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RECENT ADVANCES IN STRUCTURAL DYNAMICS OF LARGE SPACE STRUCTURES

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RECENT ADVANCES IN STRUCTURAL DYNAMICS OF LARGE SPACE STRUCTURES

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Abstract

Recent progress in the area of structural dynamics of large space structures is reviewed. Topics include system identification, large angle slewing of flexible structures, definition of scaling limitations in structural models, and recent results on a tension-stabilized antenna concept known as the hoop-column. Increasingly complex laboratory experiments guide most of the activities leading to realistic technological developments. Theoretical progress in system identification based on system realization theory resulting in unification of several methods is reviewed. Experimental results from implementation of a theoretical large-angle slewing control approach are shown. Status and results of the development of a research computer program for analysis of the transient dynamics of large angle motion of flexible structures are presented. Correlation of results from analysis and vibration tests of the hoop-column antenna concept are summarized.

Introduction

Space systems which are too large to be transported into orbit fully assembled have been proposed. Recognizing that these systems present unprecedented challenges in the areas of verification of performance and certification, NASA has for several years conducted technology programs in several related areas including control-structure interaction, structural assembly, on-orbit deployment, and materials research. Reviews of progress in the broad areas of control-structure interaction, ground test and certification issues, flight testing, and structural assembly have been presented in References 1-4.

Key research needs for design, certification, and operation of large space systems include several specific areas of structural dynamics. Structural dynamic test methods, for example, have been a subject of research for several years. Challenges and trends associated with large space structures are outlined in References 5-6. Substructure testing is one approach to the determination of characteristics of large space structures but difficulties associated with assurance that areas of the structure which are loaded during assembled operation are the same as those which are loaded during tests may limit the applicability of this method. A promising systematic approach for substructure testing is presented in Reference 7. Some structures, however, such as some large antenna concepts, Reference 8, for example, do not lend themselves easily to substructure testing. For these types of structures, inevitably there is dynamic interaction of the structure

*Assistant Chief, Structures and Dynamics Division with the suspension system. This interaction should be minimized in the test and included in the associated analysis. Another key research topic is system identification. Much progress has been made in recent years with the introduction of time-domain methods in structural testing (Reference 9, for example). An example of the synergism which can result from interdisciplinary research may be seen here as relationships among several current methods have been shown by the application of system realization theory from the controls discipline to modal identification methods used by structural dynamicists (Ref. 10). The literature in this area is extensive. Reference 11 provides an extensive bibliography in system identification as applied to both modal identification and controls. Because the large flexible systems envisioned for the future need to articulate, the problem of relative movement among interconnected bodies becomes important. The problem is difficult because of the high degree of nonlinearity and the large number of degrees of freedom involved. There are no proven general methods for design of controls for such situations. Intuition exercised by highly experienced designers presently is a necessity. Progress is impeded by the inability to perform the many iterations needed in a rigorous design process because of the enormous computational task. State-of-the-art computer programs exist which can carry out a limited number of computations but they are insufficient. One research computer program being formulated for lattice structures is the LATDYN program (Ref. 12). The purpose of this program is to help researchers define problems and to test algorithms for improvement of efficiency in these calculations. Presently the program is restricted to two dimensions. A three-dimensional formulation is in progress.

The problem areas mentioned above are not intended to be exhaustive. They do, however, indicate the degree of the difficulties which must be overcome in order to deploy confidently large systems in space. The purpose of the present paper is to review some recent progress in the areas of system identification, large-angle maneuvers of flexible structures, scaling of lattice structures, recent deployment load calculations, and to present summary results of tests and analyses of a 15m hoop-column antenna.

System Identification

System Identification can be divided into two categories for purposes of discussion. One is on-line system identification which is required for performing adaptive control. Because of the very rapid speed requirements for computation of changing system characteristics, this type of system identification remains an impediment to implementation of adaptive control for more than a few system modes. The other category of system identification is referred to as off-line system identification. This process, which is much further advanced than on-line system identification, involves acquisition of data, storage in some appropriate device, then analysis by any of variously available processes. These processes have been the subject of a voluminous literature, Reference 11, and only recently have the various methods been shown to be derivable from a common theory, Reference 10. Thus for linear systems, advantages and disadvantages of the various system identification approaches emanate from the character and volume of the data to be analyzed.

A key event in the development of system identification methods was the introduction of the eigensystem realization algorithm (ERA), References 13-14. This theory, from the controls community, has served as the basis for much of the progress. Figure 1 shows some recent developments and characteristics of these various methods. The first line of the figure shows the original ERA, the characteristics of which are shown in Figure 2. The data are first organized into a matrix known as the Hankel matrix, then the singular value decomposition is performed. Involved in this process is an assumption of the number of degrees of freedom contained in the data. A key element in this method, then, is the singular value decomposition which allows an estimation of the number of modes present. A recent development known as the ERA-FD, or Eigensystem Realization Algorithm in the Frequency Domain, is illustrated in Figure 3. This method utilizes the close conceptual relationships between time and frequency domains. The method is based on transfer functions and allows the usual advantages of frequency domain analysis such as windowing to isolate certain frequency bandwidths. The contribution here is two-fold. First an eigensystem realization algorithm in the frequency domain is developed for modal parameter identification of linear systems. Second, an explicit description of the relationship between time domain and frequency domain system identification methods is established.

As noted previously, a key element of the eigensystem realization algorithm is the application of the singular value decomposition to a matrix in which a number of modes has been assumed that is greater than the expected modal content of the data. A different approach, Reference 16, has been formulated which abandons the singular value decomposition in favor of the Gram-Schmidt orthonormalization technique. In this approach, the minimal realization of a linear system is recursively calculated from sampled impulse response data. The system matrix identified in this process is in upper Hessenberg form which has advantages for the identification of modal parameters. It also has the property that once the elements of the system matrix are computed, they are never altered as the dimension of the model is increased. Thus, in this process one builds up to the proper system order. The recursive form will produce results somewhat quicker than the nonrecursive version. However, a somewhat greater sensitivity to system noise is expected because of the use of Gram-Schmidt orthonormalization technique.

Another modification to the eigensystem realization algorithm is the ERA/DC or Eigensystem Realization Analysis/Data Correlation approach. In this method, the singular value decomposition is combined with the philosophy of the correlation fit method such that response data correlations, rather than actual response values, are used for modal parameter identification. This method has the advantage of reducing bias errors due to noise corruption significantly, without the need for model overspecification. When overspecification is used, however, the method provides estimates of modal parameters of similar accuracy to the usual ERA method. The method is described in Reference 17.

Large Angle Slewing of Flexible Structures

Performance of complex tasks on orbit with large flexible space structures involves articulation through very large angles. Not only must this articulation be accomplished with great accuracy, it must be accomplished sometimes with minimal vibration. Thus, two aspects of this problem arise: first the design of controls which will practically permit this large angle slewing vibration and secondly, simulation of the large angle maneuver with the effects of controls incorporated. Some research in both these areas is described in this section. Further details of this work can be found in References 12 and 18-22.

In Figure 4, a test setup is depicted in which a slewing maneuver of 30^o is performed in 3.5 seconds. In this experiment, a relatively simple implementation of a closed form feedback law is attempted. The figure shows on the right a comparison of the root strain both with and without control. The results indicate the method was successful. This work has been extended to a multibody problem as shown in Figure 5 and Reference 21. In this experimental apparatus, the articulation is performed by way of three motors. Each of the appendages is flexible. Each appendage has three strain gages and a root angular measurement. In addition to slewing each of the appendages, the central body also can be maneuvered. Results from this experiment are shown in Figure 6. The maneuver illustrated here shows that one panel is maneuvered through 45^o relative to the center body. The center body moves an additional 45^o while the second panel must point in one direction. The results shown are root strains for both panels one and two, with and without control. The results indicate that the maneuver was accomplished with a strain reduction when flexible motion control was implemented. The key feature of the algorithm is the separation of the rigid body large angle component of the motion from the elastic motion which is assumed to be small.

Research is underway to be able to simulate such motions as described in the experimental setups as well as to perform parametric studies for such proposed projects as the Space Station. Reference 12 describes a computer program intended for use as a research tool to isolate problem areas and to improve efficiency of computations associated with simulation. Figure 7 indicates one application of this program, called LATDYN for Large-Angle Transient Dynamics, which exists presently as a two-dimensional capability. The figure shows results of slewing a large mass (32 000 lbs) through an angle of 10^o. In this simulation, the Space Station is represented by modes and the arm is flexible, having characteristics similar to the remote manipulator system on the Space Shuttle. The maneuver incorporates analytically the slewing control demonstrated in the experiment of Figure 4. The motion of the 32 000 lb mass is shown to be quite smooth. In addition, dynamic responses are illustrated for two positions on the Space Station. One position is the tip of the transfer boom on which is located a fairly large mass which represents a solar dynamic power system. The other location is the middle of the upper boom. This location is seen to vibrate substantially as a result of the maneuver. Thus while the actual motion of the mass is very smooth, other parts of the structure may be stimulated to vibrate at fairly large ampitudes.

These results could have implications for micro-g experiments. Results of a similar maneuver on a so called "Block 1" Space Station configuration are shown in Figure 8. Again, while the motion of the mass is quite smooth, vibratory accelerations at the modules can be substantial. In addition, the results indicate that merely scaling vibratory amplitudes by a mass scaling law is not conservative.

Formulations implemented in a multibody dynamics program necessarily involve decisions concerning the degree of nonlinearity in the motion to be simulated. Figure 9 indicates that this nonlinearity must be incorporated in a very consistent manner. Otherwise, singularities and spurious results may occur. The simple problem depicted there, studied in Reference 22, indicates that spurious results can be obtained if nonlinear kinematics are not included properly. The particular result shown indicates that the physically unacceptable result of an infinite deployment time for the simple boom resulting from linear strain assumptions is accounted for properly in the formulation of the LATDYN program. The program currently is being extended to three dimensions.

Scaling of Lattice Structures

A part of the COFS program which was described in Reference 2 and depicted in Figure 10, is a scale model of the Space Station known as COFS III. The overall purpose of the COFS III program is to explore the use of scale models as a part of the certification process for large space structures. The basic concept involved in the use of scale models as a part of certification for large space structures is discussed in Reference 2. In this program, a model of the Space Station will be built, probably at 1/4 scale, and tested in a proposed facility known as the Large Spacecraft Laboratory shown in Figure 11. An investigation of the feasibility of such a model including variations on scale factor was conducted, Reference 23. Figure 12 indicates the variation of cost of such a model with scale factor. As can be seen from the figure, the 1/4-scale model costs less than the 1/5-scale model. This reduced cost is due to increases in precision required for the 1/5-scale model. Also, the figure shows that the cost of manufacturing such a model is dominated by precision requirements for joints. The assumption in this study is that precision requirements scale linearly with the scale factor. To investigate some of the limits and the quality required in such a model, tests were performed on specimens manufactured at different scales, Figure 13 (Refs. 24-25). Results of these tests shown in Figures 14 and 15 show that scaling of graphite/epoxy construction down to 1/4 scale presented little difficulty from the standpoint of quality of the scaled tube. Figure 15 shows results of static tests of some scaled joints compared to full-scale joint data. In general there is a softening of the scaled stiffness relative to full-scale results, indicating that some loss in precision is present in the manufacturing of these specimens. Figure 16 shows some comparisons of damping. Results are surprisingly consistent. The scaled data generally fall within the scatter of the data usually obtained in damping tests.

Control of Flexible Structures (COFS) Beam Redesign

The Control of Flexible Structures (COFS) program involves a flight to orbit of a beam approximately 60m long. This beam is deployable, contains a heavy concentrated mass at the end, a parameter modification device which can be used to couple and tune directional responses in modes, and an excitation/damping system. The original design had no strain in the packaged state and no strain in the deployed state. However, intermediate states of deployment involve significant strains. An evaluation of these strains, Figure 17, showed that they were too high to be acceptable. The figure shows a comparison of three analyses of the deloyment, all of which are in general agreement. The loads shown are significant, corresponding to strains as high as 0.5 percent. As a result of this situation, an activity was begun to evaluate other designs to find a design which would involve acceptable strains. Results of this study are summarized in Figure 18 which shows results of optimization of the structure with multiple design constraints. The plot indicates convergence after about eight cycles of the design process. In this design problem, the weight of the structure was used as the objective function. Constraints were that the first torsion and second bending modes were to be within a specified degree of closeness. The purpose in designing a beam with closely spaced frequencies is to challenge system identification procedures which will be used in the orbital test. Other constraints were that the first bending frequency must be greater than or equal to 0.18 Hertz to avoid coupling with the Space Shuttle control system, and that the diagonal frequency must be greater than 15 Hertz. Although an optimum beam design could be found using these parameters, the strains involved were still too large to be acceptable and so a change in the design, introduction of batten hinges, which significantly lessened strains was implemented.

Hoop-Column Test-Analysis Correlation

Antenna structures vary greatly in the variety of structural concepts. The structures vary widely in size and in weight because of the great range of mission requirements. One such antenna concept is the hoop and column antenna pictured in Figure 19. This particular structure originally was intended to be a 1/8-scale model of an antenna which would be used for mobile satellite communications. It was built primarily to demonstrate deployment kinematics. The hoop folds alternately up and down at the joints while the central mast telescopes. The mast and ring are held in proper relative position through the use of cables and the mesh is shaped by another cable system. As part of the test for this antenna, radio frequency (RF) tests were performed. After RF tests, structural dynamics testing was conducted at the NASA Langley Research Center. Some results of the testing are shown in Figure 20 with more detail given in Reference 27. The figure indicates a discrepancy between the original analysis and the test data. Such discrepancies for new structural concepts are common and should be expected. After these discrepancies appeared, procedures were initiated to determine reasons for the discrepancies and static tests were conducted on various components as a result. After variations in joint stiffness and variations in cable tension from nominal values were incorporated in the analysis, analysis and test showed good correlation. These results indicate the continuing need for test programs in structural concept development. Tests were conducted both in vacuum and in air. Results show that for this antenna concept there is little effect of the air either on damping or the structural dynamic characteristics.

Concluding Remarks

Recent results and activities related to the structural dynamics and vibration control of large space structures, concentrated primarily on work at the NASA Langley Research Center, has been reviewed and summarized. Topics discussed include system identification, large angle motions of flexible structures, scaling, optimized design with constraints, and analysis-test correlation on a new antenna concept.

Significant progress has been made recently in system identification because of the placement of various methods on a common theoretical basis. This development has resulted from the synergism possible in multidisciplinary research, in this case from the application of theory developed in the controls community to system identification approaches used in the structural dynamics community. Thus differences in various methods applied to linear systems relate to variations in data characteristics.

Both experimental and theoretical results in large angle slewing of flexible structures indicate significant progress. A progression from relatively simple to more complex laboratory experiments has been accomplished in which algorithms for accomplishing large angle articulation have been demonstrated in the presence of real hardware effects such as actuator backlash and computational delays. A two-dimensional version of a computer program being developed for research purposes is operational. A three-dimensional version presently is being programmed. The primary purpose of this program is to help indicate areas which need theoretical development or which need improvements in numerical accuracy or speed.

Application of scale models to the certification process for large space structures is under investigation. Experimental efforts with scaled specimens indicate that models of significantly reduced size are feasible for structures of a type applicable to the space station. Low frequencies inherent in these models, which are large even at scaled size, require that testing be conducted on suspensions that extend to large heights. A facility which would permit such testing is proposed.

Optimum design principles have been successfully applied to a practical structure. This redesign has been accomplished in the presence of multiple constraints on natural frequencies. These constraints require that certain frequencies be greater than specified values and that proximity of certain frequencies be maintained.

An extensive program in which the dynamics of a new antenna concept were studied both analytically and experimentally demonstrates the need for extensive testing of new structural concepts. Significant pretest errors resulted from the inability to account a priori for effects such as joint compliance.

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Algorithm \ Application*	Free decay	Forced response	Small computer	On-line	Rapid analysis	High accuracy
Original ERA	X				X	X
Frequency domain ERA		X	X			X
Recursive ERA	X			X	X	
Data correlation ERA	X		X			X

*Assumes noisy data

Fig. 1 Summary of developments in system identification which employ the Eigensystem Realization Algorithm.

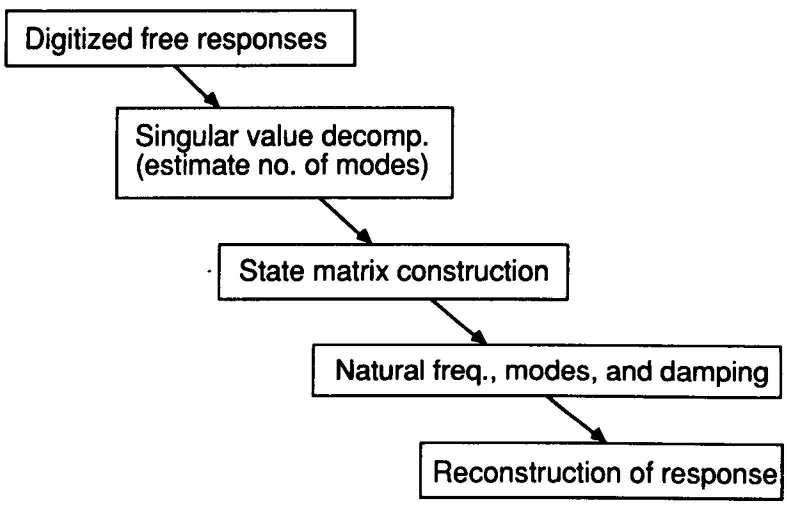
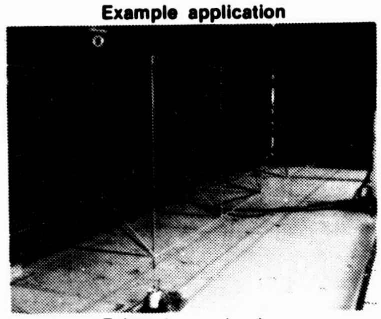


Fig. 2 Flow chart for Eigensystem Realization Algorithm.

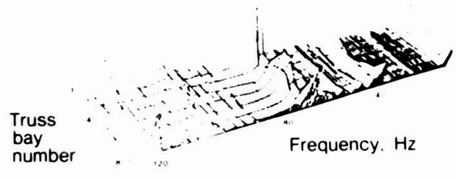
Improvements

- Direct solution without curve fitting
- Applicable with high damping
- Multi-input and multi-output capability
- Narrow-band analysis
- Lower computation and storage requirements
- Works with forced systems (not free-decay)

Example application



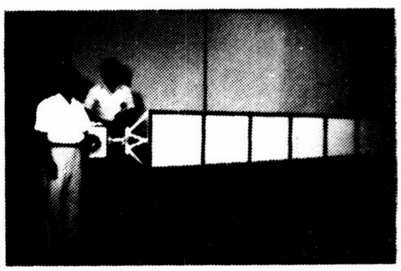
7 bay truss structure



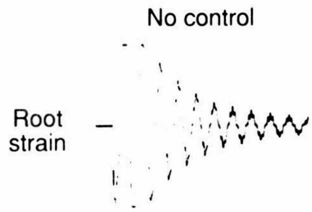
Frequency response

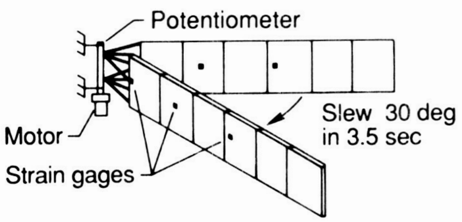
Fig. 3 Characteristics of the Eigensystem Realization Algorithm with frequency-domain data.

Test set-up



13-foot long aluminum/honeycomb panel





Experiment

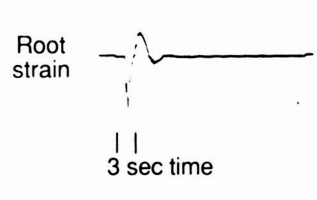


Fig. 4 Slewing control for single flexible panel with and without vibration control.

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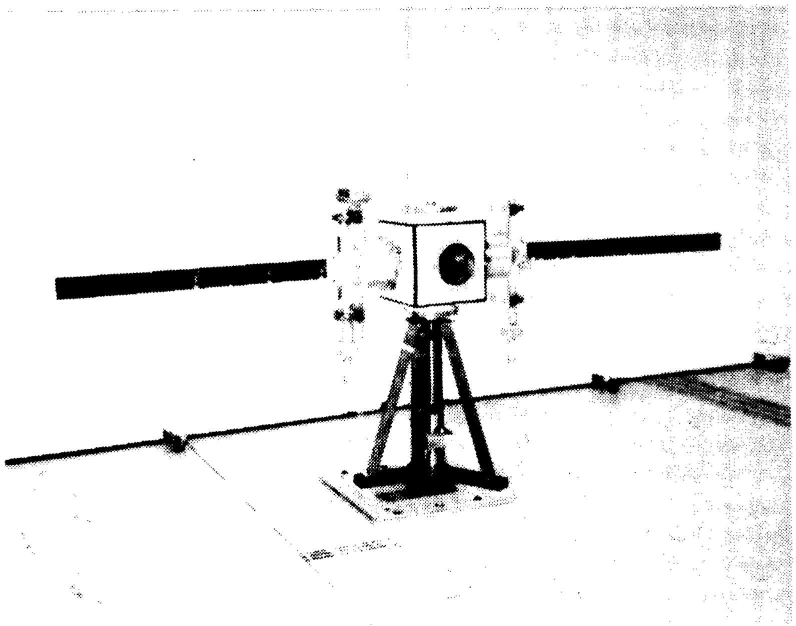

Fig. 5 Apparatus for slewing of multiple bodies with and without vibration control.

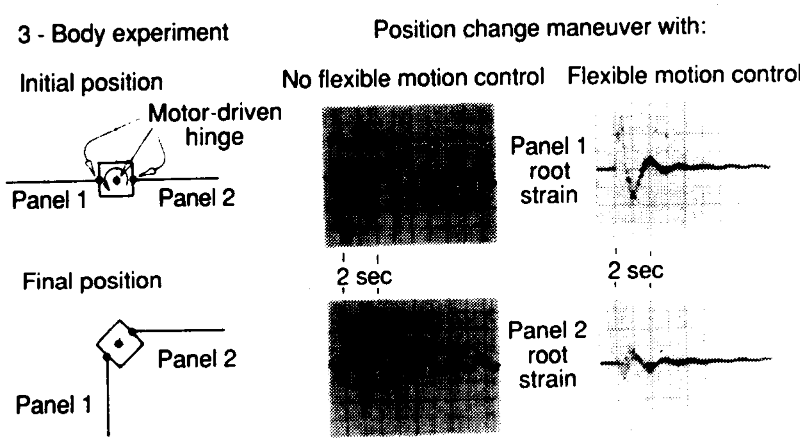

Fig. 6 Results of a slewing maneuver executed on multiple body slewing apparatus.

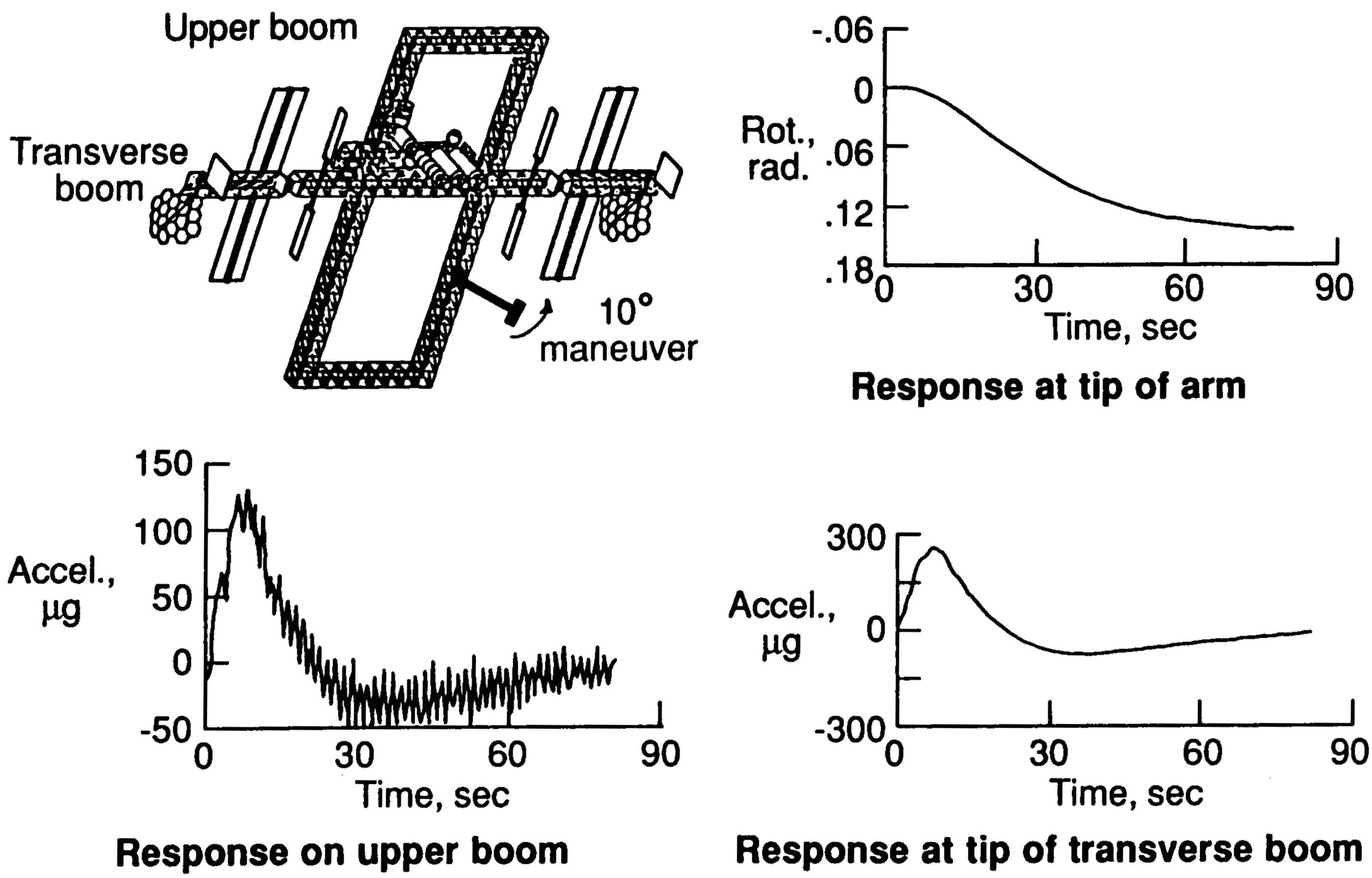

Fig. 7 Results of LATDYN program analysis of movement of a large mass by a manipulator system on the dual-keel Space Station.

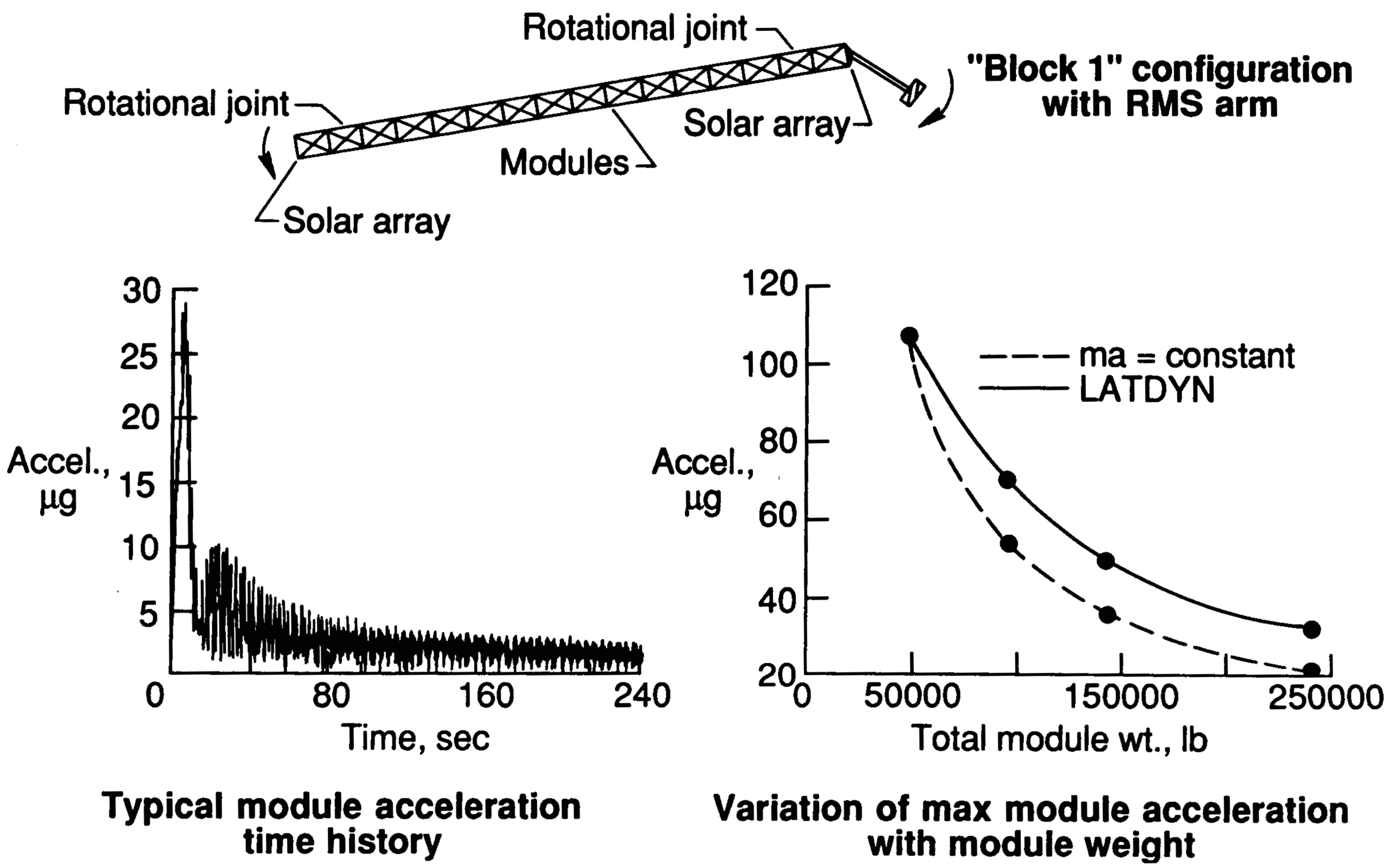

Fig. 8 Results of LATDYN program analysis of movement of a large mass by a manipulator system on the block 1 Space Station configuration.

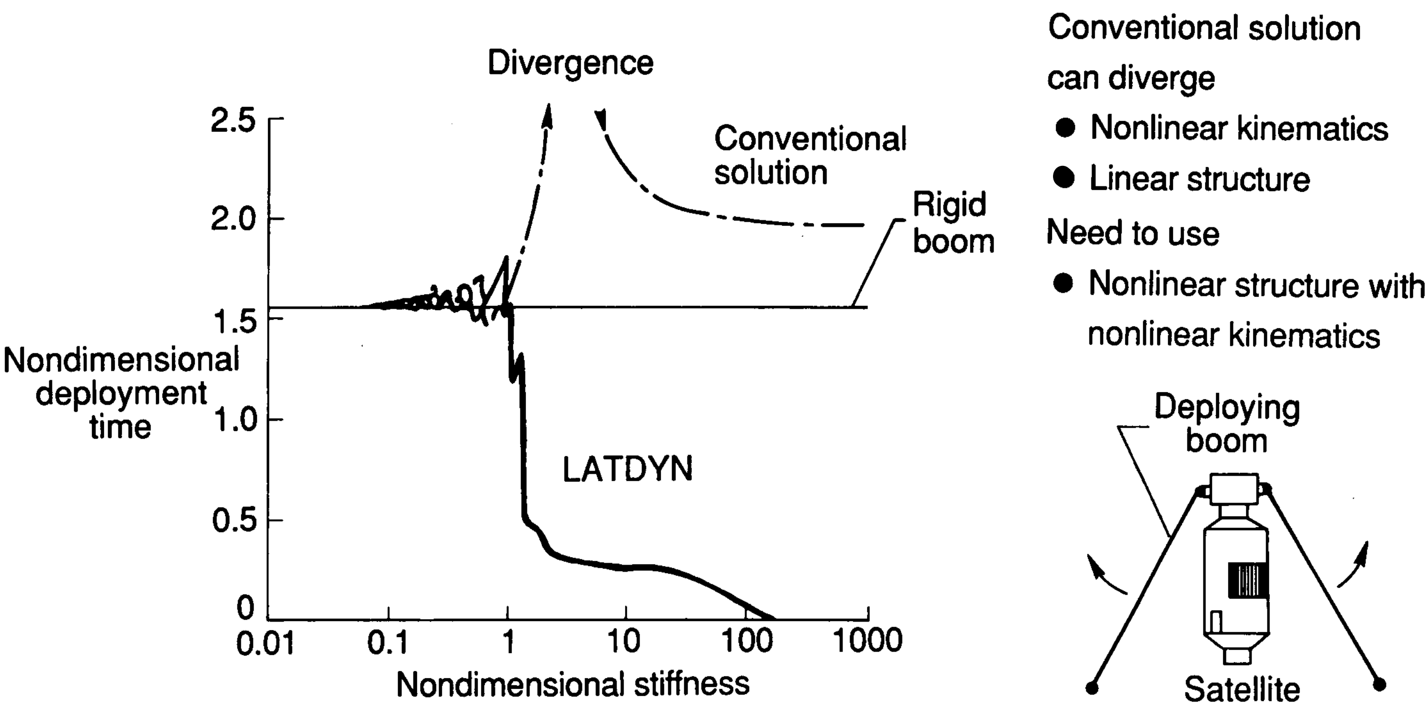

Fig. 9 Results of deployment analysis of symmetrical flexible booms illustrating need for precision kinematics.

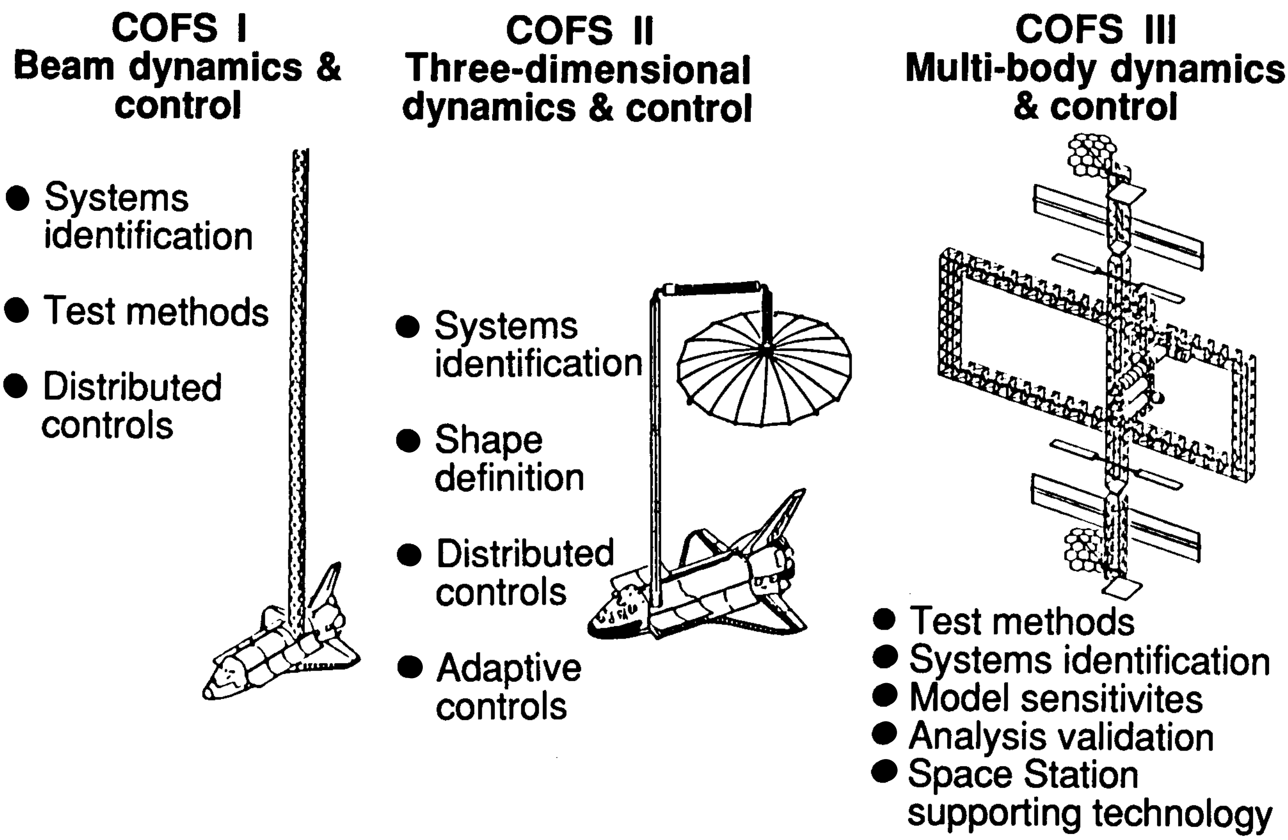

Fig. 10 Overall definition of Control of Flexible Structures (COFS) Program.

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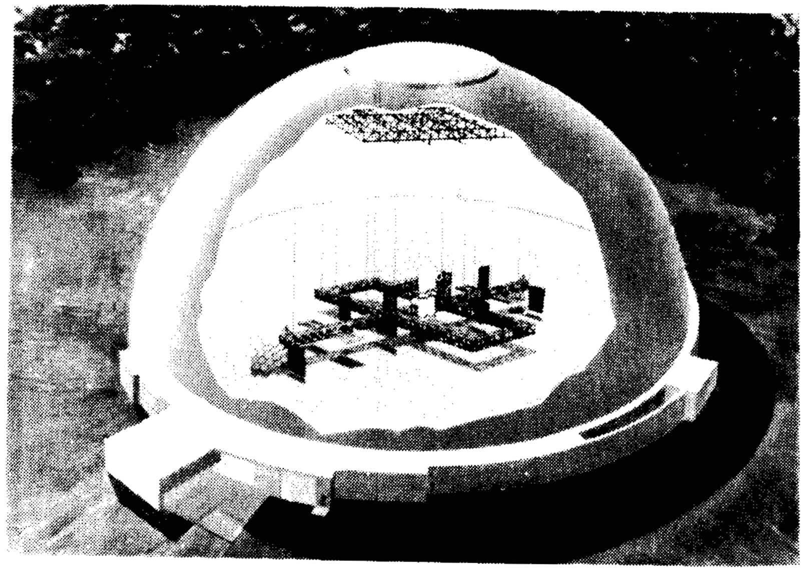

Fig. 11 Artist sketch of proposed Large Spacecraft Laboratory showing scaled Space Station model on suspension.

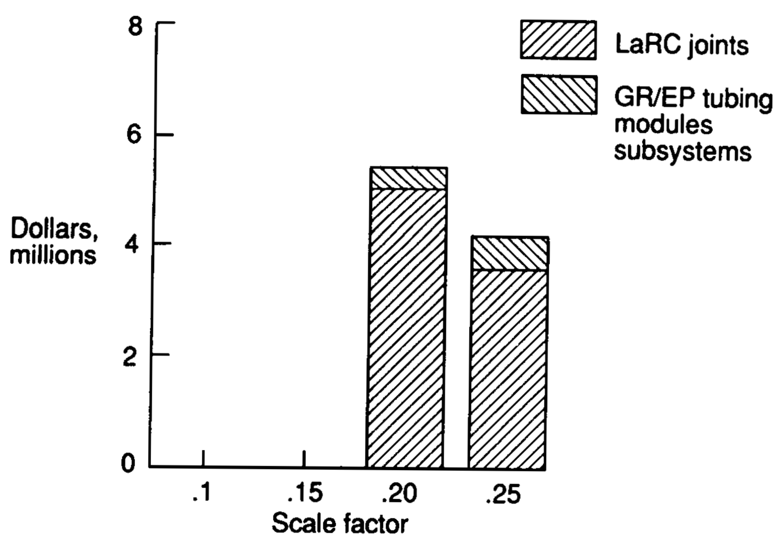

Fig. 12 Some results of feasibility study for Space Station scale model.

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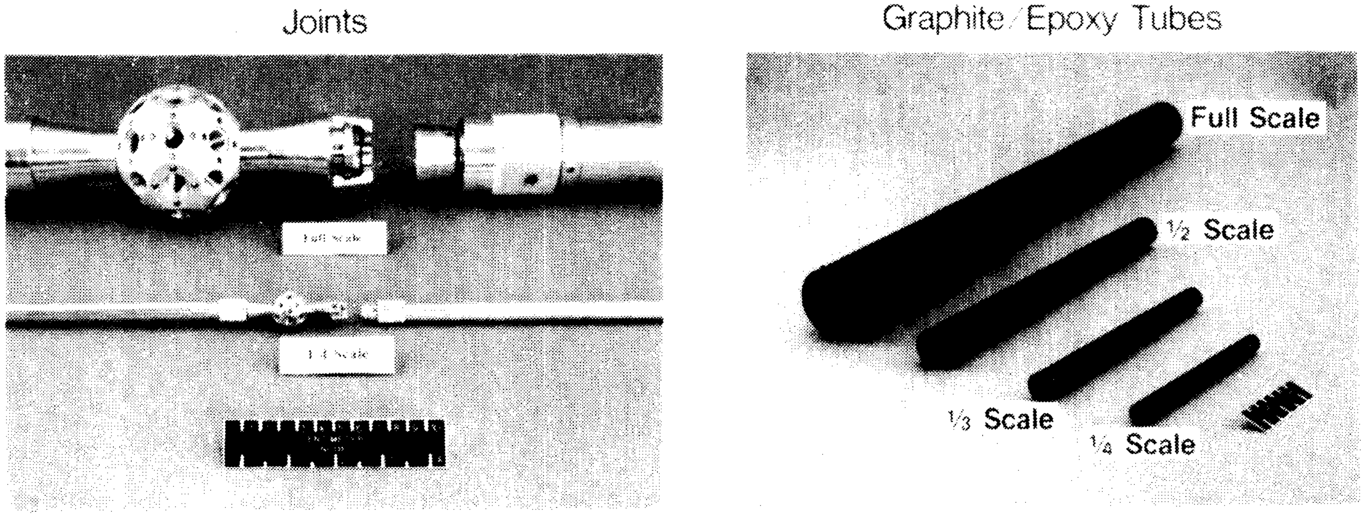


Fig. 13 Examples of structural specimens used for definition of scaling limits.

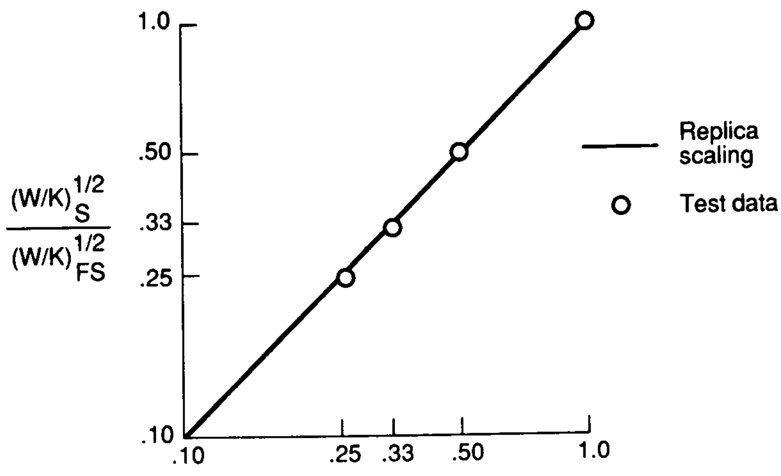
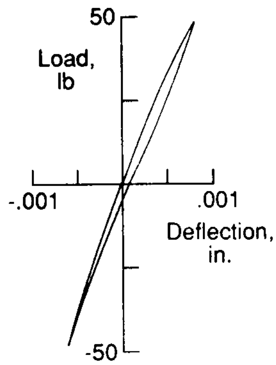


Fig. 14 Results of graphite-epoxy tube scale model tests indicating good scaling quality.

Typical joint static test data



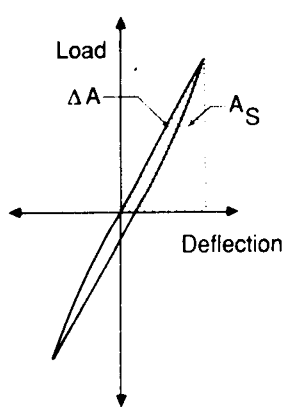
Scaled joint axial stiffness (K)

$$K = \frac{1}{\lambda}\,(EA/L)$$

Joint scale factor, λ	Avg K (lb/in.)	% Diff.
1	246,000	-
1/3	231,696	6
1/4	201,000	18

Fig. 15 Results of scaled joint tests indicating feasibility of scaling joints.

Typical static load - deflection test data



Damping loss factor (LF)

$$LF = \frac{\Delta A}{2\pi A_S}$$

Joint	Avg LF	% Diff.
Full scale	.030	-
1/3 scale	.026	13
1/4 scale	.040	33

Fig. 16 Assessment of loss factors in scaled joints showing good correlation of scaled and full-scale test results.

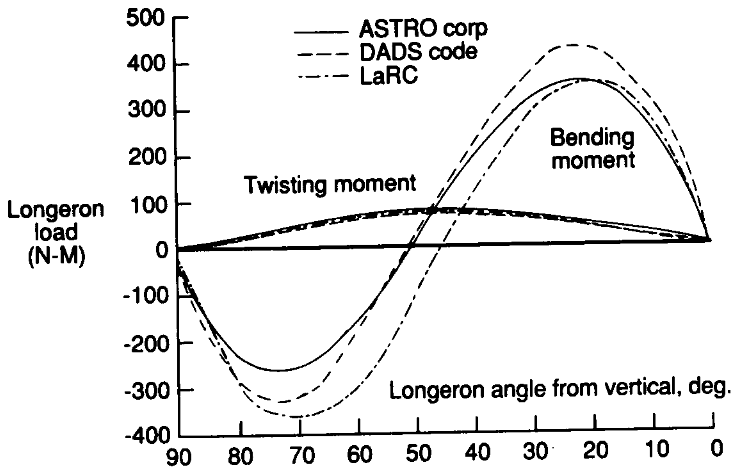


Fig. 17 Comparison of loads developed in longerons during deployment of original COFS truss configuration.

Requirements
- No diagonal buckling
- Member frequency >> mast frequency
- Minimum gage, e.g., wall thickness > 0.56 mm
- Lowest mast frequency ≥ 0.18 Hz
- 1st torsion and 2 bending frequencies within 1%

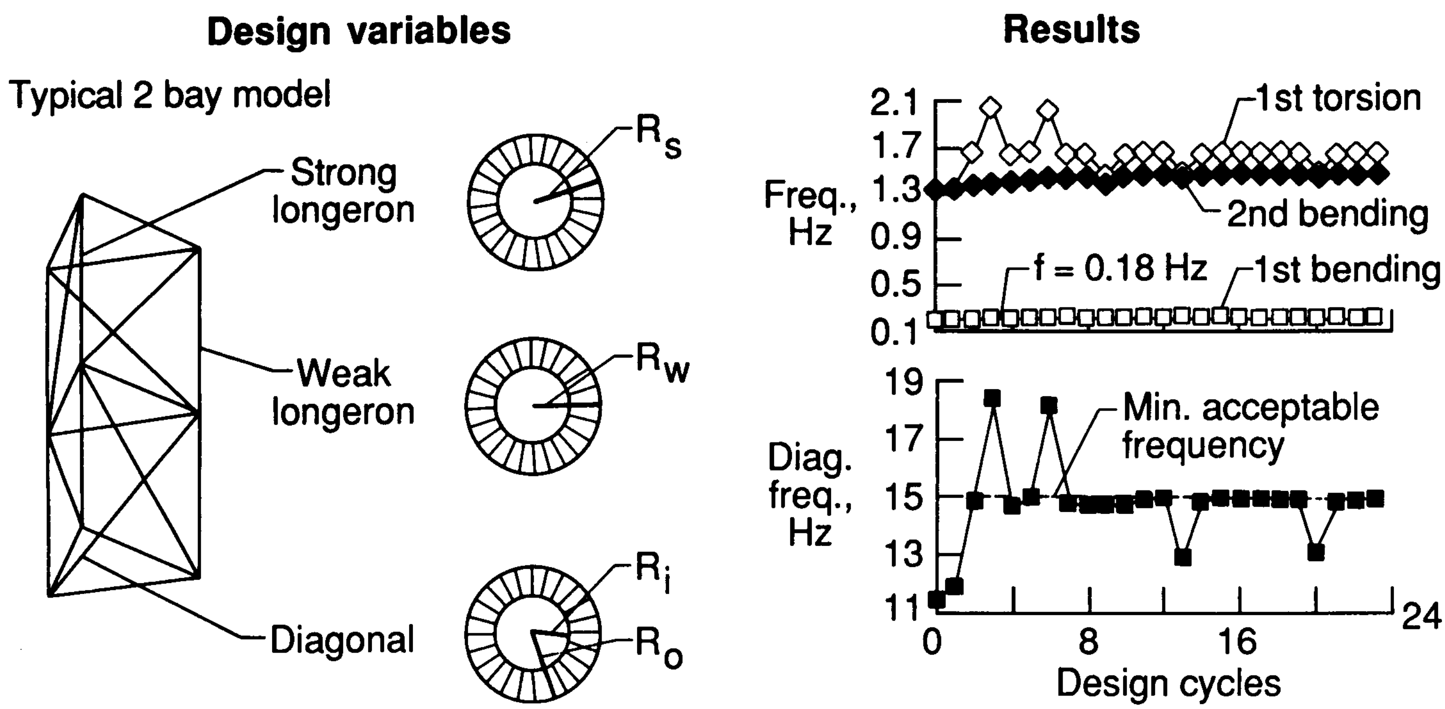


Fig. 18 Summary of optimization of COFS I truss design with multiple constraints.

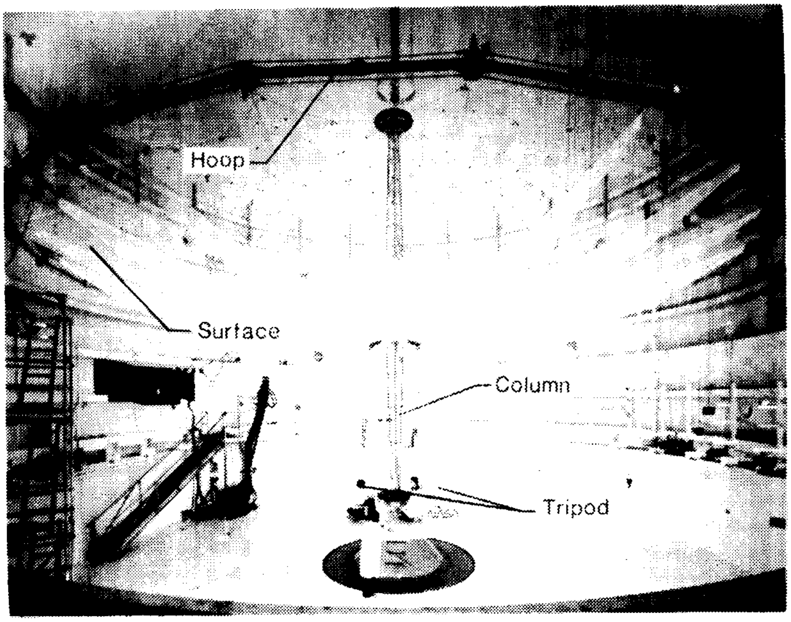
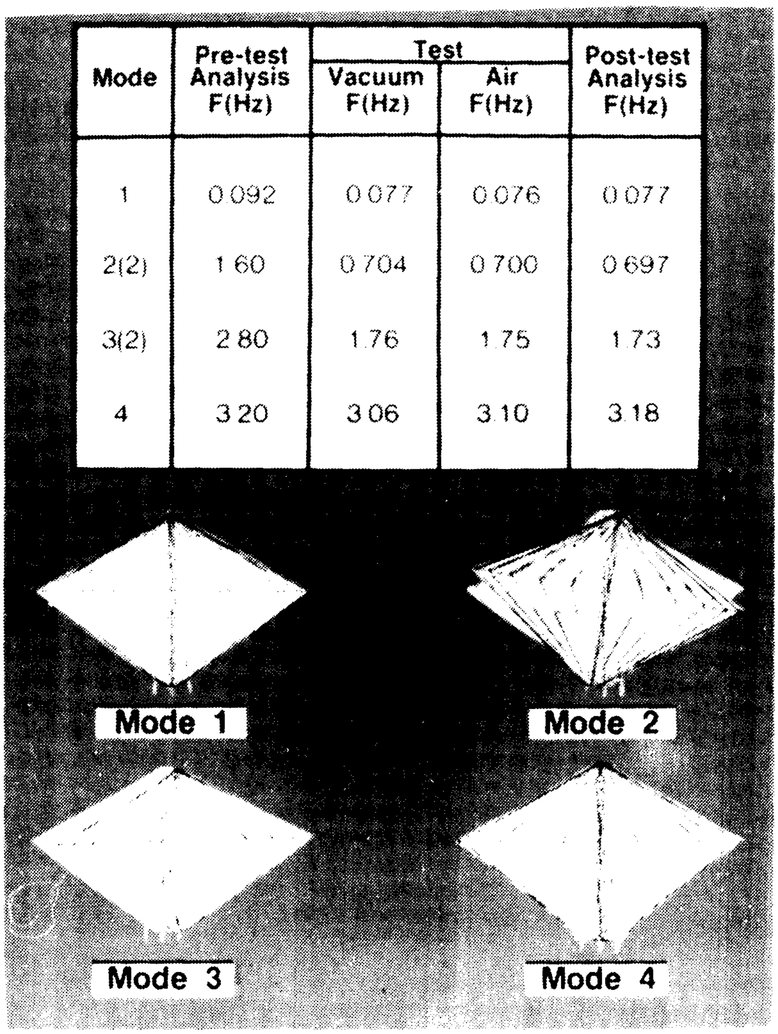


Fig. 19 Fifteen-meter hoop column multi-aperture antenna.



Mode	Pre-test Analysis F(Hz)	Test: Vacuum F(Hz)	Test: Air F(Hz)	Post-test Analysis F(Hz)
1	0.092	0.077	0.076	0.077
2(2)	1.60	0.704	0.700	0.697
3(2)	2.80	1.76	1.75	1.73
4	3.20	3.06	3.10	3.18

Fig. 20 Results of pre- and post-test analyses of new hoop-column antenna concept.

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16. Abstract

Recent progress in the area of structural dynamics of large space structures is reviewed. Topics include system identification, large angle slewing of flexible structures, definition of scaling limitations in structural models, and recent results on a tension-stabilized antenna concept known as the hoop-column. Increasingly complex laboratory experiments guide most of the activities leading to realistic technological developments. Theoretical progress in system identification based on system realization theory resulting in unification of several methods is reviewed. Experimental results from implementation of a theoretical large-angle slewing control approach are shown. Status and results of the development of a research computer program for analysis of the transient dynamics of large angle motion of flexible structures are presented. Correlation of results from analysis and vibration tests of the hoop-column antenna concept are summarized.

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