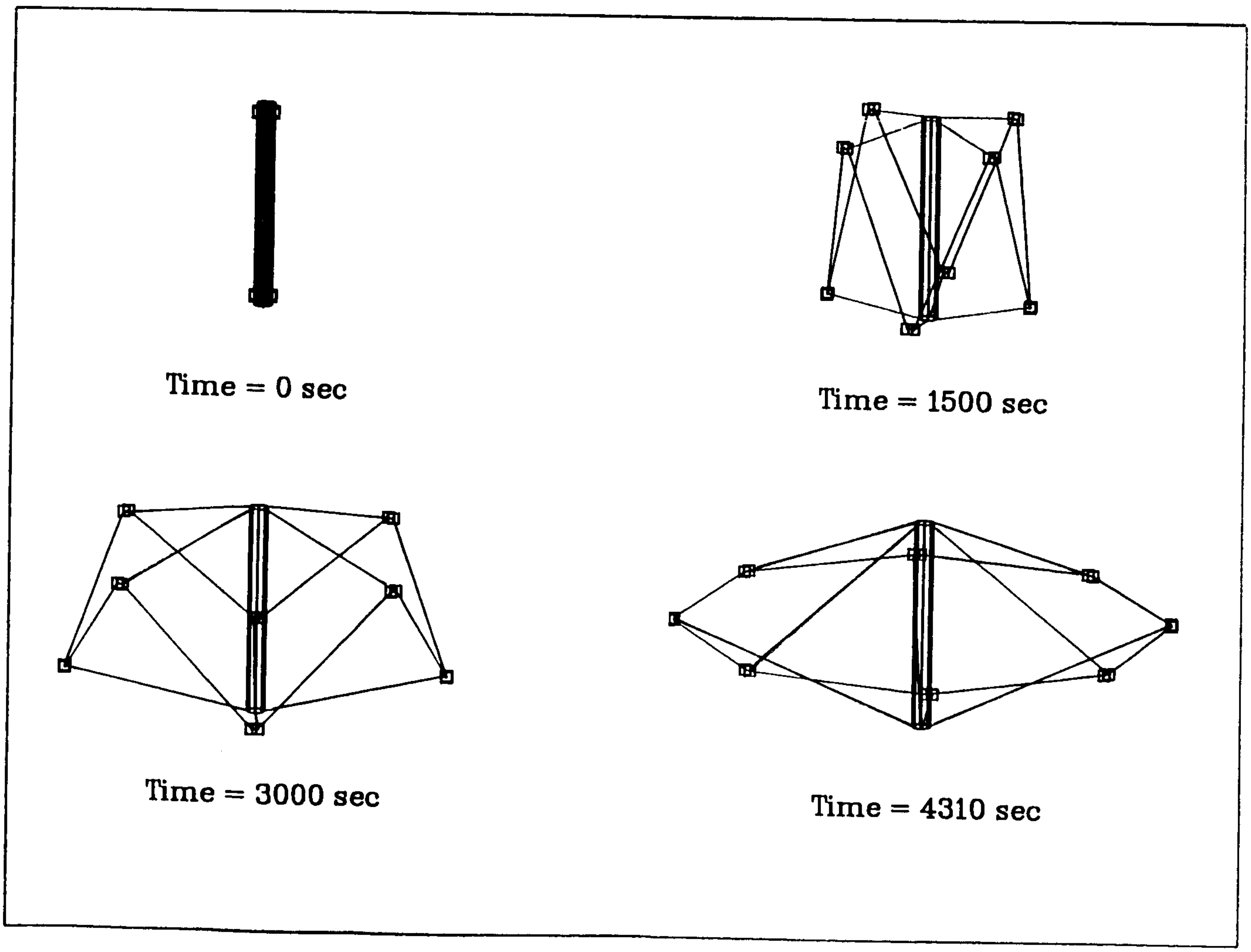


Figure 10.

The objective of the ongoing program is to develop a general purpose computer code for simulating the deployment dynamics of a large class of future space structures. The effort consists of 5 major tasks. In Task 1, future DOD and NASA missions will be reviewed for their deployment needs. Also an assessment of the state of the art in deployment technologies will be made. In Task 2, which is the heart of the effort, extended modeling capability such as active hinge point control and mass flow modeling will be incorporated in the code. The program will have the capability of evaluating the impact of distributed environmental disturbances such as gravity gradient, magnetic field torques, etc., on the deployment process. The capability of linearizing the nonlinear system about an operating point of interest so as to study the system stability will be provided. Also an entanglement indicator in the form of a post processor shall be developed. A host of extended software features will be incorporated in the code under Task 3. This is to include common I-O structure, restart capability, CAD interfaces and graphics outputs, etc. Task 4 shall investigate the impact of nonlinear structures effects. Techniques for generating open and closed loop deployment sequences shall be developed under Task 5. Also under this task the closed loop response of a number of test examples will be generated.

Deployment State-of-the-Art Assessment

Extended Analysis and Modeling

* Active Hinge Point Control
* Mass Flow Modeling Capability
* Distributed External Environment Effects
* Entanglement Indication
* Stability Analysis

Extended Software Features

Nonlinear Structure

Control of Deployment

* Open & Closed Loop Deployment
* Test Examples

Figure 11.

ON-ORBIT SYSTEM IDENTIFICATION

The design of high precision vibration and pointing control systems for future large space structures will require an accurate mathematical model of the plant. Currently mathematical models are obtained using either distributed or lumped parameter methods. In the latter category, finite element modeling codes (e.g., NASTRAN) have become very popular. However, unmodeled variations in the physical/material properties and unmodeled nonlinearities such as joints result in large errors in the frequency and shape of the higher modes. For the current class of spacecraft, extensive ground based modal testing can be done to validate/update the mathematical model. However, for future large space structures, the large physical size coupled with in some cases extreme structural flexibility will preclude accurate ground based parameter identification tests. A solution to this problem, which has gained popularity, is to perform on orbit system identification. Currently there are available a large class of methods which have been used for ground based parameter identification of diverse plants. It is, however, not clear which of these methods, if any, could be adapted to perform on-orbit system identification. With this in mind, AFRPL funded a study with the American Society of Civil Engineers. This study (being performed by a committee of experts in the area of system identification) will identify areas requiring future effort.

Need: Accurate System Model a Must for Precise Pointing and Control of LSS

Problems in Structural Modeling

- No Information on Modal Damping
- Higher Modal Frequencies in Substantial Error
- Unmodeled Variations in Physical and Material Properties
- Unmodeled Nonlinearities Such as Joints

Problems in Ground Testing

- Difficult/Impossible to Test Flexible LSS on Ground
- Gravity Bias
- Atmospheric Effects

A Solution: On Orbit System Identification

Figure 12.

NONUNIQUENESS IN IDENTIFICATION

Mathematical modeling of dynamic systems involves the creation of a model by the analyst and prediction of the response of the system to given excitations. The idea is to measure the dynamic responses for the same inputs and update the model so as to minimize the difference between the predicted and measured responses. However, contrary to expectations, it was found that elimination of the mismatch in the time histories was not sufficient to guarantee unique identification (ref. 4). Also a preliminary study revealed that by properly locating the sensors, one can obtain unique identification.

The objective of this effort is to develop and test by computer simulations a methodology for optimally locating sensors in a large space structure so as to enable unique identification of its structural model.

Problems With Current Techniques

* Identification Problem is in General ill Posed
  * Large Number of Sensors Required
  * Large Amount of Data Generated

Issues Addressed in Current Effort

* Optimal Sensor Location for Unique Identification
* Minimum Number of Sensors Required
* Data Compression Techniques to Alleviate Data Handling
* Numerical Studies to Assess the Efficacy of Methods Proposed

Figure 13.

MODELING AND CONTROL OF FLEXIBLE STRUCTURES

Recent research in control system theory showed that in feedback systems with a time delay in the feedback loop (regardless of how small the delay may be), there is a potential of instability in the system (ref. 5). Since the delay in the feedback loop could be caused by sensors, actuators or control electronics, this is of concern in many control systems. Another question which has currently received a lot of attention is at what stage of the control system design process a truncated model of the distributed system adequate. Numerous examples are available to demonstrate that a truncated finite element model which is fully adequate for determining the open loop system response is inadequate for control system design.

This program is addressing the issue of modeling and control of distributed systems with delay and inherent structural damping. The modeling approach involves starting out with the necessary partial differential equations without modal truncation. The control problem is then formulated and its "solution" determined without introducing any approximations. The system is then truncated so as to numerically calculate the time varying gains (for details of the method see ref. 5). This effort will also address the question of the feasibility of developing a general purpose computer program which can implement the methodology.

Issue

Potential of Instability in Feedback Systems Due to Time Delay in Sensors & Actuators

* **Potential of Instability Regardless of the Magnitude of Delay**
* **Addition of Damping Tends to Reduce Instability**

Current Program

* **Investigate Modeling & Control of Distributed System with Delay and Structural Damping**
* **Develop Damping Models for Adequately Modeling Joints**
* **Feasibility of a General Purpose Computer Program**

Figure 14.

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