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CONSTRUCTION AND CONTROL OF LARGE SPACE STRUCTURES

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SUMMARY

Recent NASA research efforts on space construction are reviewed. Preliminary results of the EASE/ACCESS Shuttle experiments are discussed. A 45-foot beam was constructed on orbit in 30 minutes using a manual assembly technique at a work station. A large tetrahedron was constructed several times using a free floating technique. The capability of repair, utilities installation, and handling the structures using a mobile foot restraint on the RMS was also demonstrated. Implications of the experiments for Space Station are presented. Models of 5-meter Space Station structure together with neutral buoyancy simulations suggest manual assembly techniques are feasible. Selected research on control of flexible structures is discussed. To support planned flight experiments, studies of the design and optimal placement of distributed active dampers are underway.

INTRODUCTION

On November 29 and December 1, 1985, during Space Shuttle Flight 61B, the EASE/ACCESS space construction experiments were performed. The experiments were the culmination of several years of research on the construction of large structures in orbit. A purpose of the present paper is to report preliminary results from the EASE/ACCESS experiments, and to discuss the implications of this research on studies of NASA's Space Station.

The possibility of utilizing large structures in space has led to other NASA research programs on the control of large flexible space structures. A flight program to demonstrate advanced dynamics and control on a large deployable mast has been initiated. A second purpose of this paper is to discuss recent research on the design and optimal placement of distributed active dampers to control motions of this large, flexible mast.

SYMBOLS

A	state matrix
A^T	transpose of state matrix
c	damping coefficient

c_i	damping coefficients for planar truss (fig. 20)
c_v	damping coefficient for vibration absorber (fig. 14)
EI	bending stiffness of beam
J	quadratic cost function
k_s	spring constant for vibration absorber (fig. 14)
ℓ	length of beam
m_c	control mass of vibration absorber (fig. 14)
m_t	beam tip mass (fig. 14)
P	solution matrix of Lyapunov equation
Q, Q	weighting matrices
t	time
t_o	initial time
x	axis along beam (fig. 14)
y	displacement of beam (fig. 14)
η	control mass displacement relative to tip of beam
μ_c	control mass/equivalent beam mass
ρ	mass density of beam per unit length
ϕ_i	assumed mode shape for beam (i = 1, 2 ....)

EASE/ACCESS EXPERIMENTS

The purpose of the EASE/ACCESS experiments was to evaluate manual assembly techniques for large space truss structures. In developing concepts for space construction, neutral buoyancy simulations are conducted in large water tanks located at the Marshall Space Flight Center and the Johnson Space Center. Because of water drag in these facilities, as well as the difficulty of making structures and astronauts truly neutrally buoyant, the fidelity of these simulations is in question. The EASE/ACCESS experiments afforded an opportunity to obtain flight data for correlation of assembly rates, and construction techniques projected from neutral buoyancy simulations. The flight also was a unique opportunity to gain experience in orbital construction.

EASE/ACCESS Experimental Procedures

The ACCESS experiment (ref. 1) involved use of a fixed work station to construct a 45-foot space truss beam of triangular cross-section. The truss assembly setup is shown in figure 1. Two astronauts first deployed a 10-foot revolvable assembly fixture consisting of a central tubular mast and three guide rails. Using prepackaged joints and members, they assembled a bay of the truss on the guide rails manually rotating the assembly fixture to access the three sides of the truss. When the bay was completed, it was raised and supported on the top half of the guide rails. This process was repeated to build 10 bays of the structure. A photograph of the truss under construction is presented in figure 2.

The EASE experiment (ref. 2) involved repeated construction of a large tetrahedron. The tetrahedron consisted of six 12-foot beams. In construction, one astronaut was positioned in a foot restraint located on the side of the work platform (fig. 1). The second astronaut (connected by a tether to the Shuttle) worked without fixed restraints at the tip of the structure. A photograph of the EASE construction experiment is presented in figure 3.

On the second day of the EASE/ACCESS experiments, the Shuttle Remote Manipulator, fitted with a manipulator foot restraint, was employed as a mobile work station for a single astronaut. Both the ACCESS and the EASE structures were manipulated to demonstrate ease of handling (fig. 4). In addition, after reconstruction of nine bays of ACCESS, an RMS-attached astronaut constructed a single bay and demonstrated repair by replacing a nodal joint and longitudinal member of the truss. Other tasks performed were installation of a simulated instrumentation cable (fig. 5) and assembly and handling of two EASE beams (joined end to end) as a simulated Space Station heat pipe.

Preliminary Results From the EASE/ACCESS Experiments

The EASE/ACCESS Principal Investigators: Walter L. Heard, Jr., NASA Langley Research Center (ACCESS), and Dr. David L. Akin, MIT (EASE), have only just received the photographic and astronaut debriefing information from the Shuttle flight. Hence the results reported herein must be considered preliminary. The results are based on discussions with Mr. Heard and Dr. Akin and the transcript of the astronaut post-flight debriefing.

Results of the ACCESS construction experiment are summarized in figure 6. A correlation of the truss construction times with neutral buoyancy simulations is presented. Data from simulations with trained subjects and the average of trained and untrained subjects is shown. The results presented show good correlation between the flight data and the neutral buoyancy simulations. Including setup time, the 45-foot truss was assembled in less than 30 minutes.

In the baseline EASE experiment, the astronauts were able to construct the tetrahedral structure eight times, providing data on the ability of humans to adapt to and perform strenuous tasks in weightlessness without fixed body restraints. As indicated in table I, the performance of the crew in space was excellent, with the total assembly and disassembly cycles in space requiring

22 percent less time on average than the same task during underwater training. The crew did indicate that fatigue was apparent from the intensive use of hand and wrist muscles in this assembly process, and that they would prefer a fixed platform such as ACCESS for work which could be pre-planned as an assembly-line type activity. However, for low repetition or contingency operations, they found no particular difficulty in unrestrained EVA operations.

Manual joining and maneuvering of the simulated heat pipe was performed successfully. Both the 190 lb ACCESS and 480 lb EASE structures could be manually maneuvered easily by an astronaut restrained in the RMS work station. Construction and repair of the single bay was accomplished readily, as was installation of the simulated power cable. The manipulator operator indicated the RMS construction simulations underestimated the time required in space. (At the present, there is no high fidelity RMS mockup available for neutral buoyancy training.) Operationally, the most desirable improvement in equipment was associated with the space suit gloves. The astronauts reported numbness in their hands in simulations and in the flight experiments.

IMPLICATIONS OF EASE/ACCESS FOR SPACE STATION STUDIES

Research on space construction is being applied in design studies of NASA's Space Station (see, for example, refs. 3 and 4). In figure 7, a growth configuration of the Space Station is shown. The truss structure shown in the figure has members which are 15 feet in length. Because of the size of the truss members, it is proposed to construct the trusses by Extra Vehicular Activity (EVA). A detailed scenario for EVA construction is presented in reference 3.

A comparison of EVA hours to construct initial (IOC) Space Station configurations (ref. 4) is presented in figure 8. The comparison shown is between a Station with erectable 15-foot members and a station with 9-foot deployable members for the Station trusses. The construction concept for the erectable trusses is similar to the fixed work station concepts embodied in the EASE/ACCESS experiments and the construction times are based on neutral buoyancy simulations with larger structures. The deployable structure construction times are estimates for single-fold deployable trusses under development by Rockwell International for the Marshall Space Flight Center.

Results presented in figure 8 show that the initial Station can be constructed in seven Shuttle flights. As expected, the Station with deployable structure takes less time to construct than the erectable structure. However, total EVA time differences are small due to the large amount of EVA time required to install larger utilities than can be prepackaged in the deployable truss. Thus, erectable trusses appear to be competitive with deployable trusses for Space Station structure.

In figure 9, a full-scale model of part of a Space Station truss is presented. The truss was assembled at the Langley Research Center using the mobile work station shown in the figure. As illustrated in figure 10, the model is constructed from 5-meter members attached to ball-shaped nodes using side locking joints. The joint concept is similar to that used in the EASE/ACCESS structures.

Neutral buoyancy simulations of construction of large trusses were completed in 1983 (ref. 5). In figure 11, construction of a truss structure using two astronauts on mobile work platforms is shown. In this experiment, a 38-member truss with 18-foot (5.5 m) members was constructed in 34 minutes. Based on the fidelity of simulations demonstrated by the EASE/ACCESS experiments, the construction of Space Station by EVA using manually erected structures is feasible.

Finally, the issue of the most desirable work station configuration for Space Station construction is still a subject of research and development. In figure 12, a concept for a Mobile Remote Manipulator System (MRMS), is illustrated. The concept was developed in reference 6. The MRMS is used for both construction and maintainence of the Station, as well as a mobile transporter of payloads. The concept illustrated consists of a platform which moves from node to node using a push-pull mechanical system. Issues in the development of this system are the propulsion system, (rocket, mechanical, or robotic), the degree of automation, and initial costs of the system.

CONTROL OF LARGE SPACE STRUCTURES

The Space Station has a facility in which other large structures may be constructed. For antenna applications, these structures may be much more flexible than the initial Space Station. To address problems in control of large flexible structures, NASA's Office of Aeronautics and Space Technology recently initiated a space experiments program entitled, Control of Flexible Structures (COFS). In COFS, a series of experiments of increasing complexity will be flown to verify results of advanced dynamics and control theory.

The first COFS experiment (ref. 7) is illustrated in figure 13. In the experiment, a 60-meter antenna mast structure will be deployed from the Shuttle cargo bay. The structure will be excited by an actuator system contained in the canister at the top of the mast. At selected stations along the mast, actuators which can provide active damping will be located. The masses, distribution, and control laws to be used in the experiment have been the subject of NASA research (refs. 8-11).

Design of Actuator on Flexible Beam

In initial studies (refs. 8-9), the optimal design of a vibration absorber illustrated in figure 14 was investigated. The problem was solved two ways: (1) by application of Den Hartog's vibration absorber theory and (2) by application of optimal control theory. The approach taken in the second case is illustrated in figure 15. The beam was modeled with modes satisfying the boundary conditions of the problem. A cost function to minimize the beam tip deflection was formed and solved by numerical solution of the Lyapunov equations. Results for optimal damping solutions are shown in figure 16. The results show that there is a maximum value of damping achievable in the beam for a reasonable control mass. If the beam has an initial deflection, a damping ratio of about 18 percent is achievable. If the beam has an initial velocity, 22 percent damping is achievable. Higher damping values for the beam were not achievable for beams with stiffness properties similar to the COFS mast. Thus, the flexibility of the beam and the influence of the controller mass must be accounted for in practical design for active damping.

Design of Distributed Actuators

An experimental test setup to investigate distributed active damping of a grillage plate is shown in figure 17. In this case, the active dampers are collocated actuator/sensor pairs. The dampers are designed to behave as passive dampers. A theoretical solution of the control gains for the dampers is given in reference 10. The problem solved is described in figure 18. A local disturbance force is applied to the grillage having actuators of known mass and force limits. The problem is to find the gains of the fewest number of actuators necessary to cause the vibration amplitude of the grillage corners to be less than a tenth of an inch. A constraint on the problem is that the dampers can operate for no more than 5 seconds after the disturbance is applied.

The problem was solved by forming a control cost function reflecting the actuator properties and constraints. Solutions were obtained by representing the grillage with 23 modes. A non-linear optimization procedure (CONMIN) was applied to obtain the results presented in figure 19. The problem solutions were found to be sensitive to small changes in design conditions. These solutions, however, are good examples of progress in obtaining practical design solutions from modern control theory formulations.

Linear Optimization Approaches

Using nonlinear programing to solve the grillage problem just described is computationally expensive and has the usual risks of missing global minima because of finding local minima. A promising method to alleviate these difficulties is to cast the optimization problem as a sequence of linear optimizations. Such a technique has been applied recently in reference 11. In this study optimization of dampers on a planar truss was investigated. The problem solved is described in figure 20.

The problem is to find the gains of a minimum number of dampers to ensure at least 1 percent damping in each of the 18 modes of the structure. The solution was obtained by using design sensitivity derivatives in conjunction with a continuation procedure to convert the nonlinear optimization problem into a sequence of linear optimization problems for which exact solutions exist.

Results of this study are presented in figure 21. The optimum gains for the actuators are shown for the linear programing (continuation) and nonlinear programing approaches. Cases 1 to 3 are different initial values for actuator gains used in the solutions. The results shown indicate that the nonlinear programing solutions are sensitive to initial conditions. The linear programing solutions, on the other hand, are insensitive to initial conditions and yield the minimum value of the objective function minimized. Further efforts are needed to test the rigor and validity of the linear programing approach, but the initial research is very promising.

CONCLUDING REMARKS

Some recent results of NASA research in the construction and control of large space structures have been presented. In space construction, the first manual construction experiments in space have been completed successfully. The EASE/ACCESS experiments have demonstrated the ability to construct large trusses in space using free floating techniques, and fixed or mobile work stations. Preliminary results have indicated reasonable correlations between flight data and neutral buoyancy simulations on Earth.

Implications of the EASE/ACCESS experiments on NASA's Space Station studies have been discussed. Studies of EVA time necessary to construct the initial Space Station suggest that manually erected structures are competitive with deployable structures, because of the large amount of EVA time required to install large utilities on the Station. Full-scale structural models of Space Station structure together with neutral buoyancy simulations of large truss construction using EASE/ACCESS techniques suggest that manual erection of Space Station structure is feasible. Concepts for a mobile remote manipulator system for Space Station are under investigation.

Progress in NASA programs on the control of large, flexible structures has been reviewed. A flight experiment program to evaluate advanced dynamics and control technology on a large mast structure has been initiated. Related research on design and optimal placement of active dampers to control vibration of flexible structures has been discussed. Excessive control mass has been shown to limit achievable damping in a large flexible mast. Practical problems in the optimal placement of distributed active dampers are being solved using modern control theory. Design results for a grillage have been presented. Promising research on the use of sequential linear optimization versus nonlinear optimization in such problems has also been discussed. The application of modern control theory including the physics of practical actuators to control flexible structures would appear to be a rich area for future research.

REFERENCES

1. Heard, Walter L., Jr.: ACCESS (Assembly Concept for Construction of Erectable Space Structure) - A Shuttle Flight Experiment. Presented at the IEEE 18th Annual Electronics and Aerospace Systems Conference, Washington, DC, October 28-30, 1985.

2. Anon: EASE/ACCESS, Framework for the Future. NASA 23M1085, Marshall Space Flight Center, 1985.

3. Mikulas, Martin M., Jr.; Croomes, Scott D.; Schneider, William; Bush, Harold G.; Nagy, Kornell; Pelischek, Timothy; Lake, Mark S.; and Wesselski, Clarence: Space Station Truss Structures and Construction Considerations. NASA TM-86338, January 1985.

4. Mikulas, Martin M., Jr.; Wright, Andrew S., Jr.; Bush, Harold G.; Watson, Judith J.; Dean, Edwin B.; Twigg, Leonard T.; Rhodes, Marvin D.; Cooper, Paul A.; Dorsey, John T.; Lake, Mark S.; Young, John W.; Stein, Peter A.; Housner, Jerrold M.; and Ferebee, Melvin J., Jr.: Deployable/Erectable Trade Study for Space Station Truss Structures. NASA TM-87573, July 1985.

5. Heard, Walter L., Jr.; Bush, Harold G.; Wallsom, Richard E.; and Jensen, J. Kermit: A Mobile Work Station Concept for Mechanically Aided Astronaut Assembly of Large Space Trusses. NASA TP-2108, March 1983.

6. Bush, Harold G.; Mikulas, Martin M., Jr.; Wallsom, Richard E.; and Jensen, J. Kermit: Conceptual Design of a Mobile Remote Manipulator. NASA TM-86262, July 1984.

7. Hanks, Brantley R.: Control of Flexible Structures (COFS) - Flight Experiment Background and Description. Presented at the Large Space Antenna Systems Technology Conference, Langley Research Center, December 4-6, 1984. NASA CP-2368, pp. 893-908.

8. Card, Michael F.; McComb, Harvey G., Jr.; and Peebles, Susan W.: Preliminary Sizing of Vibration Absorber for Space Mast Structure. NASA TM-84488, May 1982.

9. Juang, J.-N.: Optimal Design of a Passive Vibration Absorber for a Truss Beam. Journal of Guidance, Control, and Dynamics, vol. 7, no. 6, November-December 1984, pp. 733-739.

10. Horner, Garnett C.; and Walz, Joseph E.: A Design Technique for Determining Actuator Gains in Spacecraft Vibration Control. Presented at the AIAA/ASME/ASCE/AHS 26th Structures, Structural Dynamics, and Materials Conference, Orlando, Florida, April 15-17, 1985. AIAA Paper No. 85-0628-CP.

11. Horta, Lucas G.; Juang, Jer-Nan; and Junkins, John L.: A Sequential Linear Optimization Approach for Controller Design. Presented at the AIAA Guidance, Navigation, and Control Conference, Snowmass, Colorado, August 19-21, 1985. AIAA Paper No. 85-1971-CP.

Preliminary Results

Total Times
(Assembly + Disassembly)

Run	EVA	NBS
1	20:58	28:12
2	18:09	29:03
3	16:19	17:58
4	16:27	19:02
5	20:38	23:14
6	17:58	24:42
7	18:26	
8	18:24	

Table I. Correlation of Tetrahedron Construction Times

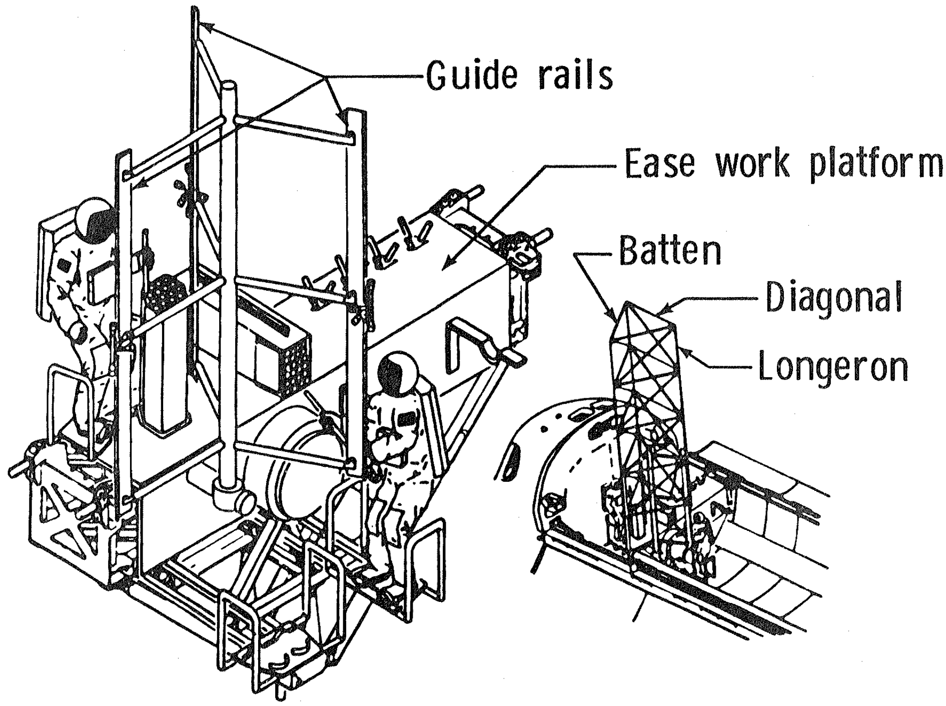


Figure 1.- ACCESS Space Truss Assembly Configuration.

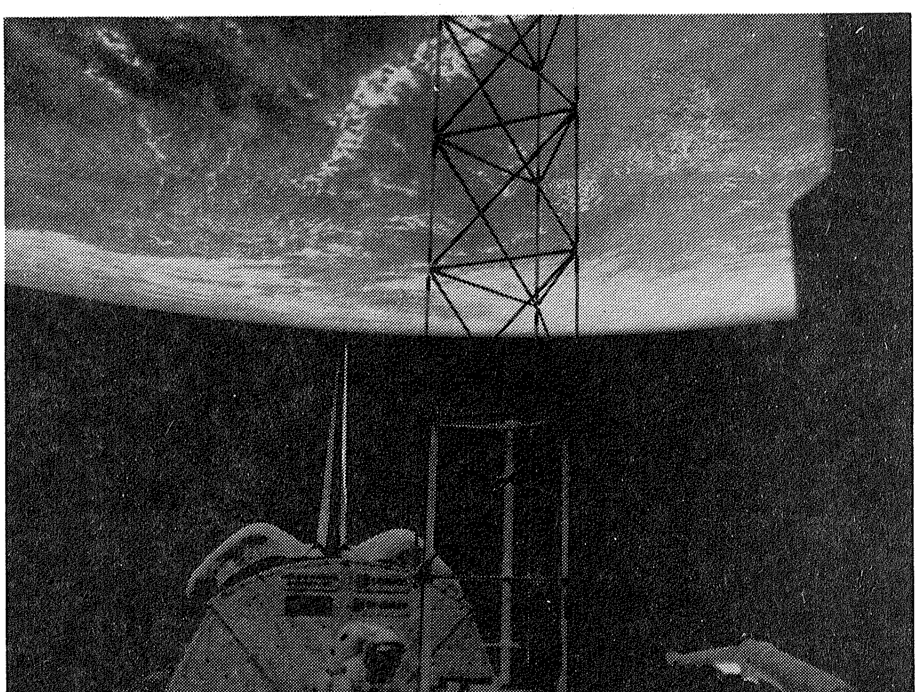


Figure 2.- ACCESS Truss Under Construction.

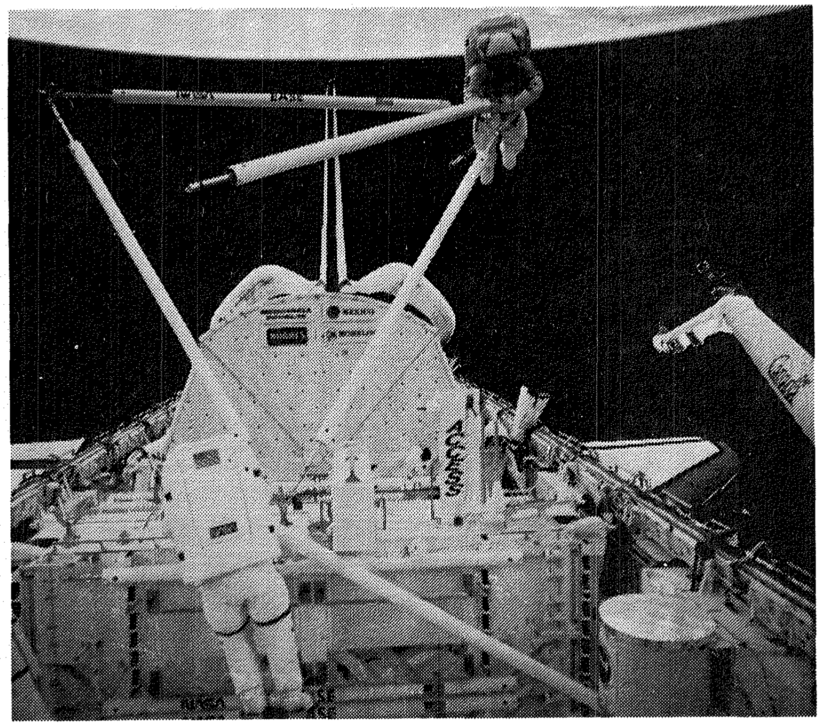


Figure 3.- EASE Tetrahedron Under Construction.

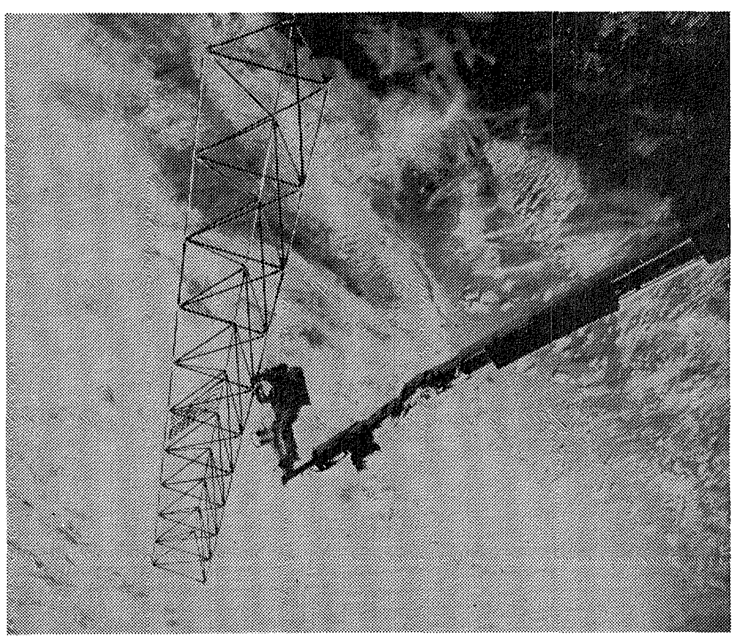


Figure 4.- ACCESS Truss Manipulation From RMS Work Station.

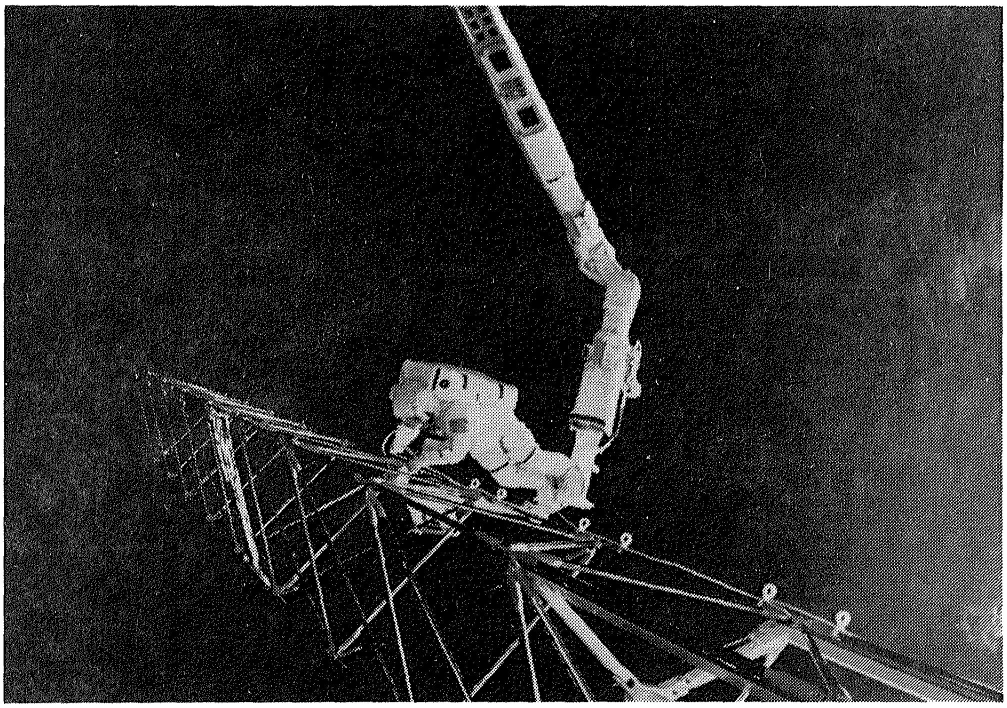


Figure 5.- Cable Installation on Truss Using Mobile RMS Work Station.

Preliminary results

Task	Time min:sec		
	NBS	NBS	Flight
	Avg all tests	Trained	Trained
Setup	4:00	3:04	3:31
Assemble 10 bays	30:13	21:44	25:27
Disassemble 10 bays	18:45	15:00	18:52
Stow and close up	5:23	4:30	4:41
	58:21	44:18	52:31

Figure 6.- Correlation of Space Truss Construction Times.

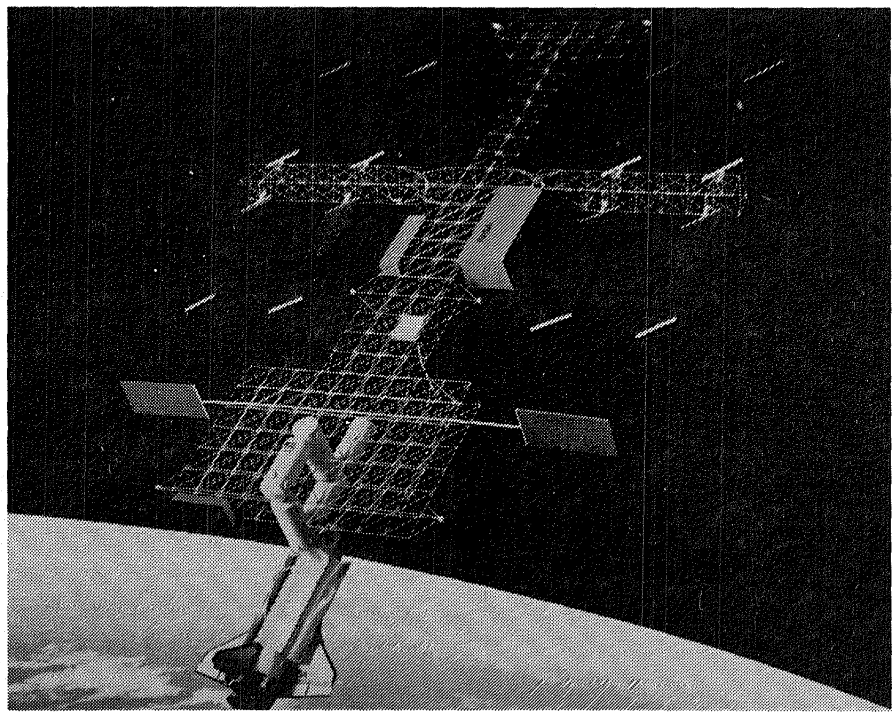


Figure 7.- Fifteen-Foot Space Station Growth Configuration.

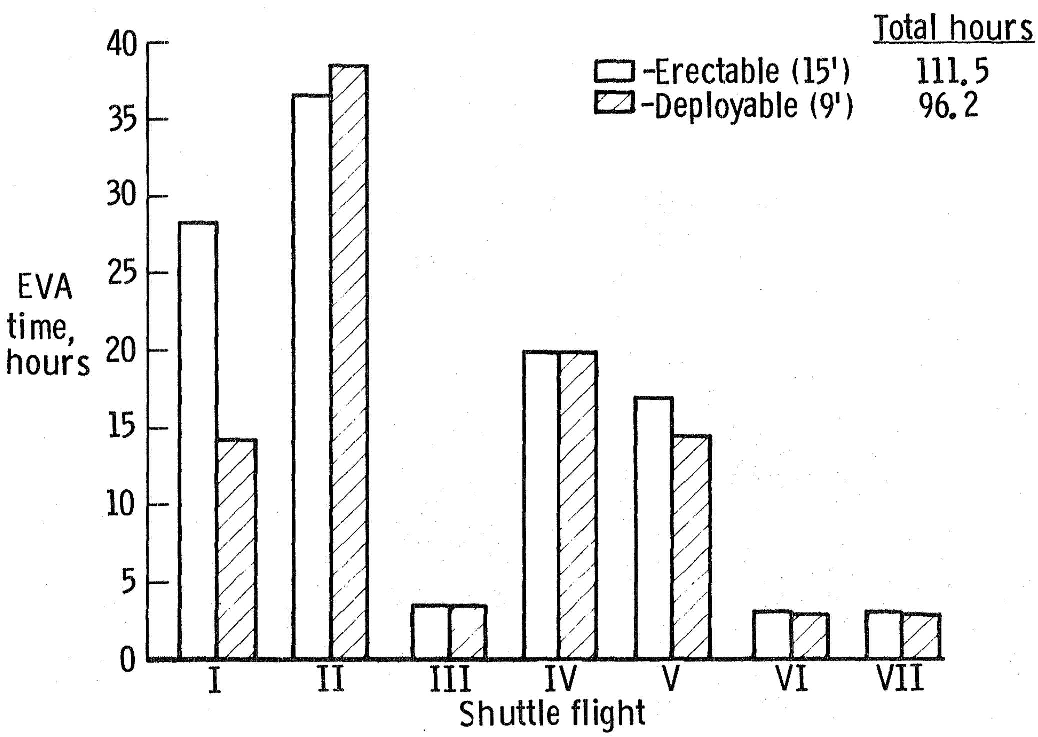


Figure 8.- Comparison of EVA Hours to Construct IOC Space Station Configurations.

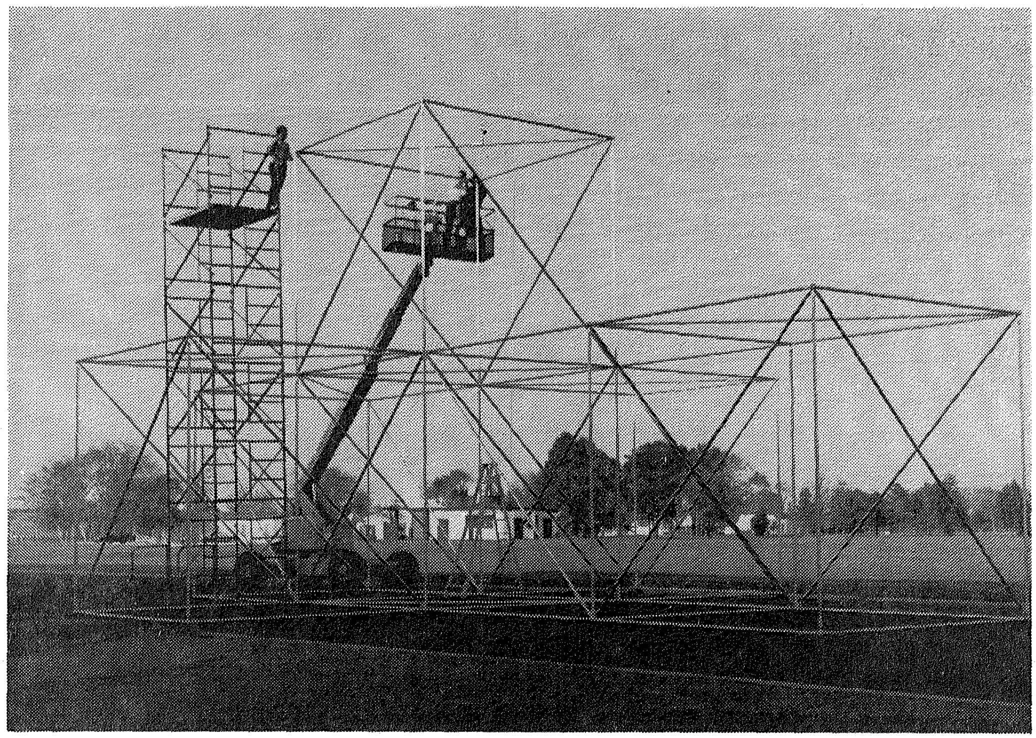


Figure 9.- Space Station Structural Model.

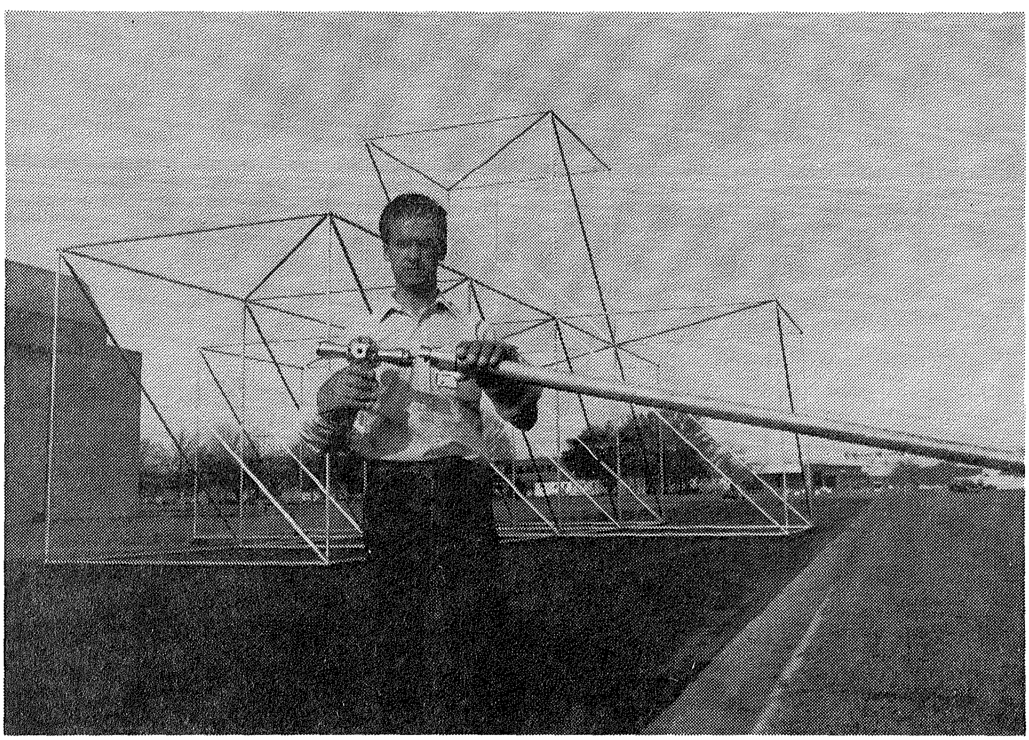


Figure 10.- Space Station Model Strut and Joint.

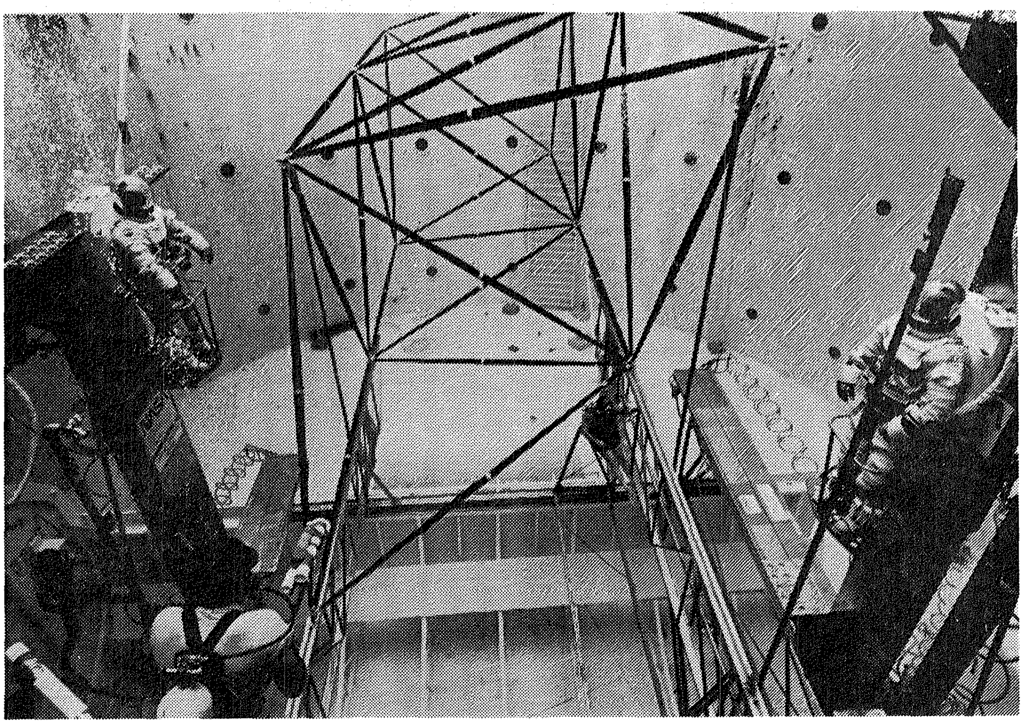


Figure 11.- Mobile Work Station for Assembly of Large Keel Beam.

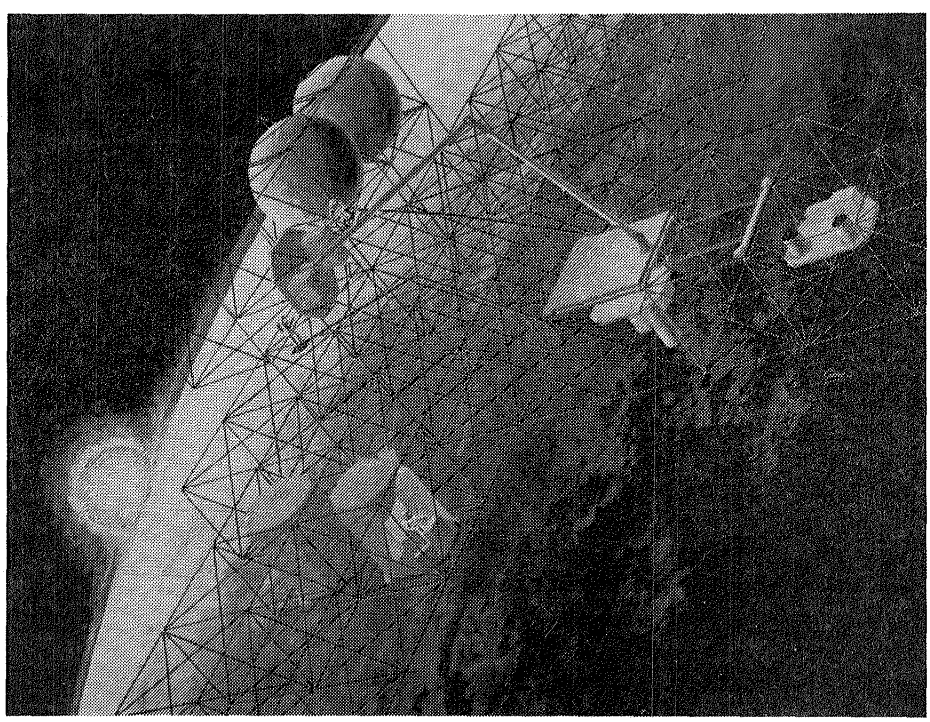


Figure 12.- Space Station Mobile Remote Manipulator System.

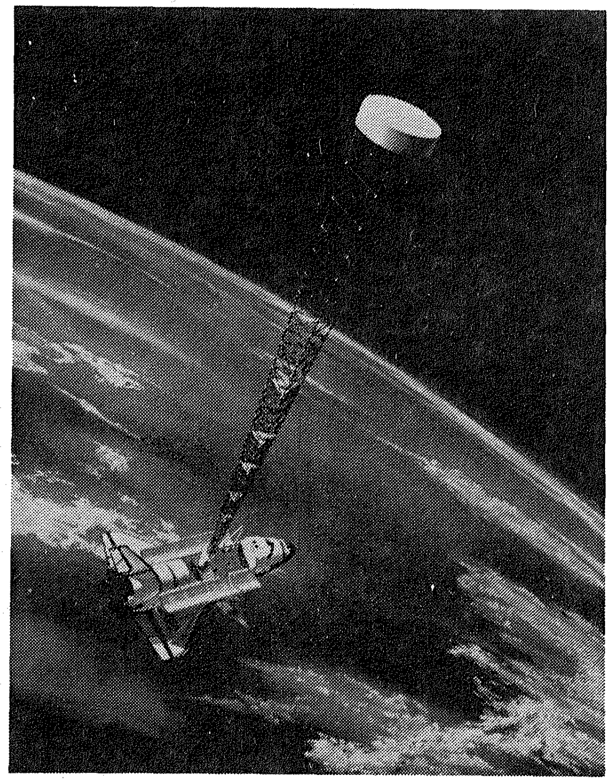
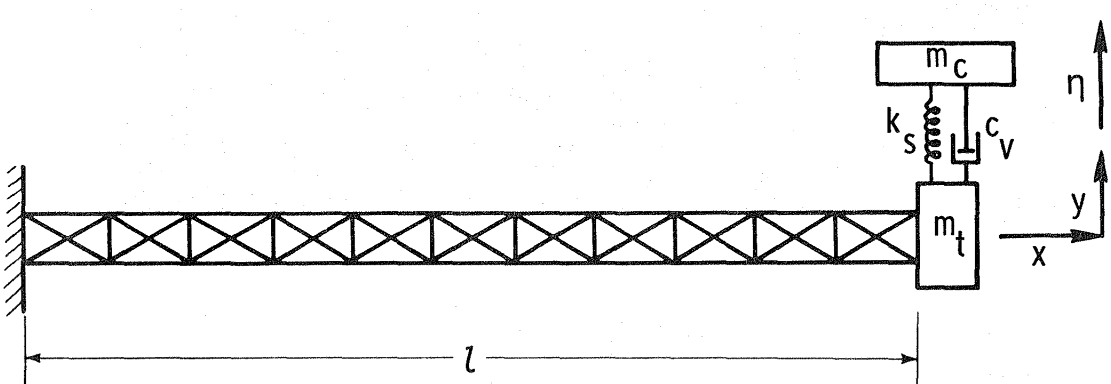


Figure 13.- Control of Flexible Structures Experiment (COFS I).

- Purpose
  - Understand limitation and characteristics of passive vibration control device for antenna applications
- Objective
  - Derive an optimal tuning absorber attached to a long truss beam



Truss beam with a tip vibration absorber

Figure 14.- Optimum Design of a Vibration Absorber For a Truss Beam.

- Use a continuum to represent a truss beam

$$EIy_{,xxxx} + \rho y = 0$$

- Use modern control theory

$$J = \frac{1}{2}\int_{t_0}^{\infty} y^2(l, t)\,dt$$

- Solve the Lyapunov equation

$$A^T P + PA = Q; \; Q = \begin{bmatrix} Q & Q \\ 0 & 0 \end{bmatrix}$$

$$Q = \left[\Phi_1(l), \ldots, \Phi_n(l), 0\right]^T \left[\Phi_1(l), \ldots, \Phi_n(l), 0\right]$$

Figure 15.- Technical Approach to Solving Vibration Absorber Problem.

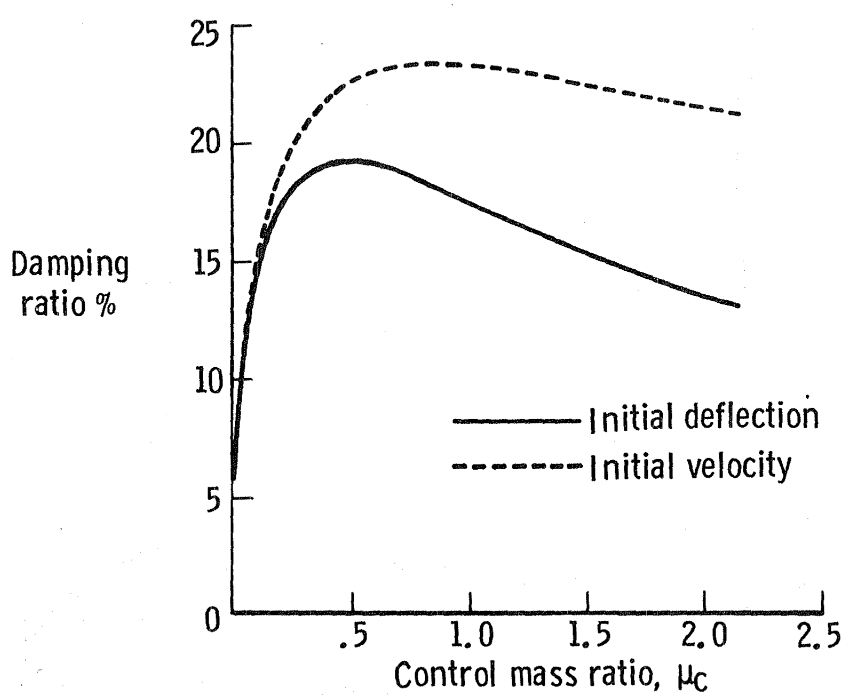


Figure 16.- Optimal Tuned Absorber Designs.

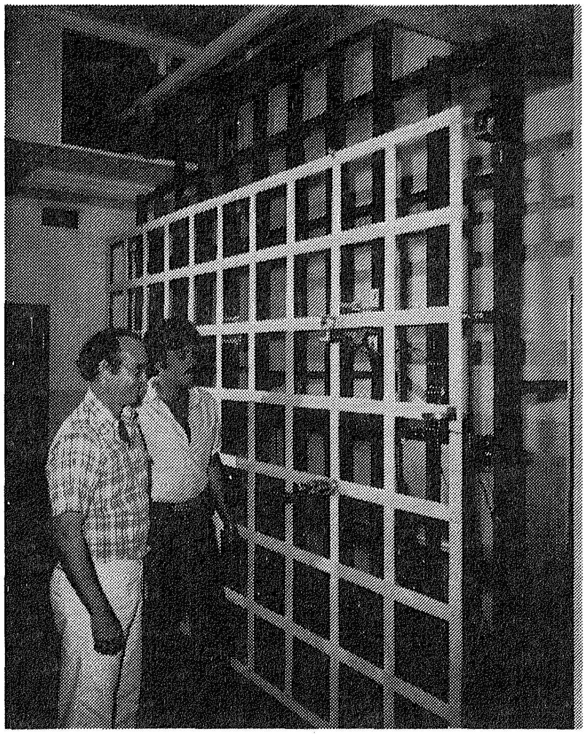
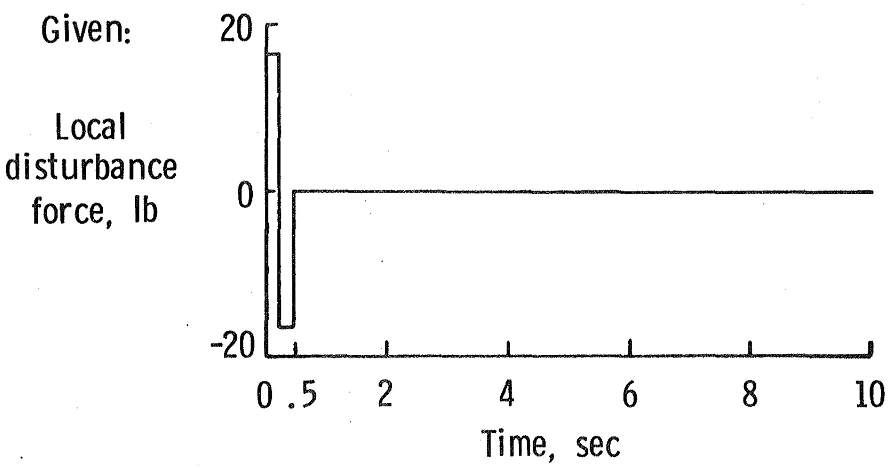


Figure 17.- Grillage Structure With Active Dampers.

Given:



Actuator weight (0.5 lbs), Actuator force limit (1 lb)

Find: Gains of a minimum set of dampers if :

1) Response of grillage corners must be <0.1 in. after 10 secs

2) Dampers can operate for no more than 5 secs after disturbance is applied

Figure 18.- Grillage Damping Problem.

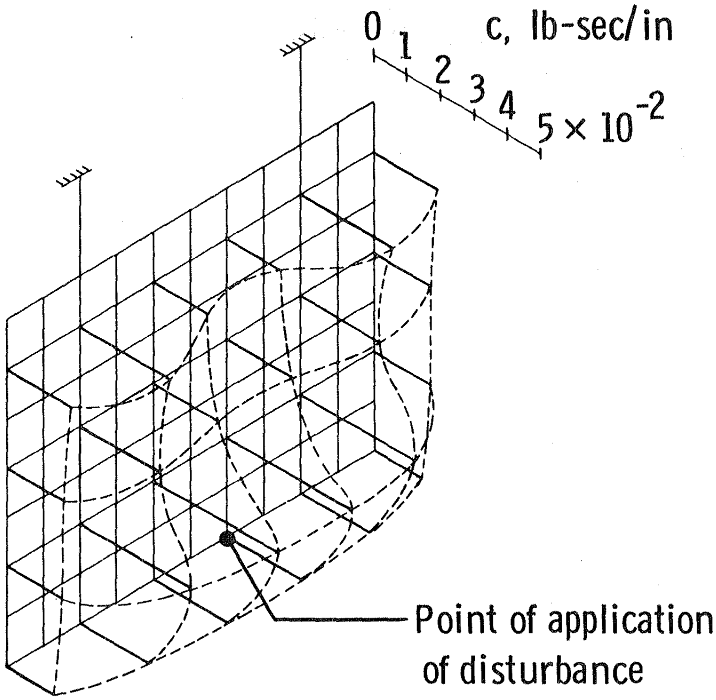


Figure 19.- Grillage Damper Design Results.

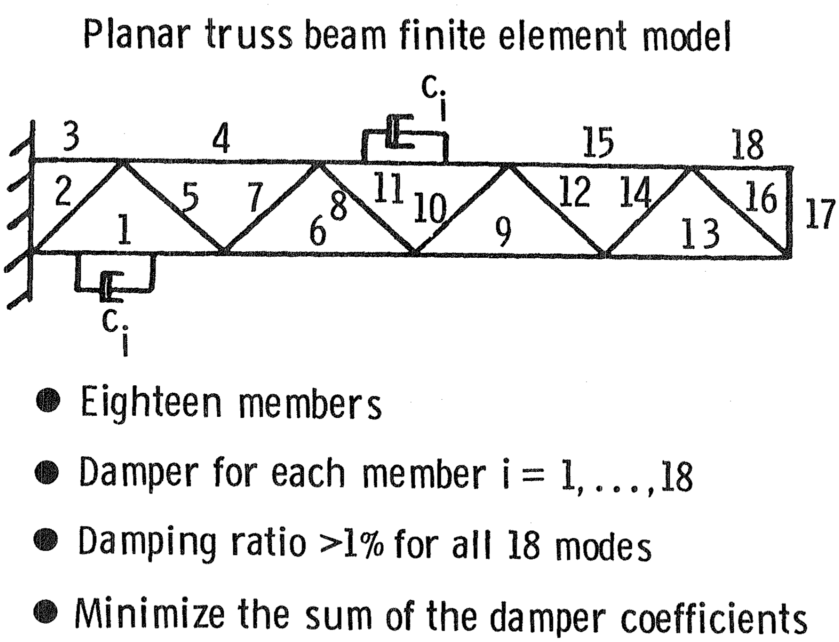


Figure 20.- Optimization of Damping in Planar Truss.

Optimum gain

Damper	Continuation approach	Nonlinear search approach (Vanderplaats)		
	Cases 1-3	Case 1	Case 2	Case 3
1	525.7	340.2	620.0	1108.0
2	60.8	203.2	47.0	9.6
3	0.0	107.5	0.0	0.0
4	0.0	226.2	0.0	0.0
5	0.0	75.9	0.0	10.7
6	32.9	195.5	56.7	112.8
7	0.0	0.0	0.0	0.0
8	0.0	10.6	0.0	0.0
9	0.0	165.0	7.0	151.0
10	0.0	0.0	0.0	0.0
11	102.3	171.9	86.8	227.9
12	0.0	12.8	0.0	0.0
13	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0
15	0.0	38.8	0.0	0.0
16	0.0	0.0	0.0	7.6
17	3.6	3.2	4.2	2.7
18	1.9	0.0	3.8	1.2
Final obj	727.7	1550.9	825.5	1631.5

Figure 21.- Optimum Damping Gains For Planar Truss.

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15. Supplementary Notes

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16. Abstract

Recent NASA research efforts on space construction are reviewed. Preliminary results of the EASE/ACCESS Shuttle experiments are discussed. A 45-foot beam was constructed on orbit in 30 minutes using a manual assembly technique at a work station. A large tetrahedron was constructed several times using a free floating technique. The capability of repair, utilities installation, and handling the structures using a mobile foot restraint on the RMS was also demonstrated. Implications of the experiments for Space Station are presented. Models of 5-meter Space Station structure together with neutral buoyancy simulations suggest manual assembly techniques are feasible. Selected research on control of flexible structures is discussed. To support planned flight experiments, studies of the design and optimal placement of distributed active dampers are underway.

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