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SPACE STRUCTURES: ISSUES IN DYNAMICS AND CONTROL

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ABSTRACT:
A selective technical overview is presented on the vibration and control of large space structures, the analysis, design, and construction of which will require major technical contributions from the civil/structural, mechanical, and extended engineering communities. The immediacy of the U.S. space station makes the particular emphasis placed on large space structures and their control appropriate. The space station is but one part of the space program, and includes the lunar base, which the space station is to service. This paper attempts to summarize some of the key technical issues and hence provide a starting point for further involvement. The first half of this paper provides an introduction and overview of large space structures and their dynamics; the latter half discusses structural control, including control-system design and nonlinearities. A crucial aspect of the large space structures problem is that dynamics and control must be considered simultaneously; the problems cannot be addressed individually and coupled as an afterthought.

BACKGROUND

During the next decade, space-related business will become a growing sector of the American and world economies. It is estimated that current world expenditures on civilian and military space developments is approximately $70 billion annually and is conservatively estimated to reach an annual expenditure of $240 billion by the year 2050. During the first week in January 1988, President Reagan signed a new National Space Policy designed to focus the activities of the civil space industries and the National Aeronautics and Space Administration (NASA). Primary goals are a manned lunar base and manned flights to Mars. As part of this support, $1 billion will be spent, $100,000,000 for fiscal year (FY) 1989 for "pathfinder" technologies which are crucial to meet some of the goals discussed later.

NASA and the Air Force have been a driving force behind the intense work on the technical issues of Large Space Structures (LSS) (Pinson et al. 1982; Amos 1986; Browning 1982; Space 1985). Large structures have potentially broad applications in space; including: (1) Low-stiffness precision shaped antennas for mobile communications satellites, narrow-band broadcast services, deep-space network, remote sensing, astronomy studies, and other applications; (2) low-stiffness planar structures for large solar arrays; and (3) high-stiffness trusses for space facilities and multipurpose platforms. Huge orbiting lightweight structures will be required for space-based radar, advanced communications, and solar-power sources.

A major requirement for an effective program to design and construct structures in space includes the need to verify the design of lightweight, flexible space structures that cannot be tested on the ground because they are designed for microgravity operations. In addition to the need to compare measured to predicted vibrational modes and frequencies, there is the need to study methods to control structure attitude, shape, and vibration. From a practical point of view, it is necessary to develop and verify on-orbit construction, assembly, and replacement techniques; candidate structures include beams, trusses, antennas, geodesic structues, modular solar panels, and lightweight cryogenic heat pipes.

Lightweight designs responding to the low gravity environment and live loads due to gravity gradients, extreme thermal variations, micrometeorite and debris impacts, and solar wind create new and challenging problems in dynamic analysis.

A recent report to the NASA administrator (Ride 1987) identifies four crucial initiatives that would provide the basis for maintaining American leadership in space. These are:

1. Mission to Planet Earth: a program that would use the perspectives afforded from space to study and characterize our home planet on a global scale.
2. Exploration of the solar system: a program to retain American leadership in exploration of the outer solar system, and regain leadership in exploration of comets, asteroids, and Mars.
3. Outpost on the Moon: a program that would build on and extend the legacy of the Apollo program, returning Americans to the Moon to continue exploration, to establish a permanent scientific outpost, and to begin prospecting the Moon's resources.
4. Humans to Mars: a program to send astronauts on a series of round trip missions to land on the surface of Mars, leading to the eventual establishment of a permanent base

In another assessment, the National Commission on Space ("Pioneering" 1986) listed 12 technological milestones for pioneering space in the next century:

1. Initial operation of a permanent space station.
2. Initial operation of dramatically lower cost transport vehicles to and from low earth orbit (LEO) for cargo and passengers.

3. Addition of modular transfer vehicles capable of moving cargo and people from low Earth orbit to any destination in the inner solar system.
4. A spaceport in LEO.
5. Operation of an initial lunar outpost and pilot production of rocket propellant.
6. Initial operation of a nuclear vehicle for high-energy missions to the outer planets.
7. First shipment of shielding mass from the Moon.
8. Deployment of a spaceport in lunar orbit to support expanding human operations on the Moon.
9. Initial operations of an Earth-Mars transportation system for robotic precursor missions to Mars.
10. First flight of a cycling spaceship to open continuing passenger transport between Earth orbit and Mars orbit.
11. Human exploration and prospecting from astronaut outposts on Phobos, Deimos, and Mars.
12. Start-up of the first Martian resource development base to provide oxygen, water, food, construction materials, and rocket propellants.

While these activities appear far-fetched and very optimistic, there is little doubt that mankind is at the inception of a new frontier that will render current Earth-based economic and scientific activities pale in comparison by the next century.

Increasing capability in space will require advances in three successive phases: development of the capability to easily access and return from space, the establishment of a permanent presence in LEO, and limited self-sufficiency of humans in space and on bases on the Moon and Mars. This self-sufficiency requires the development of closed-cycle life-support systems and large-scale industrial applications in space leading to closed ecological systems, space construction, space industrialization, and access to extraterrestrial materials.

Progress is intrinsically connected with continued advances in many key transportation-related technologies, such as design methodologies for integrated plant dynamics and control, flight mechanics, aerospace plane propulsion and aerodynamics, advanced rocket vehicles, aerobraking for orbital transfer, long-duration closed ecosystems, electric launch and propulsion systems, nuclear-electric space power, space tethers, and artificial gravity.

The rapid growth in commercially significant technologies suggests that in the years around and beyond 2000 space is likely to become a burgeoning frontier for the development of an increasing number of industrial and commercial ventures in LEO and geosynchronous Earth orbit (GEO). These activities require the analysis, design, and construction of orbiting and lunar/ planetary structures.

The space station is a linchpin to all these plans. It will provide the capabilities to establish large permanent facilities for scientific research, engineering research and development, commercial development, and operations support in LEO and GEO. These facilities will enable routine, economical, and flexible access to necessary orbital paths by human and robotic systems so that existing and future space facilities can be inspected, refueled, repaired, and upgraded. In addition, the increasingly important task of debris removal in all orbits to GEO can begin to be addressed.

By the end of this century, the commercialization of materials processing (Regel 1987; Faughnan 1985, 1987) in space is expected to be sufficiently advanced to permit manufacturing facilities in space. Materials that currently hold the greatest promise to manufacture are pharmaceutical products, high purity advanced semiconductors, and unique glass materials, glassy metals, and composites. A materials and structures research program will provide the technology to enable the development of advanced space transportation and spacecraft systems with significantly improved performance, durability, and cost-effectiveness. Major thrusts in computational material science, especially towards the development of space-durable materials, advanced thermal protection systems, analytical/experimental design methods, and advanced structural concepts are expected.

The colonization of space (Lewis and Lewis 1987) and the planets will begin with an Earth-orbiting space station, followed by a lunar base (Benaroya and Ettouney 1989). For the lunar base in particular, it will become imperative to use native materials for most, if not all, construction and operating needs (Johnson 1988). Thus, materials such as lunar soil will be useful for shielding against radiation and for mass-driver engines in space, oxygen (40% of lunar soil by weight) for rocket propellant and, as the main constituent for water, lunar glass to be used in the manufacture of structural composites, as well as iron, silicon, hydrogen, aluminum, titanium, manganese, magnesium, and chromium. Recent research indicates that Moon surface soils, composed mainly of glass, can be processed into structural composites without the need for chemical separation. Thus, the National Commission on Space ("Pioneering" 1986) recommends research to pioneer the use of such space materials as lunar glasses and metallic iron concentrated in the lunar fines in construction and manufacturing.

Critical issues to be resolved in the lunar base design process (Johnson 1988) include communications, data handling, soil mechanics, foundation engineering, controls, structures, and materials. The design of a lunar structure must take into account the lunar above-ground environment, lunar soil properties, and meteoroid impacts. For example, lunar gravitational acceleration is one-sixth of terrestrial acceleration. Lack of an atmosphere means that there are no wind loadings, but it does result in severe thermal gradients. This can be observed from data at an Apollo 17 measurement site where the lunar surface temperature ranged from a maximum of 111C to a minimum of — 171C. These variations occur at near surface depths so that the design of exposed objects must account for thermal strain rates.

Lunar surface models must be developed for solving engineering problems. Some data are available from the Apollo Soil Mechanics Experiment, the unmanned U.S. Rangers, Orbiters, and Surveyors, and the Soviet Lunas. The lunar seismic environment is benign compared to that of Earth. Protection must be provided in design to mitigate the effects of fine particles of lunar soil that tend to adhere to surfaces.

LARGE SPACE STRUCTURES

Large space structures (LSS) are being designed for future missions in space. A primary example (assuming it is not budgeted out of existence) is the space station Freedom. NASA began space-station studies in 1959 during its first year of existence (Hook 1984). More recent studies include those of the aerospace and structural engineering communities. This section provides an overview of some technical issues relating to space structures.

Environmental Aspects

Many environmental and functional factors influence the selection of materials and the design of structural members in space structures. One factor that differentiates these structures from Earth-based structures is the freedom from first-order gravity effects. (Orbiting structures experience microrgravity or free-fall.) Gravity loads are therefore reduced by an order of magnitude, permitting stiffness-designed, extremely lightweight structures that span great distances.

Environmental modeling, in part, requires an understanding of solar pressure. It becomes the dominant force (over aerodynamic forces) above altitudes of 500-800 km. This cross-over altitude depends on the solar activity, which strongly affects the density of the upper atmosphere and thus the aerodynamic forces. A basic problem lies in predicting short-term variations in upper atmospheric density.

Another aspect unique to LSS lies in the considerable breadth of environmental extremes experienced throughout the structure's life cycles. Specifically, the space structure, whether manufactured for direct deployment or packaged on Earth in raw-material form, will experience sustained gravity, handling, and ground transportation loads. A space-optimized structure, designed for microgravity, will not be sustainable in a 1-g field. Fundamental problems therefore arise when it becomes necessary to verify predicted properties and behavioral characteristics of space structures on the Earth's surface, before facing the unforgiving space environment. During transport, additional loads must be withstood; this is true, though in different ways, both for Earth-to-orbit boost and orbit-to-orbit boost. Such loads can be quasistatic and dynamic (inertial), structurally transmitted and acoustic. Environmental properties of interest include: the neutral atmosphere; the charged atmosphere, both neutral and charged extraterrestrial particles, electromagnetic radiation, and gravitational and geomagnetic fields. Important considerations include the effects of gravity and thermal gradients, solar pressure, and long-term exposure effects on materials.

Issues in Vibration and Control

Space structures will, of necessity, be designed for minimum weight and be quite flexible. A significant problem will be developing the capability to suppress and control flexible modes of vibration, some of which are closely packed. The active control of flexible spacecraft involves attitude control, vibration suppression, and shape control (Atluri and Amos 1988).

One of the first steps in control-system design is to derive a mathematical model of the physical system to be controlled. System identification is part of that modeling process. In practice, flexible structures are typically modeled as lumped-mass systems and analyzed using the finite element method. The accuracy of the method depends on the number of elements used in the model, and since high-frequency modes may be neglected, large errors may result. For control-system design, high-order models are typically reduced to lower-order models for which controllers are designed. However, controllers designed using reduced-order models can be unstable due to the truncated modes. Structural dynamic modeling for controller design is a major unsolved problem in achieving precise attitude and shape control of flexible spacecraft.

The long-range objective in active vibration, attitude, and shape control is to develop tools for design, analysis, and implementation of control systems for flexible structures. Research activities are focusing on the following areas (Hord 1985):

1. Modeling and identification procedures (Model 1988) for dynamic analysis and control; reduction of degrees of freedom in mathematical models.
2. Determination of approriate mathematical models from experimental measurements.
3. Identification of actuator and sensor locations through optimization techniques.
4. Distribution of sensing and actuation versus collocated sensing and actuation.
5. Redundant management techniques for structural systems; reliability assurance for managing large numbers of sensors and actuators.

Control is coupled to structural vibration. The response of a structure is basically governed by three sets of variables. One set of variables includes structural parameters such as structural materials, stiffness, damping, and mass distribution. A second set of variables arises from the sources of disturbances and system uncertainties, while a third set represents control-system variables. The latter variables include input variables such as forces, and state variables such as structural member displacements and velocities.

The definition of an LSS mission influences the geometry of the structure, the magnitude and distribution of the nonstructural mass, and the nature of the external disturbance. For the structural designer, the optimal design problem involves the specification of structural parameters to achieve minimum weight which satisfy the desired passive dynamic characteristics. The material selection is made on the basis of a variety of characteristics, including elastic modulus, thermal and electrical conductivity, and damping. The global stiffness of the structure depends on the geometry, materials of construction, and the cross-sectional areas of the members. Particularly important considerations in the analysis and design of an LSS are the structural connections and joint designs. LSS are called joint-dominated structures, since joint-damping properties play a dominant role in the structural behavior and control design.

The control-system designer, on the other hand, is typically involved in the sizing and placement of sensors and actuators and the design of controllers in such a way that specified performance index (objective function) is minimized. Bandwidth constraints, robustness, and subsystem interaction must be taken into account. In structural control, the dynamics of sensors and their distribution over the system is a serious concern. In addition, the design and distribution of controllers and actuators is of major importance. If the locations and the numbers of actuators and sensors are specified, then the individual actuator inputs are the variables in the optimal control problem.

The objective of integrated design is to synthesize simultaneously the structure and its control system to eliminate vibration completely or to reduce the mean square response error of the system to a desired level within a given time. To achieve the integrated-structure/control-system design, the overall system, subject to both dynamic and control system constraints, must be described in terms of all three sets of variables: system parameters and system uncertainty, disturbance variables, and control system variables. An optimal integrated system is achieved by minimizing a performance index, which is a function of these three sets of variables. During the search for the optimal design solution, adjustments of these variables must be executed simultaneously to guarantee an optimally integrated system design. In addition, constraints on the system structure, such as stress/strain specifications, and on limiting values of state and control variables, must be satisfied simultaneously to assure that the integrated system requirements have not been violated.

The integrated design for dynamics and control of an LSS requires that several challenging problems be tackled. These problems, described next, are interrelated and represent the crux of the difficult integrated-dynamics/control-system design effort.

LSS: Four Problem Areas

The first problem is the development of a reasonably accurate structural model. Due to the large number of degrees of freedom of an LSS, models are often too complex for tractable analyses. Performance specifications, and not the size of the structure, are the overriding requirements driving model size and complexity. Computational demands are influenced more by structural topology than by structural size or by the number of joints. Model reduction is often required and typically involves the investigation of mode shapes and the specification of dominant eigenvalues. To avoid neglecting important dynamic characteristics during model reduction, the application of probabilistic analyses and statistical methods are required.

The second problem is the quantification of system uncertainties and external (input and measurement) disturbances. These disturbances are typically quite complex and difficult to model deterministically, necessitating the use of stochastic models. LSS uncertainties include deployment, loading, and material properties.

Since it appears unlikely that a complete LSS will be brought into orbit, components will most likely be carried into orbit on the space shuttle and heavy boosters, then deployed and constructed. Deployment dynamics in general involve uncertain initial conditions and may depend on environmental factors such as solar radiation. Loads on the LSS will be due to either unpredicted sources or to known but very complex sources. These loads will be transient and best modeled as random processes. Examples of such loads are thermal stresses, dynamics of deployment and operation, and impulses due to various impacts. While it is expected that the properties of materials used in LSS design will be well known, certain structural types, such as composites, may be best modeled via probabilistic models. Furthermore, it will be important to consider and predict fatigue and fracture lives of LSS components. These are inherently probabilistic problems.

The third problem is the specification of desired system performance. The desired performance may be expressed in terms of a performance index, which for an LSS will be a function of structural parameters and control system variables (including state and input variables). In linear lumped-parameter optimal control theory, the performance index is typically taken to be a quadratic function of the state and control variables with appropriate weighting. The selection of the state and control weighting, which alters the closed loop system performance, represents a challenging problem and is very much an art.

The fourth problem is the design of the control system. It may be possible to modify system parameters to achieve the desired system performance; this is commonly referred to as "passive" control. In general, modulation of system parameters will not be sufficient, and active means must be sought. An "active" control system must satisfy multiple criteria in order to be effective. The control system must have natural frequencies that avoid major structural resonant frequencies. Parameters describing system properties in the mathematical model may not be well known; the control system must therefore be sufficiently robust to assure that substantial tolerance can be accommodated. However, the use of active control introduces the possibility of instability. It has been reported that the most important instability foreseen to threaten the first generation of LSS will be due to interaction with an improperly designed control system (Ashley 1986). Thus, the control system must ensure stability and provide the desired dynamic response.

Since the inherent structural damping level of flexible space structures is expected to be very low, joints and connections are designed to maximize their damping contribution. Damping poses signficiant problems for the design of distributed active control systems for LSS, especially with regard to control "spillover" into the unmodeled modes of the structure. Some internal energy dissipation must be provided by active means in order to avoid undesirable spillover and ensure the stable control of the flexible modes of a LSS.

LSS (or at least some of their important components) are continuous systems, described mathematically by distributed parameter models involving partial differential equations. Theories for the optimal control of distributed parameter systems have been developed (Lions 1971) but are quite complex. The implementation and practicability of such theories are current research issues.

In general, the discretization of a distributed parameter model results in a large number of degrees of freedom that must be controlled. In solving the optimal control problem for a large-order system, numerical difficulties are often associated with determination of the optimal solution (e.g., solving the matrix Riccati equation). Furthermore, in discretizing, i.e., "lumping," higher modes are neglected that may have a detrimental effect on the stability and control of the real system, which in theory is of infinite dimension.

Determination of the number and location of the sensors, actuators, and controllers is a nontrivial design consideration. Selection of the number and distribution is complicated by the topology of LSS, making the monitoring and controlling of the current "state" sensitive to the location of the control devices. (Here, the number and location of sensors and actuators is assumed to be a control system constraint.) Inertia of the LSS will result in a time delay between control actions and structural changes, e.g., movements, possibly producing undesirable instability effects.

Integrated Vibration and Control-System Design

The motivation has been provided for the integration of structural-system design and control-system design in the interest of obtaining an optimal total system, rather than independently optimized subsystems. In fact, it may be impossible to separate structure and control-system design. Consider, for example, an LSS such as an antenna with the dominant requirements for performance being pointing accuracy and surface precision. The ability to control structure motion and vibration becomes a primary necessity. Interaction between the control system and the structural dynamics cannot be prevented because of an overlap between the modal frequencies and the control system bandwidth. The combination of large-size and lightweight design drives vibration frequencies down, while the need for accurate pointing drives the bandwidth up. Hence, frequency separation is impossible in many LSS. It is not unusual for an LSS to have dozens of closely spaced vibration modes, many of which are below 1 Hz, raising theoretical as well as computational issues.

The structural design consists in part of defining the structural geometry, selecting materials, and specifying appropriate materials and cross-sectional areas of the members, while the control system design involves the development of an active feedback system to satisfy the specified requirements. Constraints on the structure include allowable stresses in the members, the displacement limits, the instability of the members, minimum and maximum sizes, and the distribution of frequencies. Constraints on the control-system design include location and number of actuators and sensors, actuator forces, control power, bandwidth, robustness considerations, and subsystem interaction.

Traditionally, structural systems are designed based on performance specifications, such as strength or stiffness requirements derived from peak loads expected during operation of the system. The designs are "optimized" (with respect to mass, dimensions, etc.) subject to structural constraints such that they satisfy specified performance requirements. The design is then passed on to the controls engineer whose task is to design an active control scheme for the given system. Typically, the controls engineer has little input in the evolution of the mechanical design. This practice of separating the mechanical, i.e., structural, and control system design activities is promoted by the attitude that an "optimal control system" can be designed for any system. It is clear that the control-system synthesis problem can be quite different depending on the design of the structure. The current design philosophy presumes that if each of the subsystems is optimized independently, then the total system will at least be nearly optimal. This may not be the case; ideally, an integrated approach is necessary for real systems.

The designer of the structure has freedom in components that determine its mass, stiffness, and damping properties. These properties determine the passive control of the system. Typically, there are requirements on the structure that cannot be satisfied by passive means for desired effective stiffness or desired static or dynamic response or the like, without consideration of the control objectives. However, an active-control-system design may need to consume unnecessary power to overcome deficiencies in the mechanical design, rather than merely fine-tune to achieve desired system objectives. Recent research efforts have demonstrated the feasibility of a combined dynamic-system/control-system design algorithm (Nagurka and Yen 1987).

Due to the unavailability of a systematic framework, there has been limited interaction between designers of mechanical systems and designers of control systems. Evidence for this is the lack of textbooks and research papers that develop integrated design approaches for dynamics and control. Typically one finds excellent reference sources on the dynamics of mechanical and structural systems (e.g., Crandall 1968; Greenwood 1965; Kane and Levinson 1985) and on control-system design (e.g., Friedland 1986; Kwakernaak and Sivan 1972; Owens 1981; Patel and Munro 1982; Rosenbrock 1970; Schultz and Melsa 1967; Takahashi et al. 1970), but not on integrated approaches. The interaction is probably most fostered in aerospace applications, but even here there is a substantial gap between the mechanical and control-system designs due to the lack of a unified dynamics-controls design theory.

Recently, work in the development of integrated approaches has been reported (Khot et al. 1985; Cooper et al. 1986; Venkayya and Tischler 1984; Baker et al. 1986; Lorell 1989). In Cooper et al. (1986), a computerized data distribution capability for the multidisciplinary analysis of the dynamics and control of LSS is described. In Baker et al. (1986), a computer-aided engineering tool for systems engineering and integration analysis of the NASA space station is described. Lorell et al. (1989) describe a Lockheed project called the Advanced Structures/Controls Integrated Experiment, which is a testbed for the design, implementation, and validation of technology related to the control of large segmented telescopes. The test bed is a unique research tool for assessing and validating a wide variety of control design methodologies, special components such as sensors and actuators, and software/ hardware implementation for large flexible structures.

Integrated design methodologies for optimal structural and control systems design are urgently needed, especially for LSSs that typically have stringent requirements for precise pointing and retargeting within a short time. Disturbances will result from slewing/pointing maneuvers, thermal transients, on-board machinery (coolers, generators, etc.), and other sources. LSS flexibility is dominated by long, beamlike members, and slewing maneuvers will cause large structural dynamic reactions that will have to be suppressed within a relatively brief time. Control of LSS dynamic response is essential for maintaining performance requirements and integrity of the structure. Furthermore, the optimal design solution of an LSS and its control system is required in order to satisfy the mission requirements most efficiently. Low structure weight, minimum control effort and power, high rate of stability, and/or any combination of these will be essential.

Several additional key technical areas need attention. Due to excessive computational time required for LSS dynamics and control analyses, criteria are needed for the rational reduction of the size of the structural dynamic model. 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. A challenge is the modeling of structures with low natural frequencies and high modal densities. In addition, it must be possible to analyze the system as it grows in size and complexity due to future expansion. Prediction of the effects of small configuration changes is required without retesting, since low-damped systems can tune and change characteristics by orders of magnitude with very small changes in hardware. As part of the overall structural control problem, topics that must be tailored for the LSS are state identification approaches, data quality, remote sensing, and model updating procedures, among others.

While there is a clear need to verify in advance of deployment large-scale structural designs, difficulties exist (Ashley 1986) in ground testing structures designed for the atmosphere-free, 0-g environment of Earth orbit.

While space limitations preclude a more detailed exposition, a structure of increasing importance and interest is the tether (Carroll 1985, 1986). A tether is a long, thin, wire structure that joins two orbiting masses to force them to orbit together at the same angular velocity. Since the outer body is forced to orbit faster than if it were free, and the inner one slower under the same condition, the tether is in tension. Such tethers have many potential applications: generating electric power by passage through a planet's magnetic field, raising orbits of satellites launched from vehicles such as the shuttle, and delivering payloads to a space platform from a suborbital launch vehicle.

STRUCTURAL CONTROL

The preceding discussion has motivated the need for LSSs actively controlled via a host of sensors and actuators distributed about the structure. With feedback from the sensors, on-line computer controllers can be used to adjust the actuators to meet the stringent performance specifications.

Since structural control is not a discipline to which structural engineers are generally exposed, a qualitative overview of the subject is provided in the remainder of this paper. Readers who wish a more mathematical framework for discussion of LSS control theory are referred to Balas (1982).

State-Space Description

Mathematical idealizations of dynamical systems are characterized by a set of related variables, which can change with time in a predictable manner assuming that (1) The external influences acting on the system; and (2) the "initial conditions" of the system are known. For lumped-parameter models, the mathematical framework most naturally adapted to this purpose is the so-called state-space representation, which consists of a set of first-order ordinary differential equations, describing the time evolution of variables whose instantaneous values determine the current state of the system. These variables are called the state variables and their values at any particular time theoretically contain sufficient information to predict the evolution of the system, provided that the external influences (or input variables) that act upon it are known. For notational convenience, the state variables are typically collected into a state vector x and the input variables into an input vector u, and the equation is written in the form:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, t) \quad (1)$$

where the dot denotes differentiation with respect to time t, and the functional $\mathbf{f}$ is in general nonlinear. This vector differential "state" equation can be solved for $\mathbf{x}$ as a function of t, given $\mathbf{X}_o$, the value of $\mathbf{x}$ at $t = t_0$, and $\mathbf{u}(t)$, $t \geq t_0$, the subsequent values of $\mathbf{u}$ as a function of time t.

Following convention, it is also appropriate to identify a set of output variables that represent aspects of the system's behavior that can be measured, observed, and controlled. These variables are usually a subset of the state variables but may in general depend on $\mathbf{u}$ and t as well, and are collected into an output vector $\mathbf{y}$ and written:

$$\mathbf{y} = \mathbf{g}(\mathbf{x}, \mathbf{u}, t) \quad (2)$$

where $\mathbf{g}$ is a functional that may be nonlinear. The "output" equation is a vector algebraic/transcendental equation which can be used to determine $\mathbf{y}$ once the state equation is solved for $\mathbf{x}$.

The lumped parameter description just described may be generalized. For example, systems governed by partial differential equations (distributed parameter systems) can be represented in state space form by allowing $\mathbf{x}$ (and possibly also $\mathbf{u}$ and $\mathbf{y}$) to contain an infinite number of components. Such infinite-dimensional systems, however, present various mathematical difficulties (Lions 1971) and are therefore usually approximated in practice by finite-dimensional (lumped-parameter) models. Another modification is the introduction of time-delay effects, which may arise either as a result of physical phenomena, such as the delay between sensing and actuating, or in an attempt to represent complicated dynamical features in a simple way.

By linearizing about an operating point in the state space, a lumped parameter model can be expressed by the state equation:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \quad (3)$$

and by the output equation

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \quad (4)$$

where $\mathbf{A}$ = the system matrix; $\mathbf{B}$ = the control or input matrix; $\mathbf{C}$ = the output matrix; and $\mathbf{D}$ = the transmission matrix. Vector-matrix methods for analysis of linear continuous-time models, descried by linear state and output equations (Eqs. 3 and 4), represent the thrust of modern control theory. These methods are particularly well suited for computer use and can be applied to systems with multiple inputs and/or multiple outputs (and to high-order systems) that are difficult to handle with the methods of classical control.

An alternative to the state space form is the input-output description, which relates the input and output variables of a system directly. An example is the instantaneous functional relationship

$$\mathbf{y} = \mathbf{h}(\mathbf{u}) \quad (5)$$

where $\mathbf{h}$ = a general nonlinear functional. This input-output map masks the internal dynamics of the system (i.e., given by the state), and hence is sometimes called an external description.

Introduction to Control-System Design

The last two decades have seen considerable advances in the theory and design of linear multivariable control systems. The developments of multivariable system theory and design can be summarized as proceeding along two distinct lines. One avenue deals with the state-space formulation and involves design methods such as pole assignment and linear quadratic optimal control (discussed later). The other approach adopts the input-output description and involves multivariable frequency domain techniques, attempting to generalize the powerful classical control theory. In multivariable frequency-domain techniques (Owens 1981; Patel and Munro 1982), the system dynamics are described by transfer function matrices that provide an "external" functional map between the Laplace transform of the inputs $\mathbf{u}$ and the outputs $\mathbf{y}$. Despite much activity, a fool-proof method for the design of linear control systems with multiple inputs and multiple outputs is not available, and research is active in this area.

Although system dynamics analysis provides some clues, the design of feedback control systems is a difficult and challenging task in practice. In most situations the design proceeds on a trial-and-error (iterative) basis with analysis and experimental techniques applied repeatedly.

A control system designed for a specific application has to meet certain performance specifications. Two methods of specifying the performance of a control system are:

1. By a set of specifications in time domain and/or in frequency domain such as peak overshoot, settling time, gain margin, phase margin, steady-state error, etc.
2. By optimality of a certain function, e.g., a scalar integral function.

In addition to the performance specifications, the control system design must account for constraints. These include available power, size/dimension, computational capabilities, and economical limitations.

Thus, the choice of a plant (i.e., the system to be controlled; also called open-loop system, structure, or process) is dictated not only by performance specifications but also by size, weight, available power supply, cost, and other factors. Typically, the plant cannot be chosen to meet all the performance specifications. The designer is free to choose a new plant, but this is generally not done because it too will fail to meet all the specifications, and because of cost, availability, and other constraints. In some cases, some components of the chosen plant may be modified. However, in practice, the approach is to modify the dynamics of the chosen plant actively by introducing "compensation systems," i.e., controllers that "force" or "drive" the plant to meet the specifications.

Control Design Using State Feedback

Linear state-space techniques potentially provide a feasible approach for control system design of large systems. They involve a standard matrix formulation that allows the application of standard computer programs suitable for the analysis and design of large systems.

For example, consider a plant described by a linear state-space model with all state variables available for use in feedback. Assuming zero command, i.e., reference inputs, the proportional control law $\mathbf{u} = -\mathbf{G}\mathbf{x}$ can be written where $\mathbf{G}$ represents the state-feedback gain matrix. The dynamics of the "new" system are governed by the closed-loop system equation

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} = (\mathbf{A} - \mathbf{BG})\mathbf{x} \quad (6)$$

where $\mathbf{A} - \mathbf{BG}$ = the closed-loop system matrix which must have negative eigenvalues for the response to be stable, i.e., tend to zero. A fundamental theorem of modern control theory applies to a special class of systems, called controllable systems: any specified set of closed-loop eigenvalues can be obtained by state feedback with $\mathbf{G}$ consisting of constant gains. For selecting these gains, two distinct approaches can be pursued:

1. Pole assignment: The closed-loop eigenvalues are "placed" in desired locations.
2. Optimal control: A desired mathematical performance criterion is extremized.

There is freedom in "design" with both approaches. For example, there is the choice of desired locations in pole assignment (relating to different closedloop system behavior) and the choice of weighting matrices in optimal control (relating to different performance). Thus, in general, both methods typically involve trial-and-error adjustments to obtain satisfactory transient response. Extensive work has been done to offer insight in the use of the methods, but intuition and art are still involved.

Shaping the Dynamic Response (Friedland 1986)

The linear state variable feedback law $\mathbf{u} = -\mathbf{Gx}$ implies that for a given state, the larger the gain the larger the control input. There are practical limits on the control inputs; actuators are "power-limited" and cannot supply arbitrarily large inputs. Reasons for limiting the control may be to avoid excessively large, heavy, and costly actuators and the potentially damaging effects associated with large loads (e.g., mechanical stresses on structures). If the control signal predicted by the linear feedback law is larger than possible (or permissible for reasons of safety), the actuator(s) will saturate at a lower input level. The effect of occasional control saturation is usually tolerable: in fact, a system that never saturates is very likely overdesigned, having a larger (and often less efficient) actuator than needed to accomplish even the most demanding tasks.

The pole-placement method assumes that the system is controllable and there is access to all state variables or that the state variables can be reconstructed (estimated) from input and output measurements. (This reconstruction is possible for what are called observable systems.) It is then possible to set the closed-loop poles as desired. Hence, in theory, the closed-loop dynamic performance of the system can be completely satisfied. For example, in principle, a sluggish open-loop system can be made to behave with alacrity, or a system that has very little open-loop damping can be made to have significant damping. As noted, this approach is limited by practical realities.

Given that the closed-loop poles of a controllable system can theoretically be placed anywhere, it is natural to ask where the poles should be placed. The obvious response that the poles should be selected to satisfy the performance requirements raises the question of how to relate the performance requirements to the feedback gain strategy, i.e., the gain matrix $\mathbf{G}$ used in the linear state variable feedback law.

To achieve stability, the closed-loop poles must be placed in the left half of the complex *s*-plane, being moved further interior to increase stability. Stability, though, is not the only consideration; speed of response (i.e., or bandwidth in frequency domain) is also important. For example, it is desirable to have fast response of the closed-loop system, since then the errors in following rapidly changing inputs will be smaller. This is achieved by designing the closed-loop system for high bandwidth.

It is sometimes desirable to limit the bandwidth of the closed-loop system. If the reference input is noisy, the bandwidth should be reduced to prevent the system from becoming excessively agitated by following the noise. Another reason for limiting the bandwidth of the closed-loop system is the uncertainty of the high-frequency dynamics of the process. A structural system, for example, has resonance effects (modes) due to the elasticity of its members. Typically, the dynamic model used for design ignores many if not all of these effects: Their magnitudes are small; the exact frequencies are not easy to determine; and the effort required to include them in the model is not justified. If the uncertain high-frequency modes are included within the bandwidth of the closed-loop process, these resonances may be excited and result in high-frequency oscillation, or even instability.

The bandwidth of a system is governed primarily by its dominant poles, i.e., the poles with real parts closest to the origin in the complex *s*-plane. In order for transients to decay as rapidly as is required by the poles that are further interior, it is necessary to change the energy in the system rapidly, requiring large control inputs. In contrast, the system speed of response will be slowed by the poles that are close to the origin. Hence, for "efficient" use of the control signal all the closed-loop poles should be selected to be about the same distance from the origin.

Guidelines that govern the choice of the closed-loop poles are:

1. A bandwidth high enough to achieve the desired speed of response.
2. A bandwidth low enough to avoid exciting unmodeled high-frequency effects and undesired response to noise.
3. Poles at approximately uniform distances from the origin for efficient use of the control effort.

Linear Quadratic Optimal Control

Assuming that the system is controllable and observable, it is possible to place the closed-loop poles, which determine the speed (bandwidth) and damping of the response, anywhere desired. For a single-input system the associated state feedback gains can be determined uniquely. This is not the situation for a multiple-input system. There are infinitely many ways by which the same closed-loop poles can be attained. From a practical standpoint the availability of more adjustable parameters than the minimum number needed to achieve the desired closed-loop pole locations is advantageous due to the additional freedom afforded besides placing the closed-loop poles. But the absence of a definitive algorithm for determining a unique control law is disadvantageous to the system designer who does not know how to handle this freedom. Thus, there is strong reason for choosing a control law that "optimizes" performance.

Another important reason for seeking an optimal controller is that the designer may not know the "desirable" closed-loop pole locations. Choosing pole locations far from the origin may give very fast dynamic response but may require control signals that are too large to be produced with the available actuators. As noted, because of power limitations and physical limitations of the actuators, the control signals may saturate and the closed-loop dynamic behavior will not be the desired behavior predicted by the linear analysis, and may even be unstable. To avoid these problems it often is necessary to limit the speed of response to that which can be achieved without saturation. Another reason for limiting the speed of response is to avoid noise problems that typically accompany high-gain systems. Typically, extensive experience (e.g., gained through years of product development and redesign, such as military and commercial aircraft design) is required before proper closed-loop pole locations can be selected by intuition. For controlling an unfamiliar process, another design method is useful for providing an initial design. Optimal control theory can serve this purpose.

The problem of determining the optimal control of a linear dynamic system with a quadratic performance index, referred to as the linear quadratic (LQ) problem, is usually solved by a variational approach. Mathematically, the LQ problem can be posed as a two-point boundary-value problem (TPBVP). The initial conditions are specified for the state equations and the terminal conditions are specified for another set of dynamic equations, called costate equations, with the set of state and costate equations often called the Hamiltonian system. Standard routines for solving linear boundary value problems are generally inefficient in solving such TPBVP (Stoer and Bulirsch 1980). More efficient methods specifically designed to solve the LQ problem are available. These can be classified as closed-loop and open-loop approaches.

The most widespread closed-loop approach is based upon the solution of a matrix differential Riccati equation. Various algorithms have been proposed to solve the Riccati equation (Ramesh et al. 1987). In contrast, the open-loop approach converts the TPBVP into an initial value problem by evaluating the exponential of the Hamiltonian matrix (i.e., the transition matrix of the Hamiltonian system). An example of a structural application of this open-loop approach is described by Turner and Chun (1984). A detailed discussion of the closed-loop Riccati equation approach and the open-loop transition matrix approach can be found in Speyer (1986).

The Riccati-based approach is preferred for physical implementation due to the inherent advantages of closed-loop configurations. However, it is computationally more costly than the transition matrix approach in solving time-invariant LQ problems. As a result, efficient software simulation tools for solving time-invariant LQ problems are typically based on the open-loop transition matrix approach. The opposite is true for solving time-varying LQ problems. The time required to evaluate the exponential of the time-varying Hamiltonian matrix is often greater than the time to integrate the Riccati equation.

As an alternative to these methods, Nagurka et al. (1987) proposed a Fourier- based state parameterization approach to generate near optimal trajectories of general dynamical systems. The free variables are adjusted by a nonlinear programming method to minimize a performance index. Further research (Yen and Nagurka 1990) has specialized this Fourier-based approach to linear structural systems with quadratic performance indices. Simulation results indicate computational advantages relative to other closed- and open-loop methods.

Nonlinearities (Cook 1986)

Because of the mathematical simplicity of linear systems, and hence the wealth of tools of linear systems analysis, the generally accepted advice in dealing with a nonlinear system is to linearize it around some nominal operating point if possible. The linearized approximation about the operating point may well be adequate as a basis for analysis and design over a limited range of operation. Control systems are, in fact, normally designed initially in this way. Fortunately, the application of feedback control normally tends to diminish, rather than enhance, any nonlinear effects that happen to be present, provided that the system remains adequately stable, making the system more, rather than less, nearly linear in its behavior.

If the system is required to operate over a wide range of conditions, the deviation from the operating point may be large enough to make the approximation not representative. In such cases it is possible to use a set of different linear controllers, based on linearized models corresponding to various operating points, and employ them successively as the system passes through conditions where the corresponding models are approximately valid. This strategy is sometimes called scheduled control and is a rudimentary form of adaptive control.

If the nonlinear nature of the system is responsible for poor performance, there are a number of possible remedies. One approach is to make the system more linear by injecting a rapidly oscillating signal, known as "dither," to the nonlinear element (Atherton 1975). In some cases this can effectively smooth out the effects of the nonlinearity. A "brute-force" approach is to implement a nonlinear control law that compensates for the nonlinearity of the plant. This type of direct dynamic correction is not practicable except in certain rather special cases. Another possibility is to implement an adaptive controller, in which the control parametes are altered in accordance with the observed behavior of the nonlinear system. An adaptive controller can be designed to monitor and improve its performance as it operates.

Adaptive control is generally employed in cases where some aspects of the plant's behavior are uncertain, inadequately modeled, or subject to unpredictable changes in the course of time. There are two main approaches, direct and indirect adaptive control. The indirect method assumes that if a linearized plant model with known parameters were available, a controller could then be designed (automatically) by using pole-assignment or optimal control algorithms of modern control theory. In the adaptation, the plant model is identified, i.e., model parameters are estimated from measured input and output data, and then the controller is updated in accordance with the model. By repeating these steps the controller is adapted to the most recently identified model. This process is generally known as self-tuning. By contrast, in direct adaptive control there is no explicit identification. For example, in the most common version, model-reference adaptive control, the basic idea is to compare the behavior of the controlled plant with that of a reference model, representing the desired performance, and attempt to reduce the difference between them by changing the controller parameters in an appropriate way. In such a scheme the adaptation law is used to drive the dynamic properties of the controlled system asymptotically to those of the reference model. Several different proposals for doing this have been suggested in recent decades, but none are entirely satisfactory and the subject is still in development.

CONCLUDING COMMENTS

Space structures are envisioned to be quite large and employ lightweight materials. By design, they will be relatively flexible and lightly damped. Small disturbances may cause large-amplitude vibrations at low frequencies and passive damping will most likely not be sufficient for complete dissipation of the imparted energies. Active means for vibration control and for a variety of other maneuvers, such as attitude control, will be required.

In this paper, we have attempted to provide a sense of a small subset of the challenges that face engineers engaged in the design of structures for use in orbit about the Earth and on the lunar surface. For orbital structures such as the space station, structural control becomes a crucial issue. Thus, a significant overview of structural control is provided.

While it is obvious, we need to state that our overview only scratches the surface. It is therefore likely that we have overlooked perspectives and ideas that some may believe to be important. We regret this, as we do the omission of many important works.

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