CONTROLS FOR LSS

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AGENDA

In this presentation we wish to summarize the various activities currently being carried out at JPL in the areas of control development for Large Space Structures. Secondly, we also wish to highlight some of the associated control problems.

The JPL activities are currently concentrated in 3 primary areas:

LSS MODELING

TECHNOLOGY IDENTIFICATION AND DEVELOPMENT

TECHNOLOGY APPLICATION AND PERFORMANCE EVALUATION

AGENDA

- CONTROL DEVELOPMENT OVERVIEW
- LSS MODELING FOR CONTROL SYNTHESIS
- TECHNOLOGY IDENTIFICATION AND DEVELOPMENT
- TECHNOLOGY APPLICATION AND PERFORMANCE EVALUATION

CONTROL DEVELOPMENT OVERVIEW

This viewgraph summarizes in a graphical form the interrelationships existing between the various elements of a controls development program for LSS.

A. LSS MODELING FOR CONTROL SYNTHESIS (Upper Left)

One of the areas that has been under intense investigation is that of modeling for controller design. This is widely recognized to be a major and, as yet, unresolved problem in achieving control of LSS.

B. TECHNOLOGY IDENTIFICATION AND DEVELOPMENT (Lower Left)

Another area of intense investigation is the identification and development of advanced control technology which will be required for the control of LSS. Substantial developments will be needed in the areas of distributed control, model order reduction/estimation, non-collocated sensors and actuators, static and dynamic shape control, etc.

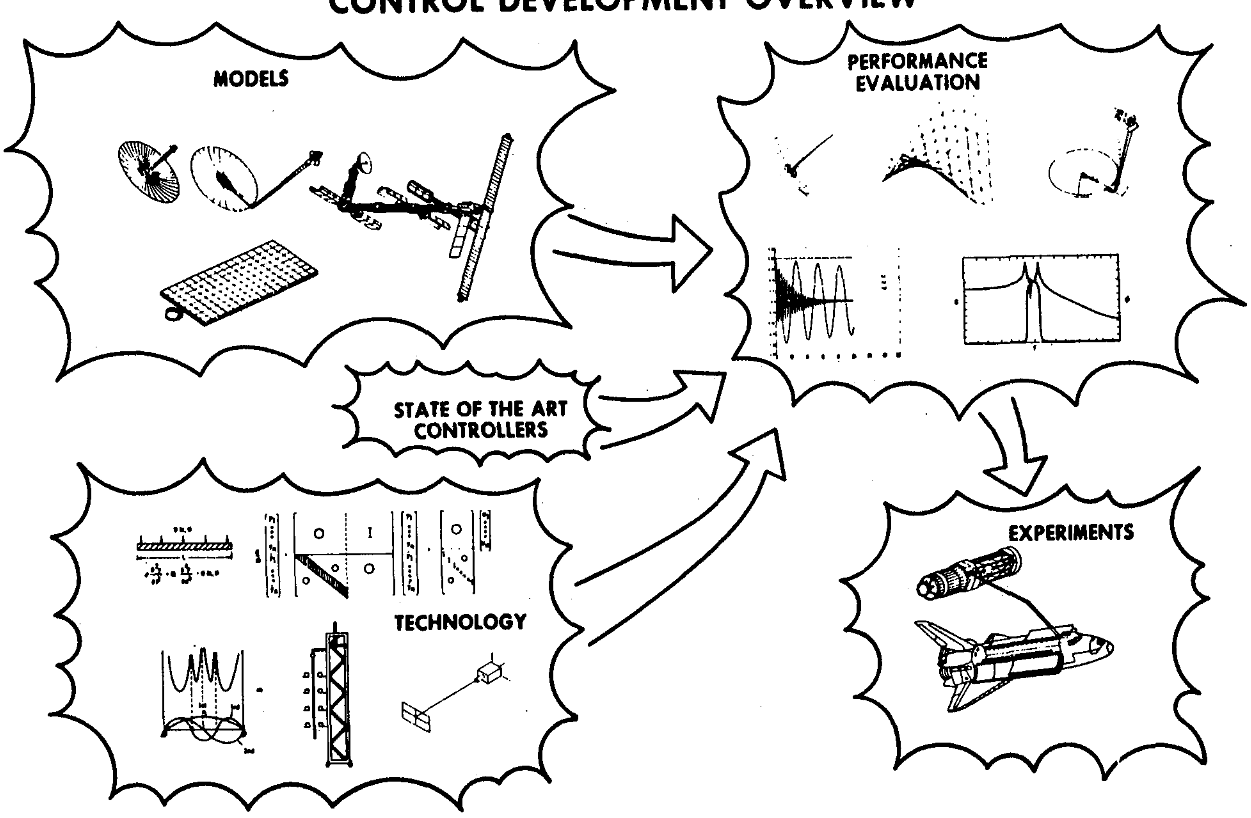
C. PERFORMANCE EVALUATION (Upper Right)

The performance afforded by current state-of-the-art control schemes as well as the limitations for their use in LSS is being assessed by means of simulations using the models developed under (A) areas found to be lacking feedback to (B) to drive the activities under TECHNOLOGY.

D. EXPERIMENTS (Lower Right)

Ultimately, the application or advanced control technology to LSS will have to be demonstrated by suitable flight experiments. Day-to-day developments will be validated through ground testing and laboratory experiments.

CONTROL DEVELOPMENT OVERVIEW



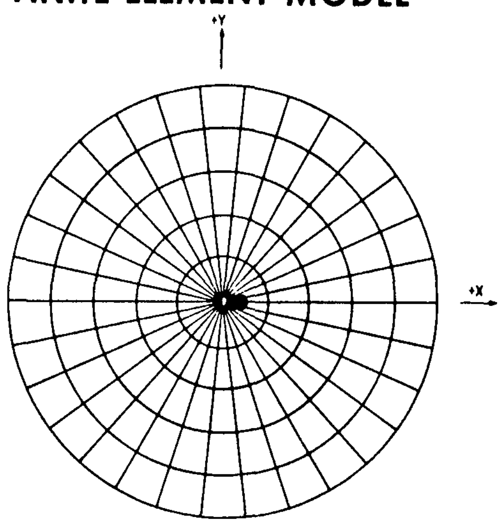
SYMMETRICALLY FED WRAP-RIB ANTENNA MODELS

A model for the 100-m diameter center-fed wrap-rib antenna has been developed to conduct attitude control and control/structure interactions analysis. The model consists of 184 nodes with 6 degrees of freedom per node. The natural modes vibration for the model have been computed and their characteristics are described on the table. The modeling activity is currently being extended to the offset feed configuration. Development of the offset feed design is required to reduce the problem of feed-support blockage.

SYMMETRICALLY FED WRAP RIB ANTENNA MODELS

- 100 meter DIAMETER
- 100 meter FEED SUPPORT
- 30 RIBS

FINITE ELEMENT MODEL



- 184 NODES PLUS REFERENCE
- 6 deg OF FREEDOM PER NODE
- 5 ELEMENT PER RIB
- GEOMETRIC STIFFNESS FOR MESH
- 4 NODES FOR BUS AND FEED

MODAL MODEL

MODE	FREQ, Hz	DESCRIPTION	CONTRIBUTING ERROR TYPE
1, 2, 3	0.00	RIGID-BODY TRANSLATION IN X, Y, Z DIRECTIONS	STATION CONTROL
4, 5, 6	0.00	RIGID-BODY ROTATIONS ABOUT X, Y, Z AXES	ATTITUDE/ POINTING CONTROL
7	0.053	REFLECTOR "UMBRELLA" MODE	DEFOCUS/GAIN
8, 9	0.065	FEED SUPPORT BENDING	POINTING
10, 11	0.073	REFLECTOR BENDING	SHAPE/GAIN
12, 13	0.094	REFLECTOR TORSION	DEFOCUS/GAIN
14, 15	0.096	REFLECTOR BENDING	SHAPE/GAIN
16, 17	0.118	REFLECTOR BENDING	SHAPE/GAIN
18, 19	0.140	REFLECTOR BENDING	SHAPE/GAIN
20	0.150	REFLECTOR TORSION	DEFOCUS/GAIN

- TO BE EXTENDED TO OFFSET FEED CONFIGURATION

MULTIPLE PAYLOAD SCIENCE APPLICATION PLATFORM (SASP) MODELS

Control technology developments are currently underway at JPL to address the attitude control of a SASP. A single axis 9 degree of freedom model has been completed. Transfer functions for this structural model have been found and controllability and observability of the 6 flexible modes has been determined. Emphasis of the study completed to date has been on obtaining a physical understanding of the parametric model developed and implications related to control system design.

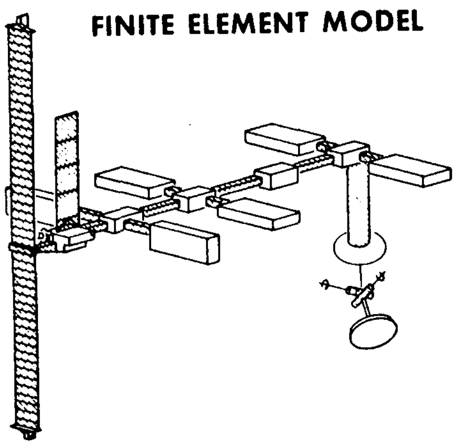
The left half of the viewgraph illustrates a fairly sophisticated structural configuration. The models developed to date consider only the solar panels, central bus structure, and the first two experiment modules (a T configuration).

The right half of the viewgraph illustrates a fairly sophisticated model for the solar panels. Such models have been developed for the solar electric propulsion vehicle and can be applied to the SASP if desired.

One of the most challenging aspects of the SASP is the interaction which results from several, possibly independent, control systems on board. Future studies will investigate the interactions of the experiment pointing control systems with the central bus control system.

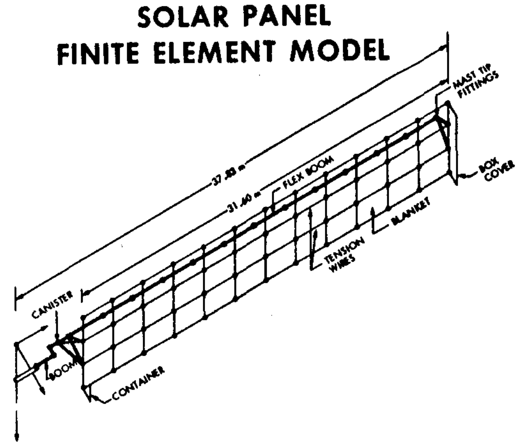
MULTIPLE PAYLOAD SCIENCE APPLICATION PLATFORM MODELS

PLATFORM FINITE ELEMENT MODEL



- SINGLE AXIS MODEL COMPLETED
- BEING EXPANDED TO INCLUDE ALL AXES AND FLEXIBLE EFFECTS
- ENABLES ANALYTICAL CONTROL/ STRUCTURE INTERACTION STUDIES

SOLAR PANEL FINITE ELEMENT MODEL



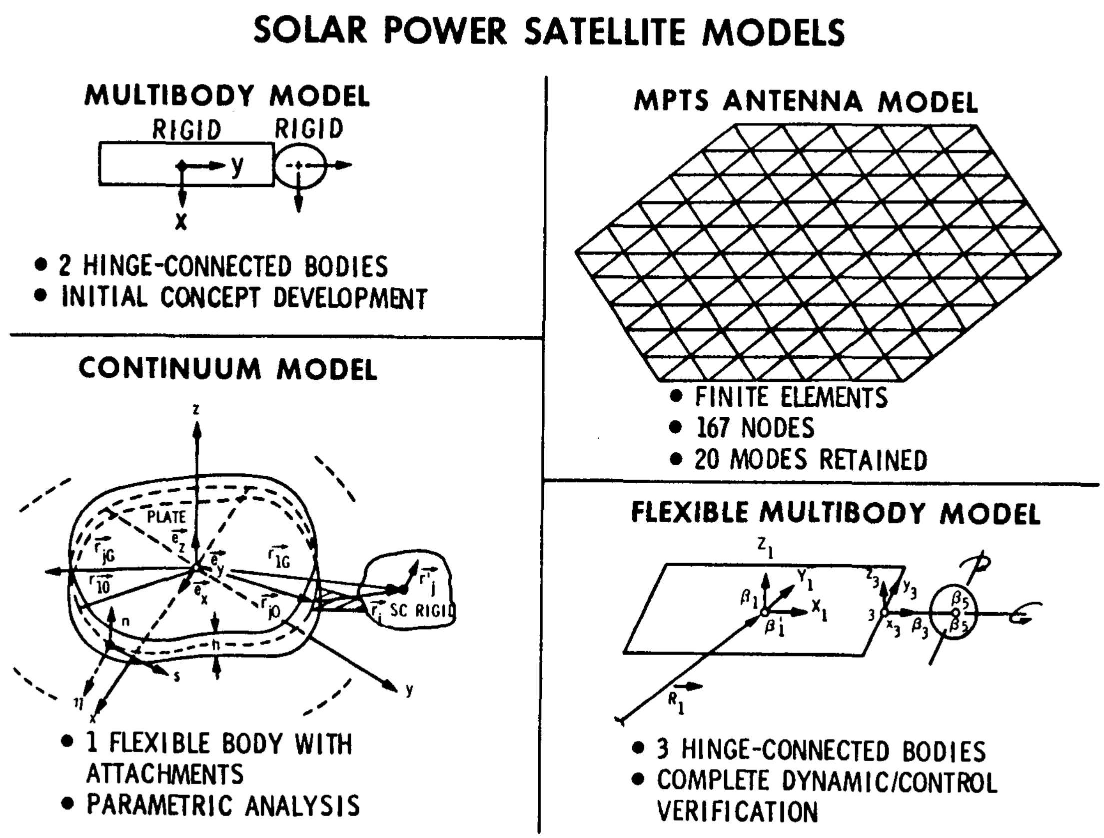
- 92 NODES
- 30 MODES RETAINED
- HINGE CONNECTED RIGID BODIES
- HYBRID COORDINATE SIMULATION
- TO BE INTEGRATED WITH PLATFORM MODEL

SOLAR POWER SATELLITE MODELS

The SPS is the largest space system conceived to date that appears feasible with reasonable extensions of existing control technology. It represents a class of large platform-like structures that are several orders of magnitude larger than any of the other large space systems planned to date. The SPS has in common with all large space systems many control problems that are widely recognized within the controls community. The greatest need at the present time is to investigate the dynamics and control problems to assess performance of selected control concepts, and to identify and initiate development of advanced control technology that would enhance feasibility and performance of the SPS system.

One of the areas that has been under intense investigation is of modeling for controller design. This is widely recognized to be a major and as yet an unresolved problem in achieving precise control of large space systems. This problem arises because, to satisfy performance requirements, the control system must have the means for predicting very accurately the vehicle dynamic response. Yet, a precise large structure model is difficult to obtain because of the infinite degrees-of-freedom, nonlinearities, parameter uncertainty, difficulties in pre-flight dynamics testing, etc. This implies that the model in the control system design is at best a truncated approximation of the actual vehicle dynamics. A systematic selection of this approximate model is required.

Four distinct approaches have been developed in order to systematically select the controller design model. The models consist of a hinge-connected multibody model to conduct attitude dynamics and control studies, a continuum model to perform parametric studies of control/structure interaction dynamics, a complete flexible multibody model for performance prediction based on a comprehensive description of the vehicle dynamics, and a finite element model for the MPTS antenna for the study of structure deformation and prediction of scan losses due to local slope variations. Dynamic studies and parametric analysis using these models have revealed significant properties and provided insight to the dynamic behavior of the system. Our current emphasis is to apply these results to investigate the control problems.



CONTROLS FOR LSS-TECHNOLOGY IDENTIFICATION AND DEVELOPMENT

As a result of the modeling activities for specific systems described in previous viewgraphs, a number of critical technology areas have been identified requiring further development. Current emphasis is in the areas of: 1) distributed control to achieve precise attitude and shape of large parabolic relfectors, 2) model order reduction required to find the best pre-flight dynamical models for controller design, 3) solution of the stability problems due to sensor and actuator noncolocation, 4) model error estimation for on-board detection and estimation of inevitable model errors such as parameter uncertainties, non-linearities, etc., 5) static and dynamic shape control necessary to remove structural biases due to thermal distortion, manufacturing tolerances, etc.

Future work will include: 1) development of adaptive estimation techniques required for on-board configuration of modeling deficiencies, 2) definition of sensing and actuation concepts for mechanization of distributed control in a representative application, and 3) laboratory demonstration of advanced concepts in a flexible-beam facility described in subsequent viewgraphs.

Space limitations preclude a detailed discussion of all of the foregoing areas. Emphasis will be focused in particular on unique approahces to the problem of shape control currently under investigation.

TECHNOLOGY IDENTIFICATION AND DEVELOPMENT

- CURRENT EMPHASIS
  - DISTRIBUTED CONTROL
  - MODEL ORDER REDUCTION
  - NON-COLOCATED SENSORS AND ACTUATORS
  - MODEL ERROR ESTIMATION
  - ⟹ STATIC AND DYNAMIC SHAPE CONTROL
- FUTURE WORK
  - ADAPTIVE ESTIMATION TECHNIQUES
  - SENSING AND ACTUATING CONCEPTS FOR DISTRIBUTED CONTROL
  - LABORATORY DEMONSTRATION OF ADVANCED CONTROL CONCEPTS

STATIC SHAPE CONTROL

Lightweight flexible space structures are being designed which will exhibit dynamic shape variations greater than those of any previous spacecraft. The technology for providing the shape control necessary for adequate performance of these structures remains to be developed.

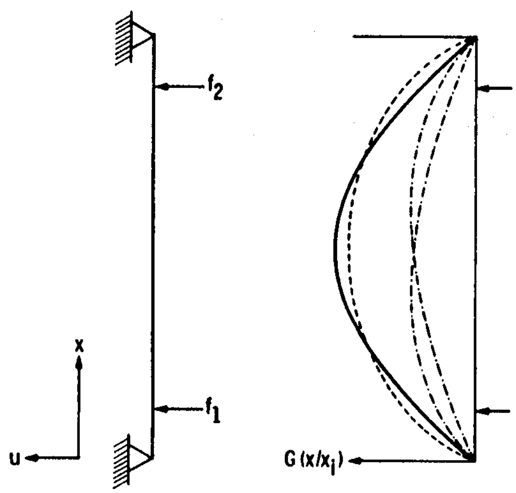
At JPL an approach using the Green's function, or influence coefficient, is being developed for representative system models. Shape control can be achieved by actuators placed at point locations along the structure. A system model consisting of a partial differential equation representing the change in shape, the right side of which represents a sum of forces f_i applied at the positions x_i, is displayed on the viewgraph.

The Green's function represents the response of the structure to a force of magnitude 1 at one point. Thus the total response (shape) of the structure is merely the sum of the Green's functions multiplied by the forces at each point. The viewgraph displays the visual interpretation of this fact for two forces.

As an example of this approach, suppose we wish to achieve some desired, say, parabolic shape U(x) by means of two forces applied as shown in the figure. The objective is to find the magnitude of the forces f_1 and f_2 which result in the best approximation to U(x) in the mean square sense. The solution to this problem is easily obtained by replacing the shape by its expression in terms of the unknown forces and the Green's functions. Standard minimization techniques can then be applied to obtain the optimum forces.

STATIC SHAPE CONTROL

SIMPLY SUPPORTED BEAM | GREEN'S FUNCTIONS | ERROR AND EFFORT MINIMIZATION



$$\frac{\partial u^4}{\partial x^4} + \Omega \frac{\partial^2 u}{\partial t^2} = \sum_i \delta(x-x_i)\cdot f(x_i) \quad (\Omega \frac{\partial^2 u}{\partial t^2} \to 0)$$

$\Longrightarrow G(x/x_i)$

$$E(F) = \int_0^{\ell} \left[U(x) - u(x)\right]^2 dx + q\sum_i f_i^2 \quad (q\sum_i f_i^2 \to 0)$$

WHERE:

$$u(x) = \sum_i G(x/x_i) f_i$$

U(x) = DESIRED SHAPE

SET: $\frac{dE(F)}{dF} = 0$ SOLVE FOR: $F = \begin{vmatrix} f_1 \\ f_2 \end{vmatrix}$

GREEN'S FUNCTIONS -·-·-·-·-
ACHIEVED SHAPE - - - - - - -
DESIRED SHAPE ————

SHAPE CONTROL - GREEN'S FUNCTION APPLICATION CONSIDERATIONS

While Green's function techniques apply to linear system models, non-linear models may be accommodated by solving successive iterations using linearized models.

In addition to the ease with which the Green's function handles a combination of continuous and discrete (pointwise) functions, and enables constrained optimization problems to be solved, the theory provides readily computed approximate solutions to any desired accuracy through the use of eigenfunction (modal) expansions. The approach possesses nearly limitless practical and theoretical advantages.

GREEN'S FUNCTION APPLICATION CONSIDERATIONS

- INFLUENCE COEFFICIENTS FOR ARBITRARY ACTUATOR PLACEMENT CAN BE DETERMINED
- BASED ON LINEAR MODEL APPROXIMATION (SMALL DISPLACEMENTS)
- NON-LINEAR RANGE ACCOMODATED THROUGH ITERATION
- PROVIDES TECHNIQUE TO EVALUATE EFFECTIVENESS OF SURFACE ACTUATION SCHEMES

PERFORMANCE EVALUATION

The performance of advanced control concepts as well as conventional state-of-the-art controllers is being assessed by means of computer simulation using the structural models described earlier. This work is being carried out in three primary areas:

100 Meter Wrap Rib Antenna

Multiple Payload Science Application Payload

Solar Power Satellite

In addition, the need for actual laboratory verification of advanced control concepts has been identified and an experimental facility has been built for that purpose. The facility will permit verification of advanced control technology in the areas of vibration suppression, shape control, distributed control, adaptive control, non-collocated sensors and actuators, etc.

PERFORMANCE EVALUATION

⟹ • 100 MTR WRAP RIB ANTENNA
  - SYMMETRICALLY FED
  - OFFSET FED

• MULTIPLE PAYLOAD SCIENCE APPLICATION PLATFORM

• SOLAR POWER SATELLITE

⟹ • FLEXIBLE BEAM SHAPE CONTROL LABORATORY EXPERIMENT

PERFORMANCE EVALUATION - SYMMETRICALLY FED WRAP-RIB ANTENNA

A substantial portion of the control technology developments currently underway at JPL pertains to the attitude control of a 100-m wrap-rib antenna. Past efforts have addressed the symetrically fed antenna configuration and have resulted in the definition of 3 controller designs, the development of computer programs for simulation of the combined control/structure dynamics, and the generation of surface performance estimates for the attitude control design.

Recent efforts are being focused on the offset-fed antenna configuration discussed later.

PERFORMANCE EVALUATION

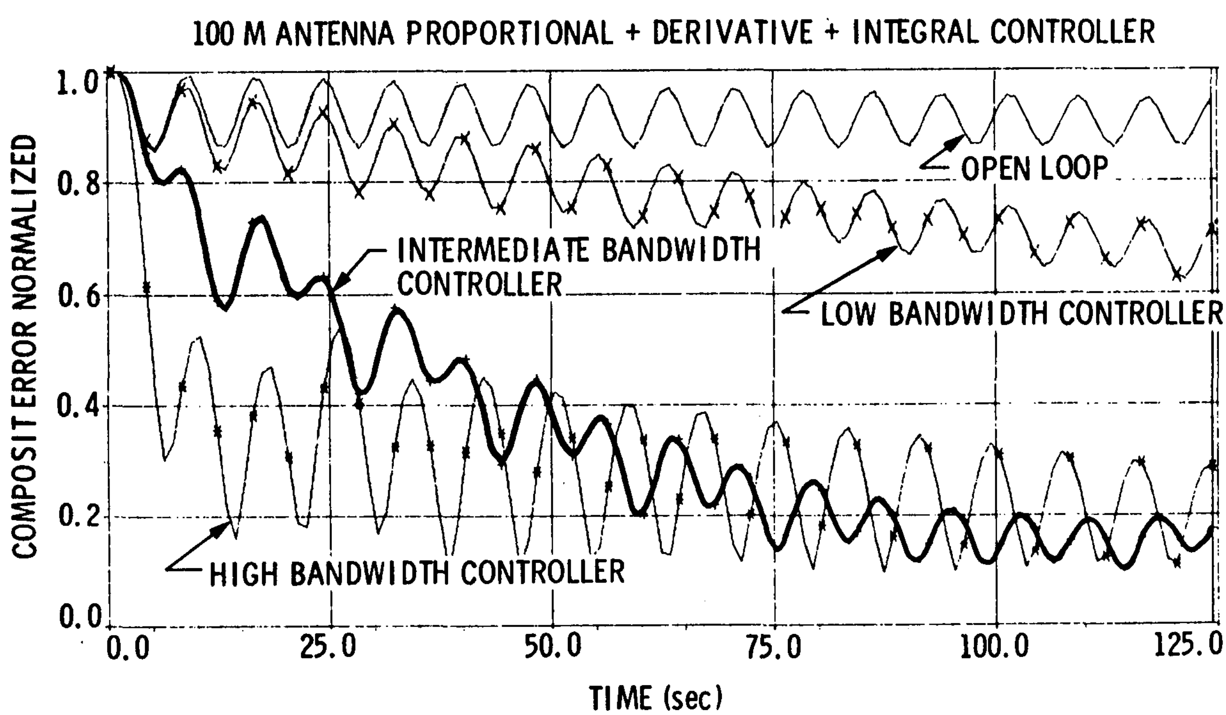
- SYMMETRICALLY FED WRAP RIB ANTENNA
  - ALTERNATE LUMPED CONTROLLERS DEFINED
    - PROPORTIONAL + DERIVATIVE
    - PROPORTIONAL + DERIVATIVE + INTEGERAL
    - OPTIMAL CONTROL DESIGN-MULTIPLE CRITERIA
  - LARGE SCALE CONTROL/STRUCTURE DYNAMIC SIMULATION
    - DISCRETE TIME-MODAL COORDINATES
    - 14 VIBRATIONAL MODES PLUS RIGID BODY RESPONSE
    - 3 DIMENSIONAL DYNAMIC DISPLAY
    - POINTING AND SURFACE DISTORTION COMPUTATION
  - COMPUTATION OF RF PARAMETERS BEING INCORPORATED

PERFORMANCE EVALUATION - SIMULATION RESULTS FOR SYMMETRICALLY FED 100-M ANTENNA

The performance of various attitude control designs has been investigated by means of computer simulations. The viewgraph shows a summary of this investigation. The quantity plotted on the vertical scale is proportional to the potential energy in the system and provides therefore a global, composite indication of the vehicle dynamic response. An initial excitation results in a lightly damped oscillatory open-loop response. Damping of 0.5% has been assumed for the simulation. The chart also displays the performance of three distinct types of controllers: (1) a "slow" controller with a low bandwidth, (2) an intermediate bandwidth system, and (3) a high-bandwidth or "fast" controller. It is of interest to note that the intermediate controller appears to perform better than both the fast and slow controllers. This result violates the intuitive notion that "slow" controllers are better because they provide for frequency separation between the controller bandwidth and the first natural frequency of the structure. Such results are to be expected because of the large number of modes and the highly interactive characteristics of the structure. Large structures do not always obey "rules of thumb" used in previous attitude control designs.

More important than the sample results displayed on the viewgraph is the development of the simulation capability itself. This simulation is currently being applied to determine the dynamic and control response of the offset-feed configuration.

PERFORMANCE EVALUATION SIMULATION RESULTS



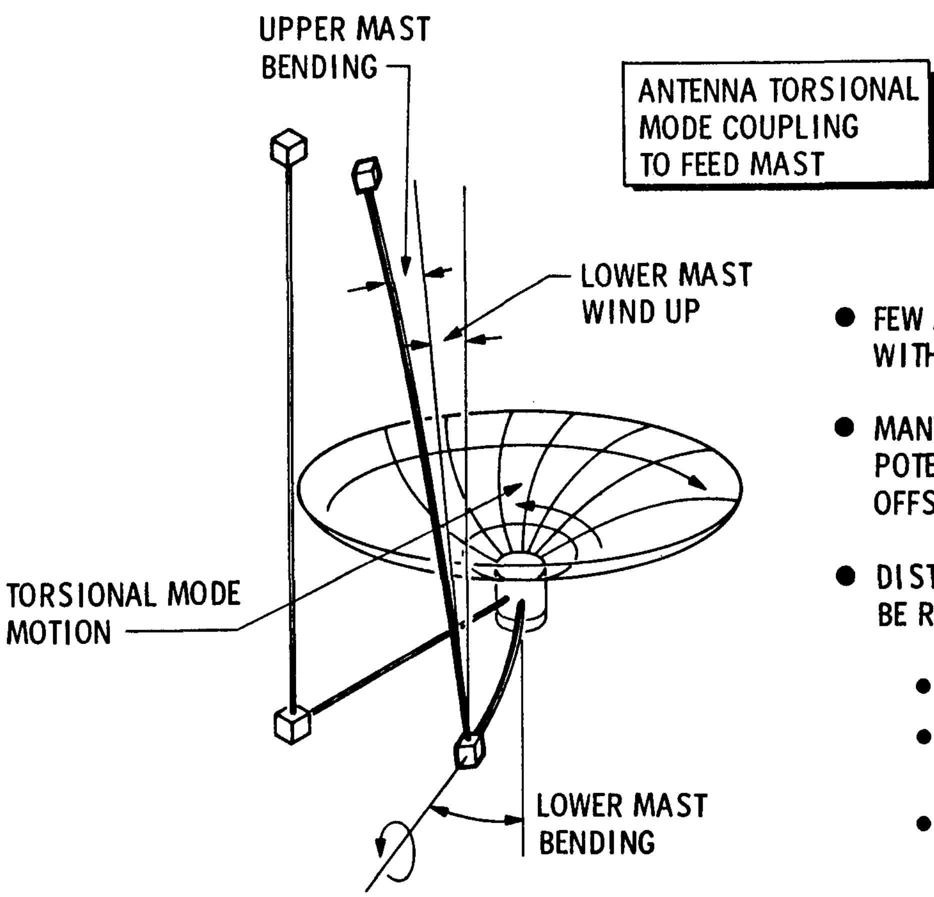
PERFORMANCE EVALUATION - OFFSET FED WRAP-RIB ANTENNA

A substantial portion of the control technology developments currently under way at JPL address the attitude control of a 100-m wrap-rib antenna configuration. The effort has resulted in the definition of preliminary attitude control designs, development of computer programs for simulation of the combined control/structure dynamics, and the generation of surface performance estimates for the attitude control design. Recent emphasis has been placed on an offset feed structure, although a center-fed antenna has also been studied in the past. Potential coupling between dish and feed mast modes makes the offset feed configuration a more challenging vehicle for control system design.

The viewgraph illustrates a total vehicle mode of the combined feed and dish components of the structure. In this mode, bending of the vertical upper mast couples with a combined bending/tension mode of the lower mast which in turn results in dish distortions. Such coupling means that the attitude control designs must account for the combined effects of overall vehicle attitude, motion of the feed with respect to the dish, and distortions of the surface shape. Additional complications arise in the offset design because of the uncertainties in the mass center location and cross products of inertia due to the lack of symmetry in the configuration.

No control technology currently exists that would guarantee successful control and inflight performance of such highly interactive systems. Substantial developments are required in the areas of distributed control, precision pointing, shape and feed location control in order to reduce the risk of attempting to fly these systems without the required control technology developments.

PERFORMANCE EVALUATION
OFFSET FED WRAP RIB ANTENNA



- FEW ANTENNA MODES COUPLE WITH SYMMETRICAL FEED MAST
- MANY ANTENNA MODES HAVE POTENTIAL FOR COUPLING TO OFFSET FEED MAST
- DISTRIBUTED CONTROL WILL BE REQUIRED FOR:
  - POINTING
  - SHAPE AND FEED LOCATION CONTROL
  - VIBRATION SUPPRESSION

PERFORMANCE EVALUATION - LABORATORY VERIFICATION

Large structures are infinite-dimensional systems that cannot be characterized fully by any model. Consequently, the controller design models will suffer from inevitable deficiencies due to truncated modes, parameter uncertainties, neglected nonlinearities and external disturbances. Such inevitable model errors will result in degraded performance and even overall unstable system behavior. The problem is not insoluble as approaches are currently under development that would guarantee satisfactory performance even in the presence of the modeling errors. However, substantial control technology developments must be carried out in the areas of distributed control, adaptive systems, and model order reduction in order to guarantee satisfactory overall system performance. Ultimately, the application of such control technology to LSS will have to be demonstrated by suitable flight experiments. However, the day-to-day developments will have to be validated through ground testing and laboratory experiments.

This viewgraph shows a photograph of one such laboratory experimental facility developed at JPL. The experiment consists of a hanging pinned-free 12-1/2 foot long stainless steel beam (6" wide, 1/32" thick). This configuration results in modal frequencies of 0.30, 0.74, 1.32, 2.00, 3.22, 5.72... hertz, and easily observed mode shapes. Four non-contacting eddy current position sensors and three brushless d.c. motor force actuators may be mounted at any station along the length of the beam. A microprocessor controller implements the estimation and control algorithms by sampling the sensors, updating the state estimates, and outputting the control command. The sample rate for a six state controller is twenty hertz.

PERFORMANCE EVALUATION

LABORATORY VERIFICATION

- VIBRATION SUPPRESSION
- STATIC SHAPE CONTROL
- DISTRIBUTED CONTROL
- ADAPTIVE CONTROL
- NON COLOCATED SENSORS AND ACTUATORS

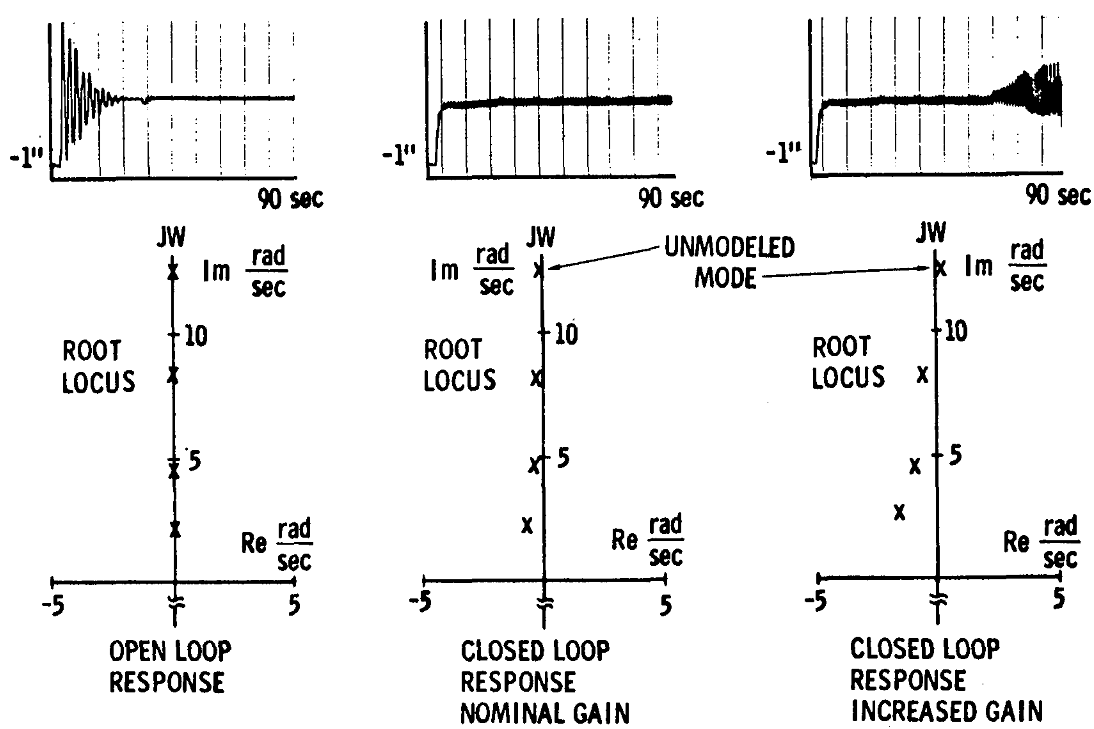
PERFORMANCE EVALUATION - BEAM EXPERIMENT

A major and as yet unsolved problem that will occur in the offset feed system is that of modeling for controller design. In order to achieve precise attitude and vibration control, the control system must have the means for predicting very accurately the vehicle dynamic response. For instance, a sufficiently precise model must be available to predict the feed-mast/dish interactions described earlier in order for the control system to reduce the resulting degradations in vehicle performance. However, paradoxically, such models are currently nonexistent for the offset-feed system and, in fact, will not become available in-flight until dynamical testing is carried out.

The viewgraph shows a concise statement of the modeling problem that is common to all large space systems including the offset-feed antenna. The viewgraph displays the response of a 12-1/2 foot flexible-beam experimental facility developed at JPL to verify control technology developments. The chart on the left corresponds to the response of the structure under an initial excitation. The response is governed primarily by a total of four natural modes of vibration. To illustrate the problems due to model truncation the control system design was based on the first three system modes without the inclusion of the fourth vibrational mode. The performance of the system is illustrated in the center of the viewgraph. The system very quickly reduces the initial excitation. However, as a result of the mode that was left out of the controller design, the system exhibits a residual oscillation that persisted throughout the duration of the experiment. The chart on the right of the viewgraph shows an even more unstable behavior due to an increase in the control system gain. The message left by this experiment is that degraded performance (as shown on the second chart) and even instabilities (as shown in the third chart) can and indeed do arise as a result of inaccuracies in the control system dynamical models.

While the hardware verification experiment has been performed on a flexible-beam model and not on the antenna systems, the results are generically applicable to both cases. A precise dynamical model for the antenna system will not be available as a result of any pre-flight analysis.

PERFORMANCE EVALUATION



CONCLUSIONS AND OBSERVATIONS

A summary has been presented of the various activities being carried out at JPL in the area of control development for Large Space Structures. From the foregoing, the following conclusions/observations can be made.

- No control technology currently exists that guarantees successful control and in-flight performance of highly interactive, flexible, large structures. A vigorous development effort in control technology is essential in order to reduce the high risk factor if we were to fly such systems without the necessary control technology development.

- New technologies should be validated, as far as possible, with ground testing/experiments design to minimize the effects of the ground environment. Larger structures not amenable to ground testing will require flight testing to characterize their dynamics and control/dynamic interactions. Such testing will be essential until control technology is sufficiently advanced to provide controllers which are insensitive or adaptive to dynamic uncertainties.

- The challenges of large structures bridge across traditional divisision by disciplines such as Controls, Mechanisms, Propulsion, Structures, Temperature Control, etc. The challenges are such that only an integrated design approach encompassing all these disciplines will enable future Large Space Systems.

CONCLUSIONS/OBSERVATIONS

- LSS INTRODUCE NEW CLASSES OF CONTROL TECHNOLOGY REQUIREMENTS AND A VIGOROUS DEVELOPMENT EFFORT IS ESSENTIAL

- NEW TECHNIQUES SHOULD BE VALIDATED WITH LABORATORY EXPERIMENTS DESIGNED TO MINIMIZE THE EFFECTS OF THE GROUND ENVIRONMENT

- LSS WILL HAVE SIGNIFICANT DYNAMIC UNCERTAINTY DUE TO MODELING ERRORS AND THE UNTESTIBILITY OF THESE SYSTEMS IN THE GROUND ENVIRONMENT

- FLIGHT TESTS WILL BE REQUIRED TO ADEQUATELY CHARACTERIZE THE DYNAMICS UNTIL CONTROL TECHNOLOGY PROVIDES CONTROLLERS INSENSITIVE OR ADAPTIVE TO DYNAMIC UNCERTAINTIES

- ONLY AN INTEGRATED CONTROL/STRUCTURE/MISSION DESIGN APPROACH WILL ENABLE FUTURE LARGE SPACE SYSTEMS