Using Adaptive Structures to Enable Future Missions by Relaxing Ground Test Requirements

Ben K. Wada,* James L. Fanson,† and G.-S. Chen†
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

Future NASA missions will require large space structures that must maintain accurate surface tolerances for up to 20 years; most flight programs require a ground test verification of the hardware. Because of the influence of gravity, the current state-of-the-art ground test technology cannot accurately determine whether the hardware complies wtih the requirements. The incorporation of adaptive structures into the spacecraft will enable a relaxation of the ground test requirements necessary to validate the hardware for flight. This paper describes the challenges in testing large precision structures, adaptive structures, the data establishing the current state of the art in ground testing, and the utilization of adaptive structures to alleviate the ground test requirements.

Introduction

INCLUDED among the future NASA missions currently under study are a Large Deployable Reflector (LDR) system (Fig. 1) with a 20-m aperture and optical interferometers (Fig. 2) with a span of 20–100 m. Many of the structures being considered are truss-type structures for efficient in-space construction or deployment. In many cases, the relative location of the structural nodes must be maintained to within a few microns or less during the observation period when they are subjected to thermal and mechanical disturbances. The observation period may be tens of minutes, whereas the total duration of the planned missions might be longer than 20 years. Many of the proposed structural systems must either be deployed or assembled in space because they will not fit within the Shuttle cargo bay or cannot be supported within the future launch vehicle shrouds.

Most space structures that are important to mission success have been directly tested or indirectly validated through test-verified mathematical models. Structures that have been tested include Titan, Atlas, Centaur, Shuttle, and most of the spacecraft flown to date. Structural concepts for spacecraft have been rejected because ground test validation programs were not feasible. Some argue that, with the improvements in computers and software, large and accurate finite element models can be developed to alleviate the need for ground test verification. The primary objective of ground verification tests is to reveal the unmodeled characteristics of the structure, such as nonlinearities and damping, that could not be established prior to the test itself. In almost every test, important unmodeled characteristics have been measured. In current classes of spacecraft where weight is still important and structural margins of safety are < ~2.0, a ground test is required to validate the structural characteristics and establish performance margins. The ground test results are also subject to various levels of uncertainties, depending on the specific parameters and on the test.

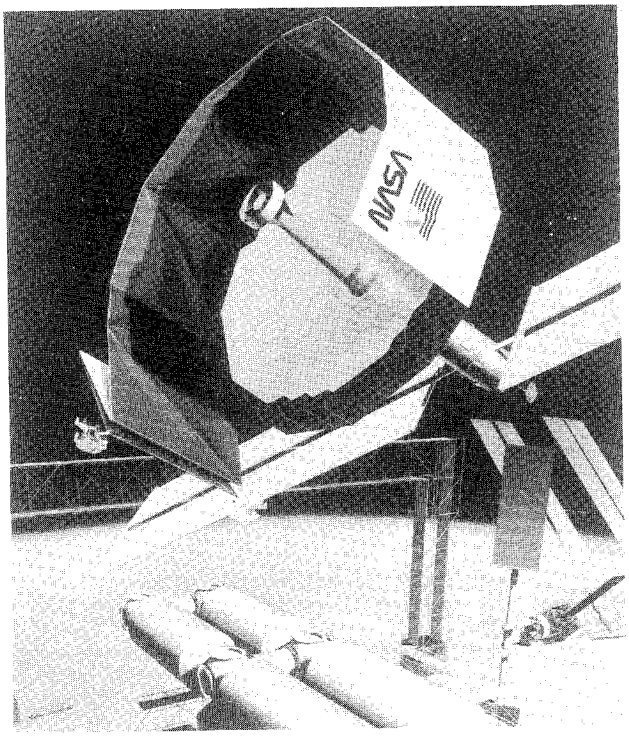


Fig. 1 Large deployable reflector.

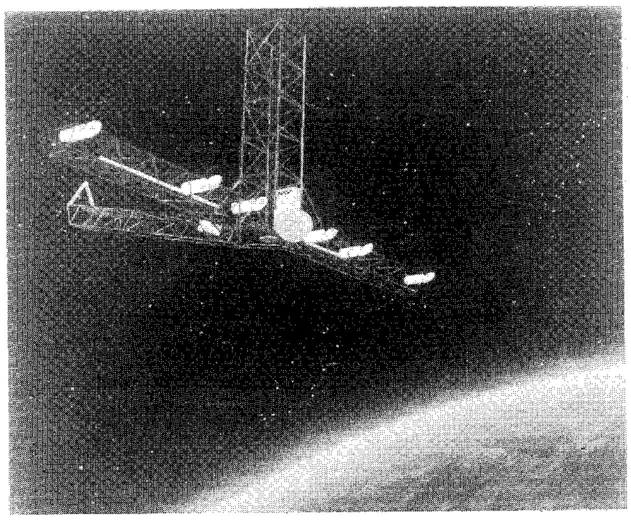


Fig. 2 Optical interferometer, a focus problem.

Received Dec. 14, 1989; revision received Nov. 17, 1990; accepted for publication Nov. 20, 1990.

*Deputy Section Manager, Applied Mechanics Technology, Building 157, Room 507, 4800 Oak Grove Drive. Member AIAA.

†Member Technical Staff, Applied Mechanics Technology, Building 157, Room 316, 4800 Oak Grove Drive. Member AIAA.

Table 1 Summary of Galileo modal test models

Number	Methods	Number of shakers	Input function	Participant/ organization	Remark
1	Sine dwell	Up to 8	Sine	Trubert/JPL[a]	Required by Galileo project
2	Multishaker random	3	Random	Hunt/SDRC[b]	Uncorrelated signals for the shakers
3	Multishaker random	4	Random	Hunt/SDRC	Uncorrelated signals shakers
4	Single-point random	1	Random	Stroud/STI[c]	
5	CHIRP	1	Fast sine sweep	Stroud/STI	
6	SWIFT	1	Discrete sine sweep	Stroud/STI	Frequency response functions are obtained between the frequency changes.
7	Tuned sweep	1	Discrete sine sweep	Stroud/STI	Sweep within narrow frequency band
8	Simultaneous frequency domain	1	Random	Coppolino/MSC,[d] Stroud/STI	Used same frequency response functions as No. 4.

[a]Jet Propulsion Laboratory. [b]Structural Dynamics Research Corporation. [c]Synergistic Technology Incorporated.
[d]MacNeal-Schwendler Corporation.

Table 2 Summary of Galileo modal test frequencies

Number	TAM[a]	Sine dwell	Four-shaker random	Three-shaker random	SWIFT	CHIRP	Single-point random	Simultaneous frequency domain	Description
1	11.08[b]	12.70	11.46	13.73	12.54	12.59	12.66	12.52	SXA[c] in *Y*
2	11.20[b]	13.11	14.02	14.10	13.78	13.86	13.88	13.76	SXA in *X*
3	14.94[b]	17.41	18.54	18.62	17.40	17.95	18.14	17.47	Global bending in *X*
4	15.08[b]	17.76	17.44	18.32	17.62	17.97	17.93	17.62	Global bending in *Y*
5	16.36[b]	18.59	19.33	19.45	18.93	19.30	——	18.93	First global torsion
6	——	——	——	——	18.22	18.54	18.54	18.37	SXA and +*X* thruster in *Y*
7	——	——	——	——	18.59	18.59	18.62	18.74	SXA in *X*
8	——	——	——	——	19.31	19.34	19.31	19.45	RRH[d] in *X*
9	——	——	22.22	——	22.04	21.98	22.08	22.03	RIG[e] in *Z*
10	20.04[b]	21.67	22.06	22.19	22.23	22.24	22.21	22.27	RIG walking mode
11	20.37	23.10	22.52	22.81	22.35	22.62	22.48	22.52	Appendages in *Z*
12	21.03[b]	25.46	25.80	25.80	25.30	25.71	25.74	25.37	Second global torsion
13	23.53[b]	23.66	25.19	25.33	27.61	——	27.63	27.62	Science boom in *Z*
14	——	——	——	——	——	——	——	24.57	
15	24.87	——	——	28.16	——	——	——	——	Sun shade in *Z*
16	25.33	——	26.36	26.64	——	——	——	——	Probe in *Y*
17	26.41	——	——	——	26.83	25.75	——	26.86	EDF in *Y*
18	——	——	——	——	——	——	——	27.08	
19	——	——	——	——	——	——	——	28.81	
20	30.67	29.71	33.42	33.46	——	——	——	——	Thruster boom in *Y* O/F
21	——	26.12	30.50	——	28.37	28.56	28.51	28.13	Damper in *Y*
22	31.77	42.20	39.14	——	——	——	——	——	Thruster boom in *Y* I/F
23	——	——	31.84	31.92	29.48	——	——	29.47	Damper in *X*
24	——	——	——	——	33.02	33.21	33.13	33.04	Probe in *X*
25	——	——	——	——	33.63	33.74	33.64	33.69	Probe and + thruster in *X*
26	——	——	——	——	33.98	——	——	33.99	Mag. can. and DDS[f] in *X*
27	——	——	33.76	——	33.40	33.80	——	33.35	Thruster in *X*
28	32.21	——	27.84	27.89	26.22	25.53	——	26.23	RRH in *Y*
29	32.78[b]	37.92	37.91	37.98	38.17	38.09	37.94	38.14	Global *Z* mode
30	33.03	——	28.29	28.58	39.70	——	——	39.75	RRH in *Y*
31	34.81	——	42.35	42.57	——	——	——	——	400 N engine in *Y*
32	35.35	——	34.50	34.32	33.75	33.85	33.79	33.76	Science boom in *X-Z*
33	35.51	——	41.73	——	——	——	——	——	400 N engine in *Y*
34	——	——	——	——	——	——	——	37.05	
35	——	——	39.77	——	——	——	——	——	Science boom in *Y*
36	——	——	——	39.88	41.01	——	——	41.11	RRH and mag. can. in *Y*
37	——	——	——	——	——	——	——	41.63	
38	——	——	——	——	——	——	——	42.04	
39	——	——	42.36	——	——	——	——	——	Thruster in *Y*
40	——	——	44.61	——	——	——	——	——	Thrusters in *Y*, in-phase
41	——	42.53	44.98	45.14	42.99	——	——	42.98	Scan platform in *X*
42	——	——	46.00	46.05	44.82	44.70	44.34	44.86	Thrusters and RRH in *Y*
43	——	——	——	——	——	——	——	44.93	
Number of mode		14	27	21	27	21	18	34	

[a]TAM = Test Analytical Model. [b]Global modes. [c]SXA = High gain antenna. [d]RRH = Radio relay hardware.
[e]RIG = Radio isotope thermoelectric generator.
[f]DDS = Dust detection system.

Ground test validation approaches, for future large precision structures with more stringent performance requirements, must be developed before they can be committed to an expensive space program. A brief survey of the current test methods indicates that they are inadequate for large precision structures. Additionally, very little effort is being expended to develop and validate new approaches. Activities are in progress to evaluate various suspension systems and to investigate the applicability of scale models; however, they do not directly address the issues of ground test validation.

Research of adaptive structures[1] has been initiated in many organizations; such activities at the Jet Propulsion Laboratory (JPL) and Massachusetts Institute of Technology (MIT), for example, focus primarily on large precision structures. Adaptive structures, as defined at JPL, refers to a structural system whose generic and inherent structural characteristics can be changed to meet mission requirements, either through remote commands and/or automatically, in response to external stimulation. Furthermore, the concept permits ground test/analysis validation of a large structural system that could not be validated by using the current state-of-the-art approaches. In this paper, the recent state-of-the-art technology in ground testing is reviewed, the potential limitations of current ground testing methods for large precision structures are presented, a description of adaptive structures is given, and the potential for adaptive structures to alleviate the ground test requirements is described.

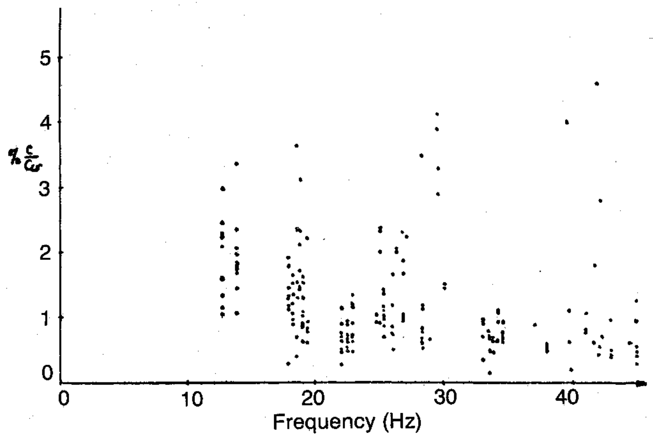


Fig. 3 Variation in modal damping, Galileo.

Current Ground Test Technology

To maintain the precision required of large space structures when they are subjected to disturbances, the dynamic characteristics of the structure are important for its control. When accurate dynamic characteristics of the structure are required, modal tests are usually performed. A few years ago, an opportunity arose to obtain modal test data on the Galileo spacecraft, which was then analyzed by the developers of many of the state-of-the-art modal analysis software/hardware techniques, as shown in Table 1.[2]

The frequency comparison of the various test/analysis methods is shown in Table 2.[2] The column TAM refers to the analytical prediction of the test configuration. Note that most of the modal test methods detected the global modes. The differing results from the various test methods cannot be attributed to major structural nonlinearities because the major structure responses appeared to be linear, based on the measured reciprocity of the transfer functions.

Wide variations of modal damping were measured for the various test methods,[3] as shown in Fig. 3. The various damping values presented for one frequency values correspond to the damping estimates obtained from various test methods for the mode represented by the frequency. The damping values changed when using the identical modal test method with a different set of forcing functions. However, the results of the modal test methods on Centaur, which utilized data from relatively low levels of excitation (e.g., random excitation), provided unsatisfactory results because of the joint slippage at the trunion through which Centaur was attached to the Shuttle.

Recently, the need for on-orbit identification of large precision structures at very low vibration levels (micron level) has prompted speculation regarding the vibrational characteristics of structures at such low levels and the ability to measure them by ground tests. Thus, whenever the opportunity arose, vibration measurements were recorded at the lowest measurable vibration levels with the available instrumentation. Data were obtained on the sensor assembly of the microwave limb

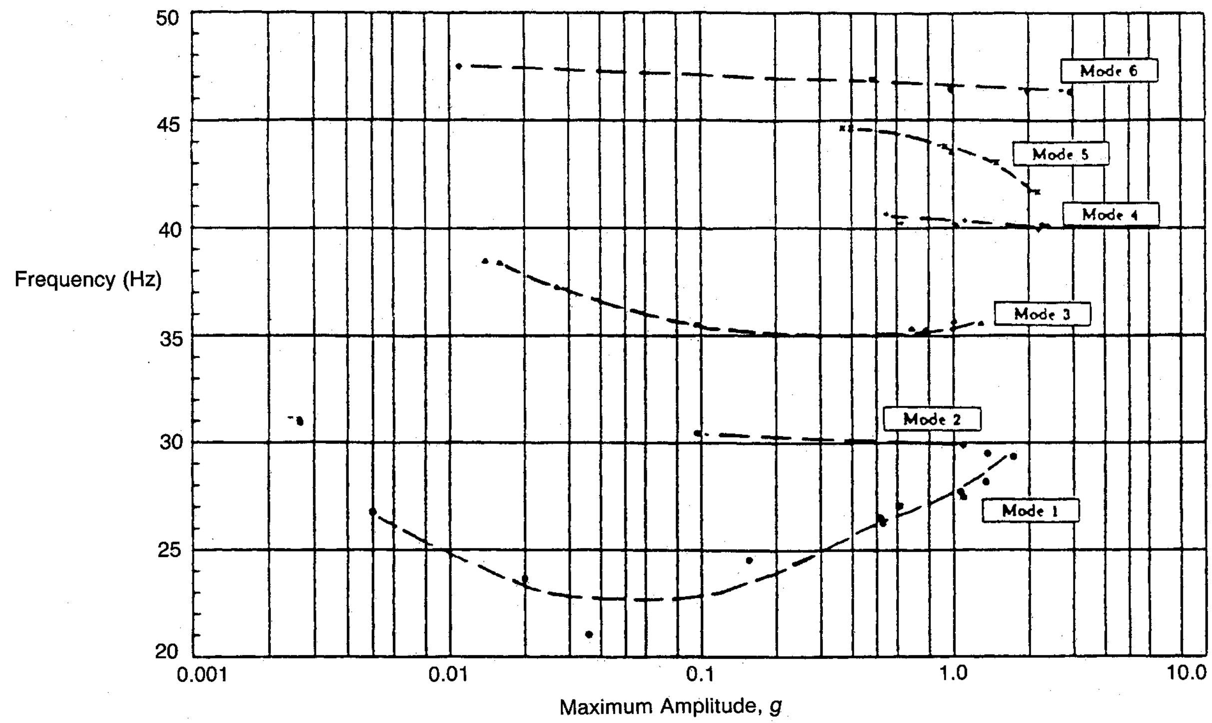
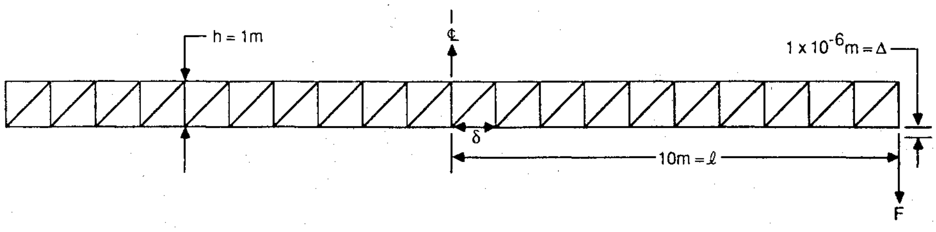


Fig. 4 Natural frequency vs response amplitude, microwave limb sander.

Table 3 Minimum and maximum orthogonality for all test modes, MLS

	1	2	3	4	5	6	7	8	9
1	0.701	0.001	0.005	0.001	0.000	0.022	0.126	0.156	0.003
	1.00	0.476	0.324	0.194	0.077	0.088	0.229	0.259	0.043
2		0.987	0.032	0.070	0.050	0.001	0.033	0.014	0.066
		1.00	0.367	0.176	0.088	0.055	0.093	0.025	0.067
3			0.821	0.000	0.041	0.014	0.047	0.002	0.016
			1.00	0.239	0.137	0.136	0.140	0.039	0.063
4				0.955	0.004	0.008	0.178	0.083	0.030
				1.00	0.322	0.139	0.277	0.140	0.071
5					0.979	0.006	0.007	0.000	0.002
					1.00	0.109	0.063	0.010	0.016
6						0.984	0.137	0.001	0.041
						1.00	0.219	0.026	0.064
7							1.00	0.018	0.032
							1.00	0.018	0.032
8								1.00	0.007
								1.00	0.007
9									1.00
									1.00



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

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

Fig. 5 Example problem.

sounder (MLS) instrument that will be flown as part of the Upper Atmosphere Research Satellite.[4] Figure 4 shows the variation of the modes as a function of amplitude, and Table 3 presents a measure of the variation of the mode shapes with amplitude. The data indicate that substantial variations can be expected with amplitude, especially on a structure such as the MLS, which has some degree of nonlinearity.

Low-amplitude modal test data were also recorded on the central portion of the Galileo primary structure[5] without the various appendages or other hardware. The data indicate very little change in the modal characteristics, as the maximum response amplitude varied from 0.002 to 0.972 g. A controlled experiment in which the gap in a structural joint was varied along with the vibrational amplitude[6] showed that, as the response amplitude decreased, the gap in the joint became more dominant and the classical modal characteristics of the structure degraded.

Several years ago, Lockheed Missiles & Space Company, under contract to JPL, fabricated a three-gore sector of a 55-m-diam wrapped rib antenna. One of the objectives was to perform ground tests to establish the dynamic characteristics of the antenna. The structure was so large and flexible that it required numerous suspension cables to prevent the structural failure as a result of the gravitational field. A meaningful ground test program to validate the mathematical models of the wrapped rib antenna was not possible. One approach to the solution of this problem that has since been under development is referred to as multiple boundary condition tests (MBCT).[7,8]

Future Ground Test Requirements

Figure 5 indicates the magnitude of the parameters that are significant in the control of large precision structures. The example is a 20-m free-free truss with only one variable member; the member is adjacent to the centerline of the structure. The figure shows the magnitude of the error in the variable member that would result in a 1-μm deflection at the tip of the truss. Note that the variations are several orders of magnitude less than values that can be controlled by using current spacecraft fabrication and control techniques. For example, the manufacturing tolerance of 0.000004 in. is several orders of magnitude less than the current manufacturing capabilities. The dynamic characteristics of structures vibrating at low levels may significantly change as a result of the manufacturing tolerances.

Unfortunately, the dynamic characteristics of a structure with loose tolerances cannot be measured because of the preloads induced in the structure by the weight (gravity) of the structure. The magnitude of the preloads in the joints due to the Earth's gravitational field exceeds the anticipated on-orbit dynamic loads. Attempts to provide suspension supports along the structure to off-load the gravitational load would be very unreliable because of the relative magnitude of the gravitational loads, as compared with the levels of excitation of interest and the small relative displacements associated with small magnitudes of joint slope.

The art of testing structure has been improving over the past years as a result of both successes and failures with testing flight hardware. Even so, the current ability to measure modal shape and modal damping is inadequate for future missions because of the following: 1) it is difficult to support the structure in its free-free condition; 2) the fidelity of the measured values requires substantial improvement; 3) the accuracy of the test data must be improved by an order of magnitude; and 4) the final flight configuration must be attained by deployment or construction. The inability to obtain test data to validate the analysis or the hardware is frustrating because of the lack of experience in modeling and analytically predicting the μm-level motion structural characteristics reliably. Only through flight data, which are difficult to obtain, can this situation be remedied. The current capability to model spacecraft is the result of repeated testing by using one of the many modeling software programs. Similar experience with large precision structures is almost nonexistent.

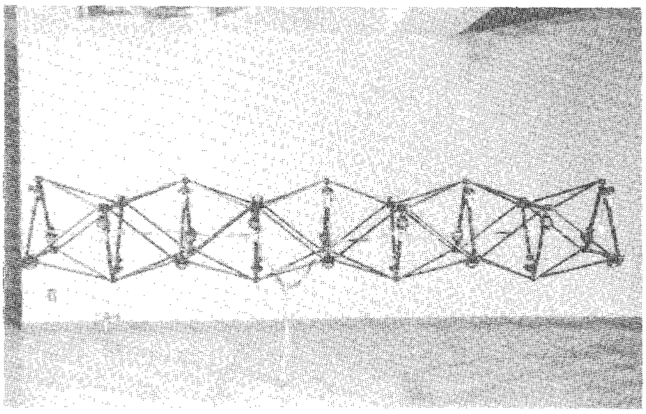


Fig. 6 Variable geometry truss.

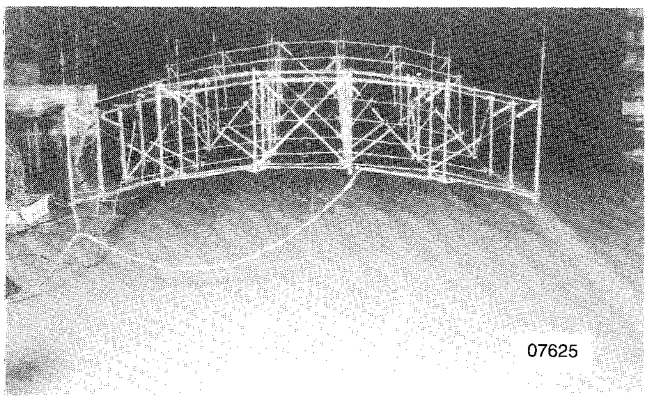


Fig. 7 Adaptive planar truss.

Fig. 8 Precision structure.

A major challenge is either to develop new ground test concepts and/or develop new spacecraft design approaches to alleviate the ground test requirements and yet validate the hardware to meet the missions requirements. A new design/test approach using adaptive structures offers a solution.

Adaptive Structures

Most structural systems are passive. They are built with specific characteristics to meet the on-orbit requirements, and the goal is to retain those characteristics despite any adverse conditions, such as ground testing and flight environments. The approach is viable, provided that the performance requirements of the spacecraft can be met and validated by ground tests and the structure stays within the allowable tolerances when subjected to the various environments during its planned mission.

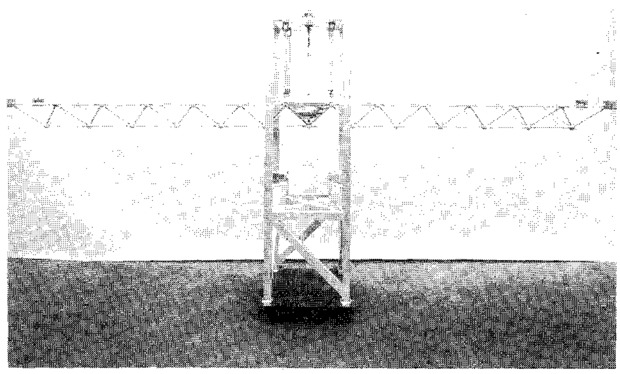
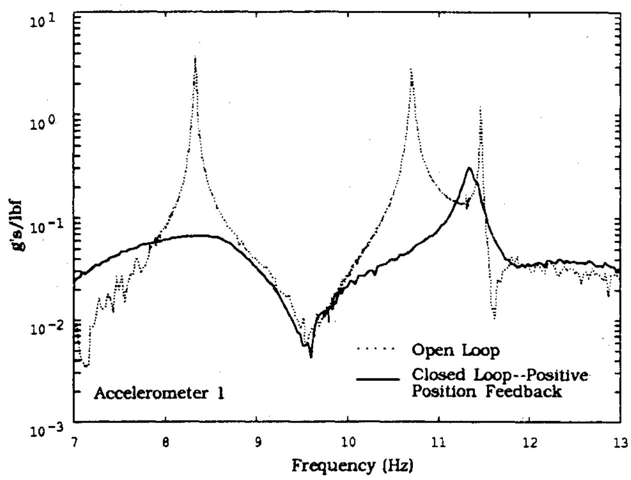
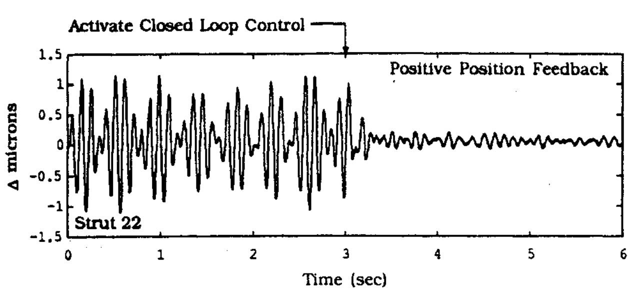


Fig. 9 Horizontal truss structure, free-free condition.



a) Open loop vs closed loop frequency response functions



b) Steady state random open loop vs closed loop response

Fig. 10 Active damping results, precision structure.

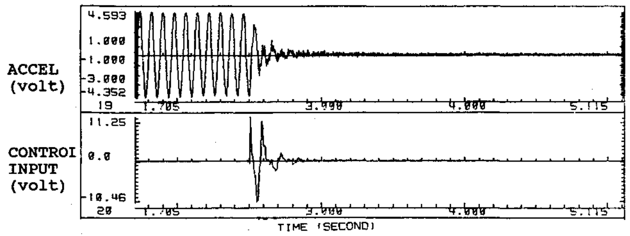


Fig. 11 Active damping results, horizontal truss.

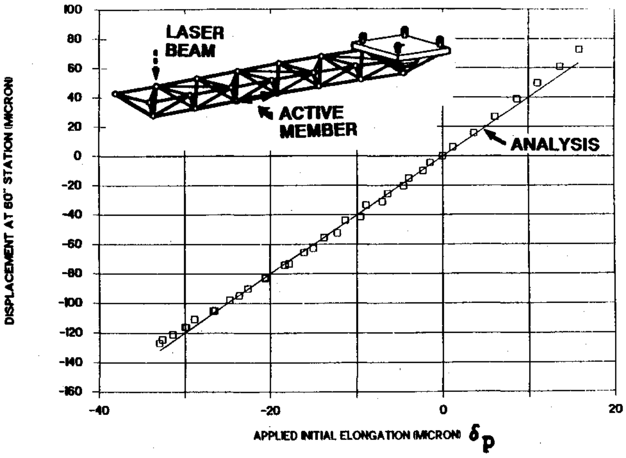


Fig. 12 Static adjustment, horizontal truss.

Adaptive structures concepts[1] have been made feasible by advances in sensors and actuators. Sensors capable of displacement resolution down to a few nanometers and actuators with submicron-motion resolution have provided the capability to control the small motion of structural elements required for precision structures. The magnitude of displacements is also compatible with displacements associated with the working stresses of the structure in its operational condition. Examples of actuated materials are the distortion of piezo-type materials when subjected to electrical fields, the predictable movement of shape-memory materials when subjected to heat, the distortion of magnetostrictive materials when subjected to magnetic fields, and the changes in the state of electrorheological fluids when subjected to electric fields. Additionally, the advances in composite materials and microprocessors provide the opportunity to directly integrate the sensors and actuators into the composite structural members along with the integrated circuits with the logic necessary to beneficially activate the active member.

Adaptive structures provide the following: they can statically position a truss structure in its operational condition in space to the desired configuration by using active members; they can quasistatically adjust the configuration of the structure to compensate for slowly varying environments, such as thermal; and they can beneficially change the structural characteristics by adding active damping and structural isolation through controlled high-frequency excitation of the actuators.

Examples of adaptive structures and select experimental results are shown in Figs. 6–12. Figures 6[9] and 7[10] show laboratory test models of deployable structures that can undergo large motions and be statically configured into selected geometric shapes. Figure 10 gives the displacement time history before and after active damping is introduced by using digital controls on the test setup, as shown in Fig. 8.[11] Figure 11 presents the acceleration time history before and after active damping is introduced using analog controls on the test setup shown in Fig. 9.[12] One of the differences between the two test setups is that Fig. 8 is cantilevered to the ground, whereas Fig. 9 can be supported in a free-free condition. Figure 12 illustrates the capability of an existing active member design to control the tip position of the structure shown in Fig. 9 to within a few microns over a wide displacement range.

The experimental test results indicate that adaptive structures concepts can be utilized to adjust the structural configuration and change the structural characteristics to meet the requirements of large precision structures.

Ground Test Requirements for Adaptive Structures

Precise static and modal-type dynamic data are not required from the ground tests because the adaptive structure can be modified in space to meet the mission requirements. The objective of the ground test is to establish the upper and lower range of the important structural characteristics and then to establish that sufficient static and dynamic range and fidelity exist within the active elements of the adaptive structure to span the bounds of the test uncertainties. The fidelity requirements on the ground tests can be sufficiently relaxed.

To make precise adjustments of a structure in space, the state of that structure must be established. As previously noted, the difficulties associated with ground tests are eliminated when one tests the structure in its operational condition. Fortunately, the active members that are used to control the structure can also be used as a forcing function to the structure in space. Since the forces generated by the active member are internally balanced, the rigid-body modes are not excited. The rigid-body modes adversely influence the accuracy of the dynamic data determined from the accelerometers. Table 4[13] gives the modal test data with active members on the precision truss; the data indicate that excellent

Table 4 Modal test data, precision structure

		Frequency, Hz					Damping				
		Excitation method					Excitation method				
Mode	NASTRAN[a]	External shakes	Strut 11	Strut 22	Diagonal		Ext	Strut 11	Strut 22	Diagonal	Description
1	8.189	8.253	8.312	8.274	8.291		0.0045	0.0037	0.0034	0.0018	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		0.0086	0.0119	0.0127	0.0102	Bending in Y
3	11.319	11.441	11.508	11.442	11.437		0.0009	0.0019	0.0009	0.0008	Torsion
L2	—	25.097	—	—	25.376		0.0024	—	—	0.0019	$-Y$ dumbbell rotation
L3	—	26.142	—	—	26.422		0.0035	—	—	0.0021	$+Y$ dumbbell rotation
4	—	28.662	29.795	—	29.014		0.0093	0.0077	—	0.0076	Y bending & boom walking
5	37.298	34.836	35.539	35.734	35.526		0.0086	0.0090	0.079	0.0068	Second Z bending
6	34.987	35.975	36.326	36.624	36.128		0.0040	0.0045	0.0061	0.0045	Y bending & boom walking
7	38.840	40.142	40.496	40.937	40.976		0.0049	0.0041	0.0049	0.0051	Z bending & torsion
8	—	43.227	43.587	43.828	43.576		0.0057	0.0023	0.0021	0.0028	$-Y$ boom in X
9	—	45.458	45.867	—	45.727		0.0043	0.0020	—	0.0025	$+Y$ boom in X
10	—	52.533	—	52.151	51.572		0.0062	—	0.0050	0.0082	Second torsion

[a]NASA Structural Analysis.

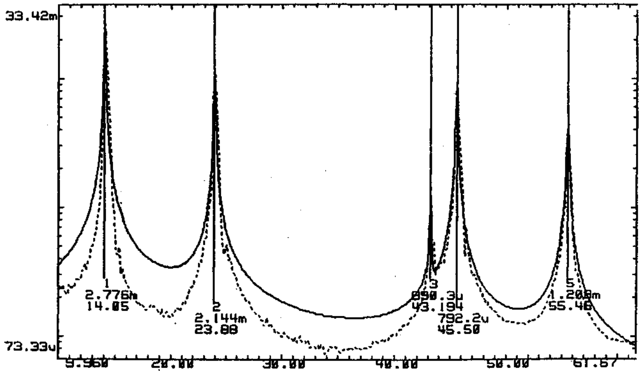


Fig. 13 Modal transfer function, free-free horizontal truss.

system identification can be performed in space. Figure 13 shows that good modal data can be acquired on a free-free system by using active members, as noted by the comparison of the test data and the analytical transfer function.

Summary

Adaptive structures for very large precision structures can successfully reduce the ground validation test requirements. Without such structures, many future missions might never be pursued because the system cannot be validated by using current state-of-the-art ground test approaches.

Acknowledgment

This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology under NASA Contract NAS7-918.

References

[1]Wada, B. K., "Adaptive Structures: An Overview," *Journal of Spacecraft and Rockets,* Vol. 27, No. 3, 1990, pp. 330–337.

[2]Chen, J. C., "Evaluation of Modal Testing Methods," AIAA Paper 84-1071, April 1984.

[3]Wada, B. K., "Prediction of Spacecraft Damping," *Proceedings of Vibration Damping Workshop II,* Vol. 2, Air Force Wright Aeronautical Labs./Flight Dynamics Lab., Wright-Patterson AFB, OH, 1986, pp. DE-1–DE-15.

[4]Smith, K., and Trubert, M., "Microwave Limb Sounder Modal Test," Jet Propulsion Lab., Pasadena, CA, Pub. D-4809, Oct. 1987.

[5]Smith, K., and Trubert, M., "Galileo Core Structure Modal Survey," Jet Propulsion Lab., Pasadena, CA, Pub. D-5602, July 1988.

[6]Blackwood, G. H., and von Flotow, A. H., "Experimental Component Mode Synthesis of Structures with Sloppy Joints," *Proceedings of the 29th AIAA/ASME/ASCE/AHS/ACS SDM Meeting,* Pt. 3, AIAA, Washington, DC, April 1988, pp. 1565–1575.

[7]Wada, B. K., and Freeland, R. E., "Technology Requirements for Large Flexible Space Structures," International Astronautical Federation, Paper 83-404, Oct. 1983.

[8]Kuo, C. P., and Wada, B. K., "System Identification of a Truss Type Space Structure Using the Multiple Boundary Condition Test (MBCT) Method," *Proceedings of the 28th AIAA/ASME/ASCE/AHS/ACS SDM Meeting,* Pt. 2A, AIAA, Washington, DC, April 1987, pp. 172–176.

[9]Miura, K., "Introducing Intelligence into Structures," International Astronautical Federation, Paper 88-267, Oct. 1988.

[10]Natori, M., Iwasaki, K., and Kuwao, F., "Adaptive Planar Truss Structures and Their Vibration Characteristics," AIAA Paper 87-0743, April 1987.

[11]Fanson, J. L., Blackwood, G. L., and Chu, C., "Active Member Control of Precision Structures," *Proceedings of the 30th AIAA/ASME/ASCE/AHS/ACS SDM Conference,* Pt. 3, AIAA, Washington, DC, April 1989, pp. 1480–1494.

[12]Chen, G.-S., Lurie, B. J., and Wada, B. K., "Experimental Studies of Adaptive Structures for Precision Performance," AIAA Paper 89-1329, April 1989.

[13]Chen, J. C., and Fanson, J. L., "System Identification Test Using Active Members," AIAA Paper 89-1290, April 1989.

David H. Allen
Associate Editor