Adaptive Structures: An Overview

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The objective is to provide an overview of what is, the importance of, and recent developments in adaptive structures for space structures.

Introduction

ADAPTIVE structures is defined in this paper as a structural system whose geometric and inherent structural characteristics can be changed beneficially to meet mission requirements either through remote commands and/or automatically in response to external stimulations. A similar definition has been used by the Institute of Space and Astronautical Science (ISAS) in Japan.[1] The author believes the concepts related to adaptive structures will make possible future NASA missions such as the large deployable reflector (LDR) and optical interferometer as shown in Figs. 1 and 2. The requirements for these missions that drive the need for adaptive structures can be generalized as micron-level precision for 20 m structures that must operate for 20 to 30 years. The number of organizations working in areas related to adaptive structures has increased dramatically, and several Centers for research have been established; examples are the Center for Space Engineering Research focused on controlled structures technology at Massachusetts Institute of Technology and the Smart Materials and Structures Laboratory at Virginia Polytechnic Institute and State University. Other organizations, such as the Jet Propulsion Laboratory and ISAS, have emphasized adaptive structures in their structures research program. The number of meetings and sessions at technical meetings related to this area has increased; as an example, three sessions on adaptive structures were presented at the 30th Structures, Structural Dynamics, and Materials (SDM) Conference in Mobile, AL, in March 1989; sessions are being developed for the American Society of Mechanical Engineers (ASME) Winter Annual Meeting in Dec. 1989, and plans are under way to establish a joint U.S./Japan meeting on adaptive structures in 1990.

This paper will summarize briefly the activities in adaptive structures; however, a large number of references are included. The author would appreciate input on inadvertent omissions of key contributions. Only information available to the author from the open literature and the abstracts submitted to the 30th SDM Conference were used. The objective is not to provide an inclusive list of references and contributors but to use references and examples available to the author to convey the intended information. Adaptive structures is a multidisciplinary activity that includes materials, actuators, sensors, controls, composites, structures, concepts, and dynamics; the emphasis is on the end deliverable hardware system, a structure that meets the mission performance requirements.

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Unusual behavior of materials when subjected to external stimuli such as thermal, electrical, or magnetic fields has been observed and reported on for many years. Examples include distortion of piezoelectric-type materials when subjected to electrical fields, predictable movement of shape memory materials when subjected to heat, distortion of magnetostrictive materials when subjected to magnetic fields, and changes in state of electro-rheological fluids when subjected to electric fields. Also, fiber-optic sensors that can be embedded in the structure have been developed to measure strain. With the capability to tailor the structural characteristics of composite materials and to embed sensors and actuators within the structure itself, the integration of the existing materials, devices, actuators, sensors, and control logic with the structure promises many design options for active structural elements.

The author's perspective of the past activities in adaptive structures before 1985 is presented. Activities to adapt space-type structures to meet precision requirements existed in 1974[2]; the objective was to correct errors in the mirror surface by application of forces through a large number of piezoelectric actuators. Efforts to develop piezoelectric actuators for use in control systems resulted in a patent in 1981 to reduce the hysteresis effects.[3] The work by Swigert and Forward[4] and Forward[5] around 1980 stimulated interests at the Jet Propulsion Laboratory (JPL) to use piezoelectric devices directly at-

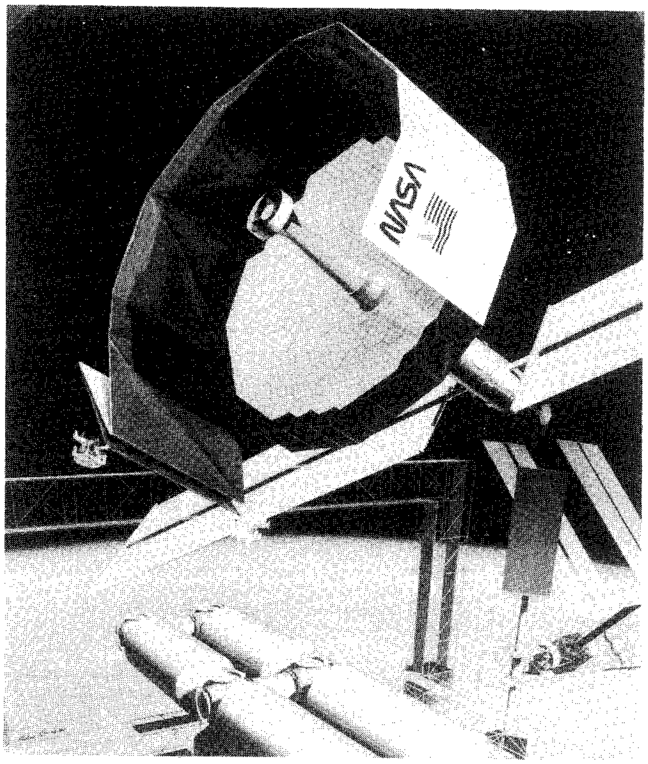


Fig. 1 Large deployable reflector.

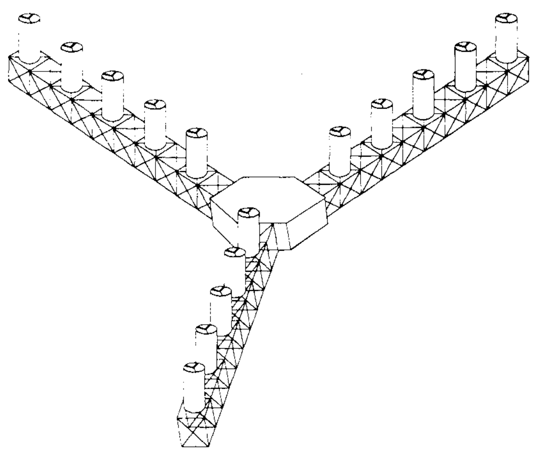


Fig. 2 Optical interferometer.

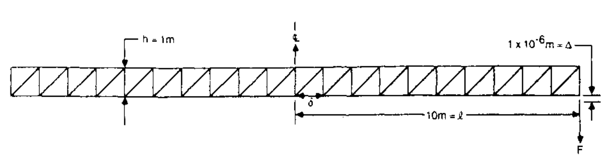
tached to the structure as a means of adding active damping. Chen[6] in the early 1980s investigated the potential advantage of adjusting the stiffness of wires made of piezoelectric-like materials to control the response of structures. The efforts by Caughey et al.,[7] Fanson,[8] and Fanson and Caughey[9] were focused on the development of a theory and an experimental demonstration of active damping of a cantilevered beam by using piezoelectric ceramic material as both a moment actuator and curvature sensor at several locations along the beam. Hanagud et al.[10] and Bailey and Hubbard[11] were engaged in similar research using piezoelectric materials. Crawley and de Luis[12,13] initiated activities to embed piezoelectric actuators in composite materials to adjust and control the surfaces of precision structures. Also in the mid-1980s, efforts by Murotsu et al.[14] on tendon control, Majors and Simonian[15] on linear magnetic actuators in members supporting a plate, Rhodes and Mikulas[16] and Miura and Furuya[17] on structural truss systems with variable geometries, and Natori et al.[18] on active vibration suppression of truss structures are reported in the open literature.

Need for Adaptive Structures

The future need for adaptive structures can be established by reviewing the state of the art and projected developments in the capability to predict analytically the structural characteristics and to measure experimentally the structural characteristics by ground tests. The projected technological advancements are then matched to the requirements for large precision structures.[19] A simple example that reveals the complexities associated with the challenge to control large precision structures to within microns is shown in Fig. 3. Assuming all members are rigid except the ones with the arrows, a 0.000004-in. change in the length of the flexible member corresponds to a micron displacement at the tip of the 20-m structure. Similarly, a change in temperature of 0.1°F or a 3-psi stress in a good composite truss design corresponds to a micron displacement at the tip of the structure. A static force of 0.17 lb at the tip of the structure results in a micron displacement at the force, assuming the structure is constrained at the centerline. Can current and projected improvements in the state-of-the-art analytical and test methods be used to establish the initial position and predict the micron-level dynamic characteristics of structures, represented by Fig. 3, that must be deployed or erected in space? Also note that the vibration level associated with a 1-μ displacement at 1 Hz is approximately 4 micro-gs.

Analytical Predictions

The capability currently exists to model accurately large complex linear structural models for static, eigenvalues, and eigenvectors for the lower 10–20 modes using finite-element



$$\delta = \frac{\Delta \times h}{\ell} = \frac{1 \times 10^{-6}\,m \times 1\,m}{10\,m} = 10^{-7}\,m = 0.1\ \text{micron}$$

SOURCES.	ERROR/CHANGE
• MANUFACTURING ERROR	.000004"
• TEMPERATURE CHANGE	0.1° F
• STRESS	3 PSI
• EXTERNAL FORCE (F)	0.17#

Fig. 3 Example of precision truss structure.

models for large (compared to 1μ) response amplitudes. However, structural damping is usually a lower bound estimate that may be in error by an order of magnitude. Current spacecraft programs and many payloads to be flown on Shuttle require a modal test to validate the mathematical model; frequently the test uncovers large errors in the engineering judgment used to model the physical hardware. In many situations, difficulty exists in updating the mathematical model to match the test data; possibly the difficulty is an indication of the fidelity of the model originally created by the engineers. Our ability to develop good models can be attributed to experience gained by the engineering community over the past 20 years.

On most structures, approximately 10% of the modes are nonlinear as a function of the amplitude of vibration. For the nonlinear modes, the mathematical model then must be adjusted to the test results at the amplitude of interest. Limited test data[20] indicate that as the amplitude of vibration is reduced, the joint "slop" becomes more pronounced and can significantly affect the dynamics of the structure. An extrapolation of current observations indicates that if the structural motion of interest is similar to the magnitude of the joint "slop," the structural characteristic may look more random than deterministic. Can joint "slop" be kept to less than 1μ? The experience base to model spacecraft responding in the micron range is almost nonexistent.

Missions that must rely only upon analytical models of large precision structures probably will never progress beyond the conceptual phase.

Ground Test

The availability of the technologies to validate mission critical structural parameters by ground tests is often a prerequisite to the initiation of a flight program. Currently, on most space systems flown to date, an adequate set of ground tests has been performed. For future precision structures, neither the current nor the projected state-of-the-art improvements in static or dynamic ground-test methodologies will be adequate to validate the structural performance requirements. An example of a large structure that could not be validated by ground test is in Ref. 21.

The magnitude of force required to displace a structure 1μ as noted in Fig. 3 is 0.17 lb. The determination of the initial position of a structure weighing thousands of pounds in a 1-g field to an accuracy in the micron range is almost impossible. The goal is further complicated if the structure is to be assembled or deployed in space.

Similarly, a modal test of the hardware to determine its dynamic characteristic would be difficult. Chen[22] has reported the small differences in modal test results using various state-of-the-art test methods. However, large differences in measured modal damping[23] of up to an order of magnitude were observed using the various state-of-the-art modal test techniques. Significant differences in damping were observed when using the identical modal test method with external excitations in different directions. The difficulty of measuring with ground test the modal damping applicable for structures in space undergoing micron-level displacements is complicated by the joint loading resulting from the 1-*g* gravitational loading.

The current state-of-the-art practice using the ground test results to validate the mathematical model, which then is used to prove the adequacy of structural performance, cannot be used. The concept of adaptive structures allows an alternate approach to validation of large precision structural systems by ground tests. The objective of the ground test would be to establish the bounds of the structural performance. Given the bounds or uncertainties of the structure, various adaptive structures concepts must be designed into the system to allow in-space adjustments to the desired performance requirements.

Recent Activities

Adaptive structures is an integration of sensors, actuators, electronics, materials, structures, structural concepts, and system performance validation approaches through ground test and analyses to achieve specific mission objectives. Currently, researchers are integrating several of the elements of adaptive structures and establishing measures of performance through analysis and experimentation.

Interaction of Sensors/Actuators with Structure

A number of different types of induced strain actuators have been integrated into composite materials and/or structural elements or have the promise of being integrated. Thermal actuators (thermal electric devices) have been demonstrated by Edberg[24] to provide actuation from about 0–2 Hz. Recent work has been performed by Crawley and de Luis,[25] Crawley et al.,[26,27] and Crawley and Anderson[28] to develop analytical approaches with experiment data to investigate the characteristics of attached and imbedded piezoelectrics in composite materials. The use of electrostrictive materials[29,30] in place of piezoelectric materials appears to provide improved characteristics for specific applications. Recently, ceramic piezoelectric materials have been integrated into a structural member with independent displacement and force sensors; the members have been calibrated for use in static displacement control and active damping[31] and are shown in Fig. 4. A piezoelectric linear actuator for incorporation into a truss-type structure has been developed recently by Takahara et al.[32]

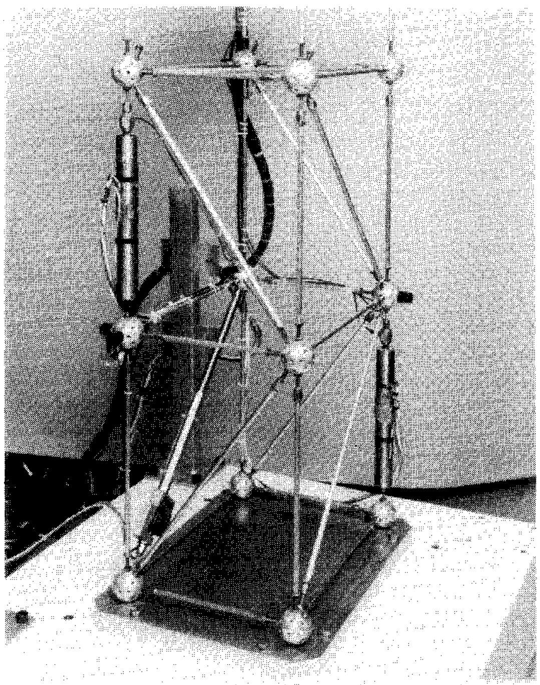


Fig. 4 Active piezoelectric element integrated into the precision structure.[31]

The integration of magnetostrictive materials in a structural member offers to provide significant advantages in some aspects[33] over the use of the piezoelectric materials.

Theoretical and experimental research on the use of shape memory alloy imbedded within reinforced composites has been performed by Rogers et al.[34,35] and Liang et al.[36] They have been able to modify the modal response of the structure by changing the stiffness through activation of the shape memory alloy with heat. Also, the shape memory alloy has been used to impart large distributed loads throughout the material to alter the strain energy distribution and, thereby, modify the modal response of the structure.

Electro-rheological fluids (ERF) contained within voids in advanced composites materials have been used by Gandhi and Thompson[37] to increase experimentally the damping of the structure by changing the electrical field on the ERF. Changes in the electrical field imposed upon the ERF can dramatically alter the rheological characteristics of the fluids. Thus, the global mass, stiffness, and dissipative characteristics of the ERF/composite system can be changed.

Other types of actuators, such as voice coils, have been used successfully in adaptive structures. One potential disadvantage of voice coil active members as part of a determinate structure is their inability to support loads without power to the voice coils. Thus, the shift in the dynamic characteristics of the structure, with and without power to the voice coils, is dramatic. Using voice coil active members in an indeterminate structure may not be effective since the actuation load can be reacted locally.

The loss factor of many passive damping materials is very sensitive to temperature. Since the operational temperature of the space system is usually within a wide temperature range, an indirect form of adaptive damping was experimentally demonstrated. Heaters and thermocouples were imbedded with the damping material into a composite beam. The structural damping of the beam was adjusted by controlling the temperature[38] of the damping material.

Sensors that can be imbedded within a composite structure include piezoelectric, piezorestrictive, strain gauges, thermocouples, etc. Research is being performed by many investigators on imbedding fiber optics within the composite material to measure internal structural displacements as well as other parameters. Some of the recent developments in embedding fiber optics are in Refs. 39 and 40.

Structural Concepts

Many of the structural configurations proposed for future space structures are truss-type structures. Truss-type structures are efficient and amenable to in-space assembly or deployment. A very important aspect of adaptive structures is the capability to geometrically relocate critical points of the structure when in space to the required positions through actuation of active members. Thus, structural configurations, which must provide for the capability to move the critical locations, is an important feature of adaptive structures.

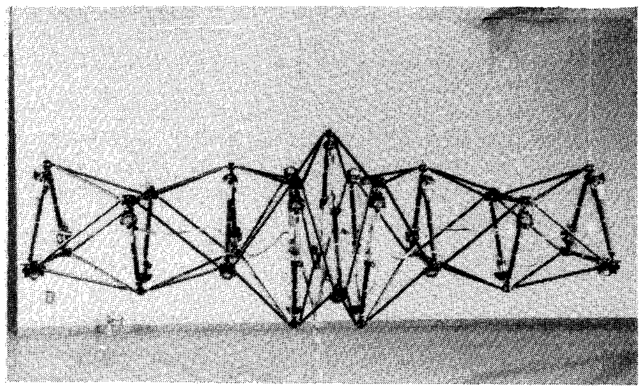


Fig. 5 Variable geometry truss.[45]

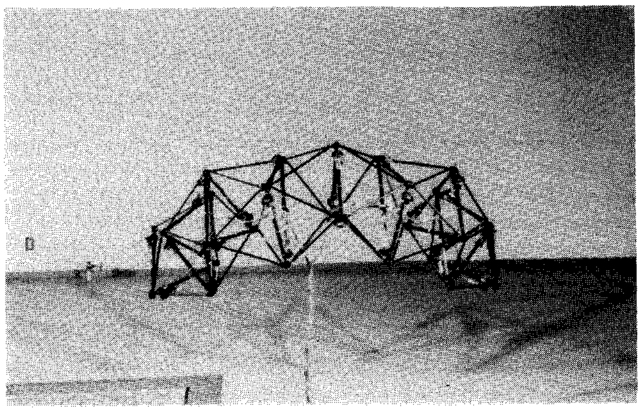


Fig. 6 Variable geometry truss.[45]

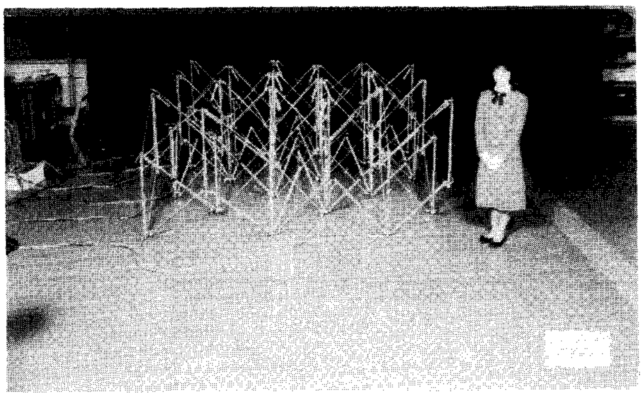


Fig. 7 Adaptive planar truss.[51]

For beam-type structures, several adaptable structural configurations have been designed, fabricated, and tested to various degrees. Robertshaw et al.[41] have used a variable geometry truss (VGT), which was initially developed at Langley Research Center,[16] for their studies. Yamamoto et al.,[42] Miura and Furuya,[43] Miura et al.,[44] and Miura[45] have been active in the development of adaptive structures; the hardware is shown in two of its many possible configurations in Figs. 5 and 6. Recently, NASA has become interested in space cranes; a preliminary concept has been developed by Mikulas et al.[46] Additional work by Utku et al.[47] is in progress to evaluate the use of adaptive structures concepts for a space crane.

For two-dimensional structures, a configuration has been built and tested by Natori et al.,[48] Onoda,[49] Natori et al.,[50] and Kuwao et al.[51]; several possible positions are shown in Figs. 7 and 8.

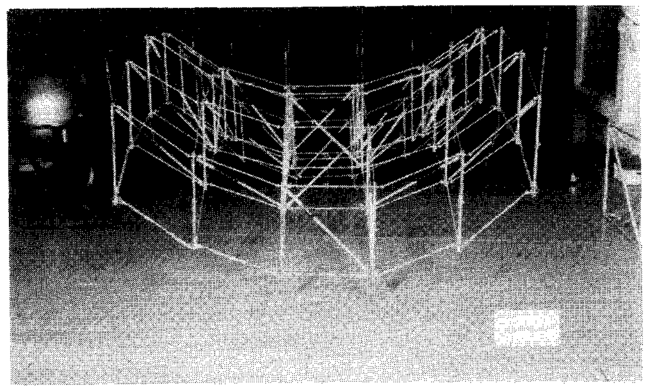


Fig. 8 Adaptive planar truss.[51]

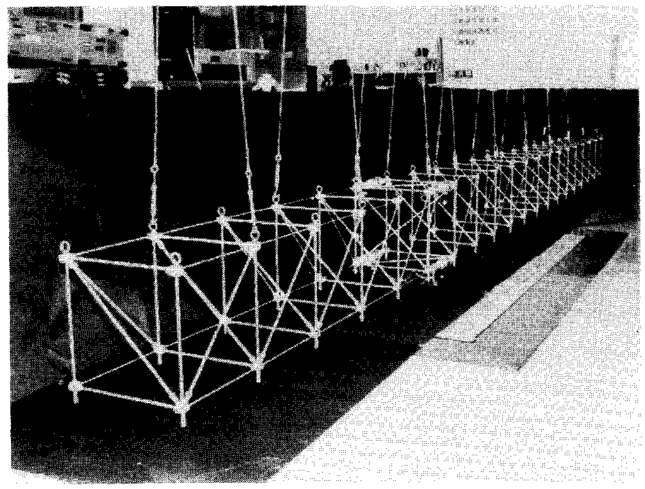


Fig. 9 Truss structure.[53]

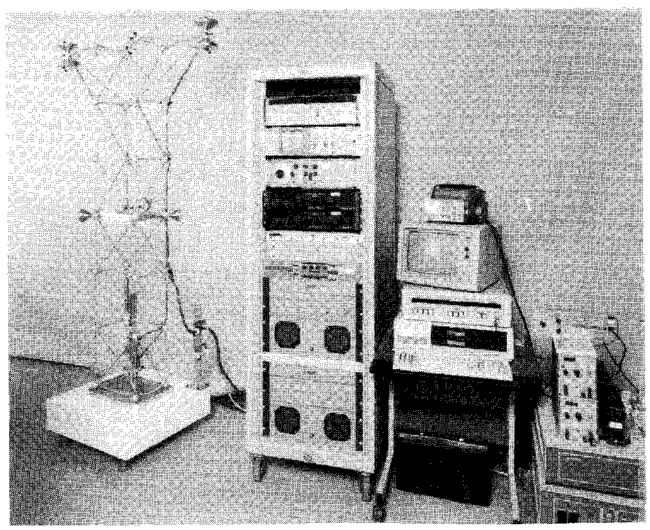


Fig. 10 Precision structure.[31]

Active Damping

The use of active members in a truss-type structure to provide active damping to the system is another benefit afforded by adaptive structures. Robertshaw et al.[41] have used a VGT with lead screw-type active elements to actively damp a long beam mounted on the VGT. Clark et al.[52] investigated the use of lead screw-type actuators at the base of a two-dimensional statically determinate truss beam to actively damp the structure and investigated the use of the lead screw actuators below the mass on the tip of the beam as a "proof mass."

Natori et al.[53,54] used voice coil-type actuators in a truss structure (see Fig. 9) and successfully provided active damping. Hagwood and Crawley[55] developed an active element by imbedding a series of cylindrical piezoelectric elements along a composite member that was placed in a truss structure. He successfully added damping to the structure by tuning the resonant-shunted piezoelectric to the resonance of the structure. Balas and Doyle[56] and Dailey and Lukich[57] recently attenuated the response of a plate-type structure supported by truss members and active members with voice coil actuators.

Fanson et al.,[31] Fanson and Garba,[58] and Fanson and Caughey[59] placed active members with piezoelectric actuators into a cantilevered truss structure (see Fig. 10) with closely spaced modes and successfully achieved active damping using a digital controller; one of the results is shown in Fig. 11. Chen et al.[60] placed active members with piezoelectric actuators into a horizontal truss structure (see Fig. 12) that can be cantilevered at the center or suspended in a free-free condition, using an analog controller. Active damping was achieved and one result is shown in Fig. 13. Using the same active

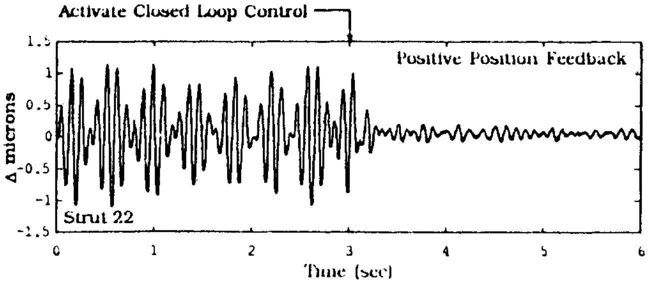


Fig. 11 Open-loop and closed-loop response to 5–15 Hz random excitation of midbay plate, precision structure.[31]

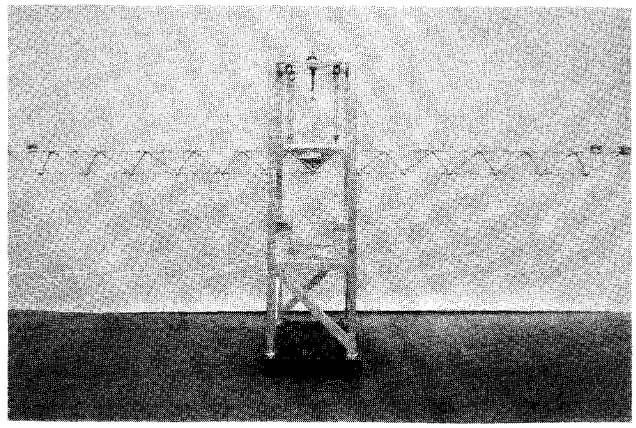


Fig. 12 Horizontal truss structure—free-free condition.[60]

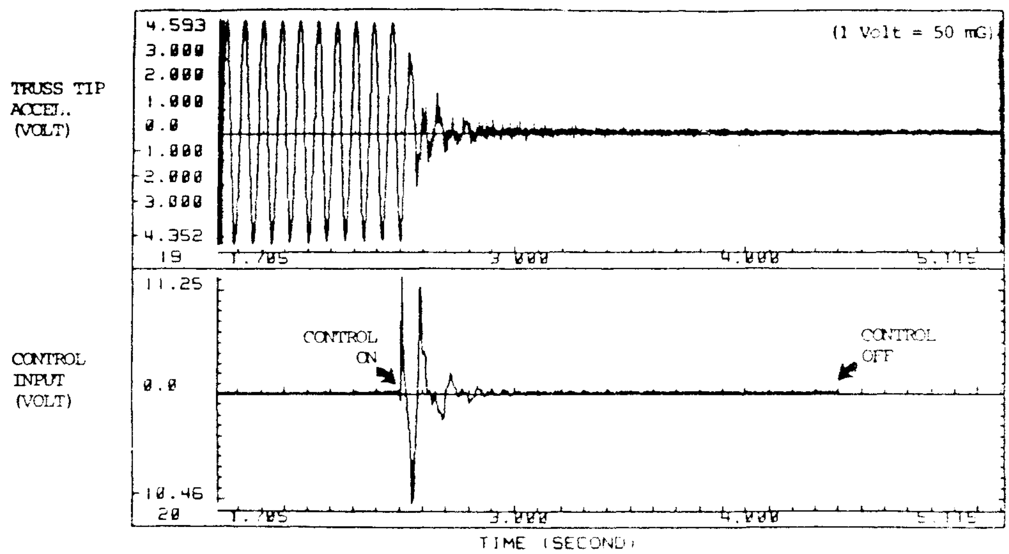


Fig. 13 Horizontal truss structure—active damping results.[60]

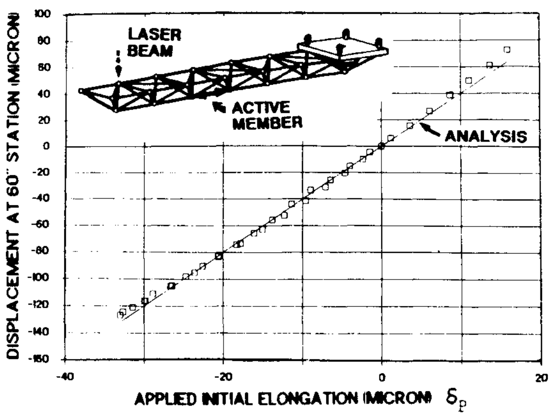


Fig. 14 Static adjustment.[60]

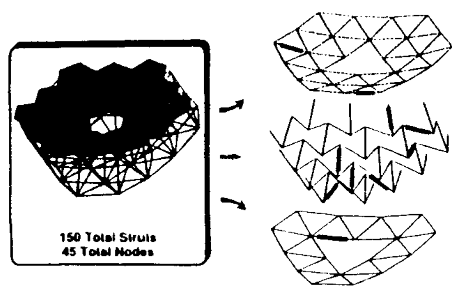


Fig. 15 Location of active members: 10 active members dissipate 50% of initial energy in about 5 cycles.[66]

member, the tip of the horizontal truss was moved linearly in the range of $+70\ \mu$ to $-130\ \mu$ with a resolution of a few microns; one result is shown in Fig. 14.

Wave Motion

In large flexible structures, wave propagation-type motions that represent transfer of localized energy within the structure become more pronounced. The analytical prediction and test validation of wave-type motions are very difficult since they are directly related to high-frequency modes. von Flotow,[61] von Flotow and Schafer,[62] von Flotow,[63] and Miller et al.[64] have developed an approach to sense the traveling wave first and then absorb the energy experimentally, using concepts compatible with adaptive structures.

Selection of Active Member Locations

Many future structures will have hundreds, if not thousands, of members; the objective is to limit the number of active elements to a small finite number. Chen et al.[65] have developed an approach to distribute a small finite set of active and passive elements[66] to provide a prespecified level of damping to a defined number of modes. Figure 15 shows that only a

MODE	FREQUENCY (Hz)					DAMPING				DESCRIPTION
	NASTRAN	Excitation Method				Excitation Method				
		ext.	strut 11	strut 22	diagonal	ext.	strut 11	strut 22	diagonal	
1	8.189	8.253	8.312	8.274	8.291	.0045	.0037	.0034	.0018	Bending in Z
L1	7.372	8.785	–	–	8.815	–	–	–	–	Mid bay shaker mass
2	10.722	10.747	10.791	10.773	10.770	.0086	.0119	.0127	.0102	Bending in Y
3	11.319	11.441	11.508	11.442	11.437	.0009	.0019	.0009	.0008	Torsion
L2	–	25.097	–	–	25.376	.0024	–	–	.0019	-Y dumb bell rotation
L3	–	26.142	–	–	26.422	.0035	–	–	.0021	+Y dumb bell rotation
4	–	28.662	29.795	–	29.014	.0093	.0077	–	.0076	Y bending & boom walking
5	37.298	34.836	35.539	35.734	35.526	.0086	.0090	.0079	.0068	2nd Z bending
6	34.987	35.975	36.326	36.624	36.128	.0040	.0045	.0061	.0045	Y bending & boom walking
7	38.840	40.142	40.496	40.937	40.976	.0049	.0041	.0049	.0051	Z bending & torsion
8	–	43.227	43.587	43.828	43.576	.0057	.0023	.0021	.0028	-Y boom in X
9	–	45.458	45.867	–	45.727	.0043	.0020	–	.0025	+Y boom in X
10	–	52.533	–	52.151	51.572	.0062	–	.0050	.0082	2nd torsion

Fig. 16 Active element system identification results on precision truss.[68]

small number of active members are required for an LDR-type structure.

On-Orbit System Identification

The successful implementation of adaptive structures depends on the capability to determine the state of the structure from which changes are made to meet the missions requirements. Current ground test approaches that use an excitation source attached to "ground" are not transportable to space. Chen and Fanson[67] performed both a state-of-the-art ground modal test, using the structure shown in Fig. 10, and then performed a modal test, using active members as the source of excitation. As shown in Fig. 16, excellent results were obtained.

Summary

Developments in adaptive structures will enable future space missions.

Acknowledgments

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