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Survey of Experiments and Experimental Facilities for Control of Flexible Structures

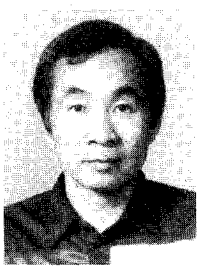
Dean W. Sparks Jr. and Jer-Nan Juang
NASA Langley Research Center, Hampton, Virginia 23665

This paper presents a survey of ground experiments primarily conducted in the United States and U.S. facilities dedicated to the study of active control of flexible structures. The facilities are briefly described in terms of capability, configuration, size, and instruments. Topics on the experiments include vibration suppression, slewing control, and system identification. The experiments are listed in tables containing the experiment's name, the responsible organization, a brief description of the test article configuration, and the actuator/sensor devices used in the experiment. Selected experiments will be further discussed to help illustrate the control problems. Some of the test facilities dedicated to ground testing of large space structures are discussed in more detail, to give the reader a better appreciation of ground-testing work. Several research issues are mentioned, including real-time computer systems, test article suspension, and new actuator/sensor technology development.

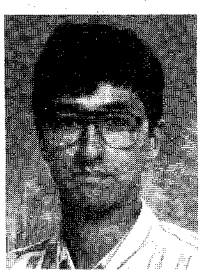
Introduction

PLANNED future space missions will involve advanced space systems, with three general characteristics. First, future space systems will be large and flexible structures (herein referred to as large space structures, or LSSs), consisting of long trusses or booms, for example. Second, they will have multiple components, such as various instruments, large remote manipulators, and mirror or antenna reflectors, located at several points along the space structure, resulting in complex designs. Third, these systems will be required to have more demanding mission capabilities than present spacecraft. Pointing accuracy needs of payloads will be more stringent, slewing will have to be done faster, and larger (nonlinear) angular motions will be required. As operations in space continue to expand, there will be an increased use of large, flexible, remote manipulators, requiring highly accurate and reliable performance for on-orbit construction, maintenance, experiment operations, etc. Permanently manned spacecraft operations will also bring in their own special needs, most notably the requirement to counter disturbances caused by human motions.

These challenges are beyond the current state of the art in space structure design. It is envisioned that new design methods will be needed to tackle these challenges. Since complex, flexible space structures are new, they must be studied and validated via thorough ground testing, both in controlled laboratory environments and in realistic operating scenarios. With the increase in size, complexity, and capability, these future space systems will be proportionally more expensive and, thus, there will be an even greater incentive to ensure that these space systems operate as designed. Ground testing will signficantly contribute to this effort.



Dr. Jer-Nan Juang is Principal Scientist of the Spacecraft Dynamics Branch, NASA Langley Research Center. He coordinates joint technical activities with other Langley and NASA organizations, other government agencies, and industry/universities on a national and international basis. He conducts personal analytical and experimental research in the fields of mechanical designs, controller designs, and system identification for control of flexible space structures including robotics. He is a Fellow of the American Astronautical Society and the American Institute of Aeronautics and Astronautics. He is the recipient of several NASA Outstanding Performance, Special Achievement, and Technical Excellence Dual Career Ladder Awards. He received the Award of Merit for a prize-winning paper on Mechanism, Design, Analysis or Application at the 21st ASME Mechanism Conference. He was an Associate Editor of the *Journal of Guidance, Control, and Dynamics* and is currently an Associate Editor of the *Journal of Vibration and Acoustics*.



Dean W. Sparks Jr. is an Aerospace Engineer in the Spacecraft Controls Branch at the NASA Langley Research Center. He is currently involved in ground test work on large space structures under the Control/Structures Interaction (CSI) Program. He is the author of several publications dealing with large space structure control. He is a Fellow of the AIAA.

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The motivation behind this paper is to identify LSS experiments and facilities, both past and present, and their contributions to the overall study of LSS control. It is hoped that readers will gain a better appreciation of ground-test work and be motivated to work on the control challenges of LSSs, particularly through ground testing.

This paper is organized in the following manner. First, the experiments are presented in three groups: 1) vibration suppression control experiments; 2) slewing experiments with vibration suppression control; and 3) experiments dealing with other test work, such as surface shape control and on-line system identification. Next, some of the test facilities dedicated to LSS ground testing are discussed. Then, a section briefly addresses several remaining research issues. Finally, a conclusion section completes the paper.

Several important points should be brought out before proceeding to the experiments section. First, with the exceptions of a Canadian and an Italian experiment, all experiments and facilities in this survey are from the United States. Second, although the U.S. Department of Defense (DoD) is heavily involved in LSS works (especially through the Strategic Defense Initiative, or SDI, projects), most of the reported experiments come from university, industry, and civil government sources. Finally, although the use of flexible robotic arms is increasing, tests involving them have been excluded from this report. It was felt that, due to the abundance of robotic manipulator work and the space limitations of this paper, they should be treated separately.

Control Experiments

In this section, approximately 60 space structure ground experiments both from the past and the the present are listed. For completeness, small laboratory experiments are included as well as those from major test programs. This survey was compiled from various sources, through a literature search[1-33] and direct contact with researchers in the large space structures field. Although this list is certainly not all inclusive, it does give a good representation of the various types of testing that have been or are still being conducted.

These experiments are separated into three groups, depending on what best describes their test objectives. The first two groups consist of the more common experiments—vibration suppression and rigid-body slew control with vibration suppression of flexible motion, respectively. These two classes of problems are basic to all LSSs. The flexible motions of LSSs must be controlled not only to ensure that the LSSs' payload mission performance is not adversely affected, but also to minimize any significant vibrational motions. The latter, if left uncontrolled, could seriously degrade or even destroy the LSSs' structural integrity and thus shorten their useful lifetime. The slewing/vibration suppression control problem is really an extension of the problem just stated. Slewing control of payloads on LSSs is a desired feature, since most LSSs will inevitably have a common requirement to slew some type of antenna/reflector or other instrument to point in specific directions in space. This can be for purposes of communications, scientific measurements, surveillance/monitoring, etc. Unfortunately, due to the coupling with the LSSs' inherent flexibility, slewing maneuvers tend to cause the aforementioned vibrational motions. These two basic control objectives tend to conflict—faster slewing motions (such as "bang-coast-bang" maneuvers) will be better for minimum time slewing requirements but they will tend to increase the vibrational motions of not only the structure being slewed, but any connecting structures as well. Thus, compromises in control designs may have to be made in order to accommodate both rigid body and flexible motions of LSSs.

The third group of experiments covers all other LSS related control testing, which will have practical implications on LSSs. Examples are system identification, structural shape control, and fault detection and control system reconfiguration after component failure(s). These experiments are designed to reveal details that are often neglected or omitted in tests in the former two groups. Any problems studied under this group, if they occur on actual spacecraft, could significantly affect overall mission performance, exclusive of the performance of slewing and vibration suppression control.

Under each of these groups, the experiments are listed in tables containing the experiment's name (in cases where there is no official proper name, a descriptive title is given by the authors), the responsible organization (in brackets) and reference number (in braces) if a written source exists, a brief description of the test article configuration, and the actuator and sensor devices used in the experiment. Also, under each group, selected experiments will be discussed to help illustrate the control problems. These particular experiments are chosen primarily due to the authors' familiarity with them and/or the authors' access to large amounts of detailed information about them. This information includes experimental test results, that have been taken directly from the cited references. The reader should be made aware that, since the results come from different sources, the presentation of the test data varies in terms of units and plots.

Vibration Suppression Experiments

This section summarizes those experiments listed in Table 1 that deal primarily with the problem of damping of flexible motion through active control. The various control schemes involved in these experiments include basic sensor output feedback control, modal control, and adaptive control.

Along with vibration suppression control, other items have been studied in several of these experiments. For example, the beam-cable and two-dimensional plane grid experiments at the Virginia Polytechnic Institute and State University (VPI&SU) have been used to compare theoretical models and experimental data during vibration suppression control tests. Based on the test results, the various assumptions and concepts used in theory are evaluated with respect to their practical value.

Other experimental structures were or are still being employed as platforms for testing improved actuator hardware for vibration damping. One such experiment is the Harris Corporation's compound pendulum experiment[8] (see Fig. 1a). This is a construction of two parallel, vertically oriented tubes with a platform connecting the ends of each tube. This connection constrains the motion of the platform to be in the horizontal plane. Situated under this platform is a Harris-developed linear direct current motor (LDCM) proofmass actuator and a collocated accelerometer. The actuation provided by a basic linear proofmass actuator is shown in Fig. 1b. The actuator consists of two parts—a primary mass, which is fixed to the structure, and a movable secondary mass. The magnetically driven secondary mass is accelerated, and the resultant force acts on the primary and thus, the structure. One problem of these actuators is the physical acceleration, and thus the force output, and displacement limits of the secondary mass.

This particular configuration results in a very lightly damped test article with two low-frequency pendulum modes at 0.24 and 1.8 Hz, respectively, as well as higher-frequency bending of the tubes which range from 10–70 Hz. The damping for these modes was estimated to be 0.1% of critical. The control problem is to design a compensator that can suppress the pendulum modes, using allowable force and stroke levels of the LDCM, while not exciting the higher-frequency tube bending modes. Sample test results are shown — LDCM input (Fig. 2a), LDCM primary response (Fig. 2b), LDCM secondary acceleration (Fig. 2c), and the relative displacement of the secondary with respect to the primary (Fig. 2d). The first and second pendulum modes are excited during the first 20 s, then the control law, based on the Harris-developed maximum entropy/optimal projection (ME/OP) theory, is turned on. Closed-loop damping of 15 and 5.7% of critical for the first and second pendulum modes, respectively, was achieved. Experiments such as these give researchers good opportunities to examine actuator dynamics and to develop better hardware ac-

Table 1 Vibration suppression control experiments

Experiment	Description	Actuators and sensors
Advanced beam experiment (ABE) [AFWAL][a] {1,2}	71-in. vertical aluminum beam, cantilevered at top	Proofmass actuators, accelerometers
12-m Truss [AFWAL] {1,2}	12-m aluminum truss, vertically oriented, cantilevered at base	Proofmass actuators, accelerometers, photodiode sensor
Large space structure truss (LSSTE) {TRW} {3}	115 × 55-in. aluminum truss box	Electromagnetic force actuators, surface accuracy measurement sensors
Composite beam [MIT]	Composite beam, horizontally suspended by wire	Embedded piezoceramic actuators, strain gauges
Joint optics structure experiment (JOSE) [AFAL-TRW-Litton-ITEK] {4}	Primary/secondary reflector optical truss (halo) structure	Proofmass actuators, optical measurement system
Free-free beam adaptive control experiment [LaRC] {5}	12-ft-long thin aluminum beam, suspended horizontally by cables	Electromagnetic actuators, noncontact position sensors
Grid experiment [LaRC] {6}	7 × 10-ft planar grid, suspended vertically by cable	Torque wheels, rate gyros, noncontact position sensors
Mini-beam experiment [LMSC] {7}	1.2-m horizontal magnesium beam, cantilevered at one end	Ling shaker, optical sensor
Maxi-beam experiment [LMSC] {7}	25-ft horizontal aluminum I-beam cantilevered at one end	Single gimbal control moment gyros, optical sensor
Observation/control spillover experiment [CSDL][b] {7}	60 × 1 × 0.25-in. aluminum beam, cantilevered at beam, cantilevered at one end	Electrodynamic shaker, piezoelectric accelerometers
TRW plate experiment [TRW] {7}	1.73 × 1.22-m thin aluminum plate, which was clamped	Bending moment actuator, rate sensors, accelerometers
Compound pendulum experiment [Harris] {8}	Two parallel vertical beams, connected such that the bases of the beams are constrained to move together in the horizontal plane	Linear dc motors, accelerometer
Transverse vibration suppression [SUNY-Buffalo]	Cantilevered beam	Proofmass actuator
Planar truss experiment [VPI&SU]	Single bay, horizontal truss, fixed on one side of the truss	Jack screws, strain gauges
Beam-cable experiment [VPI&SU]	80-in. vertical steel beam, with an aluminum cross beam, suspended by cables	Force actuators, velocity sensors
Two-dimensional pendulous plane grid [VPI&SU]	Aluminum grid with steel top beam	Force actuators, velocity sensors
Jitter beam experiment [LMSC]	2-ft aluminum beam, vertically oriented, cantilevered at base. Two mirrors are attached—one located at the midspan and one at the top	Active mirror, angular rate sensor, laser sensor

[a]AFWAL = Air Force Wright Aeronautical Laboratories. [b]CSDL = Charles Stark Draper Laboratory.

tuator devices for control use, in parallel with developing new control laws.

Slewing and Vibration Suppression Control Experiments

The next class of experiments involves the control of rigid-body slew maneuvers and the damping of resulting flexible motions. Table 2 lists these ground experiments. As with the vibration suppression control only experiments, various control techniques have been implemented. Although some experiments listed in Table 2 deal only with small angle and slow angular rates, several experiments test control laws that involve the more complex, faster angular rate, and large angle (highly nonlinear) motions.

One such experiment is the Langley Reseach Center's (LaRC's) multibody rapid maneuvering experiment (MRME).[13] The setup for this experiment is shown in Fig. 3. It includes a 2.5-m horizontal I-beam track on which an eight-wheeled, spring-suspended trolley is allowed to move back and forth. The trolley is driven by a dc motor/pulley system. Connected to this trolley is a 1.1-m-long, thin, horizontally oriented, flexible steel arm. A motor on the trolley actuates the rotational slewing motion of this arm with respect to the trolley and the supporting I-beam. A potentiometer is attached to the trolley pulley motor while another potentiometer and a tachometer are connected to the arm motor. Three strain gauges, located at the arm root, 22 and 50% of the arm span points, respectively, complete the set of available actuators and sensors on the MRME.

Because of the geometry, the rotational motion of the flexible arm couples with the translational motion of the trolley which results in significant nonlinear dynamics. These nonlinearities must be accounted for in the control law design. A relatively simple control law, based on output feedback, was designed with these nonlinearities in mind. Sample experimental data are presented in Fig. 4.

The control test objective was to move the trolley a distance of 0.45 m and simultaneously to slew the arm through 25 deg, while damping the vibrational motions of the arm. The time

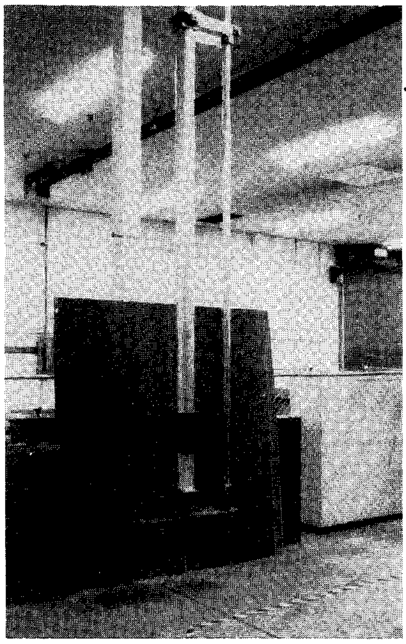

Fig. 1a Photograph of the Harris Compound Pendulum Experiment.

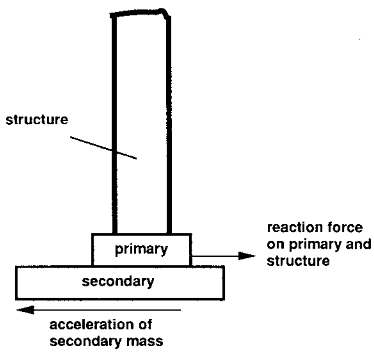

Fig. 1b Schematic of the linear proofmass actuator concept.

histories of the arm's rotation angle, the strain at the arm's root (strain #1), and the trolley's translational displacement are shown for two cases—one in which no strain information is fed back to the controlling motors, i.e., the arm's flexibility was ignored, and the other case in which the strain data were fed back. Although in the former case the objective of slewing the arm and moving the trolley was achieved, the root strain data reflect a significant amount of vibrational motion of the arm, which may be unacceptable if this were an operational space system. In the latter case, although the objective of the rigid-body motion control of the arm and trolley was not met as well as in the former case, the arm's vibrational motions were suppressed successfully.

Other Control Experiments

The first two groups of experiments mainly covered vibration suppression and slewing control. In this section, a variety of flexible space structure problems, many of which are of practical concern but not do not fit in either of the first two groups, are presented. Table 3 lists these experiments. This table has a format similar to Tables 1 and 2, except for the addition of a fourth column, that contains the particular test objective(s) for each experiment, a necessity brought on by the diversity of problems studied in this group.

One issue is the surface shape control of an antenna. Any distortions in reflecting surface shape can degrade the performance, regardless of the effectiveness of any vibration suppression and/or pointing controls. The advanced structures/controls integrated experiment[15] (ASCIE) of the Lockheed Missiles and Space Company (LMSC) is an example experimental test article that is used to study the surface shape control challenges. Figure 5 shows a photograph of the ASCIE.

Shape control need not be confined to reflector or antenna surfaces. For example, the VPI&SU spatial variable geometry truss experiment,[16] as the name implies, involves the control of the truss geometry itself. The test article is a truss structure that is capable of regulating the overall geometry via electric motors attached to selected truss members. By varying its own

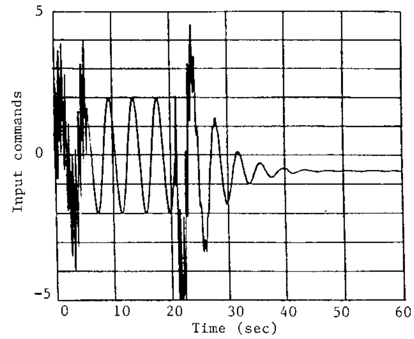

Fig. 2a Sample LDCM input command history.

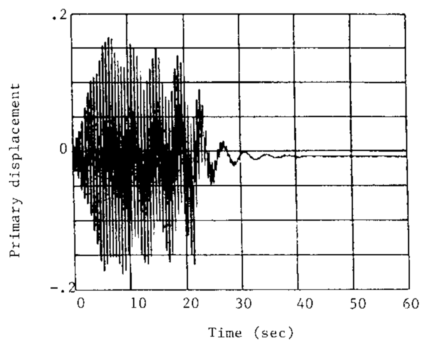

Fig. 2b Sample LDCM primary component response history

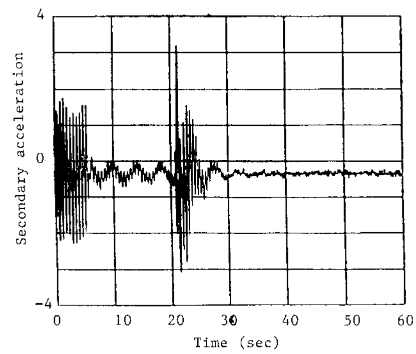

Fig. 2c Sample LDCM secondary component acceleration history.

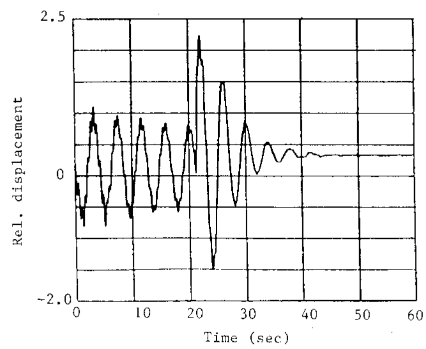

Fig. 2d Sample relative displacement history between LDCM primary and secondary components.

Table 2 Slewing and vibration suppression experiments

Experiment	Description	Actuators and sensors
Control with passive damping experiment [Georgia Tech] {9}	4-ft horizontal aluminum beam, with viscous elastic damping material, clamped on one end	Torque motor, strain gauge
Decentralized beam control experiment [Polytecnico di Milano, Milan, Italy] {10}	3.5-m thin beam, suspended horizontally by cables	Electromagnetic actuators, velocity transducer
Proof of concept [POC] experiment [LMSC] {7,11}	4.5-m-long suspended aluminum boom, with 3-m-diam antenna	Proof mass actuators, control moment gyros, accelerometers, rate gyros, laser sensors
Toysat [LMSC] {7}	Two rigid 1.6-m cantilevered beams, attached to either side of a body suspended by cables	Electromagnetic actuators, accelerometers, LVDT velocity pickoffs
Active hinge experiment [SUNY-Buffalo]	Vertically oriented aluminum beam, active hinge connecting beam to second flexible beam	Torque motor, strain gauges, tachometer
Eigenfunction slew control experiment [SUNY-Buffalo]	Horizontally cantilevered beam	Torque motor
Beam and truss experiment [SUNY-Buffalo]	Cantilevered beam and truss structure	Electric motor
Three-body rapid maneuvering experiment [LaRC] {12}	Two flexible, horizontal panels, one on opposite sides of a rigid hub which is constrained to rotate in the horizontal plane	Gear motor, strain gauges, potentiometers
Multibody rapid maneuvering experiment (MRME) [LaRC] {13}	1-m flexible panel, projecting out horizontally and attached to a cart, which is free to translate along a 3-m horizontal I-beam	Gearbox motor, direct drive motor, tachometer, potentiometer, strain gauges
Slew beam experiment [Ohio State Univ.]	40-in. horizontal aluminum beam, attached at end beam, attached at end to a hub structure, with a balancing counterweight on opposite side	Direct drive motor, motor encoders accelerometers, tachometer
Free-free planar truss experiment [VPI&SU]	Single bay truss, free to move horizontally on a support table	Jack screws, strain gauges, linear potentiometers
Slewing grid [VPI&SU]	Vertical aluminum planar grid, one side pivoting about a steel shaft	Reaction wheels, servoaccelerometers
Flexible satellite slew testbed [AFAL-CSDL] {1,14}	Rigid hub with 4 equally spaced horizontal arms (total diameter of 9 ft), all suspended on an air table	Cold gas jets, proofmass actuators, hub angle resolver, accelerometers
Circular plate experiment [LMSC] {7}	1-m-diam, thin aluminum plate, suspended vertically by springs and strings at the center, to give structure six degrees of freedom	Magnetic noncontract actuators, pivoted-proofmass actuators, laser sensor

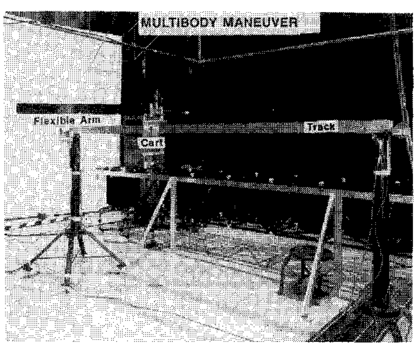

Fig. 3 Photograph of the LaRC multi-body rapid maneuvering experiment.

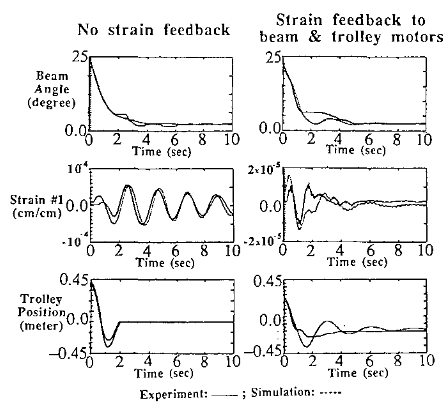

Fig. 4 Sample test results from the MRME of beam angle, beam root strain, and trolley position, with and without strain feedback to the control motors.

shape configuration, the truss can be used to suppress the vibrational motions of a beam that is suspended vertically in the center of the structure. Data from linear potentiometers are used to compute the truss geometry and strain gauges are used to relay information about the beam's motion. Figures 6a–6c show a schematic of the truss with attached beam and sample beam root strain time histories for open-loop and closed-loop vibration suppression experiments, respectively. Experiments such as this can be used for payload vibration suppression and orientation control studies.

In a related area, both General Dynamics' (GD's) deployable truss/antenna demonstrator[21] and the hoop-column antenna[22] were used in proper deployment of packaged antenna experimentation. Since many future space antennas will be of such size that packing them for stowage on launch carriers and deploying them later will become a necessary function, these deployment tests are essential.

Also important are those experiments involving the testing of new actuation and/or sensing concepts, or of improved versions of existing actuators and sensors, for possible use on LSSs. One such example is the U.S. Air Force Academy's planar truss experiment,[26] with the particular focus of developing reaction mass actuators that take advantage of structural-controls interactions.

On sensor development, the spatial, high-accuracy position-encoding sensor (SHAPES),[28,29] designed by the Jet Propulsion Laboratory (JPL), has been used with the JPL-Air Force Astronautics Laboratory (AFAL) flexible structure testbed[28] (see Fig. 7a) in static deformation measurement experiments. SHAPES is an optical-electronic range measurement sensor capable of tracking up to 16 separate target points on the structure, transmitting measurement data to the supporting MicroVax II computer for target position computations, and giving position accuracies within a millimeter. A schematic, depicting the main operations components of SHAPES, is shown in Fig. 7b. The main part is the streak tube detector, which is a Hadland Photonic Imacom 500 camera, modified to include a wide angle lens in front and a charge coupled device (CCD) detector behind the image screen. Individual

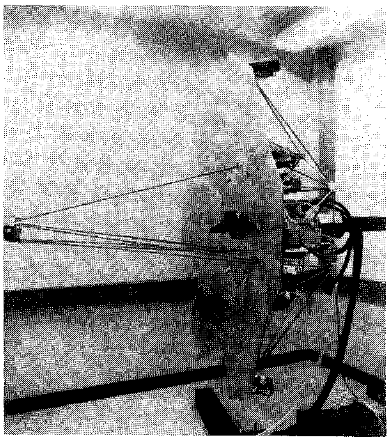

Fig. 5 Photograph of the Lockheed advanced structures/controls integrated experiment.

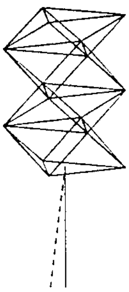

Fig. 6a Schematic of the VPI&SU spatial variable geometry truss, with connected beam used in vibration suppression experiments.

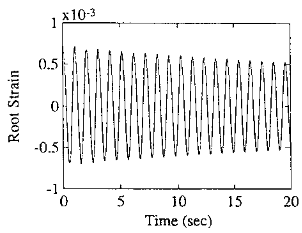

Fig. 6b Beam root strain history, open-loop case.

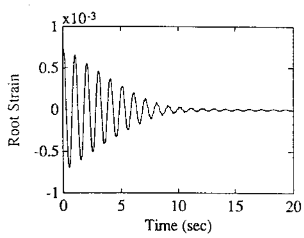

Fig. 6c Beam root strain history, closed-loop case.

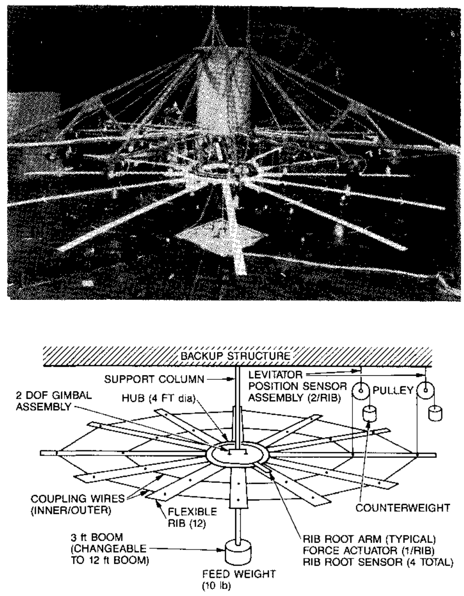

Fig. 7a Photograph and schematic of the JPL-AFAL flexible structure testbed.

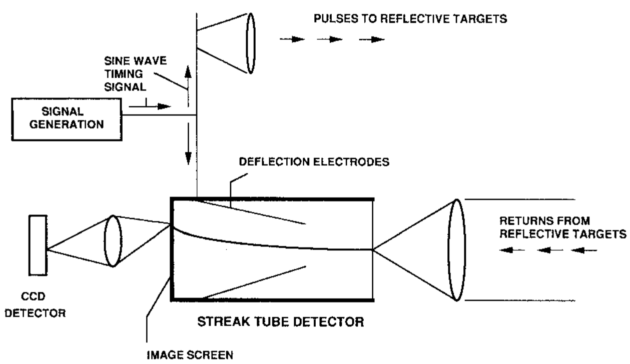

Fig. 7b Schematic of the SHAPES's components.

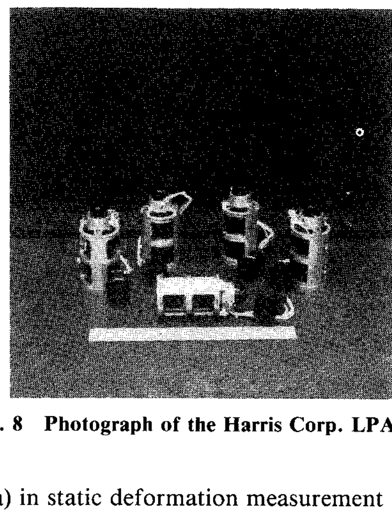

Fig. 8 Photograph of the Harris Corp. LPACTs.

Table 3 Other control experiments

Experiment	Description	Actuators and sensors	Objective
Vertical beam experiment [LMSC] {7}	Vertical aluminum beam, with attached tip masses, with fixed-free end conditions	Pivoted-proofmass actuators, accelerometers, quad-detectors photodiodes	Low authority control tests system identification
Convair plate experiment [Convair-GD] {7}	68 × 103-in. aluminum plate, with 4 × 5/16-in. welded beams, all with fixed-free end conditions	Torque wheels, rate gyro	Model-error sensitivity study
Harris plate experiment [Harris]	4-ft^2, 1/8-in.-thick, plate suspended vertically	Microshakers, accelerometers	Surface roughness control, sensor/actuator location study
Traveling wave beam experiment [MIT]	25-ft brass beam, horizontally suspended by wire	Shaker, accelerometer	Traveling wave study
Active member experiment [MIT]	Horizontal truss on soft springs	Piezoceramic actuators, PCB strucel accelerometers	Active structure study
Aluminum beam expander structure (ABES) [AFWL][a]	Space-based laser (SBL) beam expander model	Shakers, triaxial accelerometers	System identification study
Advanced structures/controls integrated experiment (ASCIE) [LMSC] {15}	Truss supporting a 2-m-diam, 7 hexagonal aluminum plated segmented, surface mirror, vertically oriented	Proportional electromechanical texture levers, optical sensor	Control testbed for segmented reflectors
Variable geometry truss experiment [VPI&SU] {16}	3-dimensional variable configuration truss structure, with a beam vertically suspended through center of truss	Electric motors, linear potentiometers, strain gauges tests	Truss configuration and beam vibration suppression control
Space-integrated controls experiment (SPICE) [AFWL]	SBL test model	Active and passive suspension systems	
Passive and active control of space structures (PACOSS) [AFWAL-MMDA][b] {17}	Dynamic test article (DTA), which consists of a $2.59 \times 2.59 \times 0.0324$-m box truss with a 2.9-m ring truss, panels (as solar arrays), and an antenna	Passive damping mechanisms, proofmass actuators, accelerometers	Truss space structure testbed
Planar truss modeling experiment [SUNY-Buffalo]	Planar truss structure	Proofmass actuator	Periodic truss structure modeling study
Active suspension experiment [SUNY-Buffalo]	Horizontal beam, with pinned-free end conditions, suspended by cable at the free end	Active track/cart suspension system	Active suspension system study
Vibration control of space structures (VCOSS) [MSFC-AFWAL-LMSC-TRW] {18}	13-m astromast, with asymmetric cruciform substructure at base, vertically oriented and cantilevered at the top	Linear momentum exchange devices (LMEDs)	General test article, precursor to ACES
Active control technique evaluation for spacecraft (ACES) [MSFC] {18}	13-m astromast, with 3-m-diam offset antenna, vertically oriented, cantilevered at the top	LMEDs, accelerometers, laser sensor	General test article, for vibration suppression and pointing control tests, system identification, fault detection and isolation studies
Daisy testbed [Univ. of Toronto] {19}	Central rigid hub, with 10 equally spaced flexible rods projecting out, total diameter is 19 ft	Thrusters, reaction wheels, accelerometers, digital angle encoders	Generic testbed for flexible satellite study
Free-free beam experiment [Ohio State Univ.] {20}	1.8-m horizontally suspended aluminum beam	Proofmass actuators, accelerometers, strain gauges	System identification study and vibration suppression control study
Deployable truss/antenna demonstrator [GD] {21}	5.6-m-diam hexagonal antenna attached to one end of a 6.5-m truss; truss pivots about base support at the same end as antenna	Noncontact sensing probe, photogrammetric measurement system	Testbed for deployment study
Hoop-column antenna [LaRC] {22}	15-m-diam mesh antenna, supported by outer graphite hoop substructure and a 13-m vertical truss column running through the center of the mesh antenna	Accelerometers, proximity probes	Deployment, electromagnetic, structural studies

Table 3 Other control experiments (continued)

Experiment	Description	Actuators and sensors	Objective
Box truss antenna [MMDA] {23}	4.5-m box truss structure with reflector mesh on the top side of the box truss	Photogrammetric measurement system	Box truss antenna configuration study
Piezoelectric active member experiment [JPL] {24}	12.5-in. horizontal aluminum beam, with clamped-free end conditions	Piezoceramic material as actuator and sensor	Active member control study
JPL beam experiment [JPL] {25}	16-ft vertically oriented beam, pinned at top end to 20-ft support tower	dc torque motors, eddy current sensors	Vibration suppression and shape control tests
Slimbeam experiment [LMSC]	Steel tube, with 1/10-in. wall thickness, suspended vertically by strings	Pivoted-proofmass actuators, accelerometers, laser sensor system	Low authority control tests
Truss wheel experiment [LMSC]	2-m-diam, three-dimensional truss, suspended vertically by strings	Pivoted-proofmass actuators, accelerometers, optical measurement system	System identification and modeling studies
Air Force planar truss experiment [USAFA-AFOSR][c] {26}	23.3-ft long, 20-bay truss, horizontally supported by bearings	Thrusters, proofmass actuators, accelerometers	Acutator/structure dynamic interaction study
Mini-mast testbed [LaRC] {27}	20-m, 18-bay, vertical truss, cantilevered at base	Reaction wheels, proofmass actuators, noncontact position probes, rate gyros, accelerometers	General test article for vibration suppression control tests, system identification, and fault detection and isolation studies
Flexible structure testbed [JPL-AFAL] {28}	Rigid hub structure with 12 equally spaced, horizontal ribs projecting out for a total diameter of 19 ft	Force actuators, position sensors, optical sensor SHAPES, RVDT angular sensors	Vibration suppression, system identification studies
Multi-hex prototype experiment (MPHE) [Harris] {8,30,31}	12.8-ft-diam testbed, made up of seven hexagonal graphite epoxy segments on a horizontal support frame, in turn, supported by six aluminum struts on an aluminum table, isolated from ground vibrations	Harris linear precision actuators (LPACTs), shakers, laser interferometer, accelerometers	Generic tests for segmented reflectors
10-bay truss experiment [LaRC] {32}	100-in., 10×10-in. bay, aluminum truss, vertically oriented, cantilevered from the top	Cold gas thrusters, servo-accelerometers	System identification, actuator characterization studies
Spacecraft control laboratory experiment (SCOLE) [LaRC] {1,33}	Rigid platform, with 10-ft beam connected to the bottom, 40-in.-diam center offset reflector frame at end of beam, all suspended by a steel cable	Cold gas jets, reaction wheels, control moment gyros, accelerometers	Slewing, pointing, vibration suppression control, system identification, fault detection, and isolation studies

[a]AFWL = Air Force Weapons Laboratory. [b]MMDA = Martin Marietta Denver Aerospace. [c]USAFA-AFOSR = United States Air Force Academy–Air Force Office of Scientific Research.

laser pulses are sent out to illuminate the targets and the reflected energy pulses are gathered in by the lens in the streak tube. Inside, deflection electrodes, driven by a 100 MHz sine-wave signal (which is simultaneously used to time the outgoing laser pulses), direct the energy onto the image screen, where the CCD detector picks up the image for processing and transmission to the computer. The outgoing laser pulses and the deflection electrodes are in synchronization, thus, the amount of movement of the targets on the structure can be determined by the amount of deflection of the collected and reflected energy caused by the electrodes.

Another example of sensor/actuator development is the linear precision actuator (LPACT),[30,31] a patented device designed and built by the Harris Corporation's Government Aerospace Division and used on the multi-hex prototype experiment[8,30,31] (MHPE) structure. Figures 8 and 9 are photographs of six LPACTs and of the MHPE test article. The LPACT is a bearing-free, linear force actuator with a proof-mass-mounted, collocated "hybrid accelerometer," which is made up of two commercial accelerometers—a Sunstrand QA-700 servoaccelerometer and a Piezoelectronics PCB-303A piezoelectric accelerometer. By combining the high-accuracy QA-700 with the high bandwidth PCD-303A, a high bandwidth (flat response from 5–500 Hz) sensing device, with accuracy at low frequencies, has been developed. An internal

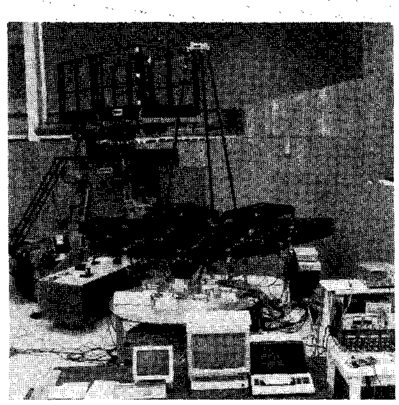

Fig. 9 Photograph of the Harris Corp. MHPE structure.

force-acceleration control loop is closed to minimize LPACT resonance response. Figure 10 shows the magnitude and phase plots of the LPACTs, with and without the force control loop; with this internal loop closed, a flat response results.

System-identification experimentation for model verification and modification work is another important topic. Since

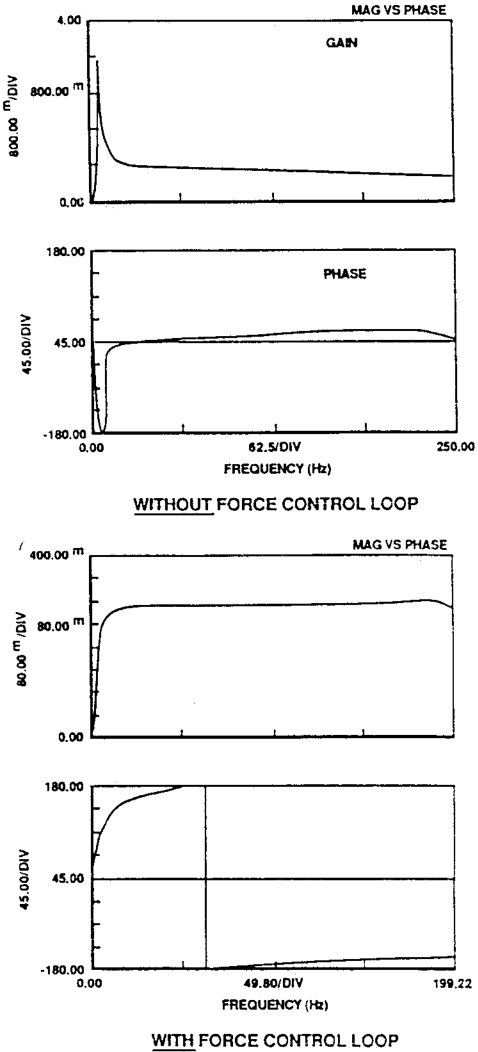

Fig. 10 Magnitude and phase plots of the LPACT response, without and with the internal force control loop.

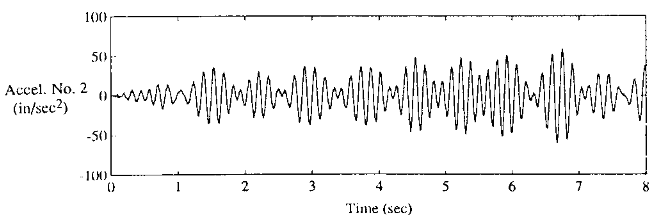

Fig. 11a Overlay plot of a 10-bay truss accelerometer test data and test data computed from identified system matrices and Kalman filter gain.

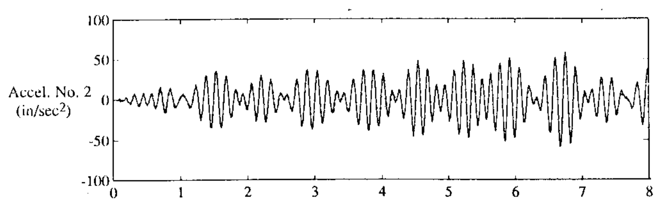

Fig. 11b Overlay plot of a 10-bay truss accelerometer test data and test data computed from identified system matrices only.

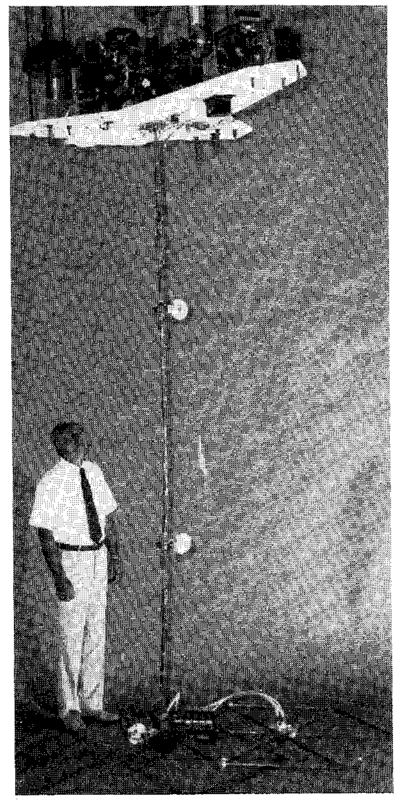

Fig. 12a Photograph of the SCOLE.

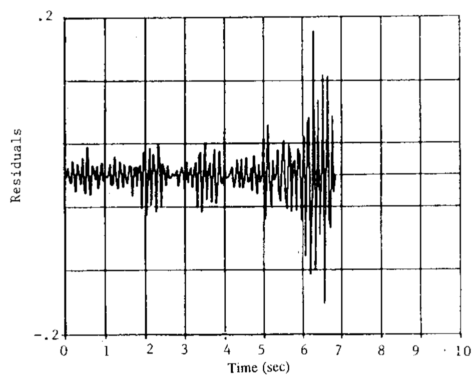

Fig. 12b Open-loop accelerometer failure residual history, computed from SCOLE data.

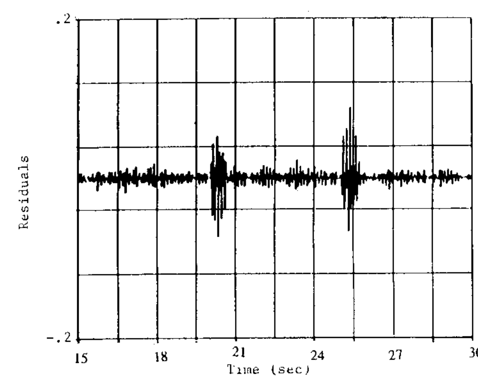

Fig. 12c Open-loop thruster failure residual history, computed from SCOLE data.

limited accuracy can be expected from even the most detailed analytical design models, open-loop and closed-loop system identification must be performed on structures to give a better understanding of the dynamics that are to be controlled. An example is the LaRC's 10-bay truss experiment.[32]

This experimental test article consists of a 100-in.-long, 10-in.-cubical bay aluminum truss, vertically oriented and cantilevered at the top. Two cold gas thrusters and two servoaccelerometers, located at the truss's tip, provide the actuation and sensing, respectively, for the experiment. The experiment itself involved the testing of an open-loop identification algorithm in which a digital representation of a system (in this case, of the 10-bay truss), in terms of state-space system matrices, and a steady-state Kalman filter gain matrix, for use in state estimation, are computed from test data. Figure 11a shows an overlay of actual accelerometer test data and estimated test data computed from the identified system matrices and Kalman filter. Figure 11b shows an overlay of the accelerometer test data and estimated test data computed from the identified system matrices only. There is more error in Fig. 11b than in Fig. 11a; however, the overall result is still good. This is important since control designs would be based on these system matrices only, and the Kalman filter gain matrix only used for state estimation.

The last problem to be discussed in this section deals with fault tolerance and detection on control systems. This is a significant practical issue which, in general, has not been examined in great detail. Future space systems will most likely contain large numbers of actuators and sensors (apart from payload instrumentation) to perform their missions. Failure of some control and sensing components will be inevitable and future space system designs must be able to detect and compensate for these problems when they occur. Test articles such as the spacecraft control laboratory experiment[33] (SCOLE) at LaRC have been used for such tests.

The SCOLE, shown in Fig. 12a, consists of a 10-ft-long slender, flexible beam, which is cantilevered vertically from the bottom of a plate. The plate is intended to represent the Shuttle and is suspended via a steel cable. At the other end of the flexible beam is an offset hexagonal-shaped frame meant to represent a reflector frame support. There are four cold gas jets located at the center of the reflector frame, torque wheels mounted along the length of the flexible beam, and control moment gyros (cmgs) situated on the Shuttle platform which provide the actuation. Rate gyros and accelerometers are used as sensors.

Researchers from the Massachusetts Institute of Technology (MIT) have performed failure-detection and isolation (FDI) studies[33] using experimental data from SCOLE. The particular FDI technique was based on general parity relations; namely, component failures were detected by monitoring the differences (or residuals) between actual sensor measurements that were based on some nominal model.

Figures 12b and 12c show the computed residuals for an accelerometer failure and a thruster failure, respectively. The accelerometer was simulated as being off in the model at time $T = 6.0$ s and compared to test data. There is a jump in the residuals at $T = 6.0$ s, indicating a failure. The thruster was commanded on in the model for the time interval from 20–25 s, but was not fired in the actual test, thus simulating a failed thruster device. The computed residuals for this show slight jumps at 20 and 25 s, marking the thruster failure interval. Both of these results are part of the overall FDI test results performed on SCOLE. A general conclusion reached by the MIT researchers, based on this work, was that any signal noise or modeling errors significantly impact the ability to detect failures. Since both signal noise and modeling are ever present, further research in FDI to account for these should be performed. On-line system identification becomes necessary to identify the characteristics of both signal noise and the system. Reference 32 presents a method to identify the system matrices for modeling and the Kalman filter gain matrix to characterize the signal noise for state estimation.

Test Facilities

All of the ground testing thus far has been reported in the form of single experiments, concentrating on the test article

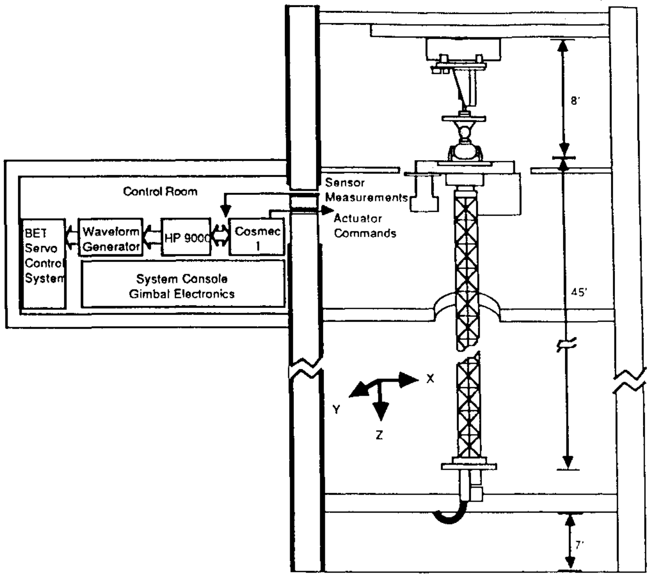

Fig. 13 Schematic of the MSFC large space structure ground test facility.

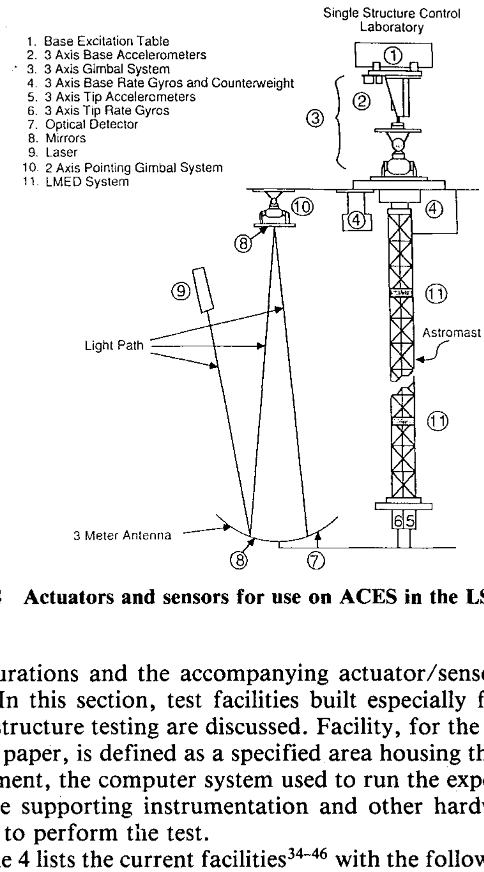

Fig. 14 Actuators and sensors for use on ACES in the LSS-GTF.

configurations and the accompanying actuator/sensor hardware. In this section, test facilities built especially for large space structure testing are discussed. Facility, for the purpose of this paper, is defined as a specified area housing the actual experiment, the computer system used to run the experiment, and the supporting instrumentation and other hardware required to perform the test.

Table 4 lists the current facilities[34-46] with the following format. Column 1 contains the name of the facility along with its experiment(s), the responsible organization is placed in brackets, and the reference(s) in braces. Column 2 gives a brief description of the facility and the experimental test article(s). The computer system used in the facility is found in column 3, and column 4 lists the actuator/sensor hardware used on the test article(s). Four of these facilities along with their respective experiments are discussed below in more detail.

The Marshall Space Flight Center's (MSFC's) large space structure ground test facility (LSS GTF),[1,16,35-37] shown in a schematic in Fig. 13, is a 65-ft tower structure built to support vertically cantilevered test articles. The computer system is made up of two parts: the modified AIM-65 COSMEC microcomputer system which handles all of the sensor signal and ac-

Table 4 Test facilities

Experiment	Description	Actuators and sensors	Objective
Large space systems laboratory (LSS Lab) [AFAL] {1,34}	30 × 20-ft laboratory area	ISI Max 1000	
Experiment:			
Grid test article	5 × 5-ft aluminum grid, oriented vertically, cantilevered at the top		Minishakers, load cells, proximity sensors, accelerometers
Large space structure-ground test facility (LSS-GTF) [MSFC] {1,18,35–37}	65-ft-tall tower structure, with test article vertically oriented and cantilevered at the top	HP 9000 and COMSEC I	
Experiment:			
ACES-I	See Table 3		See Table 3
Space structures research laboratory (SSRL) [LaRC] {38,39}	80 × 80 × 80-ft laboratory space	Genrad 2515, MicroVax III, multichannel scanner, CYBER 175, Zonic 7000	
Experiments:			
Dynamic scale model test (DSMT) structure	500-in. meriform truss, oriented horizontally, cantilevered at one end, and suspended by cables		Shakers, thrusters, accelerometers, load cells, strain gauges, laser sensor
CSI evolutionary model (CEM)	52-ft truss structure, oriented horizontally and suspended by cabling, with attached rib antenna substructure at one end		
Control technology verification facility (CTVF) [JPL] {1,28,40}	40-ft-diam, 26-ft-tall dome enclosure	VAX II, with STD bus based on 8088 microprocessor	
Experiment:			
JPL-AFAL flexible structure testbed	Rigid hub structure with 12 equally spaced, horizontal ribs projecting out, total diameter 19 ft		Force actuators, position sensors, optical sensor (SHAPES), RVDT angular sensor
MIT apparatus for structural testing and research on on-orbit vibration and control (ASTROVAC) [MIT]	10-ft-diam vacuum chamber (10E-6 to 10E-8 Torr), 14 ft in height	IBM PC, MicroVax, Lecroy and and custom built A/D, D/A components	
JPL testbed facility [JPL] {41}	1966 ft^2 laboratory space	PDP 11/73, Systolic PC-1000	
Experiments:			
Modified astromast	5-ft fiberglass model of the astromast vertically oriented, cantilevered at base		Shakers, piezoelectric actuators, vibration isolation table, accelerometers, laser interferometer
Precision truss	6-ft, 6-bay truss, vertically oriented, cantilevered at base		
Free-free truss	13-bay truss, horizontally oriented, can be either cantilevered or suspended at its midspan		
Structural identification and control laboratory [Texas A&M] {42,43}		286-based PC, Sun 2/130, video image processor	
Experiments:			
Grid structure	5 × 5-ft jointless grid structure, vertically suspended		Torque wheels, strain gauges, accelerometers, angle encoder, tachometer
Hub/arm slewing structure	Rigid hub with four equally spaced, 50-in. arms extending out horizontally, all supported by a bearing system		
Advanced space structure technology research experiment (ASTREX) facility [AFAL] {46}	40 × 40 × 40-ft environmentally controlled lab space	ISI AC-100	
Experiment:			
SBL-3 expander model	18-ft-diam primary mirror support structure with three 17-ft tubes forming a tripod shape over the primary mirror—all atop a 19-in. spherical air bearing which is on top of an 18-ft pedestal		Cold gas jets, reaction wheels, proofmass actuators, accelerometers, optical sensor, position encoders

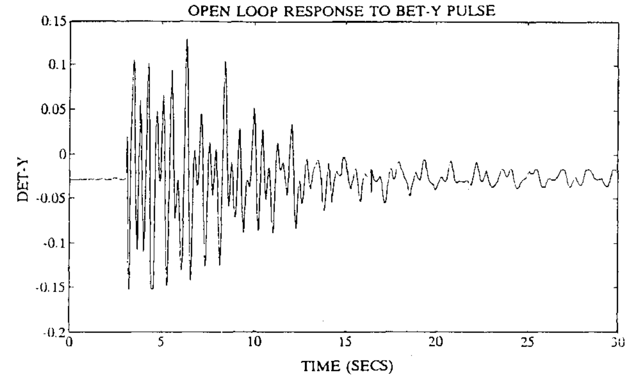

Fig. 15a Open loop response of the *y*-axis detector to a *y*-axis pulse from the BET.

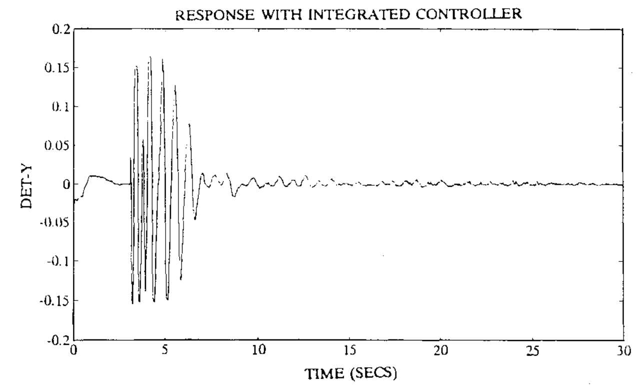

Fig. 15b Response of the *y*-axis detector, with the integrated controller on, to an axis pulse from the BET.

tuator command input/output processing, and the 32-bit Hewlett-Packard (HP) 9000 digital computer, which performs the control test algorithms, data storage, and real-time data display. Currently, the COSMEC system is set up to handle 25 sensor signals and nine actuator commands. Figure 14 shows the available actuator and sensor devices. This includes the base excitation table (BET), a hydraulically driven device that is capable of movement in two translational directions and provides disturbance inputs to the test article, and a laser imaging system to measure line-of-sight (LOS) pointing error. Although test articles are cantilevered, precluding rigid-body slewing control tests, the LSS GTF can support numerous other experiments. These include, but are not limited to, vibration suppression control, LOS pointing control, open- and closed-loop system-identification tests, and FDI tests.

For example, tests were performed on the ACES structure by Harris Corporation researchers, with the test objective being to minimize the laser LOS error using decentralized control.[35] The decentralized control was designed with three separate sets of control loops, each set involving specific actuator-sensor combinations. These are 1) the image motion compensation (IMC) system's two mirror pointing gimbals and the x and y detector position outputs, 2) the two-axis advanced gimbal system (AGS) and the x and y axes base rate gyros, and 3) the two-axis linear momentum exchange devices (LMED) force actuators and the x and y axes accelerometers.

Experimental test runs have been made using one, two, or all three sets of control loops on the ACES structure, which was excited by various applied disturbances. All control loops were run at the same sampling rate of 50 Hz. Figure 15a shows the open response of the y-axis laser detector to a y-axis pulse introduced by the BET, and Fig. 15b shows the y-axis detector response to the same disturbance input with all three sets of control loops active (termed integrated controller). It was found for this case that as each set of control loops was added, culminating in the integrated controller design, the LOS performance improved.

The overall results of these tests show that it is possible to use decentralized control laws, which generally involve low-order, simple control algorithms, in place of a higher-order, complex, global control laws. This is an important result, given the fact that actual space-qualified computers are limited in their processing powers, when compared to ground-based computers; these low-order control laws can be executed on separate, smaller processors located on a given spacecraft instead of on one, larger computer.

Similar to MSFC's LSS GTF, the LaRC's space structures research laboratory (SSRL) was built to house experiments in large-scale structural testing. The SSRL contains two separate test articles, one of which is the dynamic scale model test (DSMT) article, which is used for dynamic modeling of scaled-down space structure components such as trusses, joints, thermal radiators, etc. The other is the controls-structures interaction (CSI) evolutionary model,[38,39] or CEM, which is shown in Fig. 16a. The CEM is a 52-ft-long truss, comprised of 62 10-in. cubical bays, horizontally oriented. An 11-bay truss rises vertically from the main truss structure and supports a low-powered laser, beaming its light onto a rib-supported mesh reflector surface at one end of the main truss, which, in turn, reflects the laser light onto a photodiode array located on the laboratory ceiling support grid. The entire structure is suspended by cables, with springs in series, attached to the ceiling support grid. All of the truss struts and the reflector mesh-supporting ribs are made of aluminum. This configuration

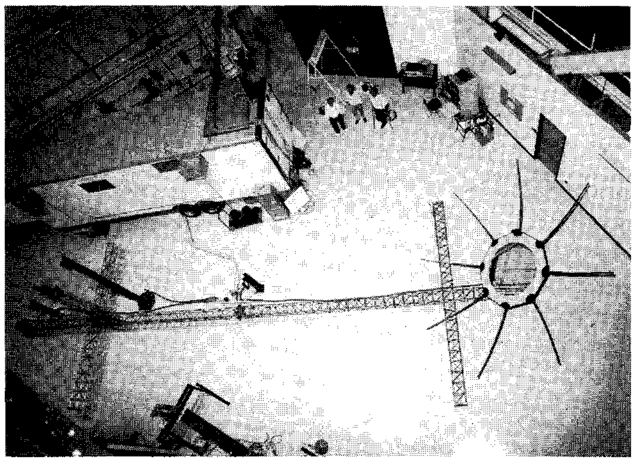

Fig. 16a Photograph of the LaRC CSI evolutionary model, housed in the SSRL facility.

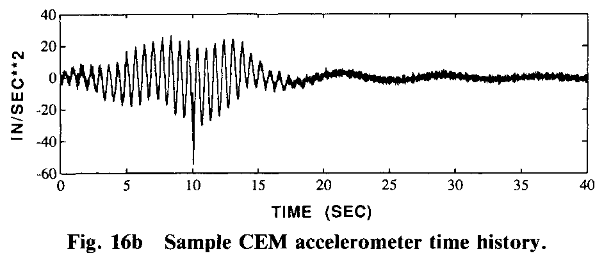

Fig. 16b Sample CEM accelerometer time history.

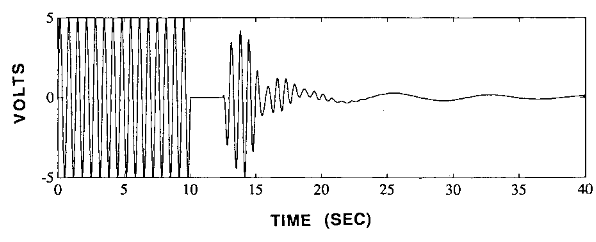

Fig. 16c Sample CEM thruster command time history.

results in six near-rigid-body, or pendulum, modes with frequencies below 1 Hz, and 25 flexible body modes under 10 Hz.

Control actuation is provided by 16 proportional, bidirectional, compressed air thrusters, capable of force levels of up to 2.2 lb. A large air tank situated on the laboratory floor supplies the thrusters with air. Also available are electromagnetically driven shakers, which can be attached to various points on the CEM, for use as disturbance sources. There are a variety of sensor devices mounted on the CEM-28 servoaccelerometers (primarily for use in control experiments), 195 piezoelectric film accelerometers (for system identification experiments), and eight angular rate gyros. The laser-photo diode array arrangement provides LOS measurements.

There are also a variety of computer systems—a CYBER 175 computer that is physically located in another building and linked to the CEM via fiber optic cable, a MicroVax 3200, and a Zonic 7000 system for system-identification purposes. Both the CYBER 175 and the MicroVax 3200 are connected to the CEM through a computer automated measurement and control (CAMAC) data-acquisition system, that handles the analog sensor signal low-pass filtering, analog-to-digital (A/D) and digital-to-analog (D/A) signal conversions. Typical control laws, involving 16 states, eight inputs and eight outputs, have been executed on both computer systems, sampling at over 100 Hz on the CYBER 175 and over 250 Hz on the MicroVax.

The CEM, like MFSC's ACES structure, is meant to be a large-scale test article on which various experiments can be conducted. The main difference between the two articles is that, due to its cable suspension, the CEM has near-rigid-body modes (some as low as 0.15 Hz), which are more representative of true space structures. The addition of these modes brings up challenges in control design. Figures 16b and 16c show a sample accelerometer time history and a thruster command time history, respectively, from an experiment,[39] with the objective being to attempt to control both near-rigid-body and flexible modes simultaneously. The near-rigid-body and flexible modes are excited for the first 10 s by the thrusters and the control is turned on after several seconds; the control law, using the 16 thrusters and eight servoaccelerometers, was executed on the MicroVax 3200 at a sampling rate of 350 Hz. In these two plots, it can be seen that the accelerometer and thruster command time histories contain both the high frequencies associated with the flexible modes and the low frequency corresponding to the near-rigid-body mode.

The third facility to be discussed is the JPL testbed facility.[41] The primary research focus is the investigation of active member control concepts, primarily for precision control. Many large space structures, such as precision mirrors, will require position control performances down to the micron level. Active member-based designs using piezoelectric devices allow for this kind of fine control. This facility contains three experimental articles—the free-free truss, the modified astromast, and the precision truss; all three structures have been constructed to allow for easy modification of their configurations, e.g., the replacement of a regular truss member with an active truss member, or the addition of masses at the joints to produce changes in the overall inertial properties of the structures. The experimental work conducted in the facility is supported by an array of equipment, including various accelerometers, some for the micro-g range, a 4 × 8-ft vibration isolation table and a laser interferometer system, as well as various electromagnetically driven shaker devices which provide disturbance force levels ranging from 2–150 lb. A PDP 11/73 computer and a Systolic PC-1000 digital computer handle the data-acquisition and control needs for the experiments, respectively. The latter computer can process 32 control states, 16 sensors and 16 actuator commands, all at a sampling rate of 2000 Hz.

Sample results taken from vibration suppression experiments[41] performed on the precision truss are shown in Fig. 17. Figures 17a and 17b show a schematic of the precision truss structure, depicting the locations of the load cells and active truss members that were used, respectively. Figure 17c shows the results of tests in which three control feedback schemes were investigated—positive position feedback, or PPF, on the plot (position feedback through a second order filter with high damping), proportional feedback (direct position output feedback), and velocity feedback (integrated accelerometer signal feedback). A single mode was excited and allowed to decay

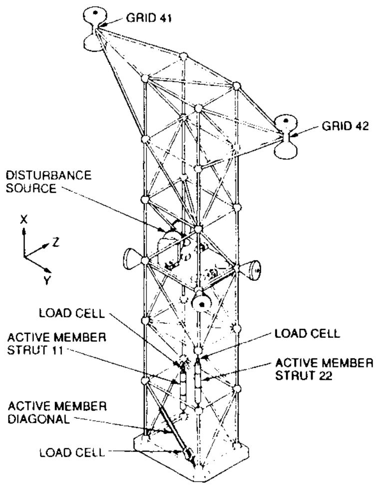

Fig. 17a Schematic of the JPL testbed facility's precision truss.

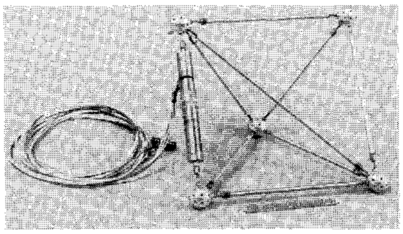

Fig. 17b Photograph of a JPL active member attached to a sample truss segment.

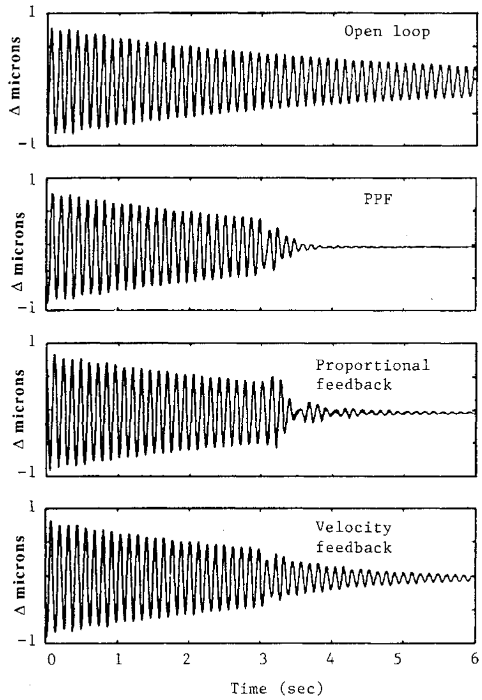

Fig. 17c Sample open- and closed-loop vibration suppression tests using active members.

freely for 3 s, then the control law was turned on. Note that the vibration suppression is down in the micron levels.

The final facility to be discussed is the structural identification and control laboratory at Texas A&M University.[42,43] The main research thrust of this laboratory is in estimation and control. Two experimental test articles are used, a 5 × 5-ft single-piece grid and a rigid-body slewing test structure, similar to the flexible satellite slew testbed listed in Table 2. A Sun 2/130 computer and a 286-based PC provide the control and data-analysis capabilities for the experiments.

The most interesting supporting equipment in this laboratory, however, is the in-house-developed electro-optical stereo-triangulation measurement system. This system is shown in Fig. 18 and consists of two NAC V-14B 200/60 cameras (for stereo effect), two NAC VTR V-32 video image recorders, and a motion analysis VP-110 video image data processor. The cameras detect images of the motions of a test article. These images are recorded during the test run and later played back through the video processor for filtering and analog-to-digital conversion. The digitized data are then sent to the Sun computer for data reduction. By use of triangulation, displacements of various points of the test article can be determined and this, in turn, can be used in system-identification algorithms, such as the eigensystem realization algorithm[44] (ERA). From ERA, the test structure's modal frequencies, damping, and mode shapes can be computed. Note that the pulse response functions used in the ERA can be computed from the observer/Kalman filter Markov parameters determined by the technique developed in Ref. 32.

The advantage of such a measurement system is that it provides large area coverage of structures. It is useful in the presence of motions with large amplitudes and low frequencies and it provides noncontacting sensing. This advantage implies that few sensors are necessary on the structures and that measurements can be taken from more convenient vantage points. An earlier flight example was the solar array flight experiment[45] (SAFE) flown on the Shuttle, which used optical measurements of the array to determine its dynamics characteristics as it was deployed from the Shuttle payload bay.

Sample identification experiment results[42,43] are presented in Fig. 19. The data were taken from the 5 × 5-ft grid that was excited by an impulse hammer. Once the grid structure was excited, its vibrational motions were allowed to decay freely, during which video as well as accelerometer data were taken at several points on the grid. The top two graphs in Fig. 19 are the time history of the displacement of a point and its fast Fourier transform (FFT) plot, respectively, whereas the bottom two graphs are the time history of the acceleration at the same point and its FFT plot, respectively. It can be noted that the video-derived data may be used to identify more accurately the low-frequency modes, whereas the accelerometer-derived data give better results when used to identify the higher modes.

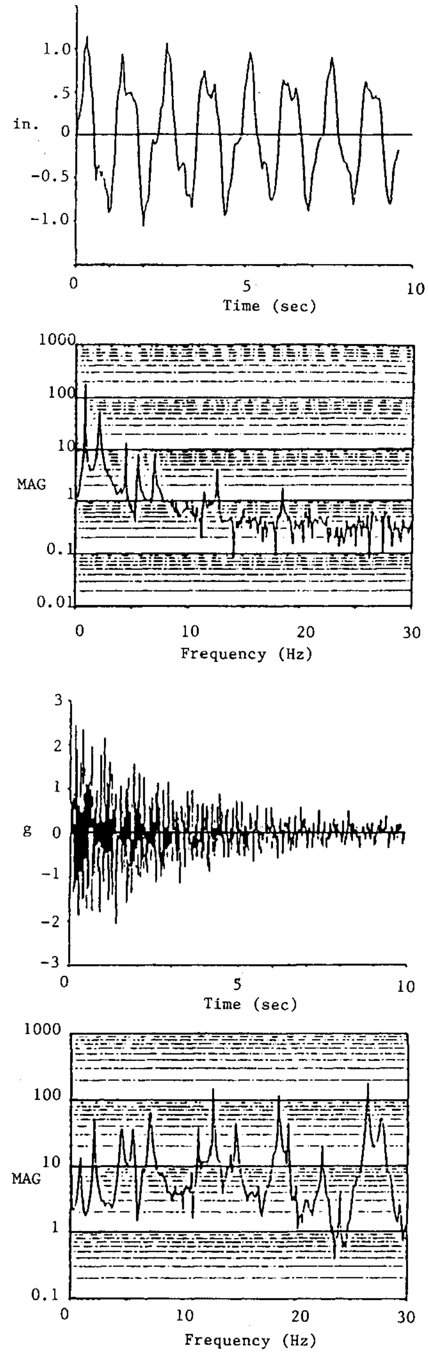

Fig. 19 Video displacement data and accelerometer data, with their respective FFTs, of a sample point on the 5 × 5-foot grid structure.

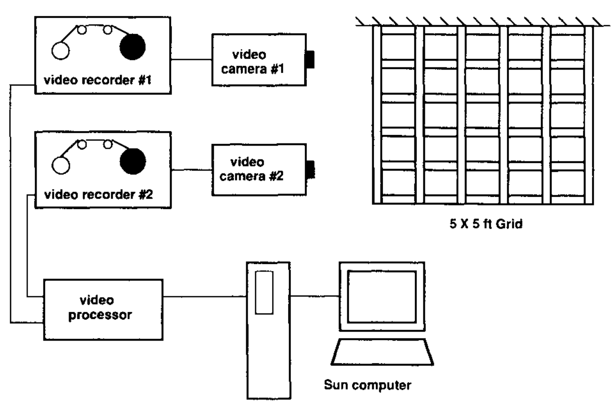

Fig. 18 Schematic of the Texas A&M stereo-triangulation measurement system.

Remaining Issues

Even though extensive research has been or is currently being performed on LSS ground experiments, research issues remain. One such issue is the need for a dedicated real-time computer system that has the adequate computational processing power, program memory, data storage space, and signal input/output (I/O) processing capability that will be required for advanced LSS gound-control experiments. Small systems such as desktop workstations and PCs, which make up the vast majority of the real-time computer systems currently being used, are only adequate for the smaller experiments. All of the individual components—computational power, memory, and I/O processing—are available, but not in one complete package working together with the necessary throughput rate to perform realistic control experiments on LSSs.

Another issue is test article suspension.[47] New suspension techniques are needed to minimize the effects of the 1-g environment, in order to model the static deformations and dynamics of space structures on-orbit better. Also, along these same lines, more LSS research should be performed under more realistic conditions, such as in vacuum and thermal chambers, to simulate further the on-orbit environment.

Certainly, research should continue in the area of new actuator and sensor technology development. For example, a practical velocity sensing device, situated on the test article, would be very useful in control, since direct velocity feedback controllers (for collocated sensors and actuators) are theoretically stable with an infinite gain margin.[48] Currently, with the exception of a few optical ranging measurement systems (which are, for the most part, located off the test article), velocity information must be estimated from other sensors, such as accelerometers.

These issues are just a few of the remaining research challenges.

Conclusions

A survey of ground experiments for flexible space structures has been presented. The experiments deal with various control problems, from vibration suppression and slew control to less basic, yet vital, studies such as surface shape control and fault tolerance and detection. Along with single experiments, facilities dedicated to housing large space structure experiments have been reported. This is by no means a complete survey of ground experiments. There are many other experiments and facilities that can be used to benefit the development of test methods for control of flexible space structures.

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