SECOND FORUM ON SPACE STRUCTURES

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ISSUES IN LARGE SPACE STRUCTURES
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This document consists of summaries of presentations and discussions from the Forum, which was a meeting for investigators of structural dynamics and control issues in large space structures technology held 11-13 June 1984. The major issues considered are modeling of spacecraft structures, passive and active control techniques, integrated design of structure and control, and experiment and implementation (hardware related) topics such as sensors, actuators, test techniques, etc. The current status of the technology is reviewed, deficiencies are identified, and recommendations for future research are made.

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INTRODUCTION

This document is the final report of the Second Forum on Space Structures held in McLean, Virginia on 11-13 June 1984. Over sixty researchers in the technology areas of structural dynamics and vehicle controls gathered to discuss issues of common interest and concern about application of their technologies to the development and operation of future spacecraft in the category generally referred to as Large Space Structures, or LSS for short. This was a follow-on to the First Forum on Space Structures held at MIT on 7-8 September 1983.

Both meetings were unusual inasmuch as there was a deliberate effort made to minimize formal presentations of technical papers and maximize informal discussion of issues. The meeting organizers felt that this would promote greater interaction and exchange of ideas among participants and lead to an effective assessment of current capabilities and future potentials. The first Forum was totally unstructured in format and was highly acclaimed by the twenty-five or so attendees for the intensity of discussion it generated. For the second Forum, an anticipated three-fold increase in the number of participants necessitated the following loose structure: each attendee selected one of five panels on which to serve during the discussions, and each panel focused on one of the following subject areas:

1. Structure/Plant Modeling
2. Active Control
3. Passive Control
4. Integrated Design of Structure and Control
5. Hardware Issues

Each panel selected one member to serve as spokesman and coordinator. Each spokesman was charged with writing a summary report on the issues discussed at the Forum that fell within his panel's focus area. The spokesmen have therefore been identified in this document as the authors of the various summary reports. The one exception is the Hardware Issues report: almost every member of that panel elected to provide a separate short report on an issue of particular concern to that individual. These short reports were organized into a single summary report by the two panel members who are identified as the authors of the Hardware Issues report.

The membership of each panel is listed in Appendix A. Appendix B is a complete list of all Forum participants, with their affiliations, addresses, and phone numbers, as well as sponsor topics and research interests. The sponsor topics are subjects of discussion that the participants proposed prior to the Forum; the eventual meeting format was based in part on these proposed topics. The research interests are subjects mentioned by the participants during the initial session of the Forum, which was devoted to brief participant self-introductions.

The five summary reports that follow are intended to capture the essence and spirit of the discussions rather than to provide a detailed record of the Forum. They reflect the perceptions and recollections of the authors and the editors of what transpired. Any errors or omissions are regretted, and the editors would appreciate being notified of such in writing.

A. K. Amos
W. L. Hallauer Jr.

1. STRUCTURE/PLANT MODELING

by Daniel J. Inman

Introduction

The members of this panel elected to split the discussion of structural (or plant) modeling into five subtopics representing five areas of research in modeling. Representatives from each subtopic made short(?) presentations and led discussions in their areas. The subtopics are:

1. Issues in Multi-Body Dynamics
2. Wave Propagation
3. Stochastic Systems (random parameters)
4. Simplified and Equivalent Models and Nonlinear Modeling
5. Distributed Parameter Approach

A summary of the discussions is presented below. Where appropriate, the original author(s) of specific comments is indicated in parentheses following the remarks.

Issues in Multi-Body Dynamics

The issue posed to the multi-body dynamics investigator is the capability and computational efficiency of available software for simulating the dynamics of any system (plant/structure) which can be adequately modeled as a collection of interconnected rigid and flexible bodies subject to active control and external loading. Basic to this issue is the perception that large rotational dynamic analysis capability for large order systems is required to handle the deployment and maneuvering of large space structures. Within the aerospace community it is recognized that the program DISCOS (Dynamic Interaction Simulation of Controls and

Structure) defines the state of the art of readily available capability. Features of the program were described by Harry Frisch, and they provided a benchmark for subsequent discussion. These features are outlined briefly below. During the introductory remarks on DISCOS, emphasis was placed on what DISCOS could not do and how the current research efforts of some Forum participants are attempting to fill this void. The efforts of some other researchers were also cited.

DISCOS has a numerical simulation capability directed toward nonlinear time domain analysis, with an ability to numerically linearize resultant equations of motion. Krishnaprasad is currently directing his work toward the analytical investigation of multi-body equations of motion via modern differential geometric techniques. This work has already led to some important stability theorems for rather simple multi-body systems. Also, feedback laws for disturbance decoupling are designed using these methods. The methodology used is not restricted to simple systems and appears to be applicable to an extremely broad range of multi-body problems. Further work in this area is strongly encouraged.

Computational efficiency is always a problem of prime importance to developers of multi-body dynamics software. DISCOS is reasonably efficient for a large class of problems of practical interest, namely, problems composed of less than about 10 bodies. If problem size grows beyond this somewhat soft limit, computational efficiency can be expected to be severely compromised. As a result, new methods are under development which permit systems composed of many bodies (i.e., >20) to be considered. DISCOS is also restricted to problems with bodies which have constant mass properties, and therefore it cannot handle telescoping or deploying flexible bodies. Turner is currently attacking both of these problems. Recent work published by Turner and his colleagues is encouraging, and further work along these lines is needed.

Typical of capabilities outside the aerospace community is the DADS (Dynamic Analysis and Design System) program described by Haug. It is an outgrowth of research driven by the needs of the mechanism and (earth bound) vehicle design industry. Their needs have to a large extent been defined by extremely complex plants, while aerospace capabilities have been driven by needs associated with extremely complex controllers and relatively simple plants. A cross-fertilization of capabilities is needed. In particular, Haug's work has led to a library of joint modeling capabilities, a different approach to equation formulation and integration, and the development of the initial inroads into a practical design parameter sensitivity capability. All of this work is relevant and should be extended to meet the needs of the aerospace community.

The subject of symbolic manipulation relative to its applicability to multi-body dynamics was also discussed. Rosenthal of Stanford University and Gluck of TRW appear to be the leaders in the USA in this area. There is also an active group in Germany in this field. The work of both of the USA investigators is strongly encouraged. In the long run, their work may hold the key to a computationally efficient multi-body dynamics software capability. During the discussion period, several questions relative to modeling of the nonlinear effects of buckling were brought up. The panel members were unaware of anyone actively working on this problem via multi-body methods.

The following observations were made in presentation and discussion:

1. Developments in software for machine dynamics complement capabilities available in aerospace:

   a. More general kinematics are treated, with primarily rigid bodies.

   b. More general purpose and user oriented codes have been developed.

   c. Open and closed loop configurations can be treated.

   d. Rigid and flexible bodies are treated.

   e. General purpose control and hydraulic subsystem modeling capabilities exist.

2. Dynamic design sensitivity analysis methods have been developed for optimization of mechanical and control subsystems.

3. Geometric nonlinearity and coupling of gross motion and flexible body elastic deformation must be accounted for in dynamic analysis of controlled articulation of space structures. First order dynamic interaction of flexible body modes and gross motion variables should be expected.

4. To advance capabilities sought in design and control of large space structures, the following are suggested:

   a. Expand multi-body dynamics formulation and computer code to account for extending components (booms) and other articulated flexible subsystems.

   b. Incorporate the full range of nonlinear space structure analysis capabilities in a user oriented formulation and computer code.

   c. Extend dynamic design sensitivity analysis methods and computer code to support design of structural-control systems. Design sensitivities of both structural and control system parameters for fully nonlinear flexible systems can then be used for design optimization. (E. J. Haug)

5. Current and proposed spacecraft designs pose new and serious challenges to the spacecraft designer. Existing tools available to the control system designer include:

a. Multi-body simulation programs for generating models of spacecraft and simulating them;

b. Control system synthesis techniques based on linear quadratic optimal control theory;

c. Linear stability analysis;

d. Experimental set-ups (for partial evaluation of control law design).

It is becoming increasingly clear that large flexible spacecraft (with extensible booms, large antennas, truss-like structures, etc.) pose fundamental problems to the designer due to the NONLINEAR rigid body dynamics and the coupling of the rigid body dynamics to the multiple ELASTIC components of the spacecraft. Large elastic deformations cause severe interactions between the actuators and the structural elements. These are subjects that have not received significant analytical treatment.

The task of the designer would be greatly facilitated by a fundamental effort towards better understanding of:

1. Analytical mechanics of interconnected rigid bodies, including nonlinear stability analysis, asymptotic behavior, equilibria and bifurcations;

2. Analytical mechanics of prototype rigid-elastic configurations (careful use of Lyapunov theory in infinite dimensions), related existence-

uniqueness theory for the models, feedback control based on boundary observations, rigorous investigation of validity of modal approximations for such a prototype problem, etc.;

3. Dual-spinners with elastic components (e.g., Galileo) and related stability problems;

4. The docking problem and stability margins;

5. Coupling between orbital motion and attitude motion in very large spacecraft;

6. Nonlinear feedback laws for disturbance rejection in spacecraft, simultaneous disturbance rejection and spin stabilization; application of such control laws under special perturbations such as docking and satellite deployment.

The methods of DIFFERENTIAL GEOMETRY and modern geometric approaches to analytical mechanics have a great deal to offer in the problems listed above. (P. S. Krishnaprasad)

<u>Wave Propagation</u>

The issues addressed included the significance of travelling wave phenomena in flexible structures, their modeling and analysis, and their impact on control design. The envisioned consequences of wave propagation included:

1. Time lags involved in transmission of signals from one part of large space structures to another;

2. Dynamic consequences of <u>sudden structural failures</u> and other impulsive inputs.

One modeling approach discussed is the "transfer matrix" method. The matrices for structural elements can be defined and these are multiplied to analyze wave transmission through a multi-element system.

A tetrahedral truss has been successfully used to study impulsive excitation, and to describe wave transmission and reflection in a nondispersive modular system. Specifically, transfer matrix formulations of one-dimensional dispersive and nondispersive systems, two-dimensional dispersive lattice systems (rectangular multi-bay) and a three-dimensional dispersive lattice system (tetrahedral truss) have been accomplished. Numerical studies should be conducted. In addition, given a one-dimensional nondispersive system consisting of several segments where the reflection and transmission coefficients for each joint are also given, the input (at point p) output (at point q) relations for arbitrary pulses have been derived. Several examples of the formulation procedure were given and possible methods of solution outlined. Again, numerical studies should be conducted. This analysis can be extended to dispersive systems. In addition, wave transmission and reflection of interfaces/joints should be considered. (J. H. Williams)

In another approach, disturbance transmission through built-up, dispersive LSS is modeled in terms of member dispersion relations involving wave-mode coordinates and junction scattering matrices. Some preliminary results using this approach were discussed. From a survey of disturbance sources to the structure, it was concluded that the most severe disturbances are those with high frequency content. It was shown how active control at one junction can theoretically isolate one portion of such a structure from wave reflections.

The ensuing discussion raised the question of linearity and superposition of responses. The speakers agreed that the wave propagation techniques mentioned above are limited to linear systems. So superposition is permissible, but the methods are not applicable for nonlinear analysis. It was suggested that the method of describing functions might successfully be applied to nonlinear wave propagation analyses.

There was extensive discussion of whether finite element models (e.g., the ACOSS structural examples) could be used to analyze wave propagation. There was agreement that a large enough finite element model can be so applied. Work was cited by S. Skaar of Iowa State University on propagation in an ACOSS example.

K. C. Park of Lockheed Palo Alto Research Lab showed an example of wave propagation following an impulsive disturbance to a lattice-truss plate with 1100 members. The calculation was done with the stiffness and mass matrices of the system equations. Computer time was reduced by suppressing degrees of freedom that were unaffected, at a given instant, by the wave. Wave reflections, scattering, and other expected phenomena were properly modeled. Asked about symmetry, Park stated that in his examples, the waves did not have perfect symmetry.

Francis Moon of Cornell University mentioned a calculation by geophysicists at Columbia University, in which a finite element model was applied to study seismic waves in the earth. (H. Ashley)

Regarding the impact of travelling waves on control design, K. C. Park suggested that time lags would affect phasing of distributed sensors and the effective gains of non-colocated sensor/actuator sets. These should be accounted for in control design. It was felt that to properly address wave motions, alternative control strategies should be explored. One alternative is to control the wave propagation paths (or spatial energy distribution associated with the wave motion) in such a way as to minimize the control cost function.

Stochastic Systems

In order to more accurately predict the behavior of structures and to control them, one must incorporate system uncertainties into the modeling. These uncertainties may be in mass, damping, or stiffness, in actuator location, or in the verification with experimental data that will always have scatter. There will always be uncertainties associated with the system parameters.

It is more rational to approach the problem by properly assigning uncertainties to the variables that are not deterministic, rather than by hoping to "average" them out in the control, even if that were possible.

The analysis of dynamic systems with parametric and input uncertainties is very complex and still requires work to reach levels beyond the present single- and few-degree-of-freedom models.

Industrial need will very soon require large scale stochastic system computation capabilities, on the level of present day finite element methods. These capabilities may be merged with control once the stochastic aspects are better understood. But there is little hope for a better grasp of structural dynamics for systems that display a scatter of behavior unless models are developed that incorporate uncertainty measures. (H. Benaroya)

Simplified and Equivalent Models and Nonlinear Modeling

One issue discussed relates to remarks made by A. Stubberud, Chief Scientist of the Air Force, at the 1984 ACC in San Diego ("A Hard Look at Software"). The basic message was:

- at the theoretical level:

"To decouple the nonlinear complexity of fast, large amplitude maneuvers from the command generation and tracking problems."

- at the level of implementation:

  "To remove maneuver-independent processing complexity from general purpose software and treat it with dedicated firmware."

A proposed realization of the objectives above consists of applying developed techniques for globally equivalent linear modeling of nonlinear plants, thus presenting the controller with an "exact" linear plant model. This is done by nonlinear feedback, together with a nonlinear change of state variables. (In cases when this cannot be done, alternative methods by Junkins of VPI & SU and associates are available.) Typically, the transformed system's commanded variables are accelerations in appropriately chosen generalized coordinates.

Implementation of the transformations can be made by means of dedicated integrated circuits, forming an interface between the command generation autopilot and tracking system on one side, and plant sensors/actuators on the other.

Using the approach above, all the accumulated experience of linear guidance and control algorithm development (including Turner-Chun-Juang LQG techniques!) can be "exactly" applied to nonlinear plants, with the dedicated interface performing "automatic gain-scheduling."

The effectiveness of this approach has been demonstrated in simulation at Colorado State University, for terminal control and time optimal control (with respect to acceleration bounds), on spacecraft models with thrusters and reaction wheels, as well as to robotic manipulators. An on-going program at CSU was also reported, involving the fabrication of a nonlinear analog spacecraft simulator that communicates with a microprocessor controller through multiplexed D/A and A/D interfaces, as well as logic-circuit-based dedicated nonlinear digital interfaces. Similar hardware for the control of an existing operational 1/16th scale model of the "Canadian arm" of the Space Shuttle (built under the supervision of G. K. F. Lee) is also under development at CSU.

It should be noted that these techniques have already been validated at NASA Ames by G. Meyer and collaborators (notably R. L. Hunt and R. Su of Texas Tech University), who have designed and successfully tested helicopter autopilots by the proposed methods. The on-going program at CSU can therefore be regarded as technology transfer from V/STOL aircraft to agile spacecraft maneuvering and robotics. (The potential of application to microprocessor guidance of BTT tactical missiles is obvious, where 100 g accelerations and 500 degree per second roll rates preclude the use of linear tangential approximations.)

Further research on the methods reported lies in the following areas:

1. Derivation of transformed input and state constraints to prevent violation of "physical" actuator and plant limitations;

2. Derivation of noise statistics for the results of white noise modeled actuator and sensor disturbances after passing through the nonlinear "mathematical" interface between the nonlinear plant and the globally equivalent linear plant model: it is the resultant nonlinearly transformed non-Gaussian statistics that will affect the equivalent linear plant.

3. Extension of the method from (multi-) rigid bodies to flexible plants, first by "exact" correction of rigid motion (i.e., regarding flexibility as

a disturbance), then by seeking global linear-equivalent transformations for the coupled flexible kinematics and dynamics. (General constructive procedures and global nonlinear models by J. Bailllievl of Scientific Systems, Inc. already exist.)

4. Design of robust compensation of nonlinear plant parameter variations, to avoid changing the interface circuitry (e.g., in robotics, when load masses change according to task). Initial results on the problem were reported on the successful use of acceleration feedback. (T. A. W. Dwyer)

Two aspects of nonlinear modeling and analysis were discussed. One aspect is the asymptotic stability of multiple rigid body systems under arbitrarily large attitude maneuvers, by casting the equations of motion in the "Lie Poisson" form, thereby permitting the construction of appropriate energy dissipation forms. A recent application has been to the verification of the presumed stability of dual-spin spacecraft. The second aspect is the use of nonlinear feedback to redundant sensors and actuators, for "perfect" disturbance rejection at other sensors, in the control of nonlinear plants. A suggested application is station keeping under changing load configurations on board a space platform, or during docking maneuvers (where the direction but not time history of disturbances may be known).

The following subjects for further research were cited:

1. Preservation of attitude stability under discontinuous plant changes, e.g., when additional modules are attached to the first stage of a permanent space station, "a la Soyuz-Salyut" (It should be noted that the problem of simultaneous stabilization of more than one plant configuration has already been treated for linear plants in the recent

IEEE literature, e.g., by Saeks of Arizona State University and by Vidyasagar of Concordia University, Canada. Automatic reconfiguration after component failures is another source of problems requiring stability preservation, where adequate plant modeling is important.)

2. Location and choice of equilibria of the nonlinear plant model, around which to construct nonlinear transformations into equivalent linear models (Previous use of the term "global" in this context has referred to the correspondence between the original and the transformed system models being exact (nominally), over the region of invertibility of the coordinate transformations: thus, more than one linear plant may exist, each equivalent to the original nonlinear plant in a different parameter region.)

3. Study of the nonlinear coupling between attitude motion and orbital motion (important for, say, an orbital transfer vehicle)

4. Simultaneous stabilization and disturbance rejection for nonlinear plants (R. S. Krishnaprasad)

The continuum modeling of discrete plants ("homogenization") was addressed for both deterministic and stochastic problems. This is an area of current interest, notably at the Aerospace Corporation, as reported by M. Aswani and G. T. Tseng. The idea is to "go the other way" in modeling by generating an "average" distributed representation of a complex discrete truss structure.

One advantage of distributed homogenization is in system identification, where a distributed model can be characterized by only a few parameters (damping and stiffness coefficients of a hyperbolic PDE), rather than the enormous number of parameters characterizing individual truss members. Such distributed models reflect the regularity (e.g., periodicity) of the underlying structure.

The homogenization-asymptotic analysis method can be used to treat the combined problem of model simplification and control filtering design. This involves the analysis of the nonlinear Hamilton-Jacobi-Bellman partial differential equation for control problems and the Duncan Moztensen-Zakai stochastic PDE (for propagation of the conditional densities). Some preliminary results on these problems have recently been reported (Bensoussan-Blankenship).

A remark from Francis Moon of Cornell University brought attention to the existence of a <u>prior literature in the solid mechanics community</u>, about 10-15 years ago, <u>on continuum models for composite materials with periodic structure</u>, that should be consulted by current investigators on the subject of homogenization. (G. Blankenship)

In the argument pitting full finite element models of complex space lattice structures against equivalent continuum PDE models of such structures, perhaps there is a useful middle ground where the advantages of each method can be exploited.

As discussed in the panel, the advantages of brute force finite element modeling include prediction of local "non-continuum" modes which may be important. Advantages of the equivalent continuum PDE approach include simplification of the complex structural description (a discrete model with a very large number of degrees of freedom) to a more tractable set of continuous PDE's. The disadvantages include difficulty working with large numbers of coupled PDE's subject to nonideal boundary conditions, difficulty handling connections to other structure, and the inability to predict local modes of the lattice.

It is perceived that it is the difficulties associated with using PDE formulations as compared to using the standard elements, algorithms, programs, and supporting software for finite element models that prevents PDE formulations from being more widely employed. As the size and complexity of space lattice structures increase, the brute force method becomes less tractable even with use of such efficiency measures as dynamic reduction, super element methods, and/or component mode synthesis.

One possibility to combine the advantages of the two methods is to generate equivalent continuum finite elements based on the PDE formulation. This allows the analyst the convenience inherent within the finite element method as regards boundary conditions and connections to other types of structure while allowing the use of much smaller and more readily understandable finite element solutions. In some cases, such as the lattice-beam continuum formulation due to A. Noor of George Washington University, existing Timoshenko beam elements can be used directly. In other cases, such as Noor's lattice-plate continuum formulation, existing elements which include the necessary strain coupling (in-plane and out-of-plane coupling, transverse shear effects, etc.) may not be readily available. However, their development and implementation is relatively straightforward.

There are many large space lattice design problems for which the equivalent continuum formulations offer considerable analysis efficiency payoffs in terms of both cost and understanding. One hopes that intelligent use of the many techniques (including that mentioned above) available for PDE analysis, even under unusual boundary environments, will lead to an enhanced understanding of the dynamics of large space structures. (S. Lamberson)

Distributed Parameter Approach

It was pointed out that a physical interpretation of Gibson's criteria for convergence and stability of finite dimensional control problems has been found, namely that the distributed structure be underdamped. This condition yields simple inequalities in the physical parameters of the structure. If the parameters are chosen to satisfy these inequalities and conditions, then one has a green light to solve finite dimensional control problems. The important point here is that the condition does not depend on modal information or finite models.

This is typical of the type of result which is desired in using distributed parameter plants. Much can be gained by using the continuum approach without actually solving a partial differential equation (or set of PDE's). This approach should not be ignored as it can provide insight and guidelines for use in the finite dimensional (FEM) approaches. (D. J. Inman)

Recapitulation of Noteworthy Points

The following lists comments and questions raised during the discussion of structural modeling.

1. From comments and responses, one can suggest the following as subjects for useful further work: the role of wave propagation methods as an alternative to modal superposition for studying response of linear LSS to disturbances with high frequency content; numerical studies of transfer matrix applications to nondispersive and dispersive systems; further study of wave transmission/reflections at interface joints; the usefulness and appropriateness of large finite element models for calculating wave propagation; the generalization of these methods, if feasible, to

systems with one or more concentrated nonlinear elements, or with significant distributed nonlinearity. (H. Ashley)

2. One should use the "bag-of-tools" approach to structural dynamics, where the characteristics of the particular structure dictate which modeling method to apply, rather than attempting to force all structural dynamics evaluation into one's own favorite modeling method.
3. Can we find a universal criterion for model size based on distributed parameters, finite control gains and performance criteria?
4. There is a clear need to develop a thorough analytical understanding of coupled nonlinear rigid-elastic dynamics and control. This will help identify the limits of various design methods and make rational choices.
5. Colocation of sensors and actuator seems unrealistic; however, in the wave approach it was pointed out that lack of colocation is desired to gain computation time (a technique used in acoustics).
6. In the area of models with uncertain or stochastic parameters the question was asked: when is the parameter random and when does it just have bounded error?
7. Can we do control design from a dynamic model based upon disturbance propagation?
8. Can we marry the disturbance propagation and the modal techniques? Can one split the dynamics and the control problem into high frequency disturbance propagation, and low frequency modal methods? Would such a split be comparable to current Low Authority/High Authority control methods?

9. Can one describe disturbance propagation in lattice structures without dealing with every truss element?

10. Disturbance propagation ideas will lead to passive disturbance path design for disturbance isolation.

11. Can super elements be used as an alternative to the continuum model?

12. What are the parameter ranges over which the continuum model is an effective approximation?

13. Can the procedure of H. Frisch simplifying the model and then designing the control system be justified relative to a combined model simplification and control design?

14. Can perturbations and noise effects in the physical structure be treated in the method?

15. Can the complex mathematics used in the methods be simplified or otherwise be made accessible, i.e., can the theory be made "user friendly"?

2. PASSIVE CONTROL

by Terrence J. Hertz

Introduction

Passive structural control is the control of the state (static and/or dynamic) of the structure without the addition of power. This is accomplished by utilizing the so-called "benign" aspects of the structure such as stiffness, damping, mass, boundary conditions, and applied forcing functions. Passive control is divided into three major areas: shape control, passive damping, and materials characterization.

Shape Control

A large space structure may distort in shape statically due to a number of environmental effects. Deviation from the desirable shape due to such causes may be as significant, if not more, as distortion due to dynamic response. Passive shape control would consist of a priori distribution of stiffness (or flexibility). If the nature of possible shape aberrations is known, then the stiffness distribution may be designed into the structure to counteract the anticipated event. When counteracting the effect of shape change in the case of antennas, it is not necessary for the structure to return to its original geometry; it would be sufficient to maintain the surface in a family of surfaces, such as a paraboloid. Under a regularly changing load environment, such as in a gravity field, this can be achieved by the use of the "homology" principle [2.1, 2.2], which consists of proper allocation of member properties of the structure. Homology can be further enhanced by proper assignment of joint location, and optimization may also be incorporated in these steps, by using the optimality criteria method and the gradient projection method, respectively. The homology technique is available and has been successfully used in design and construction of antennas for radio-astronomy telescopes. This method does not add to the cost, and should be considered in design of large space structures. The receiver shown in Figure 2.1 is suitable for application of the homology technique.

In the area of passive control utilizing the stiffness property of materials, continued work to develop higher stiffness-to-mass (E/ρ) materials that have practical structural characteristics will have a high payoff. An increase of a factor of four in E/ρ could cut the modal density in half and double the lowest resonant frequency. Industrially useful graphite fibers presently have a Young's modulus of about 33-37 x 10^6 psi [2.3]. Exotic fibers with moduli in excess of 100 x 10^6 psi have been produced, but are not yet considered practical structural reinforcement material from the standpoint of cost, fracture resistance, or aging. However, the potential payoffs for large space structures make continued research and development of light weight, ultra-high modulus composites attractive.

Passive Damping

At least three sources of energy dissipation exist in a space structure. First, material damping, due to the hysteresis associated with cyclic stress in materials, is present in all structures, but represents a low background level of damping. This damping will be characterized in a following subsection. Second, the passive energy dissipation in a structure can be increased by addition of passive damping elements, such as Coulomb or viscoelastic dampers. Third, in any large structure where joints or fittings are present, there is energy dissipation associated with impacting and sliding of surfaces in contact.

Passive damping as a control measure is useful for reducing the effects of resonant vibration. The payoffs include vibration response reduction, vibration isolator effectiveness improvement, and increased active control system robustness [2.4]. One measure of this increase is a reduction in the slope of the phase change with respect to frequency at structural resonances with increased damping levels. Filters in phase-stabilized controllers can be of lower order, or gain-stability margins can be reduced because the uncertainty in the plant model translates into a smaller phase uncertainty. The effect of damping on the phase argument of a transfer function in a large space platform is shown in Figure 2.2 [2.5]. Strategically placed, localized dampers can have a similar effect. The phase plot in Figure 2.3 is the result of placing truss members with a loss factor of 0.1 between nodes 1 and 4, 4 and 5, and 4 and 7 in the model depicted [2.5].

A second contribution to robustness is suggested by the root locus plots of Figure 2.4. Here a reduced order controller, developed by an optimal control algorithm, effectively damps the lowest mode but contributes little damping to four others. Two loci approach zero rather closely on the real axis as gain is increased. For reference, equivalent modal damping values are shown as the sloped lines. Even a small amount of passive damping (1 to 5% of critical) will provide a substantial increase in stability margin by shifting the roots to the left [2.6].

The dry friction type damping can be characterized in one of two kinds. In one, the friction force acts in the direction of the motion of the structural element. The damping associated with this friction is small for both small and large deflections. The dry friction damper of this kind must be designed for the expected motion. In the second kind of dry friction damping, the friction force acts perpendicular to beam motion. Damping is small for small motion and asymptotically approaches viscous damping for large motion.

The addition of friction dampers has been examined analytically and experimentally for a tubular member of a truss structure [2.7]. The friction damper consists of segmented damping tubes placed end to end in the tubular member. Under loading, the resultant deflection causes sliding between the structural member and the damping tubes. The sliding causes frictional heating which dissipates the kinetic energy, thus damping the structural vibrations. Experiments have shown an energy loss of approximately 60%.

Joints provide the third source of energy dissipation in space structures. Ideally, the joints are designed either to rigidize the ends of the structural member, as in a clamped end, or to allow the members one or more degrees of freedom, as in a pinned end. Realistically, motion occurs in the "rigid" joints since structural deformation causes the joint to deform elastically, and motion is impeded in the pinned joint due to friction between sliding surfaces.

Energy dissipation in both types of joints has been examined in simple analyses [2.8]. The energy dissipation in joints is due to displacement dependent friction; that is, the frictional forces are due to elastic deflections rather than mechanical preloads. In sleeve stiffened joints, Figure 2.5, a maximum friction damping is obtained when the relative rotational stiffness of the joint and beam are of the same order. For pin joints in multi-element trusses, Figure 2.6, a maximum frictional damping occurs for trusses of low length/bay-depth ratio, and large pinradius/bay-depth ratio. As shown in the figure, the loss coefficient decreases when additional bays of fixed depth are added to a truss.

Among the approaches to structural damping improvement currently being researched is the incorporation of viscoelastic materials in the joints of structures while, at the same time, making the joints slightly flexible so that non-trivial strain energy levels become resident in the joints. Figure 2.7 shows the tradeoff between level of damping and increase in flexibility of an axial truss element. Practical joint concepts are under development to implement the effect shown in the figure. One concept of such a joint is shown in Figure 2.8.

For space structures, the anticipated performance trends of active and passive damping controls are shown in Figure 2.9. At low frequencies, active controls are expected to be highly effective because the important elements of the problem can be sufficiently well characterized to create effective vibration control and body attitude control. Numerous examples exist of successful engineering solutions using low order controllers such as launch vehicle navigators, stabilized platforms for optics, and the like. However, effectiveness can be expected to diminish with increasing number of modes requiring control because of estimation errors and the generally decreasing tractability of increasing control problem size. Passive damping, on the other hand, can exercise no control over rigid body modes and frequently offers inadequate control of the lower frequency modes by itself [2.4]. Its inherent advantage comes in the higher modes which decay in a short period of time at only moderate damping levels. Explicit characterization of the plant is not critical to performance and has no bearing on stability. The ratio of realized performance to expected performance can therefore be expected to increase with frequency. When used together, favorable synergisms between active and passive control can be expected [2.4].

Materials Characterization

It is expected that materials will be an important issue in the analysis and design of large space structures. Although it is not the purpose of this group to undertake the broad and difficult topic of materials characterization, it is nevertheless considered important for both control and structural models to understand both the adverse and beneficial effects of materials.

Several potentially catastrophic scenarios have been proposed to be possible results of materials problems. However, many if not most materials problems can be minimized by the proper choice of and design with materials. Temperature appears to be a driver in the selection of materials, with polymeric composites and metals used in low to moderate temperatures. Metal matrix composites and high strength metal alloys are expected to be used in high temperature situations, with ceramics also a possibility at extremely high temperatures. Temperature will certainly be a significant variable in the dynamic response of structures, although this effect can be minimized in materials with low coefficients of thermal expansion.

Passive damping is achievable through both material inelasticity and thermoelastic damping. However, some trade-off is likely between increased passive control and the ability to model the structural response, because structural materials with significant damping are both nonlinear and history dependent. Even where constitutive models exist for these materials, analysis using them is computationally implausible for all but a few structures. It is thought that a reasonably good design will necessarily require the use of materials which may have beneficial damping amounts but must have significant support from other passive damping mechanisms, such as joints, in order to provide the levels of passive damping in the structure necessary to supplement active control.

Finally, it appears that some materials which provide passive damping control will also have long term property degradation which can significantly affect frequencies and mode shapes (Figures 2.10-2.13).

Major Issues

Passive control is part of the answer to space structure control. Though attractive from the standpoint of eliminating the need for actuation and additional onboard computational power, passive control in a space structure is limited in most applications. Passive control will necessarily be augmented by active means. However, space structures designed with passive control in mind, by taking advantage of geometric and material properties of the structures, will require less active control. In regard to the complete problem of space structure control, five major issues of passive control need to be examined:

1. Examination of the feasibility of passive control techniques utilizing stiffness, mass, boundary conditions, and input forcing functions for shape control must be continued. Homology appears to be promising. Additionally, shape control may be provided by geometric or stiffness arrangements that have not been examined.
2. Models for passive damping components require further development. The analytical models of friction damping examined to date have been rather simple. The use of viscoelastic dampers should continue to be examined.

3. Realistic passive damping elements should be incorporated into structural analysis methods being developed for space structure analysis.

4. Development of integrated passive/active control design methodology is necessary for minimum weight space structures. For example, realistic passive dampers should be incorporated in control models to assess the effect.

5. Develop experiments of passive controllers and passively controlled structures to validate analytical methods.

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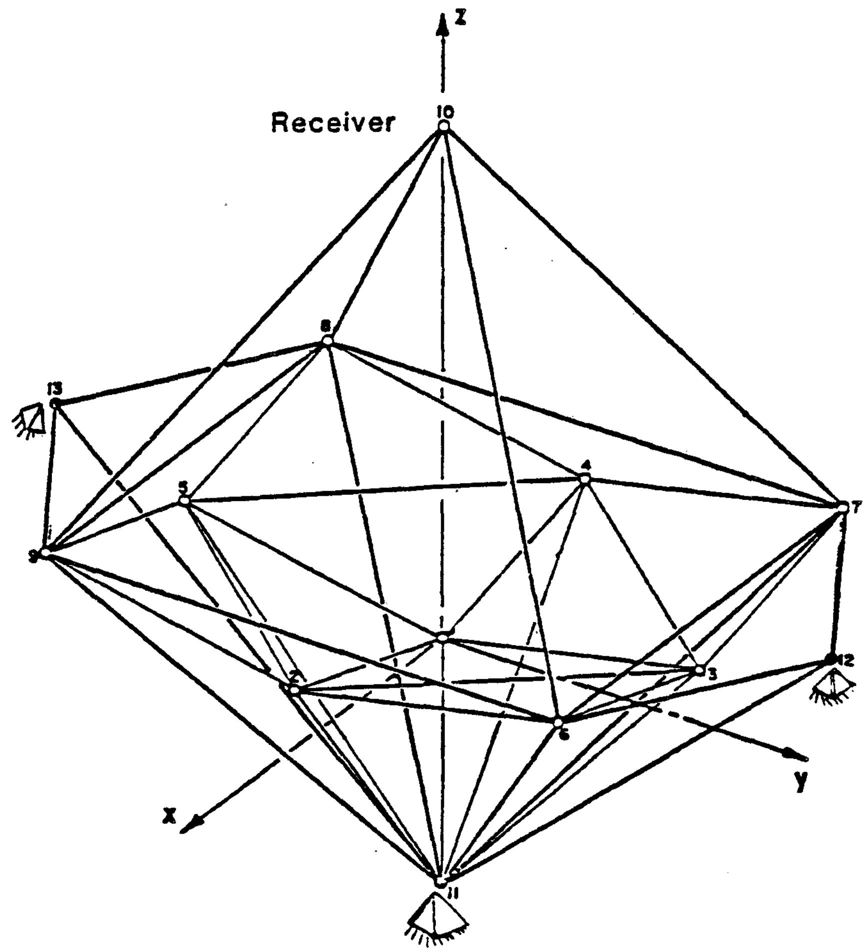


Figure 2.1

LONG T-BAR CONFIGURATION RESPONSE OF NODE 10 FROM A UNIT TORQUE

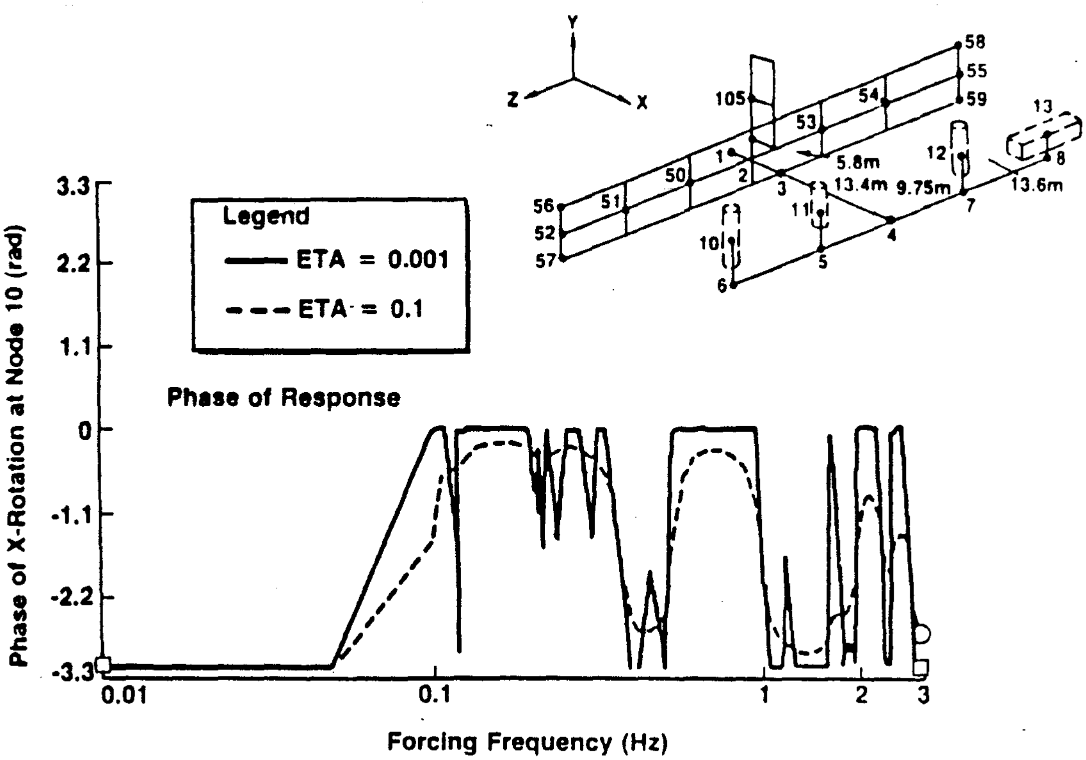


Figure 2.2

SHORT T-BAR CONFIGURATION
PHASE — ROT X10

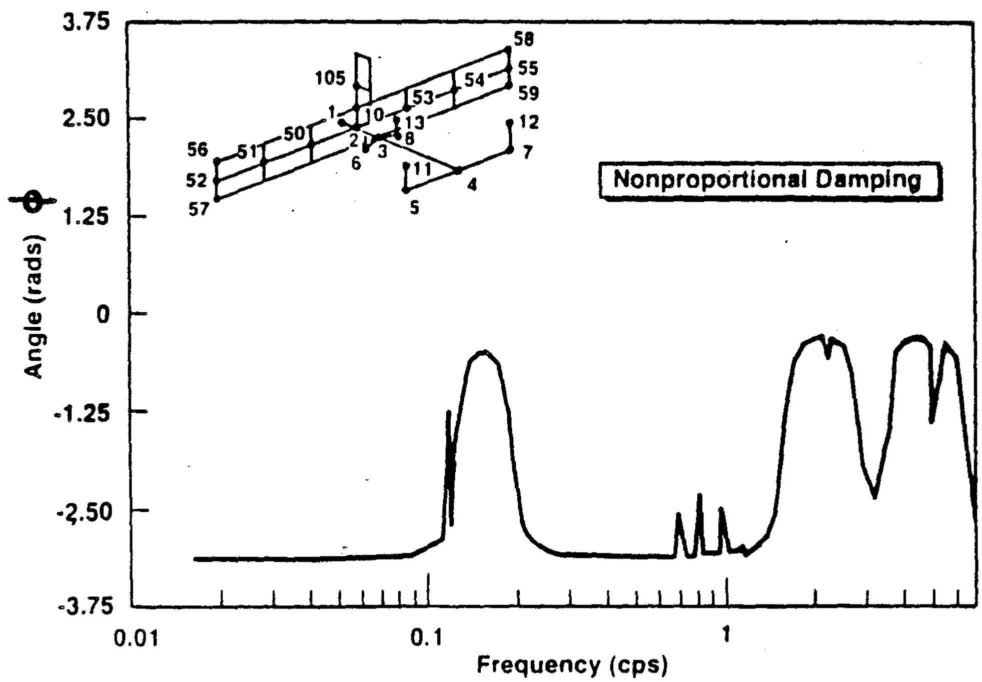


Figure 2.3

TYPICAL 4 LOOP ACTIVE DAMPING PERFORMANCE

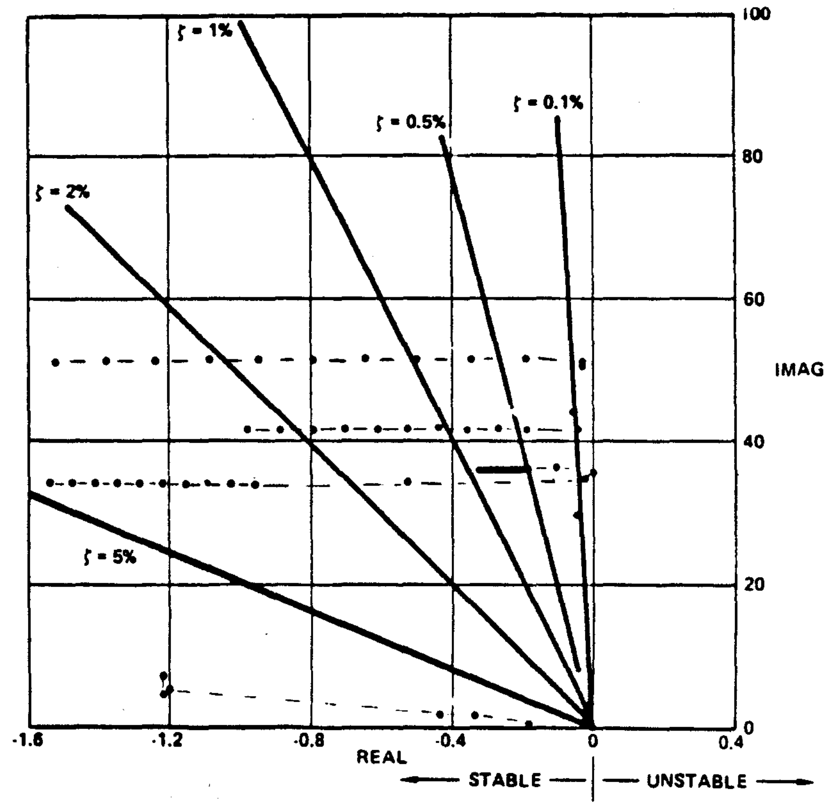


Figure 2.4

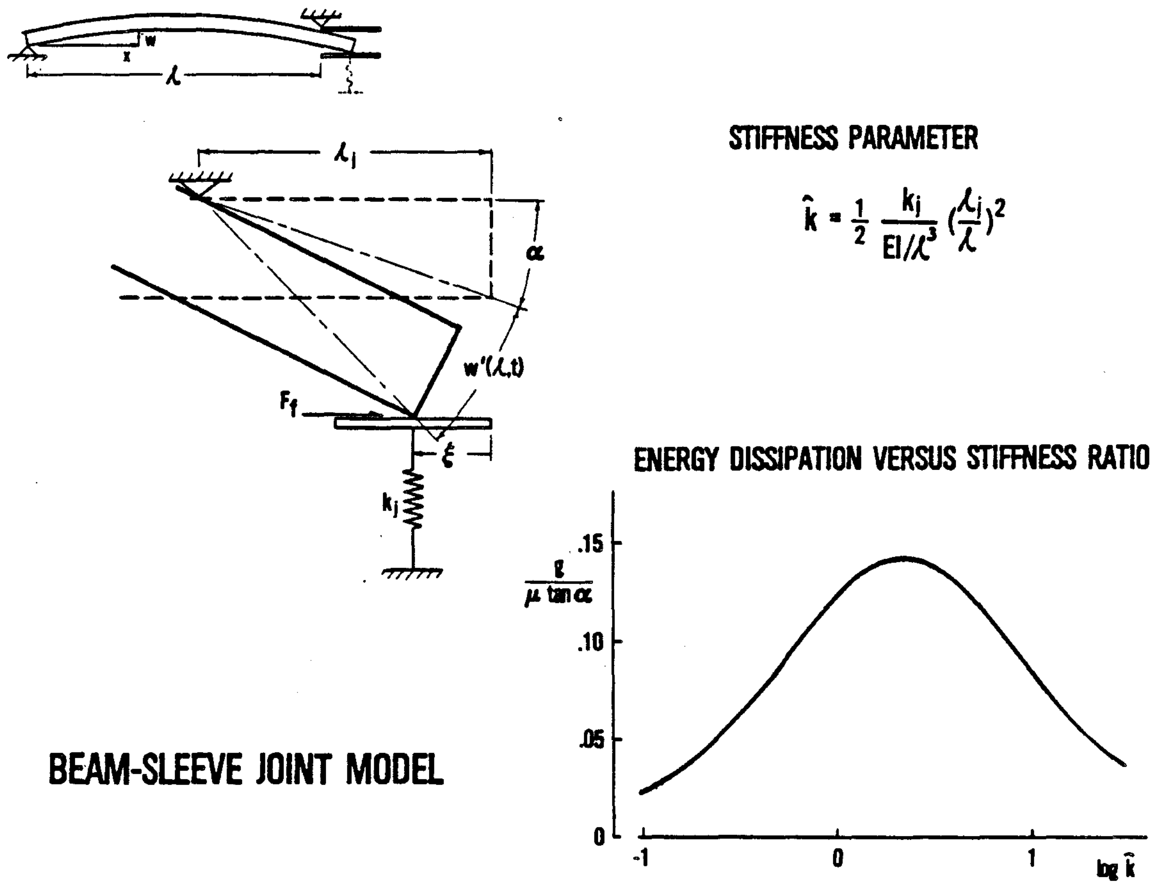

w
x
λ
λ_j
α
$w'(\lambda,t)$
F_f
ξ
k_j
BEAM-SLEEVE JOINT MODEL
STIFFNESS PARAMETER
$\hat{k} = \frac{1}{2} \frac{k_j}{EI/\lambda^3} (\frac{\lambda_j}{\lambda})^2$
ENERGY DISSIPATION VERSUS STIFFNESS RATIO
$\frac{g}{\mu \tan\alpha}$
.15
.10
.05
0
-1
0
1
$\log \hat{k}$

Figure 2.5

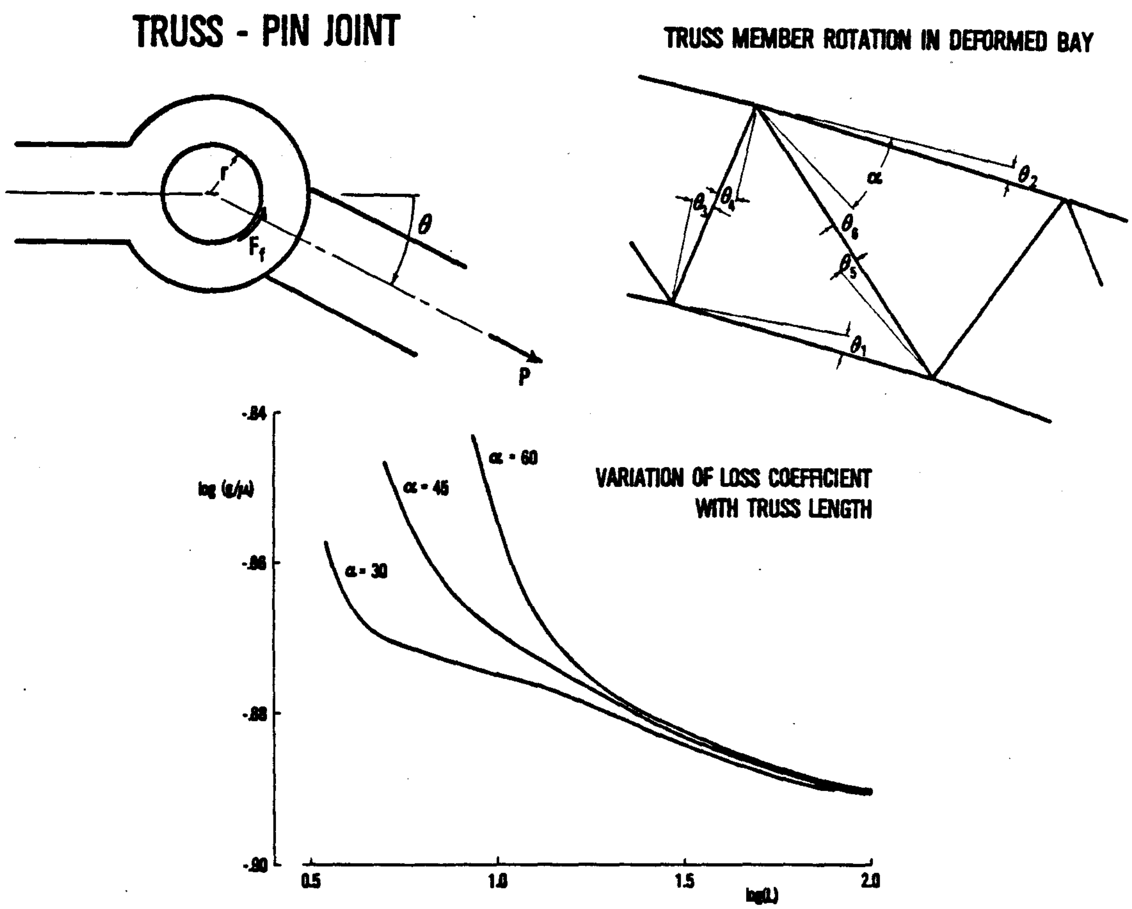

TRUSS - PIN JOINT
TRUSS MEMBER ROTATION IN DEFORMED BAY
VARIATION OF LOSS COEFFICIENT
WITH TRUSS LENGTH
α = 60
α = 45
α = 30
-.84
-.86
-.88
-.90
0.5
1.0
1.5
2.0
log(L)

Figure 2.6

VISCOELASTIC MATERIALS EFFECTIVENESS OF DAMPING TREATMENT ON STRUT EXTENSIONAL DAMPING

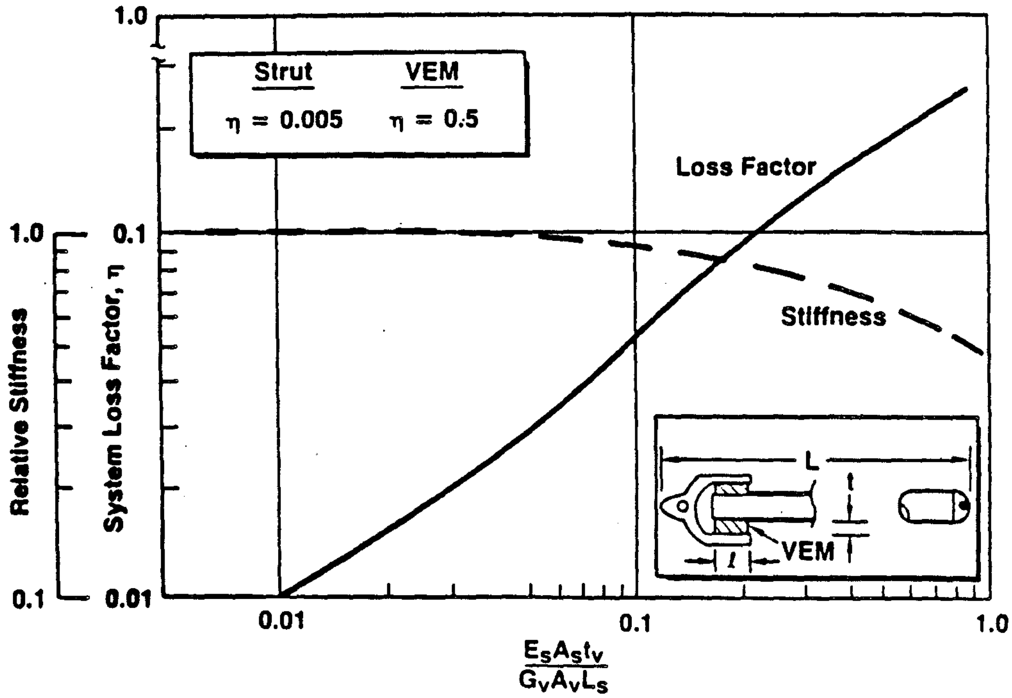


Figure 2.7

STRUCTURAL DAMPING JOINT CONFIGURATION

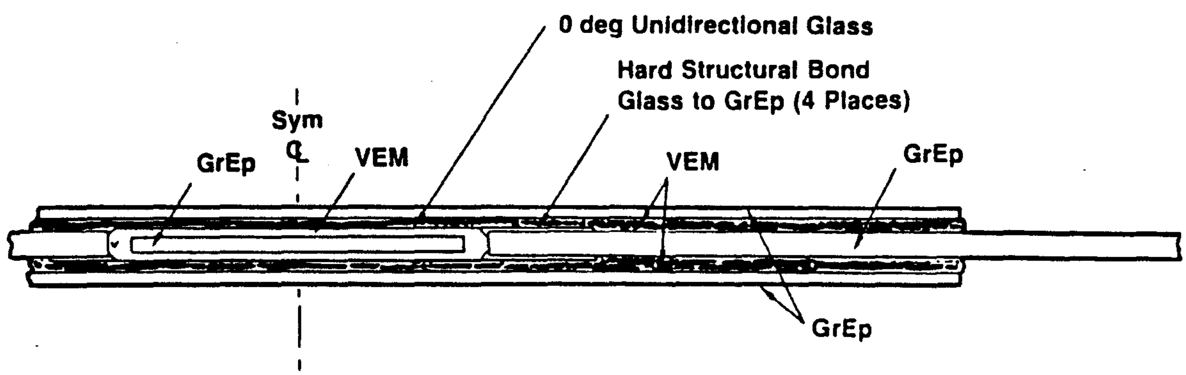


Figure 2.8

TRENDS OF EFFECTIVENESS OF ACTIVE AND PASSIVE DAMPING VS FREQUENCY FOR A COMPLEX STRUCTURE

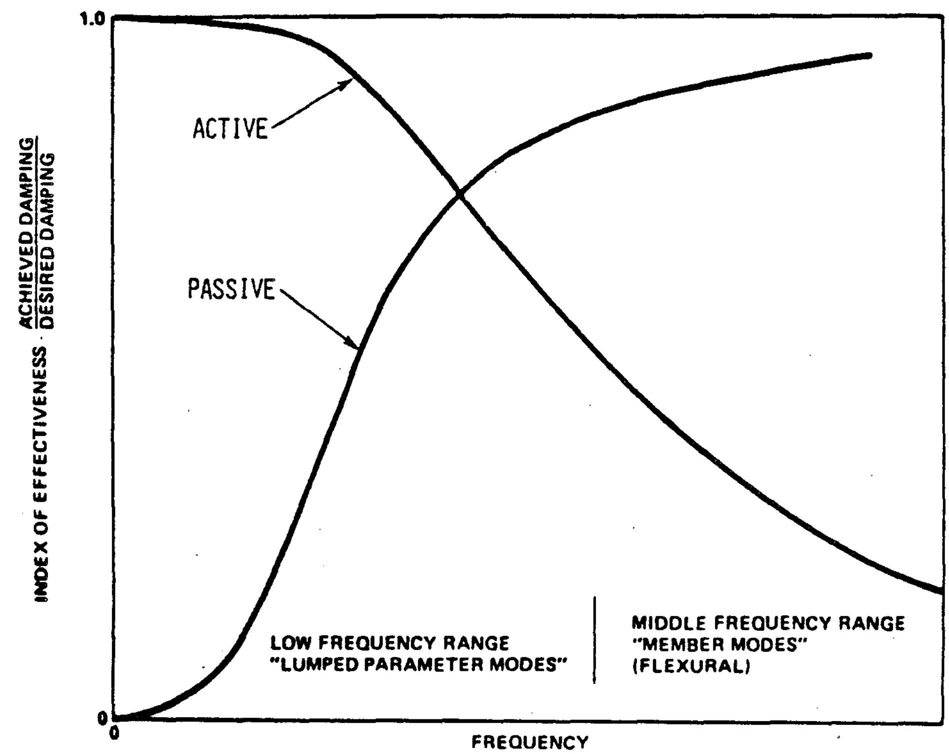


Figure 2.9

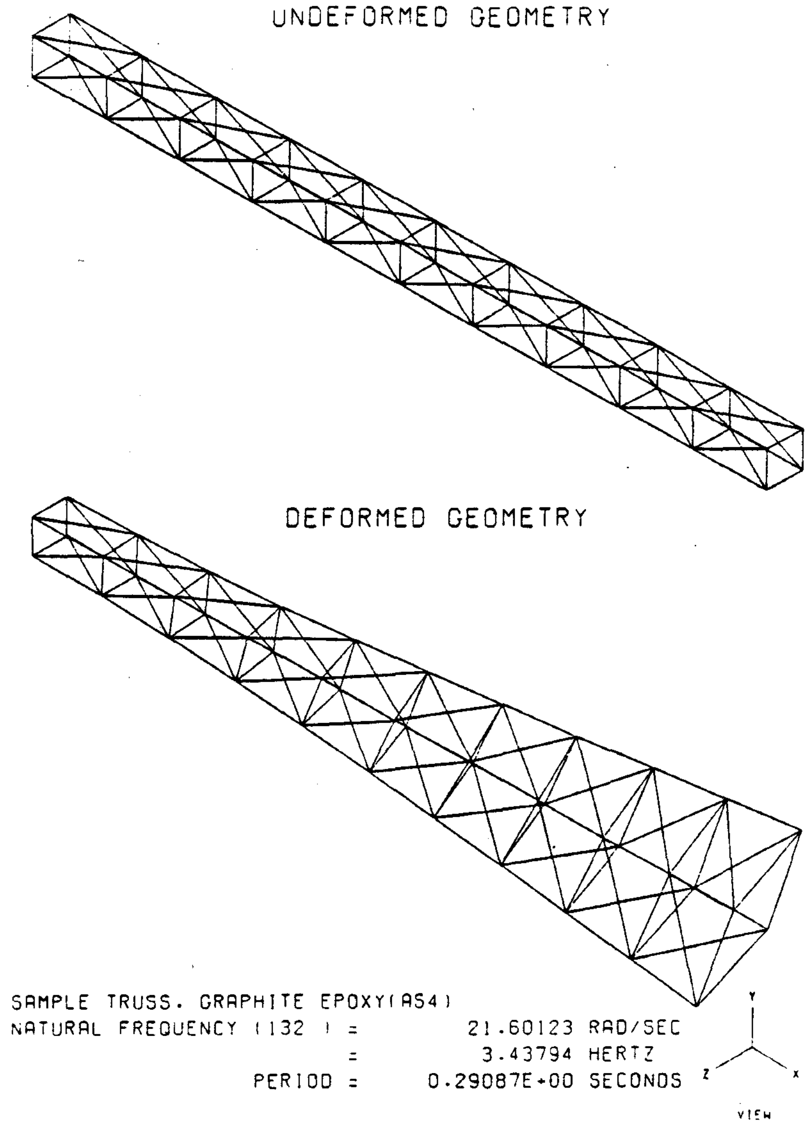

UNDEFORMED GEOMETRY
DEFORMED GEOMETRY
SAMPLE TRUSS. GRAPHITE EPOXY(AS4)
NATURAL FREQUENCY (132) = 21.60123 RAD/SEC
= 3.43794 HERTZ
PERIOD = 0.29087E+00 SECONDS
Y
Z
X
VIEW

Figure 2.10

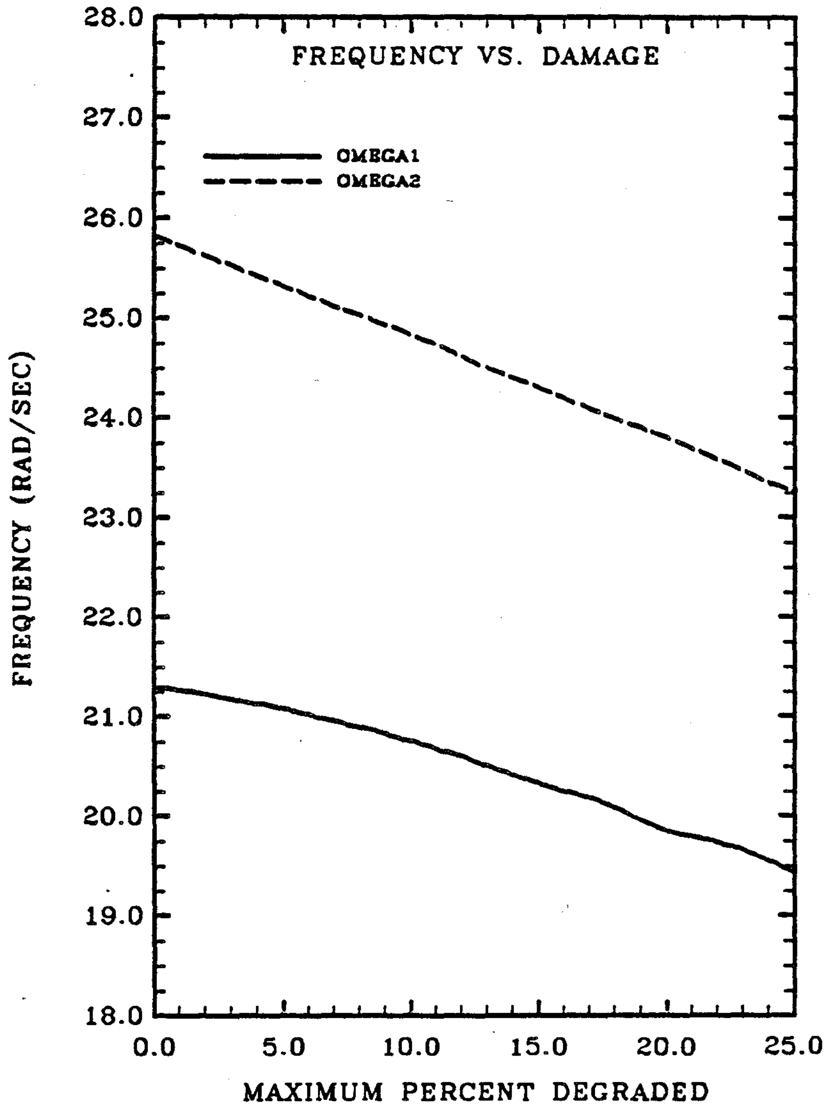
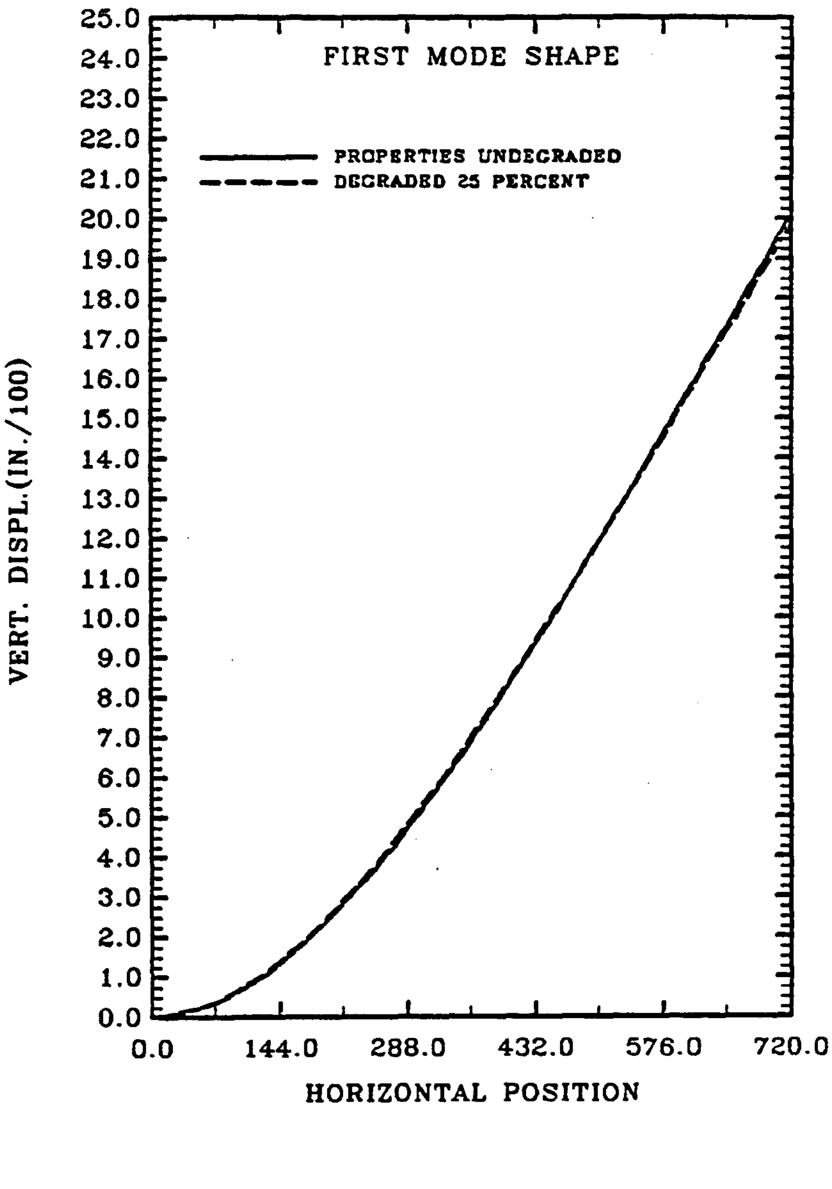

FREQUENCY VS. DAMAGE
OMEGA1
OMEGA2
FREQUENCY (RAD/SEC)
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
20.0
19.0
18.0
0.0
5.0
10.0
15.0
20.0
25.0
MAXIMUM PERCENT DEGRADED

Figure 2.11



FIRST MODE SHAPE
PROPERTIES UNDEGRADED
DEGRADED 25 PERCENT
VERT. DISPL.(IN./100)
HORIZONTAL POSITION
25.0
24.0
23.0
22.0
21.0
20.0
19.0
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
144.0
288.0
432.0
576.0
720.0

Figure 2.12

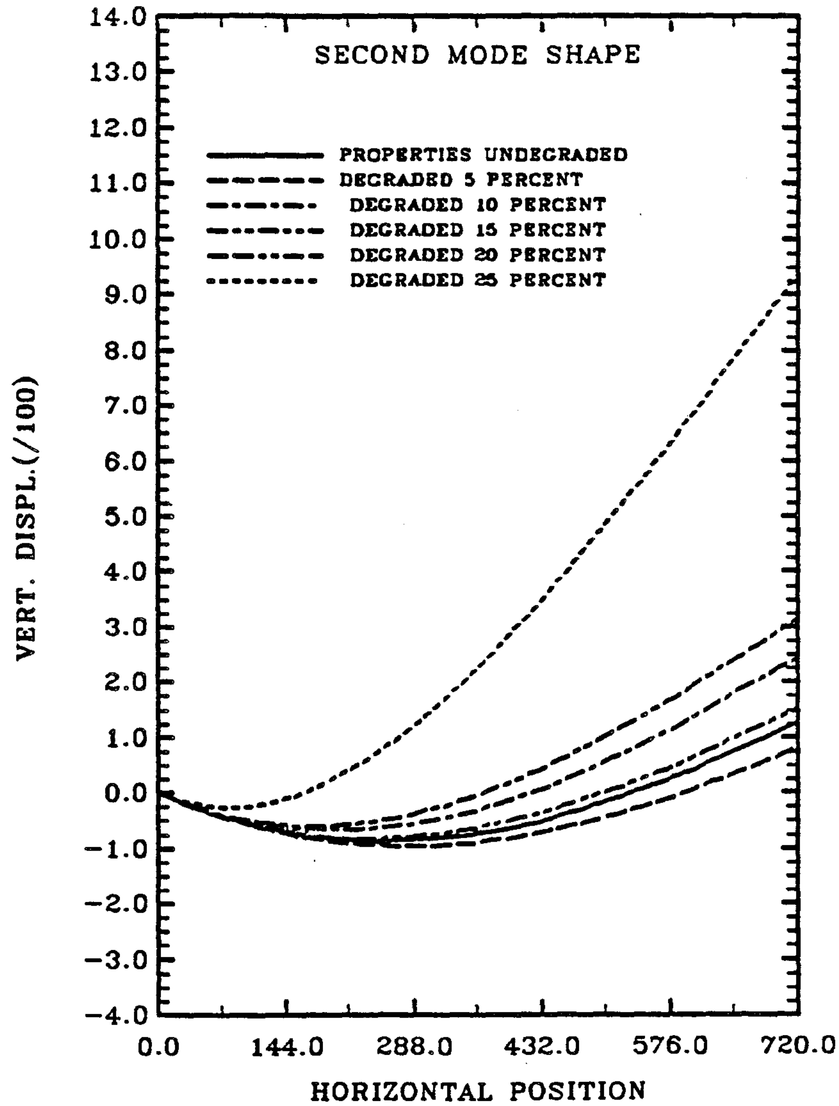

SECOND MODE SHAPE
PROPERTIES UNDEGRADED
DEGRADED 5 PERCENT
DEGRADED 10 PERCENT
DEGRADED 15 PERCENT
DEGRADED 20 PERCENT
DEGRADED 25 PERCENT
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
0.0
144.0
288.0
432.0
576.0
720.0
VERT. DISPL.(/100)
HORIZONTAL POSITION

Figure 2.13

3. ACTIVE CONTROL

by Robert L. Kosut

Introduction

This report summarizes the comments and discussions of the Active Control Panel. A great deal of discussion involved the relationships among modeling, control design, and the cost/performance criteria which motivate technology development and often instigate theoretical studies. The comments herein, thus, reflect the concerns of the researchers in their efforts to participate in the development of control technology of large space structures (LSS).

The Active Control Panel arrived at the consensus that there is no unique LSS control problem or solution. Different missions and aspects of missions will greatly influence the control structure definition. Within each mission, however, common problems exist such that a general framework which includes many of the present analysis/synthesis approaches can be defined. For example, vibration suppression is typically a "small-signal" phenomenon which lends itself to a small-signal (linear) control approach. Large angle maneuvers, however, are fundamentally nonlinear, and thus require a different analysis. The point is that although the mission may dictate the overall control structure definition and control modes, the underlying assumption is that specified performance requirements can be met for certain sub-tasks or in certain control modes. It is in these latter areas that more basic research is required and where the panel agreed that generic results can be obtained. These areas are enumerated and commented on in the next section.

Major Research Issues

LSS requirements have motivated basic research in several directions. These areas of research can be separated somewhat into the following subtopics.

Multivariable Control. The LSS control problem in many instances is truly multivariable, i.e., it is not possible to achieve specified performance by closing one feedback loop at a time, particularly when sensors and actuators are not colocated. For example, systems which use line-of-sight sensors (not colocated) to achieve high performance will require multivariable controllers.

Robust Control. LSS models will not be very accurate due to approximations as well as incomplete ground testing. Hence, the control design must be robust to modeling errors both in dynamics and disturbances. It is important to emphasize that stability robustness is not sufficient. Since most LSS missions are performance driven, the control must be performance robust, i.e., guaranteed performance tolerance to an anticipated class of modeling errors. The basic research issues involve developing a mathematical description of dynamic and disturbance modeling errors and a method for incorporating such a description in the control design. The LSS problem, from the theoretical view, is compounded by infinite dimensional system dynamics.

Adaptive Control. If the anticipated class of modeling errors precludes robustness of a fixed-gain controller which satisfies the performance goals, then it is necessary to use an adaptive control strategy. Although adaptation reduces modeling error, it is not eliminated entirely. It is this fact - that the model will always be imperfect - which motivates current adaptive control research. The aim is to develop a theory of adaptive control which accounts for modeling error in dynamics and disturbances. Such a theory is currently being developed for finite dimensional systems. In the infinite dimensional case, however, no theory currently exists, although it may be possible to extend some results from the finite dimensional case.

Nonlinear Control. Although the LSS in many instances can be approximated well by a linear model (finite or infinite dimensional), there is a great deal to be learned from studying nonlinear infinite dimensional models. For example, very little is currently known about passive damping of nonlinear systems with material nonlinearities, e.g., thermo-elastic damping. Bilinear control theory may be applicable for these systems. It is important to emphasize that other types of nonlinear controller structure can be studied, but they tend to follow the model nonlinearities. A fundamental issue then is to understand the nature of the dominant LSS nonlinearities which affect control system design.

The rapid large angle slewing maneuver is also an important nonlinear LSS problem. Rapid maneuvering can introduce dynamic nonlinearities (e.g., gyroscopic effects) into otherwise linear systems. Nonlinearity in actuators (e.g., on-off thrusters) is another area of concern.

Control and Structure Integration. The problems of modeling and control of LSS may not be separable. Hence, it is important to integrate system performance requirements with finite element modeling decisions. Finite element models which are considered to have high fidelity from the structural viewpoint may be of no use to the control designer. The control designer needs a measure of model error to build a robust control. Thus, the fidelity of a model cannot be ascertained independently from the intended use of that model. Close cooperation between structural and control system designers in the early stages of the structural design process should result in improved system performance. There are certainly lessons to be learned from the success of control-configured vehicles in the aircraft industry.

Decentralized Control. An LSS can be composed of subsystems with tasks operating or physical phenomena occurring at different places spatially or on different time scales. In these cases separate (decentralized) controllers will be allocated to the subsystems. Furthermore, each controller will not necessarily have complete access to others' sensor information or decision making processors. The two major issues are decomposition and decentralized design. Although a given LSS may present obvious temporal and spatial decompositions, a general theory of decentralized control is lacking. The problem in decentralized design is to guarantee performance with only a partial exchange of information among the subsystem controllers. An understanding of how to quantify complexity is crucial to developing a fully decentralized control theory.

Significant work is also necessary on decentralized computing architecture to support the decentralized control environment.

Actuator/Sensor Design. The type, number, and placement of actuators and sensors is a significant part of the LSS control design process. Actuator/sensor placement can greatly alter the achievable system performance. Some actuator/sensor placement theory exists in the case of known finite-dimensional models. There is also research in the case of known finite-dimensional models. Effects of actuator/sensor type have been examined using robustness theory. There is no comprehensive theory, particularly for determining actuator/sensor specifications based on closed-loop performance goals.

4. INTEGRATED DESIGN OF STRUCTURE AND CONTROL

by Vipperla B. Venkayya

Introduction

The panel identified several presentations relevant to the subject of integrated design. They included the following:

1. Ken Willmert of Clarkson University on the optimization of flexible mechanisms;
2. Mohan Aswani and G. T. Tseng of The Aerospace Corporation on continuum modeling of the plant as one means of simplifying structure-control optimization problems;
3. Manohar Kamat of VPI on the issues of plant nonlinearities (geometric and material), proposing that they be considered in control system design;
4. Moktar Salama of JPL on structure-control optimization with a single performance index consisting of the structural mass and the total control input;
5. Dale Berry of Purdue University on continuum modeling as a means of reducing plant dimensionality;
6. K. C. Park of Lockheed Palo Alto Research Lab on the use of transient energy density profiles to achieve optimum disturbance dissipation and control;
7. John Junkins of VPI on some recent results of eigenvalue placement via structural parameter optimization.

The material of these presentations was, to a certain extent, the basis for the panel discussions.

The panel proposed the following five topics for discussion:

1. Problem Definition (as motivated and influenced by end-usage): optimum structural design, optimal controls, and structure-control optimization.
2. Modeling and Analysis: for the plant, control system and actuator-sensor dynamics, and the disturbances.
3. Performance Measures: minimum mass, maximum stiffness, and shape fidelity for the structure; and quadratic performance index, minimum time control, etc. for the control system.
4. Optimization Algorithms: development for structure-control synthesis.
5. Issues of Experimental Verification

These subjects are discussed in the following sections.

Problem Definition

The concern of this panel is to explore the integration issues of structures and controls design to obtain an optimal total system rather than independently optimized subsystems. This integration task is much more involved than it appears on the surface. The interaction between the structures and the controls designers has been very minimal in the past. Traditionally the structures designer develops his designs based on the strength and stiffness requirements derived from the peak maneuver loads expected during the operation of the flight vehicle. His primary concern is to design minimum mass structures that satisfy the strength, stiffness and other performance requirements. In general the designer of active controls has little input in the evolution of the basic structural design. Similarly, the structural analyst's participation in the control design is limited at best to providing information about the frequencies and mode shapes of the primary structure. This practice of compartmentalizing designs is promoted by the attitude that optimal controls can be designed for any structure and vice versa. The complexity of the two disciplines and limited computational capabilities have left no choice except to optimize the subsystems and hope that the total system will at least be nearly optimal. Now with the accelerated development of computers, the cost of arithmetic computations, as well as storage, is becoming more attractive for thinking in terms of system integration. This integration can provide a better understanding of the dynamics of the system. Based on this understanding, analytical algorithms can be made more reliable which in turn can reduce the cost of laboratory and flight testing.

Traditionally the structural analyst works with variables that affect the mass, stiffness and damping of the structure. In control design parlance, variation of these parameters is associated with passive control of the system if these changes are made for achieving the control objectives. However, there are other requirements for the structure to satisfy besides the control objectives. The structural designer quantifies the structural requirements into a single objective function (performance index) and a number of constraint conditions. The most commonly used performance indices are the total mass, the stiffness, a certain frequency, or a composite index which highlights the static, dynamic or thermal response of the system. Similarly, constraint conditions are derived from the strength, stiffness and other dynamic characteristics of the structure. Once the objective function and constraint conditions are defined, optimum structural design involves two basic steps: a) sensitivity analysis and b) a numerical search algorithm.

The sensitivity analysis consists of determining the gradients of the objective and constraint functions with respect to changes in the mass, stiffness and/or damping parameters. In the simplest case of a fixed configuration, the properties of the elements (including the material properties) represent the structural parameters. First and second order approximations or the adjoint variable approach can be used to determine the gradients of the functions. With the help of the gradient information, numerical search algorithms can be constructed to seek the optimum point in the design space. The development of numerical search algorithms and the optimality criteria approaches have been the subjects of intense research in structural optimization in recent years. This research has been primarily focused on problems involving the minimization of mass with constraints on strength, deformations, and natural frequencies, and also other static and dynamic response constraints. With the exceptions of a few static cases, the present optimization capability is very much limited to small order systems which are not really representative of practical structures. This is particularly true when multiple design requirements have to be handled simultaneously. Most structural optimization problems are highly nonlinear, and the solution obtained is often sensitive to the initial (starting) solution. The questions of relative optimum and its relation to the global optimum cannot be resolved in any simple manner for large structures.

The developments in linear optimal control theory are extensive. Much of the insight into control system behavior is derived from single input, single output systems. Experience with multi-input, multi-output systems is limited in the applications, notwithstanding the extensive theoretical work in modern control theory. Space structures are generally articulated and naturally discrete structures (even though the individual elements are distributed parameter systems). They represent very large order systems with the possibility of numerous inputs/outputs which the control designers were unaccustomed to in the past. The experimental simulation and testing of these large order systems pose a significant challenge to researchers in space structures dynamics and controls. How to combine the structural dynamics and controls disciplines and develop a coherent system optimization scheme is the primary concern of this panel. There is general agreement in the panel that future research in large space structures dynamics and controls should develop algorithms to promote such an interdisciplinary approach to design. Recent advances in digital computers and computational algorithms provide ample opportunity for such development. However, as we embark on this combined optimization task, it would be prudent to try to identify the tangible benefits expected from such an approach. Reliable, minimum mass, maximum stiffness structures, better controllability (whatever that means), optimum actuator/sensor locations, least power requirements, and robust control systems with few actuators and sensors are some of the attributes of a good space structure design. However, such judgements tend to be subjective unless there are quantitative criteria for design evaluation. Better communication between the structure and control designers is a definite plus in favor of an interdisciplinary approach. Also this communication can significantly reduce the design effort and permit better parametric studies, which in turn is the cornerstone of an optimum system development.

<u>Modeling and Analysis</u>

Uncertainties in modeling are a major concern of the structure and control designers. Almost all large space structures are built-up structures. They are made of a number of structural elements of differing complexity. They are joined continuously or at discrete points known as node or grid points. The individual elements are distributed parameter systems. For the total structure both continuum and discrete models are being proposed. Modeling issues of the plant involve an accurate description of the mass, stiffness and damping properties of the structure. Linear models are the basis of the optimization algorithms in both structures and controls. The effects of nonlinearity in stiffness and damping can be quite far reaching in the behavior of the structure and its control system, and it is the active subject of current research. In addition, plant modeling errors due to discretization and/or other factors can raise serious concerns about the robustness of the control system. The absence (or inaccuracy) of information about the higher modes can seriously compromise control effectiveness. The spillover effect due to the absence of information about the crucial (higher) modes can introduce performance deficiencies in the control system. Similarly, plant uncertainties can also have a destabilizing effect on the control system.

Uncertainties in modeling the mechanics of the actuators and sensors can have similar effects as the deficiencies in plant modeling. A careful integration of actuator/sensor dynamics into the system dynamics is essential to achieve the control objectives. There are very few space qualified (fully tested) actuators and sensors. As the actuator/sensor technology progresses, we will have a better understanding of their dynamics and the issues of integration. The simplest and most readily available among them for space applications are gas thrusters. It should be relatively easy to integrate the dynamics of these thrusters into the system dynamics. The structural vibrations induced by thruster startup and shutoff transients may be treated as part of the input noise in the Kalman Filter which drives the optimal regulator. The major disadvantage of thrusters is that they cannot continuously vary the applied torque level. Some of the gimballed thrusters that are being developed may solve this problem. However, the most compelling argument against gas thrusters is the amount of propellant needed onboard to execute frequent maneuvers on a long term basis. The dynamics of control moment gyros (CMG), angular momentum control devices (AMCD) and other electromechanical actuators are much harder to model and integrate into the overall control system design.

Accurate disturbance modeling is very important in the design of a space structure and its control system. It is not uncommon to design flight vehicle control systems and then have to augment them with additional filters to take care of new sources of disturbance identified during flight testing. Such designs based on afterthought tend to be unwieldy and cannot be optimal. An even more compelling objection to such band-aid approaches is that the flight testing of large space structures is at best not cost effective, if not infeasible. A thorough understanding of the operational environment (space) and a diligent modeling of disturbances can significantly improve the reliability of space missions at reasonable costs. A typical space structure is exposed to disturbances caused by scanning and tracking maneuvers, impact due to docking, meteorite impact, vibration caused by onboard machinery, gravity gradient torques and distortions, geomagnetic variations, external and internal heat loads, fluid flow and sloshing, and the control hardware. Good disturbance modeling is important not only for the integrity of the control system, but also for the safe operation of the structure.

Performance Measures

Depending on the mission requirements, space structures can be optimized with performance indices (objective functions) such as minimum mass, maximum stiffness, or, in the case of antennas, shape fidelity as defined by the mean square deviation from the reference surface due to some disturbances. Such a performance measure can be minimized or maximized subject to a number of constraint conditions. Similar performance indices can be defined in the control system design. For example, in the linear optimal regulator a quadratic performance index consisting of the state and the control input can be defined. Another possibility is minimum time control. When the two systems (structure and control), are designed independently, one performance index can be assigned for each subsystem, and the optimization is carried out on each subsystem separately. A new performance index is necessary for combined structure-control optimization. At this time it is not quite clear what this index should be. A very tempting approach is to formulate a composite index consisting of the structural mass and the quadratic performance (controls) and derive the necessary and sufficient conditions for optimality from the variational approach. This approach seems to be satisfactory, at least theoretically. However, the dimensional incompatibility of the two quantities (mass and quadratic performance index) may create problems in algorithm implementation for achieving the optimality conditions. The second approach is to treat the integration as a problem with multiple objective functions (ex. pareto optimization) and use game theory to study the design trades.

Optimization Algorithms

The essential computational issue in structure-control synthesis is the development of optimization algorithms to design a space structure and its control system. It is assumed that reasonable mathematical models for the plant and the control system are available. Serious modeling deficiencies can lead to unreliable designs. The usual procedure in optimization is to define a performance criterion and a set of constraint conditions. From a variational approach, it is possible to derive necessary and sufficient conditions for optimality. Then the important step is to develop an iterative algorithm to achieve the optimality conditions. A sensitivity analysis with respect to structural variables (mass, stiffness, and damping) and control variables (actuator, sensor inputs/outputs and their locations) and a numerical search based on gradient information can be the most direct way for the solution of the optimization problem. However, this may not be the most effective or reliable solution of the problem. Exploration of direct and indirect methods is the subject of research in optimization algorithm development.

Issues of Experimental Verification

There are a number of uncertainties in modeling the plant, the control system and the optimization algorithms. We need to explore cost effective ground and space testing procedures. The issues of zero gravity, the absence of aerodynamic damping and unusual disturbances must be carefully considered in designing the experiments. How representative are the results of the scaled models to actual space structure models? These are the issues to be addressed in experimental verification.

Research Topics

After the presentations the panel discussed some of the issues that are relevant to promoting integrated structure-control synthesis. The panel briefly touched on the problem of dimensionality, the basic computational tools needed to conduct such research and the possibility of developing generic or prototype computational models with some elements of realism for verification of the structure-control algorithms. After a brief discussion, the panel compiled a preliminary list of research topics that are relevant for promoting interdisciplinary design. This list is as follows:

1. Development of integrated conceptual design methodology.
2. Development of suitable models for structure-control integration.
3. Sensitivity to control and structural parameters.
4. Pursue problem formulation involving simultaneous structure and control optimization - DEFINE objective functions and constraints from combined structure and control design point of view.
5. Evaluate computational algorithms by applying them to prototype examples.
6. New concepts in integrated structure control design approaches.
7. Developing new algorithms to solve integrated design optimization problems.
8. Impact of modeling on the above two developments.
9. Develop new and efficient algorithms to handle the additional complexity of integration.
10. Classification of problems by design space description (constraints and objective function).

11. Uncertainties in plant, disturbances and control system and the issues of performance and stability robustness.
12. Basis reduction and approximation concepts as a means of reducing the computational burden.
13. Verification of optimized designs.
14. Interaction of active controls and nonlinearities.
15. Multilevel optimization.
16. Time variant matrices.
17. Mechanical structure interaction
18. Practical applications of integrated design.

5. HARDWARE ISSUES

by Michael W. Obal and Wm. L. Hallauer Jr.

Introduction

The panel members selected several hardware issues to consider. They are:

1. Hardware Systems Overview and Research Requirements
2. Trends in Communications Satellites
3. Dynamic Testing Approaches for Large Space Structures
4. Space Structure Ground Testing in Simulated Zero g
5. Reflections on Structural Dynamics-Control Experiments
6. Electronic Damping and Feedback Control of Structures
7. Distributed Piezoelectric-Polymer Active Vibration Control
8. Piezoelectric Crystals Research at MIT
9. Application Issues for Flight Hardware

Discussion of each issue by the entire Forum was initiated with a brief presentation by a panel member. The following short reports on the issues were drafted by individual panel members (identified in parentheses) to convey the essence of both the presentations and the discussions.

Hardware Systems Overview and Research Requirements (M. G. Lyons)

The LSS structure/controls problem must be treated, at the basic research level, with more cognizance of specific system performance and hardware requirements; otherwise the research becomes so generic that the study of difficult problems is postponed indefinitely. This field has been seriously studied now since 1976, and this lack of focus is becoming evident. Major efforts are still needed in hardware experiments, system identification, and robust, high-performance controls synthesis.

Major hardware related research is required in at least the following areas:

1. System identification: algorithms, implementation, validation.

   A continuing basic issue in LSS control is system ID. Processing modal test data using traditional algorithms from the modal test industry has not produced results adequate for control-configured structures. Sophisticated theory developed for identification and signal processing must be introduced into the structural testing community and evaluated via detailed experimental research activities.

2. Model error definition vs. performance goals: role of nonlinearities and wave propagation, acceptable model error classes and limits, bandwidth and fidelity.

   Model building tasks must be integrated with control synthesis activities if each is to make sense in terms of meeting performance specifications. Many kinds of structural model errors may be admissible for certain control-configured structures. Increasing model fidelity without a specific focus is pointless in the context of achieving mission performance goals. More attention must be paid to what kinds of models are required rather than what kinds of models we now know how to generate.

3. Hardware selection vs. performance objectives: actuator design, sensor design, signal processing architectures.

   Most of the research to date in LSS control has ignored the very real questions of actuator and sensor hardware which can achieve the control objectives. At present, sensor hardware is in the highest state of development, with actuator hardware being entirely custom (i.e., no off-the-shelf actuator exists). VLSI signal processing will eliminate bandwidth and complexity constraints as far as LSS control algorithms are concerned. Architectures to achieve performance goals will have to be investigated, however.

4. Robust control design/fault tolerant architectures.

   Control design theorists have been excessively preoccupied with proving stability rather than insuring performance. Existing research, funded by DARPA, has shown that stability is relatively easy to achieve if performance is allowed to decline. More work is needed in robust/adaptive control design and the associated failure detection algorithms and hardware which will allow system designers to guarantee high levels of performance even though ground testing may be quite incomplete.

5. Cost vs. complexity vs. performance.

   Meeting mission objectives may be feasible with a variety of actuator, sensor, structure, and signal processing options. System cost and reliability are usually sharply affected by these trades. For example, the number of expensive actuators may be reduced by less costly signal processing hardware. More work is needed in this research area.

6. Sensor integration and selection: basic motion compensation and reference.

   Sensors must be selected which provide the basis for both vibration and so-called rigid body control. Frequently different sensors are used for vibration and rigid body motion. Also, optical sensing poses problems of base motion compensation. Integration of sensor systems into the overall control-configured vehicle design usually complicates the model building system identification process tremendously and cannot be ignored as is the current practice.

<u>Trends in Communication Satellites</u> (B. N. Agrawal)

The current trend in communication satellite design has been for larger and more flexible antennas and higher antenna pointing accuracy. These objectives require developments of more accurate attitude sensors and advanced control techniques. In the past, spacecraft attitude control was designed on the basis of rigid body dynamics, with sensors and actuators located on the main body. These techniques resulted in attitude control accuracy in the neighborhood of 0.15°. The next step to improve the pointing accuracy, almost by a factor of 2, has been to use RF sensors where antennas are controlled directly.

For future communication satellites with unfurlable reflectors and deployable support structure, the main problem will be to control relative motion between the feeds and the reflector. It may require use of actuators and sensors on the flexible structures. The current problems in this approach are (a) selection of actuators and sensors and (b) validation of the design on the ground. The other approach would be to increase stiffness and damping of the support structure, resulting in mass penalty but avoiding control complexity.

<u>Dynamic Testing Approaches for Large Space Structures</u> (J. Prucz)

The use of large flexible space structures involves certain peculiar features in comparison with conventional aircraft structures. The basic features that should be considered in the experimental characterization of large space structures are:

1. The full-scale structure will often be assembled or deployed in space for the first time in its operational configuration.
2. Modal instability can be expected for several reasons: nonlinear structural behavior, material degradation, and sensitivity to structural changes.

These features impose new requirements on the test data related to such structures:

1. Component testing on the ground should provide generic data that are suitable for direct design synthesis of the global properties of full-scale structures.
2. The data should cover an almost continuous frequency range, because of both the expected modal instability and the effect of the global modal characteristics of the structure on the real dynamic behavior of its individual components.

The commonly used modal testing techniques are suitable to full scale system characterization, but they do not fulfill the particular test data requirements for large space structures. Therefore, non-resonant experimental approaches that are usually appropriate for material characterization are expected to generate more useful data for space structures applications. Two new techniques that belong to this category have been developed recently at the Georgia Institute of Technology and McDonnell-Douglas Astronautics Company for the experimental evaluation of generic passively-damped joining concepts for space structures. They are:

1. The sine-pulse propagation technique. A sine-pulse of the desired frequency is applied at one end of the specimen and the stiffness and damping properties are extracted from the changes that occur

in certain pulse characteristics as a result of propagation through the specimen.

2. The simplified steady state technique. The measurement of stiffness and damping properties is based in this case on the phase lag between a cyclic displacement vector applied at one end of the specimen and the response force vector measured at the opposite end.

A schematic block diagram description of these two methods is given in Figure 5.1.

Space Structure Ground Testing in Simulated Zero g at MIT

(E. F. Crawley)

A rigorous test program for space structures would include component testing, simulated zero gravity testing on earth, and space flight testing. A weak or missing link in this sequence is the ground testing in simulated zero g. One option is to loft specimens into a vacuum to simulate the "free" fall and the environment of low earth orbit. A developmental test program to this end has been underway at MIT for six years. Precision material damping measurements have been made in a small chamber. Now a large 10 foot diameter and 14 foot high chamber is under construction at MIT capable of pulling a vacuum of 10^{-8} torr. The questions which will be investigated in this facility are the relative dynamics of model space structures in zero and one g, and the effects of long term space vacuum on the frictional damping at the joints in space structures.

Reflections on Structural Dynamics-Control Experiments

(W. L. Hallauer Jr.)

Experiments can be gratifying if things work according to plan, but more often they are exasperating (at least initially) because things don't. My experience is that there are two general reasons for things not working according to plan:

1. Operational problem. Some mistake has been made in the experimental implementation (electrical leads reversed, calibration factors wrong, amplifier overloaded, etc., etc.), or electrical noise/transients are unacceptably large. For these reasons, one always takes precautions before switching on the controller (e.g., manually restraining the structure), and one is ever vigilant for the smell of burning electrical or mechanical components while the controller is on. It is important to have a convenient panic switch that can instantly disable the controller. I will marvel at any actual LSS vibration controller that proves to be fairly invulnerable to electrical glitches.
2. Conceptual problem. In this case, the experiment performs according to nature's plan rather than the experimenter's, indicating that some of the experimenter's theoretical assumptions or idealizations were faulty. This is the best justification for conducting experiments. Experimental results that defy one's preconceptions are unwelcome initially but are ultimately beneficial if they help to correct misconceptions.

Evidently very few people are knowledgeable about the current state of space-qualified sensor/actuator hardware. To my knowledge, no participant in this Forum claimed expertise. A meeting such as the

Forum would be well served by the participation of persons who have working knowledge of actual CMG's, momentum wheels, rate gyros, reaction jets, etc.

I have difficulty believing that any theoretical method can consistently predict with accuracy more than a few of the low modes of a complex structure. The reason for my skepticism is that higher modes are <u>very</u> sensitive to structural details that may be impossible or, at best, very difficult to model theoretically. Figures 5.2 illustrate this sensitivity for a skewed plane grid laboratory structure at VPI. Each side of the structure is about 6 feet long. The figures show nodal lines of the 10th mode, the lines being curves fit through the nodal points measured/calculated on the grid members. Figure 5.2a shows poor agreement between calculated and measured nodal lines. Figure 5.2b shows good agreement achieved by simply inserting a 1.25" diameter washer in each bolted joint of the laboratory structure, thus slightly modifying the joint to conform more closely with the finite element model.

<u>Electronic Damping and Feedback Control of Structures</u>

(S. Hanagud and M. W. Obal)

Active vibration suppression using electronic damping has been experimentally verified in various applications [5.1-5.3]. The electronic damping concept basically involves sensing a dynamic structural motion using an appropriate sensor and actively reducing the motion using a negative feedback system which powers piezoelectric strain drivers bonded to the structure. Figure 5.3 is a schematic of the electronic damping concept.

Electronic damping using piezoelectric strain transducers was found to be ideal for the control of small vibrations which severely degraded sensitive optical systems. For example, electronic damping was used to reduce laser cavity resonator optics degradation by damping a large optical composite bench subjected to acoustic and structural borne vibration noise [5.1]. Additional experimental work has also shown damping performance of orthogonal bending modes of a circular satellite antenna [5.2] and an acoustically excited 25 cm membrane mirror [5.3]. From this experimental work, the feasibility of applying electronic damping to large space structures should be explored. As a space system's imaging and pointing and tracking precision requirements increase, this damping concept should be considered as a possible enhancement to current passive and active vibration control systems.

One of the most common and inexpensive piezoelectric materials available for electronic damping systems is the piezoelectric ceramic (piezoceramic). This material can be made into a variety of shapes and sizes. Other materials, such as polyvinylidene fluoride film, also exhibit a piezoelectric effect and have been used to drive deformable mirrors [5.4, 5.5]. Damping using this material is presented in the next section.

The potential benefits of electronic damping can be summarized as follows: The electronic damping system has remote tunability capability allowing for the suppression of problem modes which may shift as the LSS ages or grows. Due to the sensing nature of the piezoelectric materials, the electronic damping system can have sensor/driver interchangeability. Finally, we have strong electromechanical coupling of the drivers at a low mass.

This concept also has a variety of issues which must be addressed: How can the electromechanical coupling theory of the drivers be enhanced? Will there be problems with multimode controllability and/or wideband stability? What kind of driver aging and environmental sensitivity and power requirements should we concern ourselves with for LSS use? Finally, can we optimize the application of electronic damping with other active and passive control techniques?

One approach to understanding the electromechanical coupling has been the application of parameter identification techniques to a cantilever beam electronic active damping experiment. The parameter ID method we used provides us with reduced-degree-of-freedom mass, stiffness and damping matrices, given the experimentally obtained complex mode shapes and FEM obtained diagonal elements of the mass matrix. By computing these matrices with and without the electronic damping, we can identify changes in the damping matrix. Given this information, we will try to relate these changes to the driver characteristics, amplification and spatial location. Successfully accomplishing this will lead to a model for the electromechanical coupling between the driver and the structure.

Distributed Piezoelectric-Polymer Active Vibration Control

(J. E. Hubbard Jr.)

The use of a piezoelectric polymer has been tested as a full distributed actuator. The particular polymer is polyvinylidene fluoride, PVF2. This distributed actuator has been used to improve the damping electronically in a bench scale cantilever beam by a factor of 20. The polymer is rugged, has a large bandwidth and is lightweight. The use of PVF2 as a class of actuators/sensors suggests some interesting possibilities for distributed parameter systems.

1. They don't mechanically "load" the system, offering a relatively high performance/weight ratio.

2. While they do use relatively high voltages, the overall power requirements are small.
3. Because the electric field across the film can be spatially varied relatively easily, the "hardware" can be modified in conjunction with the control strategy to greatly simplify the resulting algorithms and the effort required to obtain such algorithms.
4. Controllers using full distributed sensors/actuators offer the possibility of controlling all modes, as suggested by simple formulations which require no truncation or discretization (modal reduction) to obtain the final control strategy.
5. Because of the polymeric nature of PVF2, it can be used to design control hardware which is a part of the structure itself. For example, the film can be "buried" in a composite beam which will later become a structural member in a LSS.
6. The distributed actuator/sensor will fail gracefully during its operation, resulting in minimum risk to the overall mission of a LSS.
7. Finally, the merits of such an actuator in figure control of antennae should be investigated.

More than just a new piece of distributed hardware, PVF2 film applications give us insight into new types of structure/control philosophies and strategies. It is hoped that with this new philosophy, completely new approaches to theory and application will evolve.

Piezoelectric Crystals Research at MIT (E. F. Crawley)

Piezoelectric crystals present the opportunity to have highly distributed actuator networks over the surface of a structure. Because of their thermal and environmental stability and higher force transmission characteristics, emphasis has been placed on piezoceramic materials. An analysis has been developed to solve the local mechanics problem of a piezoelectric crystal bonded to a passive structure. When coupled with a modal model of a beam, this analysis has successfully predicted a priori the open and closed loop response of the beam.

Application Issues for Flight Hardware (B. R. Hanks)

As the final speaker, I was requested to generate some controversy to stimulate discussion. The following comments are offered in this spirit and are based on years of experience with hardware.

Although this meeting is titled Forum on Space Structures, it is for the most part about Control Theories for Space Structures. A great deal of discussion has been generated on such topics as the relative merits of infinite-dimensional (partial differential equation) versus finite-dimensional (finite element) control design methods, independent modes versus alternatives, stochastic versus deterministic models, robustness criteria, and other similar items. These discussions have permeated all sessions, generally without regard to their practical importance. To view them in proper perspective, one must also supply a hardware "filter" to the problems.

The question of performance or cost index form and the relative weightings to be given to control and structure arose. In actual hardware applications, the real cost index to be minimized is dollars, whereas performance requirements, safety, and reliability are constraints which must be satisfied. For flight systems, questions of cost, safety, and reliability of actuators are generally overriding. To mention just a few problems: redundancy requirements create a need for extra actuators for each one used; housings and attachments add dead weight; actuator failures can cause instability; and flight-qualified devices may cost hundreds of thousands of dollars each. Hence, active control is likely to be feasible only where absolutely necessary: for rigid-body modes, articulated members, and cases where stiff structures cannot be conceived to meet requirements. Once these necessary controls are decided, then their use to improve the flexible motion behavior and/or reduce structural weight becomes feasible.

In deciding the types of algorithms to be used, questions of system modeling accuracy may never be decided exactly. Real flight structures are unlikely to be symmetric, uniform, homogeneous, or even manufactured as modeled during initial control designs. Assumptions of modal accuracy for more than a few modes, let alone an infinity of them, are in reality invalid. In fact, structural nonlinearities will likely render the use of fixed modes invalid if control systems must be highly tuned.

Finally, flight project managers are very conservative. They are likely to use high-tech control systems only if absolutely necessary and/or proven to work in tests, preferably flight tests. This chicken-or-egg situation creates the need for hardware tests of candidate methods and systems. Figure 5.4 shows a flight system to be developed by the Langley Research Center for research in structural dynamics and control. It is a deployable truss beam approximately 60 m long that will be flown in a shuttle-attached configuration. It is a research experiment open to co-investigators from universities and industry. A thorough ground test will be conducted on system and components, and scale models will be built. All hardware for advanced multivariable control will be flown on the first flight, but control software algorithms will be simple at first, becoming more complicated on follow-on flights.

This experiment and other actual hardware implementations of proposed theories are crucial to validate methods. Otherwise, all the discussion of which method is best may be met by the charge that, when applied to real structures, all of the methods may not work.

References

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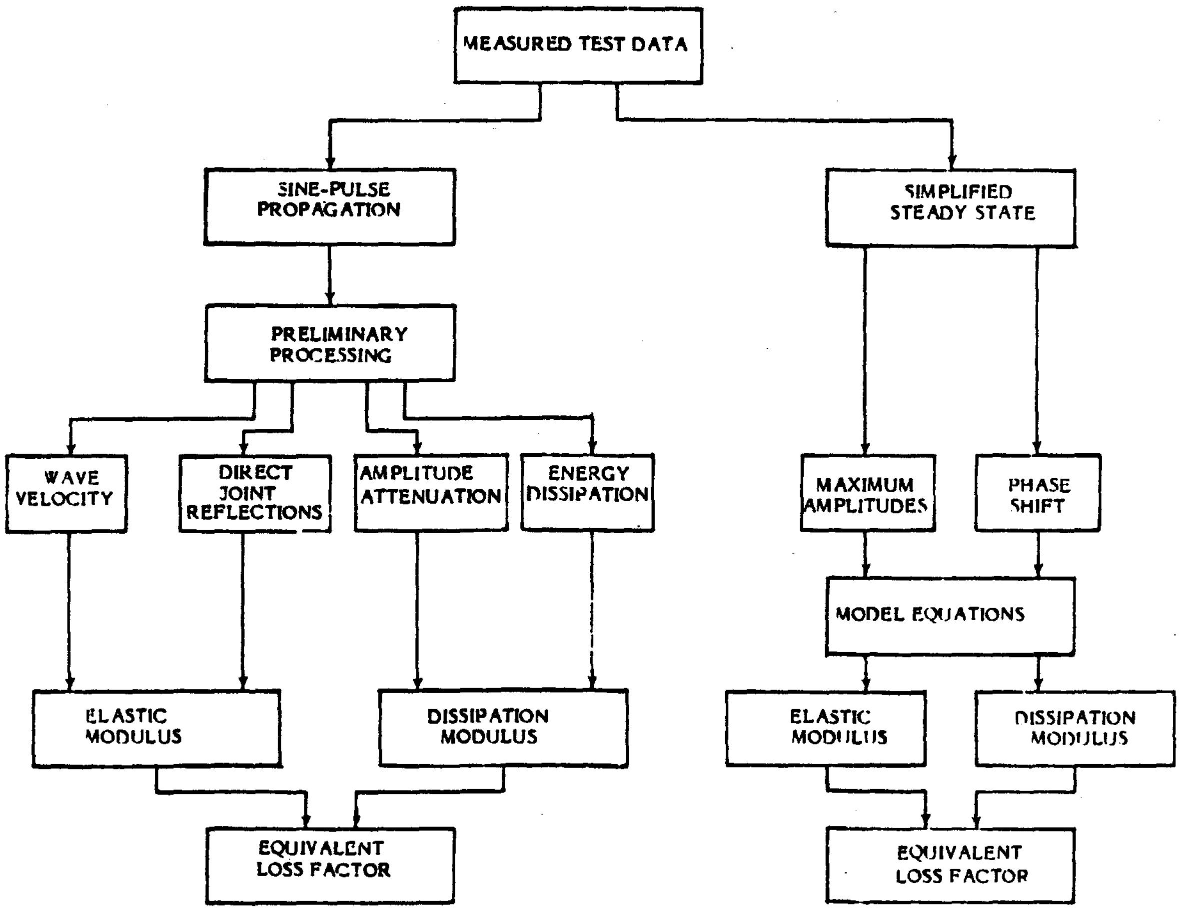
5.3 R. L. Forward. "Electronic Damping of Vibrations in Optical Systems," Applied Optics, 1979.

5.4 Takuso Sato, et al. "Adaptive PVDF Piezoelectric Deformable Mirror System," Applied Optics, 1980.

5.5 Takuso Sato, et al. "Multilayered Deformable Mirror Using PVDF Films."



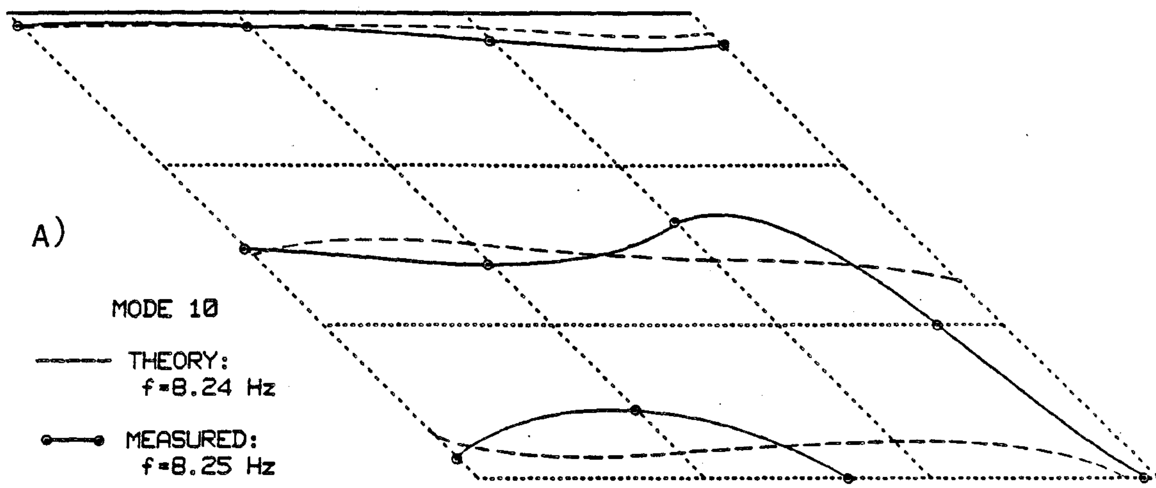
General Data Analysis Diagram

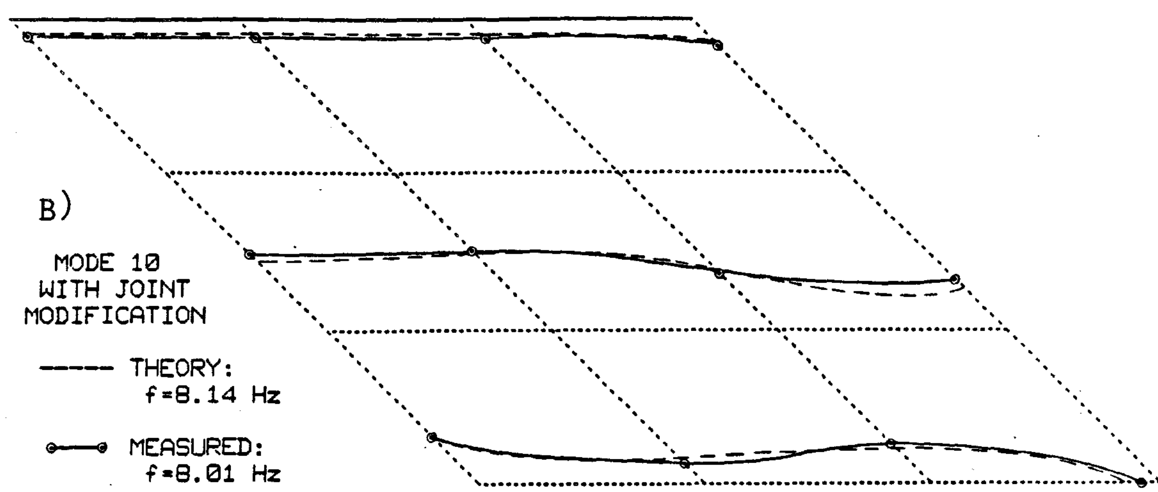
Figure 5.1

SENSITIVITY OF

HIGHER-MODE MODE SHAPES

TO DETAILS OF STRUCTURAL DESIGN





Figures 5.2

ELECTRONIC DAMPING AND ACTIVE CONTROL

* ELECTRONIC CONTROL OF MECHANICAL NOISE AND VIBRATION

    * ELECTRONIC DAMPING CAN BE ACCOMPLISHED USING PIEZOELECTRIC STRAIN GAGES

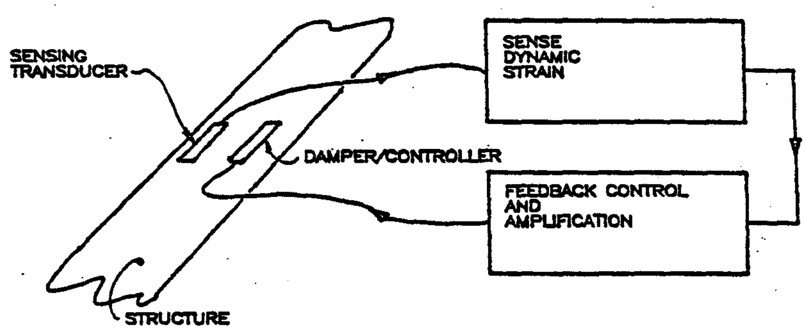


Figure 5.3

MAST GROUND AND FLIGHT EXPERIMENTS

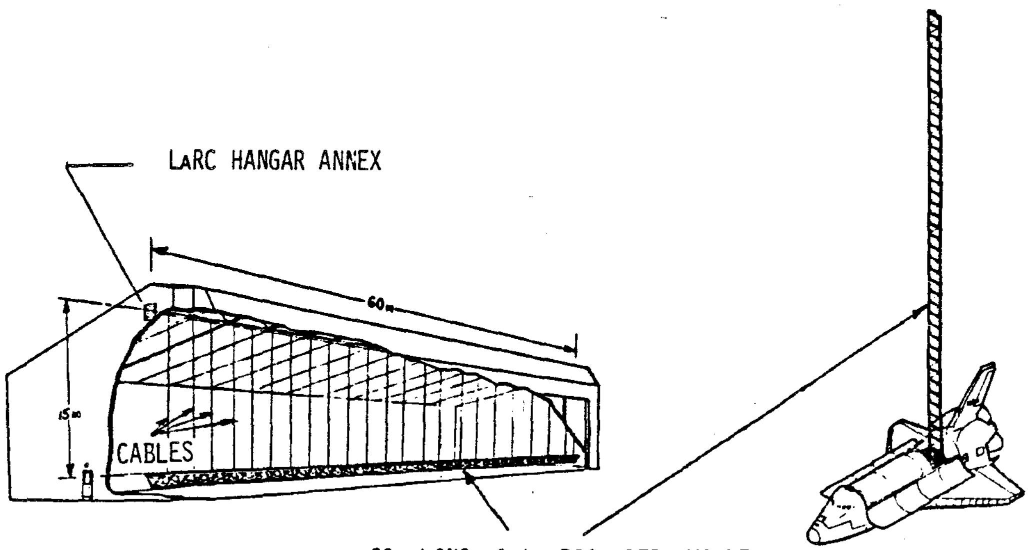


Figure 5.4

APPENDIX A

MEMBERSHIP IN FORUM PANELS

1. Structure/Plant Modeling

Holt Ashley
Gilmer Blankenship
Hyam Benaroya
Thomas Dwyer
Harry Frisch
Ed Haug
Daniel Inman
P. S. Krishnaprasad
Steve Lamberson
Joel Signorelli
James Turner
Andy von Flotow
James Williams

2. Passive Control

David Allen
Cliff Astill
M. Biswas
Earl Dowell
Walt Haisler
Terry Hertz
Ahmed Noor
Dick Trudell

3. Active Control

Mark Balas
Scott Hendricks
Anthony Hotz
Dave Hyland
Robert Kosut
Bob Lindberg
Len Meirovitch
Mike Polis
Benjamin Ward
Rama K. Yedavalli

4. Integrated Design

Mohan Aswani
S. N. Atluri
Dale Berry
Art Hale
John Junkins
Manohar Kamat
Narendra Khot
Sam McIntosh
Robert Melosh
David Miller
Dan Mulville
William Nash
K. C. Park
Robert Reiss
Moktar Salama
G. T. Tseng
V. B. Venkayya
Ken Willmert
Henry Yang

5. Hardware Issues

Brij Agrawal
Ed Crawley
William Hallauer
Satya Hanagud
Brantley Hanks
James Hubbard
Michael Lyons
Francis Moon
Michael Obal
Jacky Prucz

APPENDIX B

PARTICIPANTS IN THE 1984 FORUM ON SPACE STRUCTURES

Agrawal, Brij N.
Intelsat
490 L'Enfant Plaza, S.W.
Washington, D.C. 20024
(202) 488-0105
Research interests:
1. Unfurlable off-set reflector
   Diameter = 4-8 m, rms surface error = 10 mils
2. Deployable structures
3. Attitude control
   Pointing accuracy = 0.03 degrees, RF sensor

Allen, David H.
Dept. of Aerospace Engineering
Texas A&M University
College Station, TX 77843
(409) 845-1669
Research interests:
1. Constitutive behavior of structural materials including
   a. Polymeric composites
   b. High strength metal alloys
   c. Metal matrix composites
   d. Polythylene films
2. Dynamic response of space structures including
   a. Inelasticity in the materials listed above
   b. Environmental degradation of material properties
   c. Thermomechanical coupling

Amos, Anthony K.
AFOSR/NA
Bldg 410
Bolling AFB
Washington, D.C. 20332
(202) 767-4937

Ashley, Holt
Department of Aeronautics and Astronautics
Durand Building - Room 369
Stanford University
Stanford, California 94305
(415) 497-4236
Sponsor topic:
1. The travelling-disturbance approach to dynamics
   and control of large space structures
Research interests: focuses on "plant"
1. Damping
2. Wave-propagation models

Astill, Clifford J.
MEAM/ENG, Rm. 1108
National Science Foundation
1800 G St., NW
Washington, D.C. 20550
(202) 357-9542
Interests relevant to the Forum: To represent relevant activities within the National Science Foundation, namely
1. Solid Mechanics Program: material and joint damping, friction
2. Structural Mechanics Program: finite element and distributed parameter methods, stochastic models, vibration isolation, active control, optimization
3. Mechanical Systems Program: vibration isolation, active control, friction

Aswani, Mohan
Aerospace Corporation, M4/920
Post Office Box 92957
Los Angeles, California 90009
(213) 648-5442
Sponsor topics:
1. Modeling accuracy
2. Damping assumptions
3. Verification testing requirements

Research interests:
1. Structural modeling of large space structures
2. Integrated structures/control design

Atluri, S.N.
School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
(404) 894-2758
Sponsor topic:
1. Control of nonlinear dynamics

Balas, Mark J.
ECSE Dept.
Rensselaer Polytechnic Institute
Troy, NY 12181
(518) 266-6683
Sponsor topics:
1. Distributed parameter systems approach to LSS
2. On-line parameter identification of LSS

Research interest: finite-dimensional control of distributed parameter systems, in particular
1. State space and input-output approaches and connections between them
2. Identification, parameter estimation, and adaptive control

Benaroya, Hyam
Weidlinger Associates
333 7th Avenue
New York, NY 10001
(212) 536-5200 ext. 219
Research interest:
1. Parameter uncertainties and structural dynamics

Berry, Dale T.
School of Aeronautics & Astronautics
Purdue University
West Lafayette, Indiana 47907
(317) 494-5117
Sponsor topic:
1. Finite element modeling for LSS control
Research interests:
1. Dynamics, control and modeling of large flexible structures

Biswas, Mrinmay
Dept. of Civil & Environmental Engineering
Duke University
Durham, NC 27706
(919) 684-2434
Sponsor topic:
1. Search for minima of a nonlinear scalar function
Research interests:
1. Optimal design of servo-controlled space structure
2. Structural stability - optimum bracing stiffness design
3. Materials development and evaluation

Blankenship, Gilmer L.
SEPI
4300 Evergreen Lane, #302
Annandale, VA 22003-3211

Burns, John
Department of Mathematics
Virginia Polytechnic Institute
Blacksburg, VA 24061
(703) 961-5279

Crawley, Edward F.
Massachusetts Inst. of Technology
77 Massachusetts Ave., Room 37/361
Cambridge, MA 02139
(617) 253-7510
Research interests:
1. Characterization and enhancement of passive damping
2. Rational mixing of passive and active control
3. Scaling laws for flexible structures
4. Experimental methods for testing of structures designed for use in zero gravity
5. Design innovation for zero gravity structures

Dowell, Earl H.
School of Engineering
Duke University
Durham, North Carolina 27706
(919) 684-2214
Sponsor topic:
1. Dry friction damping
Research interests:
1. Passive control: friction, joint damping
2. Structure/plant modeling: asymptotic dynamics (statistical energy analysis)

Dwyer, Thomas A.W. III
Department of Electrical Engineering
Colorado State University
Fort Collins, CO 80523
(303) 491-5306
Sponsor topics:
1. Nonlinear interfacing circuits for exact spacecraft slewing maneuvers
2. Variable thrust actuators
3. Spacecraft dynamics testbed
Research interests:
1. Spacecraft large angle maneuvers
2. Homing missile guidance
3. Robot manipulator command generation
4. Large signal distortion cancellation
5. Flexible structure dynamics
6. Fault analysis

Frisch, Harold P.
NASA/Goddard Space Flight Center
Mail Code 712.1
Greenbelt, MD. 20771
(301) 344-8730
Sponsor topics:
1. Potential usage for an integrated analysis capability
2. Potential usage and limitations of general purpose multi-body formalisms
Research interests:
1. Control-structure interaction modelling capabilities
2. Multi-body dynamics analysis capabilities (DISCOS et al.)
3. Control system modelling and simulation capabilities
4. Integrated analysis capability (control-structure-thermal-power-etc.)

Gibson, Steve
Dept. of Mechanical, Aerospace and Nuclear Engineering
UCLA
Los Angeles, CA 90024
(203) 825-9362
Research interests: control and stability of distributed systems, in particular
1. Infinite dimensional control and estimation theory
2. Approximation theory

Haisler, Walter E.
Dept. of Aerospace Engineering
Texas A&M University
College Station, TX 77843
(409) 845-1669
Research interests:
1. Structural modeling
    a. Finite element
    b. Transient response
    c. Modal frequency analysis
    d. Nonlinear behavior
    e. Effects of damping and material degradation
2. Constitutive modeling
    a. Metals at high temperature
    b. Inelastic and creep behavior
    c. Composites
    d. Damping

Hale, Arthur L.
General Dynamics, Convair Division
P. O. Box 85357, Mail Zone 22-6020
San Diego, CA 92138
(619) 573-3585
Sponsor topic:
1. Integrated structural-control design for time-limited maneuvers

Research interests: control/structure integrated design for
1. Optimization for maneuvers (time limited)
2. Disturbance rejection

Hallauer, William L. Jr.
Dept. of Aerospace and Ocean Engineering
Virginia Polytechnic Institute
Blacksburg, VA 24061
(703) 961-6966
Research interests: experimental applications of active damping on small lab structures, with particular emphasis on
1. Validation of theory
2. Hardware (sensors, actuators, controllers)
3. Integrated design of structure and control
4. Reconfiguration of control following component failures

Hanagud, Satya
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
(404) 894-3040
Research interests:
1. Electronic damping control techniques and the development of design tools

Hanks, Brantley R.
NASA Langley Research Center
Mail Stop 230
Hampton, VA 23665
(804) 865-3055
Research interests:
1. Integrated design
2. Passive control
3. Flight experiments

Haug, Edward J.
Center for Computer Aided Design
College of Engineering
The University of Iowa
Iowa City, Iowa 52242
(319) 353-3820
Research and publication interests:
1. Geometrically nonlinear dynamics of multi-body systems with flexible components
2. Structural and dynamic system design sensitivity analysis and optimization
3. Publishing special issues of the Journal of Structural Mechanics on:
    a. Flexible machines and deployable space structures
    b. Structural control

Hendricks, Scott L.
Dept. of Engineering Science & Mechanics
Virginia Polytechnic Institute
Blacksburg, VA 24061
(703) 961-7154
Research interests:
1. System identification (refinement)
2. Dynamics and controls

Hertz, Terrence J.
AF Wright Aeronautical Labs
AFWAL/FIBR
Wright-Patterson AFB, Ohio 45433
(513) 255-7384
Research interests:
1. Damping in joints
2. Passive modal control

Hotz, Anthony F.
School of Aeronautics & Astronautics
Purdue University
West Lafayette, Indiana 47907
(317) 494-5117
Sponsor topic:
1. Finite element modeling for LSS control
Research interests:
1. Dynamics, control and modeling of large flexible structures

Hubbard, James E. Jr.
Dept. of Mechanical Engineering
Room 3-443A
MIT
Cambridge, MA 02139
(617) 253-2297
Research interest:
1. Distributed piezoelectric-polymer active vibration control

Hyland, David C.
Harris Corp., Government Aerospace Systems Division
P.O. Box 94000
Melbourne, Florida 32901
(305) 729-3030
Sponsor topics:
1. The merits of stochastic characterization of structural systems with uncertain parameters
2. Should a dynamic controller for structural control be finite-dimensional or infinite dimensional?
3. The pros and cons of characterizing real world design specifications by a quadratic performance index

Research interests:
1. Stochastic characterization of modelling uncertainty (maximum entropy approach)
2. Optimal model reduction
3. Optimal fixed-order dynamic compensation (optimal projection)
4. Optimal reduced-order state estimation

Inman, Daniel J.
Dept. of Mechanical & Aerospace Engrg.
University at Buffalo
State University of New York
Buffalo, New York 14260
(716) 636-2733

Research interests:

1. AFOSR
   a. Qualitative results for distributed parameter systems subject to point forces
   b. Results independent of discretizing/truncating
   c. Models of distributed controls-composites (both active and passive damping)
   d. Existence of finite controls converging to stable distributed systems
   e. Bounds on residual modes
   f. Decay rates and response bounds (in terms of physical parameters)
   g. Extensions to non-self-adjoint systems
2. Experimental verification
   a. NASA-UVA proof mass actuator/digital control
   b. NASA active "hinge"
   c. DoD digital control experiments

Junkins, John L.
Engineering Science & Mechanics
Virginia Polytechnic Institute
Blacksburg, VA 24061
(703) 961-5916

Sponsor topics:

1. Placement of closed loop eigenvalues via continuation methods: Does the dual curse of nonlinearity and high dimensionality defeat this approach?

Research interests: dynamics and controls, in particular

1. Large angle maneuvers of rigid, multiple rigid, and flexible bodies
2. Eigenvalue optimization (closed loop) in terms of structural parameters, control gains, and sensor/actuator locations
3. System identification/estimation

"Thought for today" in self-introduction session:
An "optimal" control would be nice ... but for n > 50 dof, I'd settle for "feasible".

Kamat, Manohar P.
Engineering Science & Mechanics
Virginia Polytechnic Institute
Blacksburg, VA 24061
(703) 961-6062
Sponsor topics and research interests:
1. Reducing the degree of nonlinearity through structural optimization; improved controllability
2. Optimization of laminated composite structures for frequency response

Khot, Narendra
AF Wright Aeronautical Labs
AFWAL/FIBR
Wright-Patterson AFB, OH 45433
(513) 255-6992
Research interests:
1. Structural design
2. Structural optimization
3. Interaction of structural and control design of LSS

Kosut, Robert L.
Integrated Systems Inc.
101 University Ave.
Palo Alto, CA 94301
(415) 853-8400
Sponsor topic and research interest:
1. Adaptive techniques for large space structures

Krishnaprasad, P.S.
Dept. of Electrical Engineering
University of Maryland
College Park, MD 20742
Research interests:
1. Control theory of nonlinear and distributed parameter systems
2. Differential geometry of multi-body systems

Lamberson, Steven E.
School of Aeronautics & Astronautics
Purdue University
West Lafayette, Indiana 47907
(317) 494-5117
Sponsor topic:
1. Finite element modeling for LSS control
Research interests:
1. Dynamics, control and modeling of large flexible structures

Lindberg, Robert E. Jr.
Code 7926
Naval Research Laboratory
Washington, D.C. 20375
(202) 767-2827
Research interests:
1. Actuator and sensor placement techniques
2. Large angle maneuvers
3. Spacecraft control laboratory experiment (NASA/IEEE design problem)

Lyons, Michael G.
Integrated Systems Inc.
101 University Ave.
Palo Alto, CA 94301
(415) 853-8400
Research interest:
1. Adaptive techniques for large space structures

McIntosh, S.C.
McIntosh Structural Dynamics, Inc.
887 Warren Way
Palo Alto, CA 94303
(415) 865-0635
Research interest:
1. Integrated structure and control design

Meirovitch, Leonard
Engineering Science & Mechanics
Virginia Polytechnic Institute
Blacksburg, VA 24061
(703) 961-5146
Sponsor topic:
1. The role of orthogonality of modes in the control and state estimation of space structures

Research interests:
1. Dynamics and control of structures

Melosh, Robert J.
Dept. of Civil & Environmental Engineering
Duke University
Durham, North Carolina 27706
(919) 684-2383
Sponsor topic:
1. Search for minima of a nonlinear scalar function

Research interests:
1. Optimum design of actuator-driven space structures
2. Characteristics of design space hypersurfaces
3. Development of mesh-insensitive finite element analysis

Miller, David F.
Dept. of Mathematics & Statistics
Wright State University
Dayton, OH 45435
Research interests:
1. Combined structural and control optimization problems (vibration suppression)

Moon, Francis C.
Cornell University
Dept. of Theoretical & Applied Mechanics
Ithaca, NY 14853
(607) 256-7146
Research interests:
1. Nonlinear dynamics: chaotic vibrations of structures
2. Stiffness control of flexible structures
3. Magneto-mechanical devices

Mulville, Daniel R.
Air-310B
Naval Air Systems Command
Washington, D.C. 20361
(202) 692-7448
Research interests:
1. Structural dynamics
2. Structural optimization
3. Integration of control systems

Nash, William A.
Dept. of Civil Engineering
University of Massachusetts
Amherst, MA 01003
(413) 545-2521
Sponsor topic:
1. Behavior of inflatable LSS

Research interests:
1. Blending structures and controls
2. Inflatable structures
3. Traveling waves

Noor, Ahmed K.
George Washington University
Mail Stop 246
NASA Langley Research Center
Hampton, VA 23665
(804) 865-2897
Research interests:
1. Continuum modeling for large repetitive lattice structures, application to thermal and control problems
2. Incorporation of damping into continuum modeling, passive and active controls
3. Deployment dynamics
4. Computational algorithms for strongly coupled problems (structural/control problems)

Obal, Michael
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
(404) 894-3094

Sponsor topic:

1. Active damping with piezoelectric actuators

Research interests:

1. Electronic damping control techniques and the development of design tools

Park, K.C.
Lockheed Palo Alto Research Lab
Dept. 92-50, Bldg. 255
3251 Hanover St.
Palo Alto, CA 94304
(415) 858-4007

Sponsor topics:

1. Transient dynamics of lattice space structures
2. Computational issues in deployment dynamics
3. Structural dynamics of active control interactions

Questions posed in self-introduction session:

1. Structure-control interactions: do we mean equation-equation or hardware-controller interactions?
2. If modes and shapes are the major information control engineers need from structural engineers, how can joints and other non-modal information on models be accommodated?
3. What do we mean by "structural dynamics" and "controls"?

Polis, Michael P.
Division of ESCE
National Science Foundation
1800 G St., N.W.
Washington, D.C. 20550
(202) 357-9618

Prucz, Jacky
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
(404) 894-3022 ext. 215

Sponsor topics:

1. Discuss the tradeoff between active and passive means of vibration management of spacecraft structures
2. Ascertain the status of actuator and sensor technology, now and projected, for application to active control of spacecraft vibrations
3. How will space structure concepts and control system designs be validated by test before deployment?

Research interest:

1. Passively damped joining concepts for space structures: experimental approach

Reiss, Robert
Dept. of Mechanical Engineering
Howard University
Washington, D.C. 20059
Research interests: optimization, especially relative to
1. Laminated composites
2. Space lattices
3. Passive control

Salama, Moktar
Mail Stop 157-316
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109
Sponsor topics:
1. The potentials of parallel processing in structural dynamics and control problems
Research interests:
1. Coupled structure-control optimization
2. Integrated models and formulations
3. Computational techniques
   a. Algorithms
   b. Accuracy
   c. Concurrent processing

Signorelli, Joel
AF Rocket Propulsion Lab
AFRPL/DYS/STOP 24
Edwards AFB, CA 93523
Research interests:
1. Deployment dynamics
2. Large space structure slew control

Slemrod, Marshall
Dept. of Mathematical Science
Rensselaer Polytechnic Institute
Troy, NY 12181
Research interests:
1. Distributed parameter control
   a. Feedback stabilization, especially nonlinear systems
   b. Bilinear infinite dimensional control
2. Continuum mechanics, nonlinear waves, shockwaves

Trudell, Richard W.
McDonnell Douglas Astronautics Co.
5301 Bolsa Ave.
Huntington Beach, CA 92647
(714) 896-4377
Sponsor topic:
1. Role of passive damping in the performance and robustness of active control systems
Research interests:
1. Passively damped joint concepts for advanced space structures

Tseng, G. T.
The Aerospace Corp. MS M4/971
P.O. Box 92957
Los Angeles, CA 90009
Sponsor topic:
1. Vibration isolation in precision space structures
Research interests:
1. Integrated structural/control design
2. Vibration control
3. Multivariable control
4. Robustness/performance enhancement
5. Modeling
6. Test and experiment

Turner, James D.
Cambridge Research Associates
Home address:
33 Sylvanus Wood Lane
Woburn, MA 01801
Sponsor topics:
1. Deployment dynamics for LSS
2. Dual structure-control optimization
3. Riccati equation research for finite-time control problems
Research interests:
1. Deployment dynamics
   a. Multibody theory
   b. Computational methods
2. Structure/control optimization
   a. Minimum mass designs
   b. Projected gradient algorithm
3. Riccati equation research (finite time)
   a. Tracking problems
   b. Terminal tracking problems
   c. Tracking/disturbance accommodation
   d. Perturbation feedback
      i. Coupled systems of Riccati-like equations (closed form solutions)
      ii. Spacecraft (rigid/flexible) slewing maneuvers

Venkayya, Vipperla
AF Wright Aeronautical Labs
AFWAL/FIBR
Wright-Patterson AFB, OH 45433
(513) 255-6992
Research interests:
1. Structural dynamics
2. Optimization
3. Finite elements
4. Controls

von Flotow, Andreas
Dept. of Aeronautics & Astronautics
Stanford University
Stanford, CA 94305
(415) 493-8124
Sponsor topic:
1. The travelling-disturbance approach to dynamics and control of large space structures
Research interests:
1. Wave-propagation models

Ward, Ben
Dept. of Aeronautics & Astronautics
MIT, Room 37-327
Cambridge, MA 02139
Research interests:
1. Development of intelligent structural elements for use in hierarchic control of flexible space structures, in particular, requirements and strategies for local control in developing smart structural elements

Williams, James H.
Dept. of Mechanical Engineering
MIT, Room 3-360
Cambridge, MA 02139
(617) 253-2221
Research interests:
1. Composite materials and nondestructive evaluation laboratory
2. Wave propagation in space structures

Willmert, Kenneth
Mechanical and Industrial Engineering
Clarkson University
Potsdam, NY 13676
(315) 268-2323
Sponsor topics:
1. Efficient nonlinear deformation analysis of mechanical systems
2. Optimal design techniques requiring a small number of function evaluations
Research interests:
1. Optimal design of mechanical and structural systems
2. Nonlinear deformation analysis of mechanical devices undergoing dynamic rigid body motion

Yang, Henry T.Y.
Engineering Administration Building (ENAD)
Purdue University
West Lafayette, Indiana 47907
(317) 494-5346
Sponsor topic:
1. Finite element modeling for LSS control

Research interests:
1. Finite elements
2. Structural dynamics
3. Structure-control integration

Yedavalli, Rama K.
Dept. of Mechanical Engineering
Stevens Institute of Technology
Hoboken, NJ 07030
(201) 420-5574
Sponsor topics:
1. Robustness and sensitivity issues in the control of LSS

Research interests:
1. Robustness and sensitivity studies in LQG regulators with applications to large space structures
    a. Robust control design combining stability robustness and performance robustness
    b. Critical parameter selection in the control of LSS with uncertain modal data
2. Model/controller reduction with applications to LSS
    a. Reduced order controller design for sensitivity reduction
    b. Comparison of different model/controller reduction techniques from stability and performance points of view
3. Optimal control and estimation of dynamic systems
4. Dynamics of flexible structures