# Dynamics and Control of Large Space Structures

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## Introduction

WITH the advent of the capability of placing large complex structures into orbit, new challenges have evolved. These systems and their associated performance requirements and physical properties necessitate design considerations not encountered with classical spacecraft. References 1-6 give a general overview of potential future missions that fall into the category of large space structures. They range from large optical systems with subarcsecond pointing requirements to extremely large solar power stations.

This paper will present a survey of developments of particular importance to dynamic modeling and control of large space structures. Our objective is to provide material which will be useful to those entering the field, particularly through inclusion of a large bibliography. A working definition of "large space structure" will be given, followed by an enumeration of four challenges in large space structure modeling and control and a brief historical account of efforts to treat the four challenges. A section on structural dynamics discusses modeling, testing, and relationships with allied areas of engineering such as flutter analysis. Aerodynamic modeling and problems in predicting atmospheric density at orbital altitude are summarized in a section on aerodynamics. Finally, a control systems section includes a description of the control problem, model reduction, suggested structural models, controller formulation, controllability and observability, control design methods, identification and adaptive control, maneuvering, and experiments.

Although several definitions have been proposed for the term, for purposes of this paper, we shall define large space structures as those structures which are designed exclusively for the near zero-*g* environment of space and are large by some measure. In addition, we will limit our consideration to those structures which are under active control. It should be noted that, in this definition, we have left the term large ambiguous, but as a point of reference we will assume that the structures should be at least the size of Skylab (largest dimension approximately 33 m). Some of the properties of such structures will be discussed below.

No satellite has yet flown which adheres strictly to this definition of large space structure. While it is true that Skylab had extendable solar arrays and other structural members which were designed for near zero acceleration, other parts

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such as the primary structure itself were inherited from the Saturn V vehicle. A device adhering strictly to the definition would, of necessity, be constructed or deployed on orbit since it could not withstand the rigors of launch.

The strength requirements of large space structures are minimal. For unmanned satellites they are determined by gravity gradient, aerodynamic, control system, and deployment or docking forces. For the manned case, crew disturbances and the requirement to contain gas pressure comparable to 1 atm must be added. Structures designed to these requirements generally have vibration characteristics which include normal modes of extremely low frequency compared to launch vehicles and ordinary spacecraft. In addition, the normal mode frequencies and mode shapes are imprecisely known because the structures generally cannot be tested in 1-*g*, design of joints is different from ordinary ground-constructed structures, and material selected includes items generally not used for launch vehicles and spacecraft.

When pointing requirements for such missions imply control with substantial bandwidth, control system primary resonant frequencies may be above several of the low-frequency modes of the structure. The first challenge in controlling large space structures is to design control systems with natural frequencies above several major structural resonant frequencies, and to ensure that the design is sufficiently robust to assure that substantial tolerances can be accommodated in the structural model.

The second challenge arises from the need to establish the most reasonably accurate structural model. The modal frequencies are typically closely spaced, and the need for precise data dictates many degrees of freedom in the finite element representation. Numerical methods to solve the resulting eigenproblem have been, and still are, a topic of research. Model order reduction is required to deal with such high-order systems. Reduction is applied both to the final and substructure models as the system model is constructed. Modal synthesis methods which do not require inordinate substructure model bandwidth are a subject of research. The need for more accurate methods to predict modal damping is no less critical.

When disturbed, a large space structure is likely to remain excited for some time because of its low-frequency modes and possibly small damping. Many performance indices such as root-mean-square (rms) measures taken over long periods of time, or indices which count periods of excitation as lost time, demand that the low-frequency modes be damped. Current research addresses augmentation of natural damping through passive means as well as through the control system.

Auxiliary control laws have been studied in an attempt to reduce the effects of such disturbances. These control laws are called disturbance "isolation" or "accommodation" systems. They cover the range of simple and intuitive feedforward systems to complex and high-order control through state reconstruction. The problem of plant excitation is, thus, the third large space structure design challenge.

A fourth challenge is involved in maintaining the shape of a large space structure. The criterion may be simply to maintain a set of points in a plane, or to keep the wavefront of electromagnetic radiation flat at a sensor. The latter case arises in shape control of antennas, optical reflectors, etc. The dynamic portion of this problem is solved if the flexible body modes can be damped as discussed above. The fourth challenge requires establishing the desired structural shape as a static equilibrium by proper choice of control law, sensors, and actuators.

## History

Even though, strictly speaking, no system has flown which meets the requirements of a controlled large space structure, there have been several flights which required consideration of some of the problems listed in the Introduction. This very brief history will recount the flights known to the authors in which these problems were first encountered. Projects in the last stages of preparation for flight are included even though they have not flown; however, systems in advanced development or preliminary design were not considered. Unfortunately, primary documentation on some of these efforts has been lost. The authors can only state, with some chagrin, that once again the volatility of internal institutional documentation has been demonstrated.

The Jupiter Weapons System Project flew an autopilot in 1958 which actively damped the rocket's first six structural modes. However, since the Jupiter was essentially symmetrical about its long axis, there was negligible cross coupling between pitch and yaw; therefore, the autopilot for each plane only had to deal with three modes. Active damping was employed in an autopilot for the B-52 aircraft, the Saturn launch vehicles, and doubtless other systems as well.

Control systems to reduce structural loads from wind gusts were flown successfully in 1955 as closed-loop angle-of-attack control experiments on the Redstone rocket. Body-fixed accelerometer control was attempted unsuccessfully on the Hermes in 1948.[7] The same sort of control is planned for the Instrument Pointing System to be flown on Spacelab by the European Space Agency. The purpose of this accelerometer system is to reduce jitter due to Orbiter disturbances.[8]

Many degree of freedom structural models were generated during development of the Saturn launch vehicles. Substructuring and modal synthesis were employed with model reduction to equivalent beams applied to the substructures.[9,10] Reduction also was applied to the system model for control system design and dynamic analysis such as that required in determination of loads. Rules of thumb for tolerancing models of untested structures were developed in the same period; however, they applied only to strength-designed structures of the type used for launch vehicles and spacecraft.

Primary mirror shape control actuators and an optical wave front sensor are to be flown on the Space Telescope in an effort to control the mirror shape on orbit.[11] However, computation of actuator adjustments will be accomplished on the ground rather than via an onboard closed loop.

The authors know of no planned or historical system which requires a control frequency above that of primary structural resonances. Systems have flown in which minor and local resonances were below the control frequency; however, those modes had low gain compared to the primary modes. There have been ground demonstrations of such control, and a discussion of these tests can be found in the section on hardware experiments.

The authors consider that the history of launch vehicle and satellite flight only superficially addresses the four challenges listed in the Introduction. The solution, maturation, and flight testing of these problems lie in the future.

## Structural Dynamics

Although great strides have been made in the accuracy of structural representation (largely because of increased computer capacity), no engineer can model all of the structural dynamic characteristics inherent in a given configuration. Structural dynamic models are merely simplified abstractions of the actual structure. Ideally, those characteristics of greatest concern should be modeled in substantial detail while still maintaining the general characteristics of the structure in areas of lesser concern.[12] Models and model details are a direct function of the problem being analyzed, the analyst's understanding of the problem, and the mission, mission requirements, and mission timelines. In other words, the performance requirement instead of the size of the structure configuration dictates the modeling details and determines the model complexity and size.

Structural dynamics is probably the most widely documented field in the aerospace industry with international contributions ranging from general theory to detailed empirical and analytical treatments of specific items. Textbooks abound by such noted experts as Myklested, Den Hartog, Minorsky, Timoshenko, Hutton, Craig, Bisplinghoff, Ashley, Meirovitch, Lackie, etc. In addition, NASA has published a series of space vehicle design criteria documents that are generally available.[13] From a purely large space structure standpoint, however, there are only a limited number of references, probably due to the relatively small flight experience base and limited time these concepts have been under evaluation. These limited references[13-23] primarily deal with modeling. An extensive number of papers, well known to all in the field, exists in the literature that deal with modeling techniques of typical structural elements, such as beams, plates, and shells. Several survey papers contain excellent background data for use in the area of large space structures even though they do not concentrate on this subject directly.[24-31]

Based on the literature available, the conclusion can be reached that present analyses of large space structures have used standard analysis techniques exclusively. While these techniques can solve presently envisioned problems, the computer cost and schedule impacts involved are often excessive, due to the number of degrees of freedom (DOF) required. The problem is not only due to the large size of the structure, but is also associated with the high performance requirements, high accuracy pointing, shape control, overall orientation in space, plus configuration growth, which dictates detailed definition of the structural characteristics and, therefore, many degrees of freedom and large models. These large models create a second problem: control system analysis techniques are not compatible with these large systems. This leads to the additional requirement for techniques that can reduce the overall system size while maintaining the essential features required in design and verification of the control system performance. The size of the structure is not the overriding requirement driving model size and complexity; performance requirements are the culprit. Two examples demonstrate this difference. The Skylab pointing requirements were influenced very little by the overall spacecraft dynamics, but were very sensitive to the nonlinear flex springs between the telescope and the mount.[32-34] This allowed use of fairly simple models for pointing control system design. The Space Shuttle main engine nozzle model is very sensitive to the fluctuating pressure of the nozzle flow during startup which requires a very detailed finite element model plus extensive dynamic test verification.[35,36] In summary, to achieve usable accuracy, a model must have several joints per mode to be calculated (4-10 as a rule of thumb). Each structural element must be simple enough to match the available repertoire, otherwise submodels are developed. The total number of operations in the solution is proportional to $Nb^2$, where $N$ is the number of joints and $b$ is the modal frequency bandwidth or its equivalent. Thus, the resource requirement for solution is more sensitive to the topology of the structure than to the number of joints required in the model or to the size of the structure. In order to expand our available analyses tools to solve these problems several areas must be addressed. These are: 1) excessive computational time; 2) reduction of the size of the structural dynamic model (which is not amenable to control analysis); 3) change in size and shape of modeling structures (configuration growth); 4) shape control; 5) geometric and material nonlinearity modeling; 6) damping synthesis; 7) verification of the predicted structural dynamic characteristics where ground tests are not applicable; and 8) dynamic analysis of spinning flexible structures.

In general, the structural dynamicist is faced with describing the elastic and mass characteristics and their coupling in a dynamic manner. To accomplish this one starts with the static model of the stiffness and the mass and then proceeds to a solution for the dynamic characteristics. While some might argue that the static solution is not necessary, most find it a fundamental part of the dynamic solution. Many approaches are available for formulating and solving for the dynamic characteristics. The choice must be based on judgment, mathematical and physical compatibility, and solutions expected. Several textbooks and reports go into these details.[37-41] Several special programs (e.g., NASTRAN, SPAR)[42] exist to perform the basic steps required. SPAR (Structural Performance Analysis and Redesign) is a collection of modules which provides capability for static and dynamic analysis of structures and fluids. SPAR features a large problem size capability and fast compiler speed achieved by the use of a data base in secondary storage, sparse hypermatrix logic, and efficient I/O operations. NASTRAN is a familiarity to industry and government alike and exists in two versions, COSMIC and McNeil-Schwendler. However, even though these programs do much of the work, accurate modeling is still an art based on experience and not a science. An intimate knowledge of what one is trying to describe is essential.

The difficulty of selecting techniques can be illustrated with one example: determination of the response of a large flexible structure in a pointing mode. The avenues open to the structural dynamicists, as stated previously, depend on the performance requirement of the mission and, therefore, how much detail is required to meet these accuracy requirements. The model may be formulated using simple models if accuracy requirements are not stringent or very complex finite element models if the user has high accuracy requirements. An apparently simple model may mask a wealth of detail in submodels used to generate coefficients; however, it meets all of the user requirements, while in another application all details are needed. The choices also depend, to a large extent, on the availability of programs. In fact, several industries have their own special programs, in addition to NASTRAN and SPAR, which are generally available.

Early aerospace structural dynamic analyses used two basic approaches: 1) the equivalent beam models using Rayleigh-Ritz, Stodola, or Galerkin methods, and 2) lumped mass models connected by equivalent springs. These approaches are fairly accurate since early space vehicles could be approximated as long cylinders or beams and the frequencies were fairly high and not strongly coupled with loads and control.[43] Judgment and physical intuition were required in order to make proper decisions for formulating these equivalent models. For example, solid propellants act mainly as mass additions without stiffness; whereas, liquid propellants act as spring/masses describing sloshing (propellant oscillations). Sloshing, coupled with the Jupiter control system, led to the loss of a vehicle.[44-46] Sloshing is modeled by assuming a single mass or pendulum and fitting its solution to the terms in the solution of the Navier-Stokes equations or by determining the constants empirically.[35,47,48] Zero-$g$ sloshing (propellant behaviors under capillary forces instead of gravity forces) has been studied extensively and may have some basic use in large space structures.[49-51] It is generally accepted that high-$g$ propellant analysis methods have proven accurate at low-$g$ levels greater than $1 \times 10$ $g$. Equivalent small numbers of degrees of freedom models (equivalent beams, etc.) will also serve well in large space structures if chosen properly (equivalent plates, etc.).

Early control-structural interaction studies raised a serious question for the concept of the Saturn I and IB, since the first stage was composed of a center tank surrounded by a cluster of eight tanks. The problem was solved using full-scale test-verified dynamic models based on either lumped mass or equivalent beams. The use of equivalent beams was a unique approach at the time. Modes were generated for the eight clustered tanks assuming fixed end conditions at one end and pin conditions at the other. The thrust frame and spider beams to which they were connected were modeled as circular plates, while the core tank and upper stages were connected to a beam. Using Lagrange's equations, the modes from these individual parts were coupled together with appropriate boundary conditions. Later, modal coupling techniques evolved into what is now a classical approach.[9,52]

Saturn V Apollo used equivalent beam analytical models with scale-model and full-scale dynamic testing for verification.[36-55] As problems became more apparent, a combination of finite element models and equivalent beams or lumped mass models was used. Computational techniques were still limited and computer time was at a premium; hence, model complexity was limited by the degrees of freedom that could be accommodated. Special-purpose (i.e., configuration-dependent) computer programs were developed.[43,54] This meant understanding the problem and only modeling required characteristics. Only four or five basic modes were required. POGO during Apollo also became a real problem for modelers. POGO is a structural propulsion system coupled oscillation that is a closed-loop unstable phenomenon. The results are a high-*g* oscillation in the longitudinal axis of the vehicle that creates structural problems as well as concerns for the astronauts. In this case, the S-II stage POGO problem was very complex, requiring a detailed hydroelastic model of the propellant lines in conjunction with engines and pumps, the latter being determined experimentally. The POGO problem in the line, pump, and engine was nonlinear in nature.[56] This modeling problem was solved by coupling linear equivalent models of all elements and systems that were linear and connecting them with nonlinear springs. This technique, i.e., coupling linear element models with nonlinear connecting models, has merit for application to large space structures although hydroelastic modeling, per se, does not. This modeling problem had much to do with the development of finite element techniques applicable to all structural dynamic problems.

Skylab is the largest controlled structure orbited to date. Dynamically modeling its orbital configuration was a real challenge. The configuration had large solar arrays, a pointing telescope, the Apollo Telescope Mount (ATM), and a large workshop with a docking module. The ATM had nonlinear springs. Since nonlinear techniques were not available, approximately 20 different conditions were analyzed and a linear stability analysis run for each. The system was modeled using finite element models of the basic structure and beams for the arrays and panels. Dynamic tests were run on each of these various elements. The average correlation between test data and post-test analysis was only around 90% on frequency; mode shape correlation was around 80%. In fact, one mode that showed up during operations was never found analytically; however, control system gains were changed in orbit and no additional problems ensued.[32]

The Space Shuttle, from the standpoint of subsystem interaction, was a new challenge. Strong coupling existed from both a static and dynamic sense, resulting in a high modal density. For example, in the launch configuration at liftoff, 400 bending modes were required to describe its modal characteristics through 15 Hz. In contrast, Saturn/Apollo could be described with less than 20 modes. Loads, aerodynamics, environment (winds), trajectory, thermal, propulsion, and control are strongly coupled requiring unique trade studies, simulations, and tests for design and verification.[33,35,57,58]

Again, scale-model and full-scale dynamic tests were used to verify the dynamic models. The quarter-scale model was manufactured to one-fourth the normal joint manufacturing tolerances to account for gravity effects. Testing a quarter-scale in 1-*g* environment without these tolerance changes is equivalent to testing full scale at 0.25*g*. An automatic multishaker blending, modal selection, and data acquisition system was developed and implemented, reducing test time and increasing accuracy significantly. This complex coupling of the many technical disciplines led to the development of a comprehensive set of design criteria in order to get proper design trades and verification. A review of the state-of-the-art in dynamic testing, including a summary of all the testing accomplished for the Space Shuttle, can be found in Refs. 36 and 59.

Classically, modal dwell has been the testing approach taken for space structures. Modal dwell is a technique that uses several shakers located at discrete points on the structure, blending them in terms of amplitude at one frequency to produce a normal mode. Phase displays are used to determine the normal modes. Current techniques use verified software packages with minicomputers to accomplish this. Random and time-domain approaches have been established and are well documented. Random modal testing uses a known random input at a shaker for determining response. Since the force is known, the vehicle responses can be analyzed for its frequency content and mode shapes determined. Time-domain testing uses a known time signal or a free response; however, it determines the modal characteristics by operating on the data in the time domain. These approaches offer many advantages in both test time and number of modes available.[36] Two disadvantages, however, are apparent: 1) the forcing function must be known (free decay can be used for Ibrahim's method), and 2) classical mode orthogonality checks are not applicable. While these approaches are applicable to large space structures, special problems do exist since these structures are difficult to test on the ground and their large size creates instrumentation and excitation problems.

The use of finite element methods in structures has greatly influenced the tradeoff between analysis and test.[10,24,33,39,58,60,61] Continuous improvements in both flight- and ground-based microcomputers, in conjunction with parallel processing and new software techniques, have altered tremendously the balance between analysis and test and the development of more efficient test approaches. For example, real time domain test and flight data analysis procedures provide new tools and insight into the whole area of testing. These approaches have added to our analytical ability and enhanced our test approaches. A major improvement in knowledge of structural characteristics has resulted from these technique developments. The basic problem with large-scale testing, however, is still with us. Large-scale verification testing necessarily must occur at a time when most of the structural characteristics have been frozen in detailed design drawings and flight hardware. Consequently, if a problem is uncovered at this point, there is either large cost and schedule impact or the solution options are narrowed, usually resulting in degraded performance. With this in mind, the discussions that follow will address excitation approaches, data acquisition methods, scale-model testing, test hardware and facilities, and general limitations.

The current state-of-the-art consists of two basic testing techniques: multiexciter normal mode approach and single excitation source frequency response matrix approach. Time-domain analysis is rapidly approaching state-of-the-art status. In the frequency response matrix approach, the modal parameters are estimated from the frequency response using curve fitting techniques. Each of the approaches has advantages and limitations.

Clearly no single approach is best in all circumstances. The dynamicist and the test engineer must choose from the available techniques based on objectives and hardware.

Regardless of the test approach, one must deal with several other areas. Instrumentation is a key area. Accelerometers are very accurate and are proven. Rate indicators are available; however, in general, only control rate gyros are used which are bandwidth limited. Displacement gages are available, as well as strain gages. Accuracy is a question in these cases, but the characteristics of these instruments are well known and documented. The major problem with this class of instrumentation is the requirement for large, expensive cabling and data collection systems. This is not a major problem on present launch systems; however, this will be a major problem for very lightweight structures and testing of large systems in space. Techniques using remote sensing are under development to eliminate this problem. NASA will fly the Solar Array Flight Experiment (SAFE) in 1984 with an objective being the validation of on-orbit testing using remote sensors. Initial work on orbiting space stations was accomplished by many in the time frame of Apollo and Skylab. Typical examples of this type of analysis are given in Refs. 49, 59, and 62.

As a result of preliminary analyses conducted on large space structures, some basic techniques have evolved. To date, three key requirements are apparent: 1) regime of finite elements to macroelements or equivalent elements to save cost and computer time, 2) treating both geometric and material nonlinearities, and 3) handling growth in analysis since most large space systems will not be static but will grow in size and complexity. Testing technology must parallel these requirements. For example, testing a full system on the ground is practially impossible; however, testing of elements on the ground is not. One potential ground test approach conceivably could be testing these elements to determine and verify macroelement or equivalent elements for use in large system models in conjunction with scale-model system test to verify coupling. Many of the proposed large space systems appear to have the potential for representing major areas with linear models, coupled with a selected coupled element test. Initially, the test program must isolate the problems discussed in detail in the section on state-of-the-art and future technology to determine critical areas. Some are obvious if the assumption is made that final system test verification is required. In this case, on-orbit testing must be done in order to duplicate the environment and test the system simultaneously. To achieve this verification, unique remote sensing and sophisticated excitation techniques are required. Structural dynamic evaluation and data extraction tools that do not require knowing the forcing function would be highly desirable and unlikely. In addition, model selection and verification criteria that do not require excessive experimental data to insure orthogonality, etc., are mandatory. Only after these techniques have been developed and basic data acquired can the approaches be defined, tools developed, and systems verified in space.

Key issues that are apparent in the test and structural dynamics area are: 1) zero-*g* effects, 2) low natural frequencies with high modal density, 3) joint/interface characteristics, 4) damping (distributed and lumped) 5) thermal vacuum effects, and 6) large space structures experiment excitation methods.

Two key dynamic problems that have been identified in the current literature are excessive use of computer and modal truncation or model size reduction. Technically, computer time usage is only a cost problem and not a design limiter. Also, most control stability and optimization techniques are limited to only a few modes. Basically, then, dynamics technology needs to be advanced in two broad areas: analysis techniques and testing techniques. The better the dynamic characteristics can be predicted analytically the less testing required. A summary of some of the key technical areas needing attention follows.

1) State identification approaches. Present techniques require that one either know accurately the forcing function or eliminate it in order to identify the dynamic characteristics. Development of techniques that will allow identification of the dynamic characteristics without knowledge of the force is very important, particularly for on-orbit testing where elimination of time varying forces, such as gravity gradient and solar pressure, is not possible. An alternative is to have techniques that will separate the response to the known forcing function from the residual response to the unknown forces.

2) Data quality. Present techniques require many data points and tend to break down when closely grouped modes decrease the purity of the mode. Techniques are needed to eliminate these shortcomings and consider complex modal characteristics (damping and nonlinearities).

3) Sensing. Remote sensing is mandatory for on-orbit testing of large space systems.

4) Model updating procedures. Procedures must be improved drastically. How to input test data into models with a large number of degrees of freedom, for example, is still an unanswered question.

5) Boundary conditions in substructuring. This is a key area if element testing becomes the basic approach. The problem here is the choice of the constraint and its quantification.

6) Nonlinearities. Analysis of nonlinearities is currently accomplished on a case by case basis. More general methods are needed.

7) Sliding connections. A special case is that of nonlinear sliding connections. Mounting of payloads in the Space Shuttle, large space systems in orbit, and many operational payloads have this type of connection. How to test and quantify dynamic characteristics under these conditions is a major problem.

8) Prediction of the effect of small configuration changes is required without retesting. In large, highly coupled, multielement, dynamic systems, the prediction of effects of small changes is difficult. Low damped systems can tune and change characteristics by orders of magnitude with very small changes in hardware. This is a key area to reduce risks and insure success.

9) Environment simulation. This is a crucial area where the environment affects the characteristics. Temperature, static loading of joints, etc., are important.

10) Model or modal truncation or simplification tools. Present systems contain large numbers of modes and degrees of freedom. Research is needed jointly between test and analysis that will produce verified models that contain essential characteristics but eliminate all others.

## Aerodynamics

In low Earth orbit, aerodynamic moments on orbiting vehicles with large surface area elements such as solar arrays are frequently the largest torques which the control system has to handle. For any orbital altitude which produces a useful life, the vehicle will be in the free molecule flow regime. Free molecule flow has been the subject of a large number of investigations in the past 35 years, and the basic kinetic theory for the analyses is well founded. An excellent summary is given in Ref. 63, Sec. 4, Chap. 2. The basic theory has been formulated into a working computer program for complex vehicle configurations as described in Ref. 64.

The free molecule flow regime is the regime of extreme flow rarefaction. The molecular mean free path is much larger than a characteristic length of the body which is assumed to be located in a gas flow of infinite extent. Thus, it is valid to neglect the effect of the gas molecules re-emitted from the body. Further, the basic free molecule flow theory assumes assumed to be entirely undisturbed by the presence of the body. Further, the basic free moleculer flow theory assumes the body surface is everywhere convex toward the gas stream which excludes the possibility of molecular interreflection.

In general, these assumptions have been found to be satisfactory for the calculation of the aerodynamic forces and moments for complex configuration spacecraft. As an example, there was excellent agreement between calculations and measured flight data for Skylab placed in a torque equilibrium attitude. However, some of these assumptions may not be as good when applied to multielement, large space structures. For example, the assumption of no molecular interreflection may be violated if two large planar surfaces are in certain spatial and angular locations with respect to each other. Interreflection has been considered for free molecule pipe flow using Monte Carlo techniques. These procedures are much more complex than basic free molecule flow theory and it would be very difficult to mechanize these procedures into a computer code for application to multielement large space structures. Research to define the interactive effects of multiple elements on the basic free molecular flowfield is needed.

The solar flux, sometimes called light pressure, exerts small forces and moments on spacecraft. In addition to solar flux, radiation from Earth and the spacecraft's own emission can produce noticeable effects. While aerodynamic forces and moments decrease rapidly with increasing altitude, due to the decrease of atmospheric density, the solar pressure is essentially independent of altitude in Earth orbit. It becomes the dominant force above altitudes of 500-800 km. This crossover altitude depends on the solar activity which strongly affects the density of the upper atmosphere and thus the aerodynamic forces. Radiation pressure is calculated with procedures that resemble those used for the calculation of aerodynamic pressures. The results agree well with spacecraft measurements.[65-67]

A basic problem associated with application of the aerodynamic theory lies in predicting short-term variations in upper atmospheric density. Long-term variations have been investigated through experimental orbital decay data from satellites; however, control system design is sensitive to variation over hours or possibly minutes as opposed to weeks or months as is the decay problem. In addition, solution of the control problem requires a density model which represents the sunlit and dark sides of the Earth rather than an average. Even though some data exists for short-term temporal statistical modeling of the solar flux and the atmospheric density, the needed models are not available and much work remains to be done.[68]

The effects on control system design are threefold. First, the aerodynamic moment must be considered when sizing the storage capacity of momentum exchange systems. Second, aerodynamics cause significant alteration to equilibrium dynamics which, for example, can render gravity gradient parking attitudes unstable.[69,70] Finally, tumbling motion, such as that dealt with in the re-entry of Skylab, is significantly complicated by aerodynamic forces.[71,72]

## Control Systems for Large Space Structures

This section will summarize significant aspects of the large space structure (LSS) control problem that have been reported over the last few years. A concentration of published information is available in Refs. 21-23 and 73. Previous surveys[74-78] on the subject have covered the period through 1978, and while some of the early references will be repeated here, the emphasis will be on more recent work. This survey is not intended to be one of control techniques in general but one of control techniques as they have been applied to LSS. Consequently, only those works that show a direct application to LSS will be covered here. Complete references to the more general topics of control system theory and methodology are referenced in the LSS-related work. The major topics to be reviewed are: a description of the LSS control problem, models and model reduction, controller formulations, maneuvering, and experimental results.

### LSS/Control Problem Description

Numerous authors have described the aspects of control system design that are peculiar to the LSS/control problem (Refs. 74-77). These will be summarized briefly in this section. Figure 1 is a block diagram of a control system for a LSS. The spacecraft dynamics represent the structural characteristics of the LSS and relate the dynamic responses at prescribed locations in the structure to torques and forces that act upon the system. The structure of the spacecraft is in reality a distributed parameter system and as such is mathematically characterized by partial differential equations (PDE). This approach, however, is impractical for all but simple structures; and most representations, as described above, are based on a finite element model of the form

$$m\ddot{q}+kq=Q \tag{1}$$

where $q$ is an $n$-dimensional vector of generalized element displacements, $Q$ the generalized force vector, and $m$ and $k$ $n \times n$ symmetric mass and stiffness matrices. A similarity transformation can be performed on Eq. (1) employing a transformation such that

$$\Phi^T m \Phi = I$$

and

$$\Phi^T k \Phi = \Omega^2$$

where $\Phi$ is an $n \times n$ matrix whose columns are the structural mode shapes. An equivalent modal representation becomes

$$\ddot{\eta}+\Omega^2\eta=\Phi^T Q \tag{2}$$

where $q=\Phi\eta$. If $Q$ includes only controller forces then $Q=B'u$, where $B'$ is an $n \times \ell$ actuator influence coefficient matrix for the control elements $u$. Equation (2) can be written in a state space form by defining $x=(\eta,\dot{\eta})$, then

$$\dot{x}=Ax+Bu+v \tag{3}$$

where

$$A=\begin{bmatrix} 0 & I \\ -\Omega^2 & 0 \end{bmatrix} \qquad B=\begin{bmatrix} 0 \\ \Phi^T B' \end{bmatrix}$$

and $v$ is the disturbance vector.

The block in Fig. 1 entitled sensor dynamics represents the means by which certain states of the LSS are measured. For a finite number of ideal position and velocity sensors, the measurement vector $y$ is given as

$$y=Cx+w \tag{4}$$

where $y$ is an $r$ vector, $C$ is $r \times n$, and the vector $w$ is the sensor noise. Since $r$ is limited by practical considerations there is often a requirement to synthesize additional state variables in order to make use of certain controller designs. In addition, there is usually a need for additional filtering. These functions reside in the block following the sensors. Based on some function of the measured, estimated, and filtered states, commands for the actuators are generated in the controller block. These commands, shaped by the actuator dynamics,

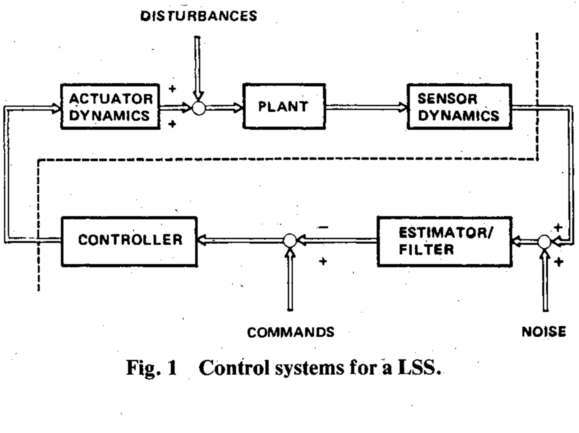

Fig. 1 Control systems for a LSS.

are applied to the spacecraft together with disturbances. Commands to the control system depend on the mission requirements and can be generated either onboard or from the ground. All functions below the dotted line are performed in an onboard digital computer and, hence, represent difference equations.

The problem, then, is to select sensors, actuators, and the connecting software so that a stable control system results that meets mission requirements and has adequate sensitivity characteristics. The difficulties in dealing with the design in a straightforward manner arise from a number of properties inherent in the LSS.[78] The approximate structural model, developed by the structural dynamicist, in spite of its being a reduced representation of an infinite dimensional system is generally too large for the control designer to cope with. Thus, the size of the model must be reduced further to perform the control system design. The effects of the unmodeled part of the LSS on the closed-loop controller must be dealt with. Consequently, two models must be considered in the design process: a reduced-order control system design model and a higher-order evaluation model. In addition to the dimensionality problem, the LSS has resonant frequencies that are within the bandwidth of the control system and are closely packed. Furthermore, the modes associated with these frequencies have damping factors as low as 0.1% of critical. As if these difficulties are not enough, the structural properties of a LSS cannot be tested before it is put into orbit, so that sizable uncertainties in modal parameters must be assumed. In applying the various control theories to the solution of any LSS control problem, the designer must recognize the handicap of the practical limitations on what can be accomplished with today's onboard computers.

## Model Reduction

Because of the large size of the matrix $A$ in Eq. (3), the controller design must be performed on a truncated model for the structural dynamics. Hence, Eq. (3) can be rewritten as

$$\begin{bmatrix} \dot{x}_c \\ \dot{x}_R \end{bmatrix} = \begin{bmatrix} A_c & 0 \\ 0 & A_R \end{bmatrix} \begin{bmatrix} x_c \\ x_R \end{bmatrix} + \begin{bmatrix} B_c \\ B_R \end{bmatrix} u \tag{5}$$

where $v$, the disturbance vector, has been ignored for the purposes here, $A_c$ and $B_c$ represent that part of the LSS upon which the control design will be based, and $A_R$ and $B_R$ are what remain. Equation (5) suggests the two-model aspect of the LSS control problem, a truncated control system design model and what has been referred to as evaluation model comprising the totality of Eq. (5) (Refs. 79-81). Thus, any design based on a truncated LSS model must be evaluated for some far more complicated model that may be the full finite element model or more likely some reduced version of it.

There remains the very significant question as to how the decomposition suggested in Eq. (5) is to be accomplished. The truncation of modal coordinates based on various criteria commonly has been used. These criteria are based on frequency and bandwidth considerations or relative modal gains. For the purposes of the LSS control system design, a more sophisticated selection process must be employed. The placement of actuators and sensors based on control system performance criteria, disturbances in the total system, and the system controllability and observability influence the choice of retained modes. References 82 and 83 describe an aggregation procedure where the modes are aggregated according to the influence of sensors and actuators. In this technique, the coupling coefficients for the unmodeled modes are independent of controller parameters. The model reduction and the controller design problems are not independent, and the methods developed in Refs. 80 and 84-89 take into account model sensitivities and modeling errors in a cost functional, so that a compromise can be found between control system performance and complexity. The model validation procedure in Refs. 90 and 91 recognizes the connection between model reduction and control system design and outlines a process by which closed-loop suboptimal control performance is compared to that of a full-order system. A method for the projection of the exact generalized coordinate vector onto a subspace of smaller dimension is described in Ref. 92.

## Suggested Structural Models

The true test of any control system design procedure is to apply it to a realistic LSS system model that includes a detailed structural model that has sufficient fidelity for verification and a set of performance requirements that the controller must satisfy. Reference 93 proposes a structural model that is representative of large array-type structures such as the solar power station but contains no mission specifications. A more complete problem definition is described in Refs. 94 and 95. In Ref. 94, commonly referred to as Draper model 1, a tetrahedral structure attached to ground is proposed with requirements for pointing certain elements of the structure. Draper model 2 in Ref. 82 is representative of a more realistic large optical system. In addition to a detailed structure a line-of-sight specification is included and internal periodic disturbance forces are prescribed. This model has been used as a reference in the Active Control of Space Structures (ACOSS) program. Reference 91 suggests modifications and improvements to Draper model 2.

## Controller Formulation

For the dynamical systems described by Eq. (5), a controller that is some linear combination of the states is assumed as

$$u = -Kx \tag{6}$$

where $x$ corresponds to $x_c$ in Eq. (5). The gain matrix $K$ can be chosen in several ways. It is often selected to minimize a performance index of the form

$$J = \int_0^\infty (x^T Q x + u^T R u)\,\mathrm{d}t \tag{7}$$

where $Q$ is positive semidefinite and $R$ is positive definite.[96,79] The gain matrix $K$ is then

$$K = R^{-1} B^T P \tag{8}$$

where $P$ is the solution to the Riccati equation

$$A^T P + PA - PBR^{-1} B^T P + Q = 0 \tag{9}$$

The gain matrix $K$ can also be found based on pole assignment for the closed-loop system.[97,98]

Since in LSS control problems all of the states, $x$, are not measurable, the form of Eq. (6) is impractical. Estimation for the inaccessible states can be constructed from

$$\dot{\hat{x}} = A\hat{x} + Bu + G(y - C\hat{x}) \tag{10}$$

where $G = \hat{P} C^T \hat{R}^{-1}$ and $\hat{P}$ is the solution to the Riccati equation

$$A\hat{P} + \hat{P}A^T - \hat{P}C^T \hat{R}^{-1} C\hat{P} + \hat{Q} = 0 \tag{11}$$

where $\hat{Q}$ and $\hat{R}$ are the covariance matrices of $v$ and $w$.[79,99,100]

In the design of a control system for LSS, in addition to the large dimensionality of the dynamics and the uncertainty in the models of these dynamics, a significant difficulty that must be overcome involves the activity of unmodeled modes influencing both performance and stability. Unmodeled modes are excited by control system actuators producing "control spillover" and are measured by sensors giving "observation spillover."[101] In the control design theories and methods that are discussed subsequently, a central issue is the reduction or elimination of spillover and the achievement of stability characteristics that are insensitive to parameter and model variations, a quality often referred to as robustness.

## Controllability/Observability

The ease and quality with which a control function can be performed closely depend on the controllability and observability of the controlled system. These in turn are dependent on the type, number, and location of actuators and sensors used in the control system. The relationships derived in Ref. 102 are aimed at providing physical insight and practical guidance in selecting actuator and sensor configurations based on controllability/observability concepts. References 103 and 104 show how these concepts can be used in determining the minimum actuator/sensor complement for a given design goal. In general, the actuator/sensor configuration depends on the type of controller that is being considered and can be traded against other complexities in the system.[105]

## Control Design Methods

Optimal control theory has become a popular basis for the design of control systems for LSS's.[79,75] References 106 and 107 apply optimal control techniques to reduced-order controllers; an augmented state vector is defined composed of plant and controller states, and a parameter optimization is performed by solving a Lyapunov equation for the selectable parameters. In Ref. 106, an integrated approach to the controller design problem is offered for a variety of problems with different cost functionals. The Kosut method of suboptimal output feedback has been extended in Refs. 108 and 82 so that free parameters resulting from rank deficiency in the observation matrix can be chosen to improve performance. Stability theorems and conditions for the methods in the frequency domain have been derived in Refs. 109 and 110; other stability conditions appear in Ref. 111.

References 101 and 112-115 define the origins of the control and observation spillover phenomena from unmodeled modes and show that if they are not considered in the controller design, instabilities can be expected. In Ref. 114 a uniform beam example is used to demonstrate these effects. Controllability and observability conditions for various sensor and actuator types, number, and location are covered. Several methods for eliminating spillover effects are proposed, including the selection of sensor/actuator parameters and the use of prefilters. In particular, a prefilter scheme involving phase-locked loops tuned to known residual modal frequencies is proposed to reduce observation spillover. Reference 81 introduces additional terms in the controller and estimator equations to decrease sensitivity to spillover. An "innovation feedthrough" term is added to the control equation derived for the reduced-order system and an aggregation term to the observer. The method does not eliminate spillover effects but gives the designer the capability of adjusting these effects between modes. It shows how this procedure is similar to those using direct velocity feedback (DVFB).

Termed singular perturbation, an approach to model reduction and spillover problems is described in Refs. 116 and 117. In this approach forced singular perturbation is applied to the equations for known residual modes. Hence, $\dot{x}_R = 0$, and $x_R$ is solved algebraically and substituted into the $\dot{x}_c$ equation. At the same time, the performance index is augmented to include a term that minimizes spillover. The method is applied to a low-order platform structure and shows substantial reduction in the influence of known, truncated modes. References 118, 119, and 79 describe an analogous approach wherein the performance index is modified to suppress certain selected known modes. Termed model error sensitivity suppression (MESS), the scheme tends to minimize the excitation of these modes, although in Ref. 120 a direct feedback term is added to the control to increase the damping in the suppressed modes. This technique leads to a concept of decentralized control as in Refs. 117 and 121.

Reference 122 shows that transforming the control vector space into orthogonal subspaces eliminates control spillover for known, truncated modes and that this procedure is equivalent to the singular perturbation approach.[79] A similar method to cancel out observation spillover is investigated in Ref. 123.

In Refs. 124-131 a modal control technique has been developed that involves a modal decoupling procedure, which uncouples the system equation of motion as in Eq. (4). This allows individual modes to be dealt with independently which greatly reduces the computation aspects for certain design implementations. For instance, the minimization of certain cost functions requires the solution of many second-order Riccati equations rather than large dimensional coupled equations. This allows phase plane design techniques for nonlinear elements such as on-off thrusters. The control implementation requires the construction of an observer to estimate the modal coordinates. The method has been developed for gyroscopic and nongyroscopic systems and has been applied to an example spacecraft having a rigid control section with two appendages. The effect of structural damping was investigated,[130] and consideration of placement of actuators and sensors is discussed for the example. The design procedure has been applied to reduced-order systems, and it is shown that for known residual modes spillover effects can be eliminated. In Ref. 132 the decoupled formulation is compared with others for three different controller design techniques, and certain advantages are postulated. A different approach to the LSS control problem employs the use of direct output feedback (DOFB) control. Whereas modal control requires an estimator to synthesize the modal coordinates that drive the controller, DOFB makes uses of the measured signals directly. Reference 105 describes this method and compares it with the modal control technique. In Ref. 133 it is shown that direct velocity feedback with collocated actuators and sensors is useful in suppressing vibrations provided certain conditions are met, one of these having to do with not exciting rigid-body modes.

Direct velocity output feedback leads to the concept of a modal dashpot, that is an electronic feedback that results in the addition of damping to certain modes. Reference 134 compares various methods for augmenting damping and Ref. 135 is concerned with optimal damper location. These concepts are further pursued in Ref. 136, where for velocity feedback and collocated sensors and actuators stability conditions are shown to depend only on controller parameters. An example problem is worked for a large pointed antenna. In Refs. 137-140 the use of an annular momentum control device is examined as a means of performing both primary and secondary control functions. The secondary function is defined as damping enhancement, for which stability conditions are given. A low authority controller method for collocated sensors and actuators is described in Ref. 141. For the low gain controller, perturbation methods are used to calculate root movements and mode shape changes; these are verified by numerical examples. In Ref. 142 a modal dashpot design philosophy is developed involving a biobjective optimization procedure that minimizes feedback gains and maximizes damping in critical modes. Sensitivities to parameter variation, spillover, and noncollocation are shown. In Ref. 143 stiffness as well as damping augmentation through output feedback is investigated. The idea of active structural stiffness and damping, employing an optimal local control, is investigated in Ref. 144.

In Refs. 145-149 the concept of positivity is applied to stability of the LSS control system. The idea is to make the closed-loop system appear to be passive which guarantees stability. An embedding technique[146-149] is used to produce a form for which conditions for positivity can be applied. The method is insensitive to modal truncation and modal parameters, and a positivity index, a frequency-dependent function, shows stability sensitivity to system parameters.

Methods other than those employing optimal control techniques have been used in the LSS control system design. Pole placement methods are used in example designs in Refs. 97 and 98, as well as in conjunction with parameter plane techniques in Ref. 150. Stability boundaries resulting from parameter plane methods are used in Ref. 151 to show stability margins resulting from a control system design based on positivity criteria.[146] Reference 152 derives stability criteria based on frequency response techniques for a spacecraft with flexible appendages. Such techniques have been used in the design of OSO-8 (Ref. 153) and the Skylab/ATM (Ref. 154). While these spacecraft certainly can be termed flexible structures, their controller designs were not complicated by high gain modes within the controller bandwidth. However, the Space Telescope,[155,156] presently being designed, has significant appendage modes within the control system bandwidth and conventional frequency response methods are used.

The design of a control system for a real LSS will make use of a number of the methods described above. Reference 157 shows, for example, how better control of spillover effects is maintained by employing a systematic use of actuator/sensor placement, control synthesis, and filtering. The effectiveness of filtering is emphasized in Ref. 158. This approach is further exemplified in Refs. 95 and 159-161, where a design exercise is shown for several spacecraft configurations including the Draper model 2 in Refs. 159 and 161. In this particular example, mode selection and the choice of actuator/sensor locations are made based on performance and controllability/observability conditions, and a high authority controller is designed and complemented by a low authority controller to suppress certain modes and reduce spillover. The high authority controller is designed based on frequency shaping of a cost functional[162,163] which produces attenuation of high-frequency modes. Disturbance rejection is also a design consideration.

## Identification and Adaptive Control

A significant difficulty in designing controllers for LSS is precipitated by the uncertainty in the model of the LSS itself. Simplifications to the maximum likelihood estimation technique are investigated for LSS applications in Ref. 161. References 164-171 describe methods based on the principle of least-squares that attempt to minimize a cost functional of model errors, and examples are worked. In Ref. 166 a prediction error approach is used to obtain auto-regressive or auto-regressive-moving-average models which are applied to a tetrahedral example. The method in Refs. 171 and 166 attempts to best fit a linear representation of measured data to a set of approximation functions that is updated until the estimated parameters become time invariant. This method is demonstrated in an analysis of the Solar Array Flight Experiment[171] and a hardware experiment consisting of a 12-ft beam. The adaptive orthogonal filter design in Refs. 167 and 168 reduces modeling errors due to truncated modes and neglected disturbances as well as parameter errors. A frequency-domain method that identifies the mass, damping, and stiffness matrices is given in Ref. 169.

The capability of measuring the plant parameters method enables one to adjust the controller accordingly; an adaptive controller results. Reference 172 gives a performance assessment for several adaptive control techniques using uniform beams and a geostationary spacecraft as examples. References 173-177 describe various adaptive control designs.

## Maneuvering

In many LSS missions there is a requirement for reorientations involving large-angle rotations. In the case of the Space Telescope[155,156] an attitude reference is commanded in a (1-cos) jerk profile about an arbitrary eigenaxis in order to keep solar array excitation to a minimum. A pole placement technique for performing fast planar maneuvers in the presence of fine pointing is shown in Ref. 178 for a three-body spacecraft. Optimal methods are applied to single-axis maneuvers in Refs. 179-182. These techniques lead to open-loop profiles. A feedback approach using optimal control together with experimental verification of the method is given in Ref. 183. Also in this work it was found that although modeled modes could be controlled, those that were unmodeled showed unacceptable excitations.

## Hardware Experiments

A variety of hardware experiments have been performed involving beams, plates, and other structures. The beam experiment in Ref. 184 used a separated actuator and sensor with an optimal controller implemented in a digital computer. One problem encountered was the inherent damping in the voice coil actuator that had to be compensated. Other beam experiments are described in Refs. 166 and 185-187. The results of a plate experiment are shown in Ref. 149. A more ambitious undertaking is described in Refs. 188 and 189 where a spacecraft model of an off-axis feed antenna has been built and suspended on a three-axis air bearing. Control Moment Gyros (CMG's) will initially provide the control authority for both rigid- and flexible-body modes, but the addition of other types of actuators is planned. One of the difficulties experienced in performing experiments is the lack of inertial actuators that do not push against ground. A device that remedies this problem is a small reactive force mechanism that has been proposed for low authority controls or modal suppression.[190] Other recent experimental results are found in other papers in this special section.[191-193] Reference 194 is a description of what may be the first flight test of a LSS.

## Conclusion

The foregoing has presented a survey of those areas of particular importance to the development of large space structure dynamics and control analysis. The techniques of structural design and dynamics analysis define in a mathematical form the characteristics of the structure that is to be controlled. The authors maintain that the techniques in current use are inadequate to deal with large space structure dynamic problems properly and that advancements must be realized in the areas of computation time, substructuring, efficient modeling of changeable configurations, nonlinear analysis, and model verification. Model verification includes the development of practical methods for on-orbit measuring such as remote sensing, state identification in the presence of unknown disturbances, and updating mathematical models based on measured data.

With the extensive size of proposed structural designs, the problem of dealing with significant pressure-induced forces and moments becomes significant. The aerodynamic torque is particularly troublesome because of uncertainties in short-term variations in the atmospheric density and unknowns concerning the mechanism for particle/surface interaction. Improved models may be forthcoming only after some flight experience has been accumulated.

The section on control systems surveyed the large space structure control problem and indicated recent activities in solving various aspects of the problem. The task of designing a controller for an incomplete and uncertain plant is indeed difficult. And while there have been many fine works that have defined theoretical solutions, some of commendable completeness, maturity has not been reached since conventional control design techniques were sufficient for the missions flown to date. Indeed, unforeseen difficulties were experienced in some ground tests, as outlined in the previous section. When one compares the relative complexity of these experiments with what is proposed for flight, even the most optimistic must question the universality of solutions at hand. Maturity will come as missions are flown, and it is for that reason that actual flight experiments[194] are so important.

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