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Chapter 18

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Introduction

THIS survey covers literature published primarily during 1985–1989 that is relevant to experimental study of the dynamics and control of large spacecraft structures (LSS). Most of the references cited report research in the United States, but a few report research conducted abroad. All of the literature surveyed should be readily available in U.S. research libraries, or from standard sources such as the National Technical Information Service, the American Institute of Aeronautics and Astronautics, and the American Society of Mechanical Engineers. The references cited consist primarily of articles published in archival journals, papers presented at major conferences and printed in the proceedings, formal reports issued by research laboratories, and books.

The principal subjects surveyed are experimental studies, facilities, and methods relevant to LSS in the areas of structural dynamics, passive control, and active control, with an emphasis on the last area. Most of the references cited discuss specific experimental studies and present experimental data. The others either describe existing or planned experimental facilities and programs or discuss experimental methods that are already well established or that hold promise for future application to LSS.

Almost all of the experiments conducted to date have involved structures that were not truly LSS, but rather terrestrial laboratory structures, also called testbeds, intended to be representative dynamically in some respects of LSS. Some of the desirable characteristics of such laboratory

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structures include high flexibility, low inertia, light inherent damping, as many undamped rigid-body modes as possible, low natural frequencies, high modal density, some joint nonlinearity, space-qualified sensors, actuators and computers, onboard power, and a laser and pointing system. Probably no terrestrial structure will ever have all of these characteristics, but even a very simple laboratory structure can have at least a few of them. Indeed, relevant and valuable experimental research has been conducted on structures ranging from simple and inexpensive spring-inertia systems to highly complex and costly models of generic spacecraft. Consequently, no report of an experimental study has been excluded from being cited because the laboratory structure was considered too trivial.

However, many possibly relevant reports published during 1985–1989 are not cited. Among these are conference papers that eventually appeared substantially unchanged as journal articles, which are cited. Also not cited are less formal publications, such as slide/viewgraph presentations, that seem to be superseded by subsequent publications that are cited. Finally, researchers in this field publish their work in a great variety of journals, conference proceedings, and reports, and it has not been practical for the author to search all of these sources. The reader who checks almost any publication cited in this survey will find in its reference list relevant publications that are not cited here. However, an attempt has been made to cite at least one publication of every research group known to be doing experimental work, especially in active control, so that the reader will be informed of who is doing what type of work. The reader interested in a particular research group or type of work discussed here should then check the appropriate cited publications not only for details of the work but also for references to other related publications that are not cited in this survey.

Four sets of conference proceedings[1–4] are very helpful general references for LSS dynamics and control, particularly with regard to major U.S. Government experimental facilities and programs. These proceedings document recent government-sponsored control/structures interaction (CSI) conferences that are convened irregularly every one to two years. The facilities and programs are described in general terms by slide/viewgraph presentations reproduced in Refs. 1–4. The following is a short list of presentation topics, which may be of interest by itself and also will familiarize the reader with some of a long and confusing array of acronyms:

1) the Control of Flexible Structures (COFS) program[1–3];

2) the Large Space Structure Ground Test Facility at the NASA Marshall Space Flight Center (MSFC)[1,3];

3) the Spacecraft Control Laboratory Experiment (SCOLE) at NASA Langley Research Center (LaRC)[1];

4) the Solar Array Flight Dynamic Experiment (SAFDE or, more commonly, SAFE)[1];

5) the Flexible Structure Slew Testbed (CSDL testbed) at the Charles Stark Draper Laboratory (CSDL), sponsored by the U.S. Air Force (USAF) Astronautics Laboratory (AL)[2,3];

6) the Large Flexible Structure Test Facility at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology (Caltech), sponsored jointly by USAF AL and NASA[2,3];

7) programs, facilities, and experiments at or sponsored by the USAF Flight Dynamics Laboratory (FDL), including Vibration Control of Space Structures (VCOSS II) and the Large Space Structures Technology Program (LSSTP)[2-4];

8) the Active Control Evaluation of Spacecraft (ACES) programs at NASA MSFC[2];

9) the Passive and Active Control of Space Structures (PACOSS) program at Martin Marietta Astronautics Group, sponsored by USAF FDL[2,4];

10) the USAF Joint Optics Structures Experiment (JOSE)[2];

11) the Advanced Space Structures Technology Research Experiments (ASTREX) Laboratory at USAF AL[3,4]; and

12) two flight experiments planned for the near future, the Controls, Astrophysics and Structures Experiment in Space (CASE), and the Low Power Atmospheric Compensation Experiment (LACE).[4]

Structural Dynamics

The literature cited in this section deals primarily with modal and other structural dynamics testing methods relevant to LSS, and with testing done to date on laboratory structures that are representative in some sense of LSS. Most of the testing methods discussed are applicable mainly to ground testing, but the subject of on-orbit testing has been explicitly addressed in a few studies.

The state of the art in modal testing of all kinds of structures has advanced steadily since the early 1970s, when the fast Fourier transform and small but powerful computers were first unleashed on the field. Several comprehensive references on modal testing have been published recently, of which the following are cited: the textbook by Ewins,[5] another textbook that emphasizes multiple-exciter methods by Zaveri,[6] an article by Stroud,[7] a six-volume contract report by Allemang and Brown,[8] and a handbook chapter also by Allemang and Brown.[9]

Ground testing of an LSS prior to launch into orbit will be required in order to validate mathematical models and to qualify the structure for flight. But an LSS may be so weak and flexible that it would collapse under its own weight if completely assembled on Earth and supported in a manner that permits the freedom of deformation possible in flight. Researchers are developing three general methods for solving this problem: multiple boundary condition testing (MBCT), experimental component mode synthesis (CMS), and testing of scale models.

References 10–12 are representative of a number of publications on MBCT by authors at JPL. The method is summarized as follows. First, support the fully assembled LSS at enough points so that its structural integrity is not jeopardized, and test the restrained structure. Next, change to another set of safe supports and test again. Repeat this procedure until enough data have been assembled that the unrestrained structure's stiffness and mass matrices can be inferred mathematically with confidence. To date, MBCT has been applied experimentally only to correct large errors intentionally introduced in the mathematical models of two beams, one uniform and the other nonuniform.[10]

The general approach in experimental CMS is first to isolate each major component, or substructure, of the structure and test it individually, and then to assemble mathematically the data from all the component tests into data characterizing the full structure.[8] One frequency-domain CMS method was proposed by Ewins[13] and applied by researchers at the Massachusetts Institute of Technology (MIT) to a structure consisting of two beam substructures.[14]

The third general method for ground testing of LSS is to test fully assembled, reduced-size scale models of an LSS, and then mathematically extrapolate the data to infer the characteristics of the actual structure. References 15 and 16 discuss scale model technology development centered at NASA LaRC and focusing on the proposed Freedom Space Station.

An important adjunct to an LSS scale model is a vertical suspension system that supports the model's weight without significantly changing the modes of vibration relative to those of the unrestrained structure. Two approaches were evaluated experimentally for the Freedom Space Station scale model: a zero-spring-rate mechanism (ZSRM) and a hybrid pneumatic-electromechanical device.[17]

The SAFE structural dynamics testing on Space Shuttle flight STS-41D in September 1984 was evidently the only relevant on-orbit experiment conducted to date. A 4 × 32 m solar array was extended from the Shuttle's cargo bay and was tested at two different deployment lengths. Some of the measurements are discussed in papers from the Lockheed Missiles and Space Company[18] and NASA LaRC.[19] Both papers focus on inherent damping characteristics.

Frequency-domain methods for on-orbit system identification of LSS are being developed at JPL.[20,21] The principal objectives are to identify only the information essential for the design of robust control and to do so using automated operations that fit within the constraints of flight. The methods have been tested on a very flexible, antennalike laboratory structure.

Several generic models of different types of space structures have been tested dynamically at NASA LaRC.[19,22-25] In most cases complementary mathematical analyses were conducted, and test results were used to refine the mathematical models. Planar, cable-stiffened frame structures are the subjects of Refs. 22 and 23. Laboratory hoop and radial-rib structures were dynamically similar to the frameworks of proposed space antennas and solar power stations, and the results of conventional linear finite-element analyses agreed well with modal test measurements.[22] A laboratory guyed boom was a pinned beam with two taut cables attached to its tip, a possible design for a spacecraft appendage.[23] Inertial loads on the guyed boom from, for example, a slew maneuver could cause cable slackening and lead to nonlinear transient response. This type of loading was simulated, and the nonlinear mathematical analysis was validated by good agreement with measured dynamic response.

References 24 and 25 describe analyses of two much more complex laboratory structures: a generic space station model consisting of five substructures which ranged in stiffness from essentially rigid to extremely flexible[24]; and a cable-stiffened hoop-column antenna complete with a surface mesh.[25] Cable suspension systems were evaluated in both experiments. Each structure was tested within both atmospheric and near-vacuum air pressure levels. For both of these complex structures, extensive refinement of the mathematical model based on static measurements was required before reasonable agreement was achieved between predicted and measured modal parameters.

A modal test conducted at NASA LaRC on a beamlike space truss is discussed in Ref. 19. The truss members had relatively low bending stiffness; consequently, local member bending vibration modes coupled with and obscured the global truss modes. Sensors were mounted only on joints connecting the members; hence, the available response data were inadequate for accurate measurement of modal parameters. Exactly the same problem appeared in an independent experiment on a beamlike planar truss at Martin Marietta.[26]

Martin Marietta's testbed for the PACOSS program was designed to represent a flexible satellite.[27,28] It consists of several different types of substructures, and the entire assembly is supported by ZSRMs to simulate unrestrained flight. The results of extensive modal analysis and testing have been reported for several of the principal substructures[27] and for the full assembly.[28]

Researchers from Japan's Toshiba Corporation and Institute of Space and Astronautical Science built a space truss with the basic form of a 3.5-m-square by 0.7-m-thick flat plate.[29] The basic form can be adjusted into different shallow-shell forms with the use of variable-length truss members, so that this testbed can assume various different antenna shapes. Modal analysis and test results for five configurations are presented in Ref. 29.

Vertically suspended planar grids have been used often to represent LSS dynamics.[30-33] This type of structure is relatively simple and inexpensive to build, yet can have two-dimensional, very-low-frequency modes and high modal density. A planar grid at NASA LaRC was the testbed for several experiments, including a study of identification by least-squares lattice filters.[30] Reference 31, from Virginia Polytechnic Institute and State University (VPI&SU), presents a study of transient flexural waves in a planar grid. A planar grid at USAF AL was used in studies of modeling and identification techniques[32] and of the influence of gravity on accelerometers.[33] It was demonstrated that gravity can seriously contaminate low-frequency acceleration signals, and an estimation method to compensate for the contamination was tested on the planar grid.

Several publications describe structural dynamics identification methods designed to be applied eventually to LSS, but actually applied first to specific active control testbeds.[34-40] These reports are discussed in the context of the active control experiments in the section on active control.

The subject of nonlinear structural dynamics is obviously important, but the author has found only one recent experimental paper specifically oriented toward LSS applications: Ref. 14 assesses the effect of a sloppy joint on the application of experimental CMS to a joined-beam structure. It should be noted also that a book by Moon[41] describes in detail several experiments on chaotic vibration of beam structures. There is certainly much more literature on experimental nonlinear structural dynamics; thus, the interested reader should search elsewhere.

Passive Control

Some representative publications dealing with the passive control of global structural response are cited in this section. References 42 and 43, the proceedings of recent major conferences on damping, include many papers of this orientation. They also include many papers reporting the latest research on material damping properties, which is not considered here.

"Passive control," as used here, implies the dissipation of vibrational strain energy by mechanisms that do not require a source of power. Three general types of passive control are considered: the inherent damping that exists in any structure; damping that is designed into a structure with the use of special, highly dissipative materials; and energy absorption by mechanical or electromechanical components.

All structures have inherent damping due to mechanisms such as conversion of strain energy into heat and friction at joints and fasteners. Much effort has gone into the measurement of global inherent damping in structures and components related to LSS. The damping of the SAFE solar array was measured in space.[18,19] In a series of experiments conducted by Stanford University at NASA Ames Research Center, modal damping factors of aluminum and composite beams and plates and aluminum planar frames were measured in spacelike conditions: the test articles were catapulted into free flight in a vacuum, and their vibration responses were telemetered to recording units.[44] Researchers at Utah State University evaluated the inherent damping of a laboratory space truss due primarily to its joints; they found different levels of damping for different orientations and levels of static loading.[45]

An assumption shared by many researchers is that it will be necessary to design additional passive damping into most LSS. However, Ashley and Edberg[46] used data collected from spacecraft, aircraft, and laboratory experiments "to advance the claim that the modal damping naturally available in most large structures deployed in space will be more than adequate to permit the successful design of active control systems, without the use of special measures to augment passive energy dissipation."

Despite the arguments made in Ref. 46, research continues in the area of passive damping augmentation, particularly with the use of viscoelastic damping materials. In work by CSA Engineering for the PACOSS program, integral viscoelastic damping was used in an 18.3-m beamlike space truss; high levels of modal passive damping were measured for the truss, and the theoretical model accurately predicted the damping performance.[47] In a somewhat similar study JPL researchers tested several different viscoelastic member designs as the single integral damping member in a small beamlike space truss.[48] Viscoelastic materials designed into joints also can produce substantial passive damping, as was demonstrated by experiments conducted at the Georgia Institute of Technology.[49]

Martin Marietta's passive control experiments in the PACOSS program were probably the most ambitious attempted to date.[28,50] Several different types of viscoelastic passive damping components were used in the complex testbed, including rotational and extensional shear dampers, distributed constrained layer damping, and tuned-mass dampers. This research demonstrated that it is possible to design significant and predictable levels of passive damping into LSS.

A group at MIT has done extensive research on damping augmentation using passive vibration absorbers, including both tuned-mass dampers and piezoelectric truss members.[51-53] The types of absorbers used are capable also of providing actuation for active vibration control, and some were used both passively and actively in the MIT experiments. Accordingly, these studies are described in more detail in the next section.

Active Control

"Active control," as used here, implies closed-loop feedback control with the use of sensors to generate electrical signals representative of motion quantities; controllers (either analog or digital) to accept sensor signals, execute control algorithms, and generate command signals; and actuators to accept command signals and effect control forces and moments. Both control of vibration alone and simultaneous control of maneuvering and vibration are included in this definition.

If a translation or rotational sensor occupies physically the same motion degree of freedom as, respectively, a force or moment actuator, then the sensor and actuator are said to be collocated, or dual. "Active damping" is a subset of active control, the simplest form being direct feedback (without dynamic compensation) of velocity to a collocated actuator. Some authors refer to any form of velocity feedback as active damping.

There were a few active control experiments prior to 1980, but most were related to subjects other than LSS, such as acoustics. The first major U.S. Government program was the Active Control of Space Structures (ACOSS) Program started in 1978 and completed in 1984, and it produced many of the first experiments related to LSS. The September–October 1984 issue of the *Journal of Guidance, Control, and Dynamics* focused on the early experiments.[54] A general survey of LSS dynamics and control in that issue cited only 14 reports of active control experiments in a list of 194 references.[55] Another article in that issue[56] and an article published a year earlier[57] tabulated the experiments then known by their authors to be in existence; each identified fewer than a dozen experiments in the entire United States, and most of those had not yet been reported in the open literature.

However, the trickle of experimental studies that began in the late 1970s grew into a healthy stream by 1985, and in late 1989 they seem to be approaching flood level. Abundant evidence of this growth is presented in a recent survey of past, present, and future experiments and experimental facilities in the United States and Canada.[58]

A few publications give extensive descriptions of experimental facilities and programs for active control. Reference 59 describes a facility at CSDL, the primary component of which is the CSDL testbed. This structure consists of a rigid central hub mounted on a vertical-axis air bearing, with four horizontal flexible beams extending radially from the hub. The SCOLE facility[60] at NASA LaRC is based on a laboratory model of a rigid orbiter with rotational freedom about two axes, to which is attached an offset antenna reflector by means of a long, flexible beam. The Daisy facility[61] at the University of Toronto is based on a testbed consisting of a rigid hub with rotational freedom about three axes, to which 10 rigid spokes are flexibly attached. References 36, 62, and 63 describe the Flexible Structures Facility at the Ohio State University (OSU); experiments conducted there include vibration control of beams, slewing of one- and two-link flexible beams, and slewing of a satellite emulator. The Large Flexible Structure Test Facility[64] at JPL is based on an antennalike structure consisting of a central rigid hub with rotational freedom about two axes, a long, flexible beam hanging vertically from the hub, and 12 flexible ribs radiating horizontally from the hub. The ACES programs[65,66] consist of a series of activities at NASA MSFC involving several different complex flexible structures.

Any active control experiment has certain essential components: a laboratory structure, sensors, controllers and control techniques, actuators, and a system for data acquisition and analysis. It might seem that these components are all roughly equal in general importance and that any one except the last could be a logical basis for organization of a survey of the experimental active control literature. However, the practical experience of many researchers has been that actuators play the dominant role in determining the nature and success of an active control experiment. For this reason, the publications cited later are organized on the basis of the types of actuation used in the experiments reported.

An actuator capable of influencing motion of a spacecraft flying beyond the atmosphere obviously cannot be mechanically "grounded," i.e., reacted by the Earth or by atmospheric forces. Therefore, many researchers strive to use what are described as "structure-borne" or "space-realizable" actuators in their laboratory experiments. (The former term evidently was coined by Rockwell[67] many years ago, and the latter by Miller et al.[51] very recently.) However, for various reasons many experiments also have been conducted with the use of grounded actuators. Therefore, the two major subsections of this section on active control are, first, experiments based on grounded actuators and then experiments based on structure-borne actuators. This order of presentation follows from the experience in some cases that grounded-actuator experiments of a research group logically and chronologically preceded the same group's structure-borne-actuator experiments.

Experiments Based on Grounded Actuators

Active control experiments have been conducted with the following types of grounded actuators: force motors, torque motors, tendons, and airjets.

Active Vibration Control Using Grounded Force Motors

Researchers at the TRW Corporation have conducted experiments since 1984 on a laboratory structure consisting primarily of a heavy plate supported horizontally on top of a one-story, four-column frame structure. References 37 and 68–71 are representative publications, with Ref. 71 being a summary and retrospective of the work through mid-1988. The actuators used were magnet-coil force motors mounted in diagonal truss members attached to the grounded base and top of adjacent frame columns. The TRW experiments implemented advanced system identification and vibration control techniques and included testing of passive damping.

A two-story, three-column hanging frame structure is the testbed for experiments at Caltech.[33,72] As in the TRW experiments, grounded magnet-coil actuators are mounted to diagonal truss members of the first story.

A research group at VPI&SU has conducted several vibration control experiments using magnet-coil force motors. A principal objective of this work has been achievement of good agreement between theoretical predictions and experimental measurements. The laboratory structures used were a beam mounted on taut cables and a pendulous, skewed planar grid. Experimental results have been reported on different types of modal-space active damping,[73-75] the sensitivity of control system performance to structural modifications,[76,77] and comparisons of various active damping techniques with optimal control.[78,79]

Researchers at Italy's Politechnico di Milano used three independent control units (ICUs) on a 3.5-m beam suspended horizontally by cables.[80,81] Each ICU consisted of a velocity sensor, an analog controller, and a grounded electrodynamic shaker collocated with the sensor and serving as a force actuator. Direct feedback of velocity and position produced an active viscous dashpot and an active spring at each sensor-actuator location.

References 35 and 82–85 report experimental work at the German Aerospace Research Establishment (DFVLR), with Ref. 84 being an overview of studies through 1987. Electromagnetic force motors were used as actuators on two laboratory structures: a hanging cantilevered beam and a pendulous rectangular plate suspended from cables. (This was evidently the second experiment on a thin flat plate, the first being the Lockheed circular plate experiment.[56]) Vibration control was implemented using velocity feedback from sensors collocated with and dislocated from actuators. Also, wave-absorbing controllers were applied on the beam using control hardware located at its free end.[83]

Yet another experiment on a hanging plate was conducted at the Harris Corporation.[86] Grounded magnet-coil force motors were collocated with accelerometers to test a maximum entropy/optimal projection design for vibration control.

Some of the first experiments conducted on the JPL antennalike structure involved methods for active damping[64] and model reference adaptive vibration control.[64,87] Adaptive control is an important subject for LSS due to the likelihood of inaccurate mathematical models, slowly time-varying dynamics as LSS are constructed and modified in orbit, and in-service failures of control system components. In the JPL experiments, grounded magnet-coil force motors acted on the antenna hub through moment arms about a two-axis gimbal assembly, thus effecting rotational control moments. The control sensing used was essentially collocated with the actuation.

Studies conducted at the University of Cincinnati used electrodynamic shakers as force actuators for control of beam vibration. The researchers evaluated dislocation of control accelerometers from the single actuator supporting a beam at its center[88] and multivariable control of a cantilevered beam's tip response when the beam is excited by a disturbance having a single dominant frequency.[89] Reference 89 also describes a method to account for the time delay introduced by digital processing of the control algorithm. This important issue was addressed in the earlier articles on Lockheed experiments,[56,57] and one finds some discussion of it in most recent reports that describe applications of digital controllers.

Active Control Using Grounded Torque Motors

An article by Stanford researchers reports one of the earliest experimental studies of adaptive vibration control.[90] The laboratory structure was a two-degree-of-freedom spring-inertia system, and the control components were a rotational position sensor and a dislocated torque motor.

There have been several experiments in which flexible beams were rotated (slewed) about a vertical axis by torque motors. In general the control objectives were to slew a beam quickly through a prescribed large angle in a horizontal plane while minimizing excitation of vibration, and, simultaneously, to suppress vibration. In experiments at NASA LaRC comparison of theoretically predicted with measured motion indicated that aerodynamic drag significantly influenced the dynamic response.[91] In follow-on experiments, slewing response of a beam was measured both in atmospheric pressure and in an evacuated vacuum chamber, and mathematical modeling of the aerodynamic drag was validated.[92] In Ref. 93 authors from the Tokyo Metropolitan Institute of Technology demonstrated application of the "mission function control" algorithm for slewing a spacecraft with flexible appendages.

Slewing of beams is a subject of interest in robotics research, since it is often desirable to minimize the mass, and hence increase the flexibility of manipulator arms. Two articles by OSU researchers report experiments in which beam tip position accuracy (rather than global vibration control) was a principal control objective.[94,95] These articles are representative of many more relevant publications in the robotics literature that are not cited here.

Active Vibration Control Using Grounded Tendons

The use of tendons is considered promising for motion control of large civil structures, as discussed in Refs. 96 and 97 from the State University of New York at Buffalo (SUNY Buffalo). The authors of Ref. 97 document the sources of delay between sensors and actuators in the SUNY Buffalo control system due to all the hardware, not just the digital controller.

Researchers at Japan's University of Osaka Prefecture have proposed and tested a type of tendon control intended to suppress vibration and to control the static shape of a flexible beamlike appendage attached to a massive spacecraft.[40,98-100] The testbed was a hanging cantilevered beam, and the tendon actuator was a grounded magnet-coil force motor. Velocity feedback has been applied with both collocated and dislocated sensor-actuator pairs.

Active Control Using Grounded Airjets

A unique experiment at the University of Washington was based on a laboratory structure consisting of a rigid hub and six flexibly attached rigid spokes.[101] The hub rested on a flat disk that, in turn, floated on the air cushion of a pressurized air table, giving the structure freedom to translate and rotate in the horizontal plane with very little friction. Control force was provided by airjets flowing from nozzles fixed to the table and inpinging on fins attached to the structure.

Experiments Based on Structure-Borne Actuators

In contrast to most motion sensors and grounded actuators, structure-borne actuators appropriate for laboratory experiments generally are not available commercially; they must be designed, fabricated, and assembled in-house, usually with the use of purchased hardware components. Therefore, many researchers in this field have devoted major efforts to building and testing actuators. The types of structure-borne actuators used for active control range from conventional rigid-body control devices such as reaction wheels and gasjets to recently developed devices based on constitutive properties relating material deformation to electrical, magnetic, and thermal fields.

Active Vibration Control Using Active Members

An active member is defined as a member capable both of the standard structural function, i.e., passively reacting and transmitting loads, and of simultaneously generating active control forces or moments. Some authors define active members as being capable of sensing as well as actuation. The functioning of active members involves only internal, self-equilibrating actions; hence, active members cannot influence rigid-body motion.

Wada[102] presented a general description of research in the area of adaptive structures, which by definition consist at least partly of active members. Wada discussed the literature on all aspects of active members, including theoretical studies and experiments intended primarily to explore the characteristics of the active members themselves. We consider here only experiments in which active members have been applied to effect vibration control.

The most common form of active member used to date is a beam element with a composite cross section. Typically, the cross section consists of a metallic core and thin layers of active material bonded to both top and bottom surfaces of the core. When one active layer is caused to expand along the beam axis and the other is caused to contract, then a spatially distributed bending moment is induced in the beam. The expansion and contraction can be produced in conventional metallic active layers by heating and cooling. In fact, this simple thermal actuation was applied in an experiment at JPL to dampen the first mode of a cantilevered beam at about 2 Hz.[103]

Better and more diverse performance can be achieved with piezoelectric active layers, which are caused to expand or contract by a voltage difference across the layer thickness. Researchers from CSDL and MIT have used piezoelectric polymer active bending elements to apply, primarily, a type of nonlinear active damping similar to Coulomb friction. Their reports discuss spatially uniform[104,105] and nonuniform[106] actuating layers, active layers for both actuating and sensing,[107,108] and an extensive series of experiments that culminated in active damping of the complete CSDL structure.[109]

The spatially distributed character of piezoelectric bending elements is well suited for application of modal-space control techniques, as illustrated by three studies on vibration control of cantilevered beams. Researchers at JPL and Caltech reported the first experimental implementation of "positive position feedback" (PPF), a technique involving modal position feedback and dynamic compensation; as many as six bending modes were controlled simultaneously with the use of ceramic sensing and actuating layers.[110] A modified form of PPF was applied with ceramic actuators in subsequent experiments at the Catholic University of America.[111] Researchers at the IBM Corporation used polymer sensing and actuating layers to achieve critical active damping of the fundamental bending mode.[112,113]

Piezoelectric material can be embedded in truss members as well as beam members and, when activated by voltage differences, can generate control forces in a truss structure. The application of this mechanism to vibration control of laboratory space truss structures has been explored in four studies using several different passive and active truss member designs. In experiments at MIT the inner and outer surfaces of thin-walled tubular piezoelectric truss elements were connected electrically (shunted) through simple resistor-inductor networks; the electromechanical characteristics of the ceramic material combined with the shunting networks to increase passively the first-mode damping of a laboratory truss.[53] In two sets of experiments on different space truss testbeds, JPL researchers applied a patented active truss member design and single-input/single-output vibration control. In one study a digital controller was used to implement four different control techniques; the most successful at controlling three truss modes was PPF between a dislocated sensor-actuator pair.[38,114] In the other

JPL study three types of feedback compensation between a collocated sensor-actuator pair were implemented by analog circuitry, and effective control of the first truss mode was achieved.[115] In experiments at Sandia National Laboratories, signals from four piezoelectric strain sensors were fed through a digital controller back to four Sandia-designed active truss members, which were dislocated from the sensors. Several modes of a cantilevered space truss were controlled by implementation of linear-quadratic Gaussian[116,117] and optimal projection[117,118] techniques; the latter was more successful but required an extraordinarily accurate mathematical model of the structure.

Another type of active truss member is a jackscrew driven by a torque motor. Such an actuator can be designed to be a very stiff, extensible link in a "variable-geometry truss." Researchers at VPI&SU have used these active members in space truss[119] and planar truss[120] linkages to control the first-mode vibration of highly flexible beams attached to the trusses.

Active Vibration Control Using Structure-Borne Force Motors

Magnet-coil force motors were used as active truss members by researchers from Japan's Institute of Space and Astronautical Science and the Toshiba Corporation.[121] They collocated relative displacement sensors with four of these motors to suppress first-mode vibration of a beamlike laboratory space frame.

Magnet-coil motors applied directly (not through gears) are unsuitable for general purposes as primary load-carrying structural members because 1) without electric power, they have zero stiffness; and 2) even with power, they are almost certainly much more flexible than other geometrically similar structural members, including the other types of active truss members discussed earlier. However, such motors may be practical if they are mounted in parallel with primary load-carrying members so that the general structural integrity does not depend on the motors. For example, a force motor attached through posts to two points along the span of a beam can introduce equal and opposite control moments into the beam by virtue of its force axis being offset from the beam's neutral surface. This approach was demonstrated at the U.S. Air Force Academy (USAFA); the fundamental mode of a hanging cantilevered beam was suppressed by a magnet-coil force motor dislocated from a position sensor.[122]

In the JPL antennalike testbed, structurally parallel magnet-coil force motors are attached between the hub and an inboard point of each rib.[64] Four of these rib actuators were used in concert with two hub actuators and six collocated sensors to implement probably the most complex system to date for multivariable adaptive vibration control.[123]

Active Vibration Control Using Structure-Borne Torque Motors

The authors of Ref. 124, SUNY Buffalo and NASA LaRC researchers, report an experiment on a long, hanging, cantilevered beam with an interior pin joint. The joint served as an "active hinge," since it consisted of a hinge, a torque motor, and a collocated sensor connecting the ends of the two beam segments at the joint. Substantial active damping was achieved in the second and third modes of the beam.

The ACES-I testbed at NASA MSFC was designed to present a great number of challenges in vibration control representative of those expected for LSS.[65,66,125] The principal components of this complex structure included the following: an extremely light and flexible 14-m mast hanging from a grounded three-axis gimbal assembly; several flexible appendages attached to the mast's base and tip; and an optical system consisting primarily of a grounded laser source, a mirror, and a two-axis laser detector fixed to one of the tip appendages, and a mirror actuated by a two-axis gimbal assembly mounted on a base appendage. The laser ray reflected off both mirrors to reach the detector, and the control objective was to minimize deviation of the ray from its target on the detector caused by excitation at the mast's base. Torque motors in the two gimbal assemblies provided actuation for three general control methods that had been developed in the ACOSS program.

The other experiments in this category all followed earlier studies of single-beam slewing. They involved multibody structures and two or more torque motors, one motor grounded and actuating an "inboard" body, and the others connecting the "outboard" bodies to the inboard body through hinged joints. The general control objective was to maneuver the articulated flexible structure from an initial position to a specified final position while minimizing vibration.

In one robotics experiment at Stanford the inboard and outboard bodies were, respectively, a flexible beam and a short rigid link, and the specific control objectives were to achieve timely and accurate positioning of the link tip and to maintain proper contact force between the tip and a target object.[126] In another Stanford experiment the inboard and outboard bodies were, respectively, a long rigid link and a flexible beam.[127,128]

Experiments in progress at OSU include one in which both inboard and outboard bodies are flexible beams and another in which mirrors are mounted through motors onto a flexible beam, and the specific control objective is to maintain the position of a reflected laser ray during a slew maneuver.[63]

One laboratory testbed at NASA LaRC was a three-body structure consisting of a rigid inboard hub and two separate outboard flexible beams.[129] Complex large-angle slewing maneuvers with active vibration suppression were achieved. Another NASA LaRC structure consisted of a rigid trolley, actuated to translate horizontally in one direction by a motor-cable system, and an outboard flexible beam pinned to the trolley.[130] A maneuver combining trolley translation and beam rotation was executed for four different output feedback designs intended to suppress beam vibration.

Active Vibration Control Using Reaction-Mass Actuators

A reaction-mass actuator (RMA) exerts an inertial control force or moment on the structure bearing it. The reaction mass is attached to the structure by a spring (mechanical and/or electromechanical); thus, an RMA cannot effect control of rigid-body position. Other names used in the literature for actuators that use reaction masses include proof-mass actuator, linear momentum exchange device, and linear dc motor.

A research project at MIT focused on the application of moment-generating pivoted proof-mass actuators (PPMs) for vibration suppression of a 7.3-m beam suspended horizontally by wires.[51,52] Four PPMs, which included collocated motion sensors, were mounted on the beam. An RMA can function as a passive vibration absorber if its natural frequency and damping are tuned appropriately, and the MIT PPMs were used as both passive absorbers and active actuators. The principal control technique applied was direct output feedback. Significant levels of damping were produced in several beam modes.

The PPM design used at MIT was based on an earlier Lockheed design.[56] In subsequent studies at Lockheed a PPM was mounted on the tip of a cantilevered beam and used as the actuator in a control system intended to maintain pointing accuracy of a laser ray.[34,131] Reflecting mirrors attached to both the PPM and the beam midspan were disturbed by the beam's vibration. The control technique used was a combination of high-authority dynamic compensation and low-authority direct-rate feedback.

Three main types of linear, force-generating RMAs, called types 1–3 here, have evolved in the past few years. Types 1 and 2 are based on the force between a current-carrying coil attached to the structure and the field of a permanent magnet assembly, which is the reaction mass. Type 1 RMA (short coil, long field) was developed in a project involving USAF FDL, NASA MSFC, and their contractors,[132] and it has been applied in experiments at USAF FDL[133,134] and at Martin Marietta.[28,50] Type 2 RMA (long coil, short field) was developed jointly by researchers at NASA LaRC, the University of Virginia, and SUNY Buffalo,[135] and the design has been modified at MIT.[53] In the type 3 RMA, a development of the Harris Corporation, it appears that a magnetic reaction mass is accelerated by the field of an electromagnet attached to the structure.[86] Although all of the RMAs previously discussed weigh at least several pounds, a miniature RMA similar in principle to type 1 has been fabricated at OSU.[62,63]

Researchers from the Air Force Institute of Technology[133] and OSU[134] conducted experiments at USAF FDL on a hanging cantilevered beam with a platform attached to its tip. Four type 1 RMAs were mounted on the platform in an arrangement providing control authority over torsion and bending in two orthogonal directions. Several different control algorithms were implemented, including a modal decoupling technique[133] and optimal projection and decentralized linear-quadratic Gaussian techniques.[134] Martin Marietta used active control effected by six type 1 RMAs distributed over the PACOSS testbed to complement extensive viscoelastic passive damping; the combined passive-active control was predictable and very effective.[28,50]

SUNY Buffalo researchers used a single type 2 RMA in experiments to control vibration of a cantilevered beam; one of their main objectives was to demonstrate that the dynamics of an RMA are intrinsically coupled with the controlled structure's dynamics and that the system's mathematical model should account for this coupling.[135-137] MIT's type 2 RMAs were used either to excite or to passively dampen a 5-m space truss suspended horizontally by wires; the electromechanical design of the tuned-mass damper permits adjustment of both frequency and damping factor for optimal performance on different modes of vibration.[53]

Harris' type 3 RMA was mounted at the tip of a 5-m compound pendulum and served as the actuator for a maximum entropy/optimal projection control design. Harris has also developed a precision linear actuator that appears to be a type 1 or 2 RMA.[86]

Active Control Using Reaction-Wheel Actuators

A reaction-wheel actuator (RWA) exerts an inertial moment on the structure bearing it. Unlike a reaction mass, a reaction wheel is not attached to the structure by a spring; thus, an RWA has control authority over both vibration and rigid-body angular position.

RWAs were used by OSU researchers in an experiment implementing a form of decentralized model reference adaptive vibration control of the NASA LaRC planar grid.[138] Also at NASA LaRC, two different types of RWA were installed on the SCOLE testbed.[60] In one SCOLE experiment a single RWA was used to effect indirect rate-feedback control: the feedback signal was estimated angular velocity at the RWA location, as calculated by a Kalman filter from the signals of dislocated sensors.[139]

A laboratory structure at Texas A&M University is similar to the CSDL testbed, with a rigid central hub mounted on bearings and four horizontal flexible beams extending radially from the hub.[140] The hub is restricted to slewing about its vertical axis. The unique characteristic of this testbed is the single hub-mounted RWA, which is the actuator for both hub slew angle and suppression of beam vibration. The authors of Ref. 140 report the performances in large-angle slewing maneuvers of two control laws.

Active Control Using Control-Moment Gyros

A control-moment gyro (CMG) is, like an RWA, an inertial moment-generating actuator. However, CMGs are more complicated, expensive, and dangerous (to operate in a laboratory) than RWAs; thus, they have been used only rarely in active control experiments. One of the few applications reported was an early Lockheed experiment.[57] The SCOLE testbed was equipped with CMGs,[60] but they have not been used for active control.

Active Control Using Structure-Borne Gasjets

Gasjets, or thrusters, are relatively simple force actuators that can effect control of both rigid-body motion and vibration. However, they have not been used widely for active control. The conventional gasjet is a nonthrottleable on/off actuator, and its highly nonlinear functioning appears to be incompatible with the linear control methods that many researchers consider essential for precision control. Moreover, gasjets require nonrenewable compressed gas or chemicals; hence, they may not be as practical for flight operation as actuators that function on electrical power. Nevertheless, cold-gas gasjets have been applied in a few active control studies, in particular, on the CSDL and SCOLE testbeds.

In one of the first experiments on the CSDL testbed, nitrogen jets located at the tip of a flexible appendage provided actuation for large-angle slewing maneuvers.[59] The principal achievement of the study was establishing the feasibility of gasjet actuation for combined slewing and vibration control of LSS.

Airjets were installed on the SCOLE antenna reflector, which is attached to the rigid orbiter model by a flexible beam.[60] In one experiment a thruster was used to produce a large-angle slew without exciting the fundamental vibration mode.[141] The SCOLE thrusters were applied also in studies of methods for detecting failures in sensors and actuators.[142,143]

Active Control Using Two or More Types of Actuators

Several active control testbeds have been equipped with more than one type of actuator, but few experiments have been conducted in which two or more types were operating simultaneously. The following two studies are perhaps the only that have been reported.

In an extensive set of experiments on the CSDL testbed, various combinations of gasjets, RMAs, and a grounded hub torque motor were applied simultaneously.[144] The gasjets effected coarse actuation of large-angle slewing but were unsuitable for precision control. Integration of the linear actuators into the control system significantly improved the performance in fine pointing and tracking and in vibration suppression.

Finally, airjets and RMAs were used together to actively dampen the vibration of a 7.1-m cantilevered planar truss at the U.S. Air Force Academy.[145] The airjets were effective at low frequencies and the RMAs at higher frequencies; the objective of the study was to combine the two types in order to produce effective control over a greater frequency band than that of either type alone.

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