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GROUND TEST OF LARGE FLEXIBLE STRUCTURES

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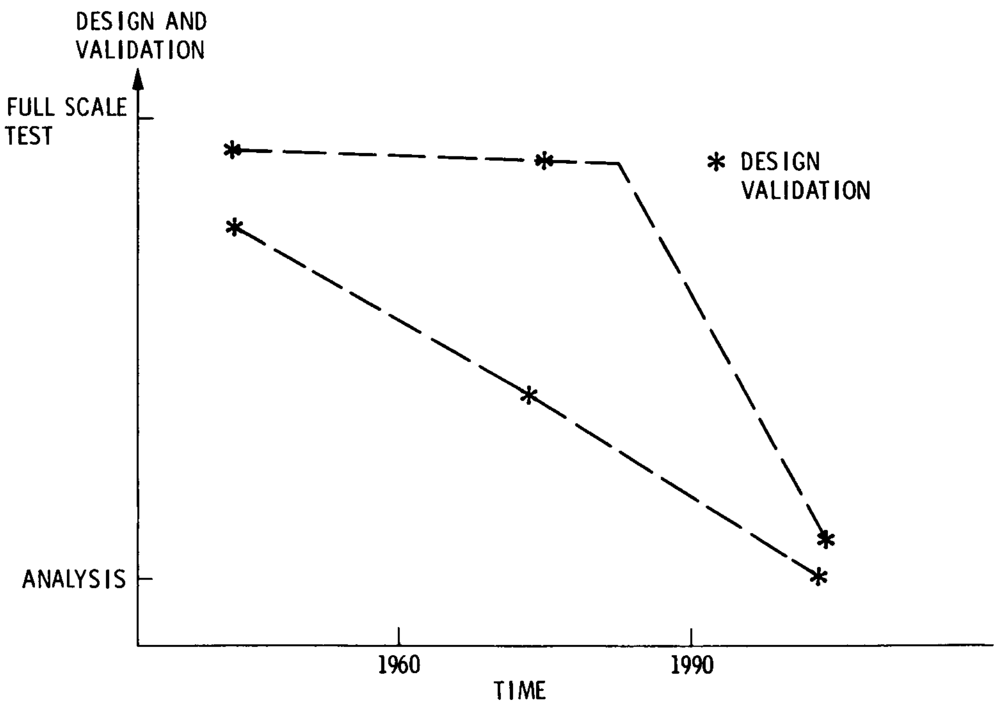
MOTIVATION

Many future mission models require large space structures which have accurate surfaces and/or the capability of being accurately aligned. If ground test approaches which will provide adequate confidence of the structural performance to the program managers are not developed, many viable structural concepts may never be utilized. The size and flexibility of many of the structural concepts will preclude the use of the current state-of-the-art ground test methods because of the adverse effects of the terrestrial environment (atmosphere, gravity, etc.). The challenge is to develop new test approaches which will provide confidence in the capability of large space structures to meet performance requirements prior to flight. The development of ground test methods for large space structures is one of most significant challenges to the structural dynamicists to meet the needs of future space structures.

The objective of this paper is to describe the activities at JPL on ground testing of large space structures. Since some of the proposed structural systems cannot be tested in entirety, a coordinated ground test/analytical model program is required to predict structural performance in space. This paper addresses selected concepts under development at JPL.



STRUCTURAL VERIFICATION

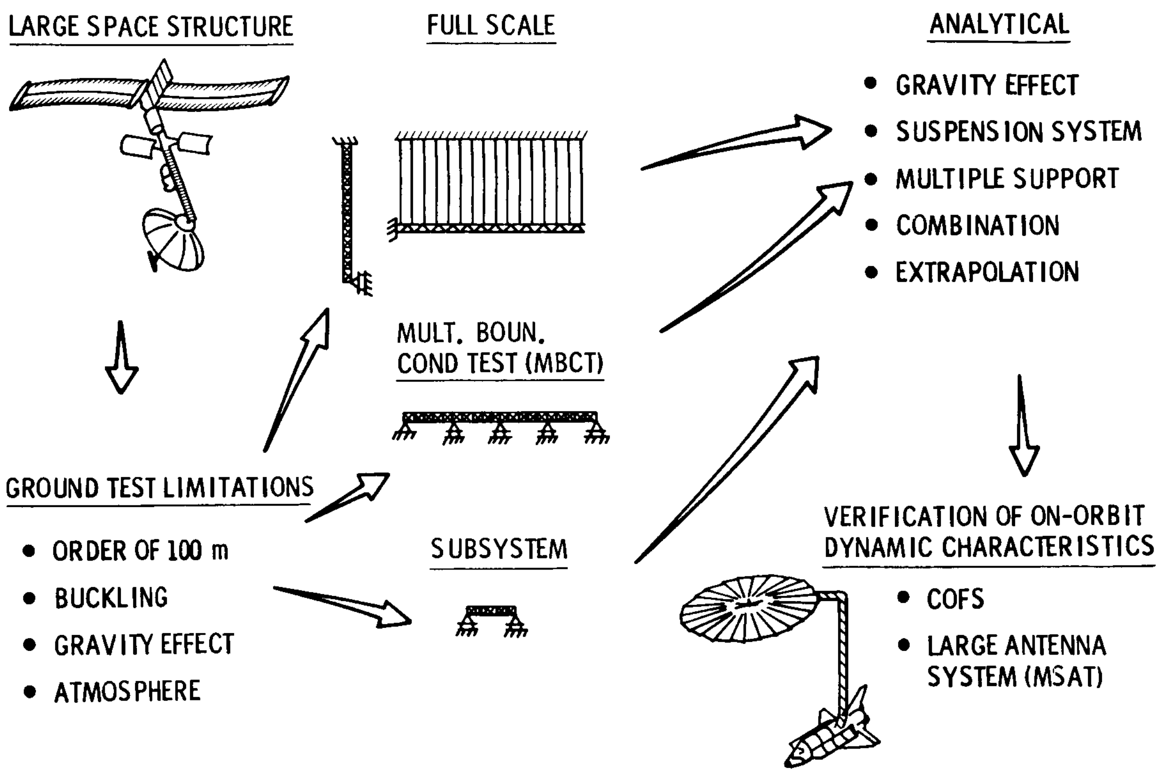
When large flexible space structures cannot be ground tested in an operational configuration because of the adverse terrestrial environment (such as gravity and air), a ground test program must be developed to validate a mathematical model which in turn can be used to demonstrate the performance of the total structural system in space.

The two approaches most often used are to either test the full-scale structure using artificial restraints with the objective of simulating the operational configuration or to ground test some or all of the subsystems comprising the total system. The removal of the effects of the artificial restraints from the full-scale test or the assembly of the subsystems to predict the dynamic response of the full-scale hardware is accomplished by analysis. A third approach referred to as the Multiple Boundary Condition Tests (MBCT) is a hybrid of the two approaches where the total structure is tested, but the objective is to use artificial restraints to allow for good ground test data and to obtain added test data by utilizing a large number of different sets of artificial restraints. The analysis procedure is then to update and validate the analytical model using a large number of experimental data and to remove the influence of the artificially imposed boundary conditions.

Finally to validate the techniques, the ground-tested hardware along with its analytical prediction should be tested in space to validate the approach. Confidence in the technology to combine ground tests along with analytical models to accurately predict the on-orbit dynamics will increase our ability to design and fly large space structures to meet future space program challenges.

In this paper, the basic ideas which form the foundation of the research at JPL in structural verification by ground tests will be presented. Since many investigators have evaluated full-scale testing approaches, this paper concentrates on the MBCT and some aspects of subsystem tests.

STRUCTURAL VERIFICATION



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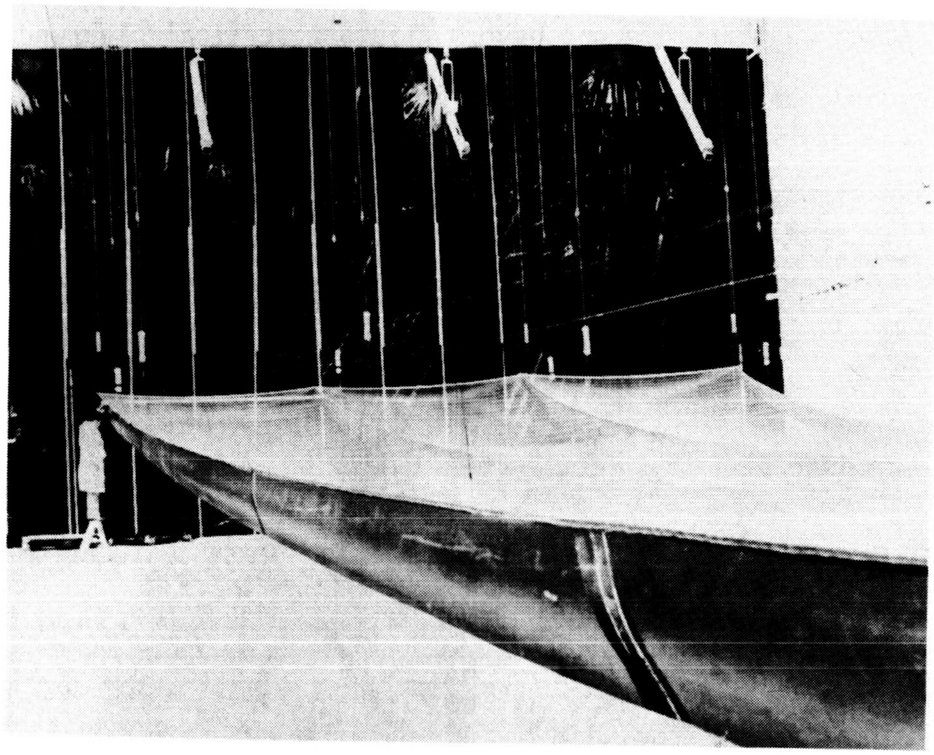
WRAPPED RIB ANTENNA

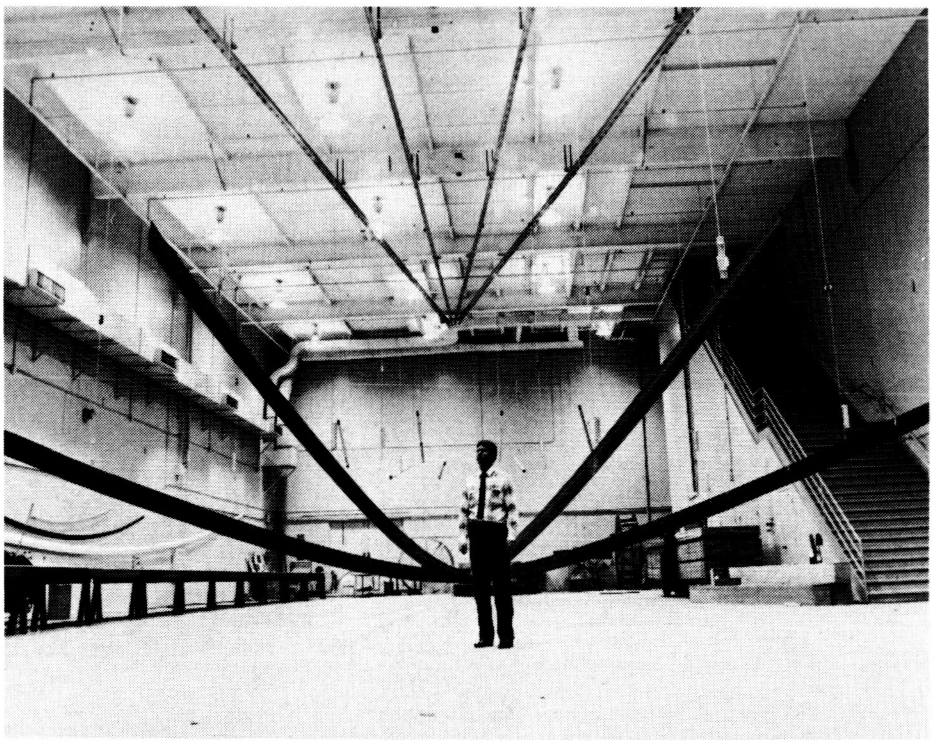
This figure represents a sector of a wrapped rib antenna built under contract to JPL by LMSC Co. The sector is part of a 55-meter-diameter antenna and thus is approximately 27 meters in length. Since the antenna could not survive the 1-g gravitational field, it was supported along each rib by about 7 suspension cables. The affect of the gravitational field on distorting the structural characteristic can be seen by the "sag" in the lightweight mesh which must be near horizontal in space to meet its desired performance.

One of the objectives of this program was to evaluate different ground test methods from which experimental data could be used to help.



Rather than to initially explore ground tests methods to validate a sector of the rib, the goal was to ground test a single rib of the antenna. After observing the adverse affects of the terrestrial environment on the very large flexible structure, the difficulty of performing a meaningful ground test seemed to be a formidable task. The initial goal was to test a single rib in a configuration that simulated the in-orbit configuration. Subsystem test concepts for a single rib were not feasible because the structure was one continuous graphite/epoxy structure which could not be divided into subsystems without cutting the structure. Test methods considered included incorporation of active controls in the suspension system to eliminate their affects and vertically suspending the rib in a vacuum chamber. Neither appeared feasible within the available funds and schedule. The active control of the suspension system appeared to be a technical development program in itself, and the existing known vacuum chambers did not have sufficient vertical clearance.

One quickly concluded, after observing the vibration of a single rib which was supported by cables, that meaningful vibration data couldn't be obtained by testing in the configuration.



OPERATIONAL STRUCTURE SYSTEMS TEST

In many of the modal tests of the operational configuration performed to date, the objective has been to measure the largest number of mode shapes and frequencies and to attempt to identify the parameters (mass and stiffness) which should be modified to correlate the mathematical model with the test data. Difficulties exist in obtaining accurate test data as the mode number increases, and the sources of errors are difficult to isolate and identify because the number of parameters in the mathematical model may be in the tens of thousands and the number of experimental data may be in the hundreds.

B.C.* = 0

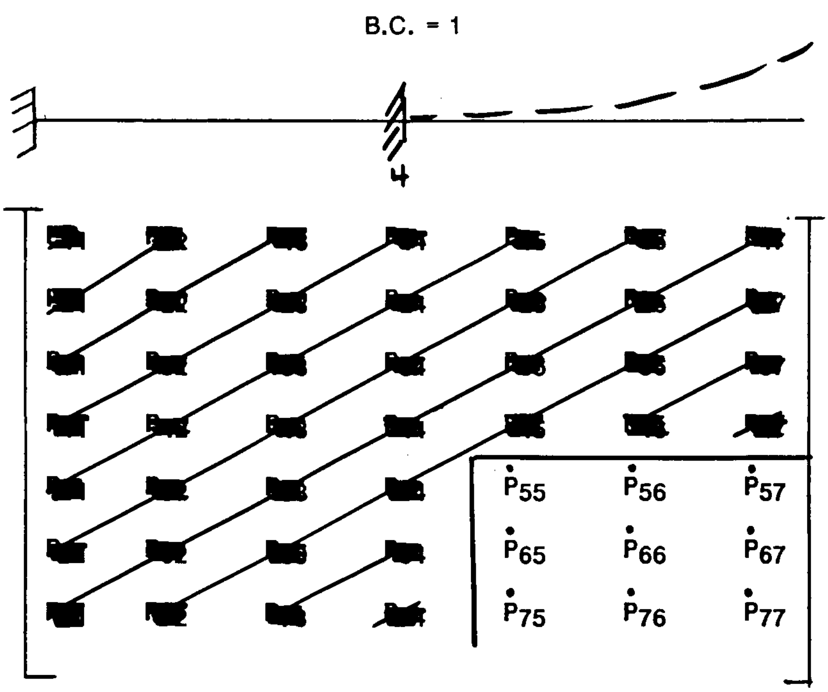
$$\begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} & P_{16} & P_{17} \\ P_{21} & P_{22} & P_{23} & P_{24} & P_{25} & P_{26} & P_{27} \\ P_{31} & P_{32} & P_{33} & P_{34} & P_{35} & P_{36} & P_{37} \\ P_{41} & P_{42} & P_{43} & P_{44} & P_{45} & P_{46} & P_{47} \\ P_{51} & P_{52} & P_{53} & P_{54} & P_{55} & P_{56} & P_{57} \\ P_{61} & P_{62} & P_{63} & P_{64} & P_{65} & P_{66} & P_{67} \\ P_{71} & P_{72} & P_{73} & P_{74} & P_{75} & P_{76} & P_{77} \end{bmatrix}$$

*Boundary condition (BC)

MULTIPLE BOUNDARY CONDITION TEST (MBCT)

In an attempt to determine an alternate test approach to validate the mathematical model of a rib of the wrapped rib antenna, the concept of the MBCT approach was devised. A subsystem test approach could not be directly used because the continuous rib could not be physically "cut" for the subsystem tests.

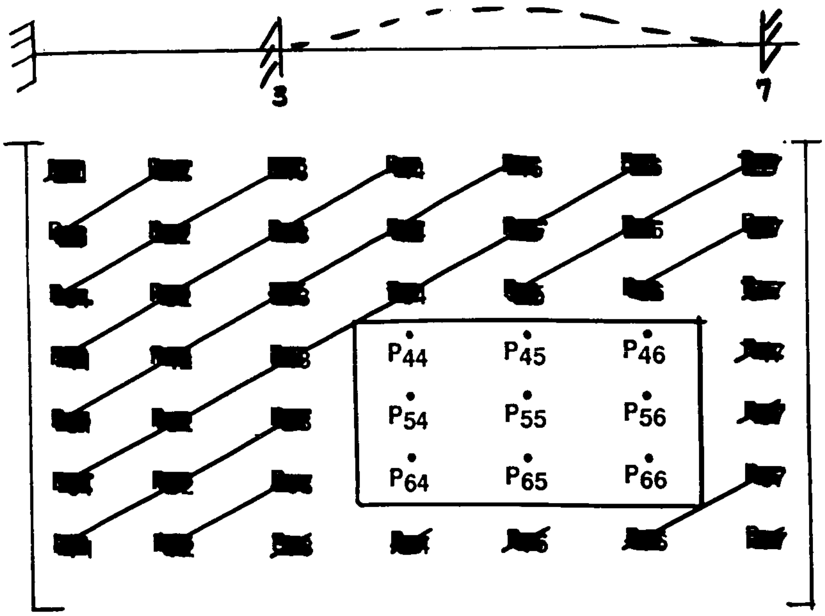
The approach is to place artificial restraints along the structure in order to measure valid ground test data. In this example, when the artificial restraint is placed at node four, the dynamic test of the structure will only impact the parameter terms in the lower right-hand corner. Thus with this set of data, one estimate of the analytical parameters can be more easily obtained.



ANOTHER SET OF RESTRAINTS

If another set of restraints is selected, the resulting test data only affect another subset of the total mathematical model of interest. Note that in Boundary Condition (BC) #2, the updated terms of the mathematical model are shown. The engineer can arbitrarily select the restraints in order to isolate and concentrate on the parameters that are considered to be significant.

B.C. = 2

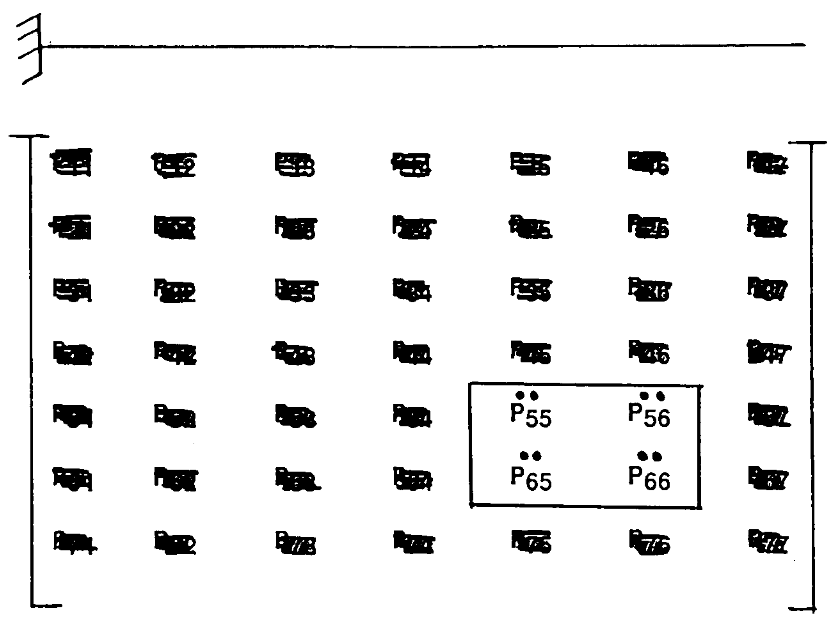


COMBINING THE RESULTS FROM TESTS PERFORMED
ON BC #1 AND BC #2

Note that by combining the results of the updates of the mathematical terms from tests of BC #1 and BC #2, two estimates of the parameters associated with nodes 5 and 6 are obtained. By extending the steps illustrated, a large number of estimates of any parameter can be obtained by the selection of the restraints. The large number of parameter estimates can be obtained by obtaining a large number of modes from a few tests or a small number of modes from a large number of tests with various restraints.

A statistical analysis has indicated that by using the MBCT approach, a better estimate of the parameters can be obtained than if good test results from a modal test of a large space structure can be obtained.

B.C. = 1,2



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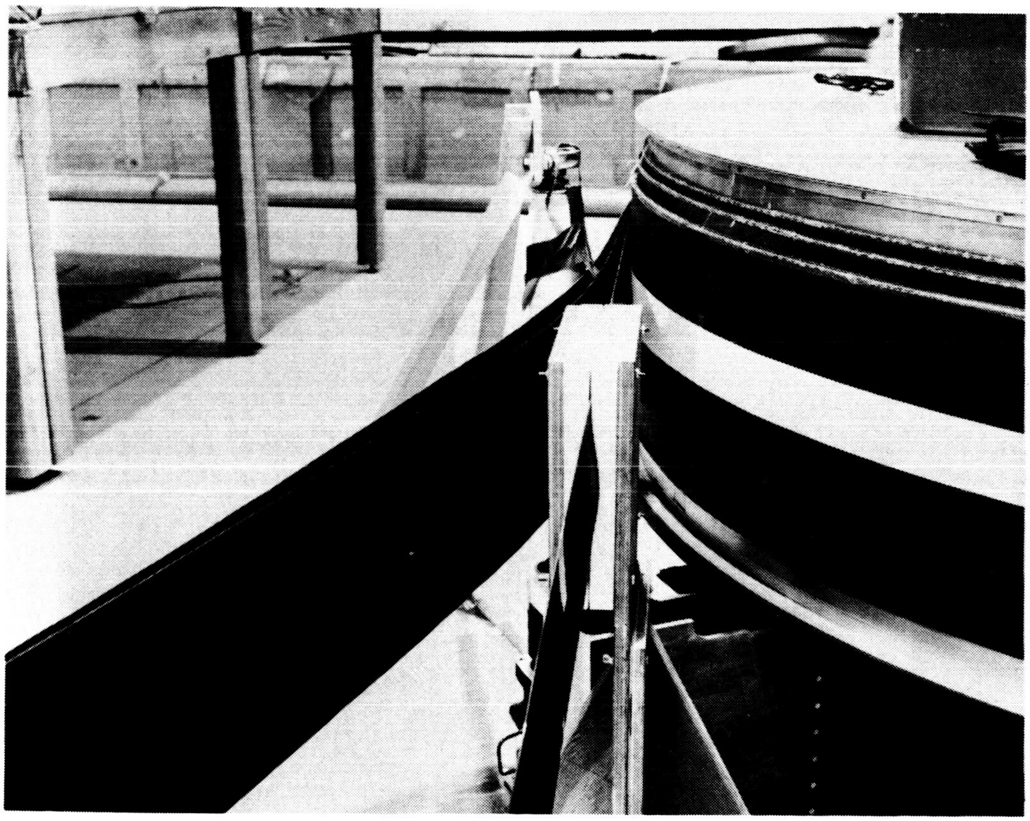
CAN TESTS REQUIRED FOR THE MBCT BE PERFORMED?

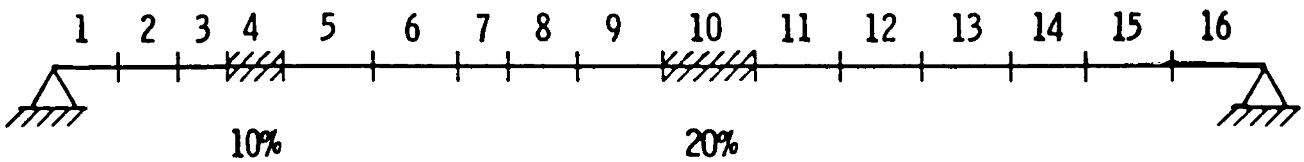
Since the concept of the MBCT is only valuable if the tests necessary to obtain good experimental data can be performed, a modest test program was undertaken. As noted in this figure, sectors of the antenna rib were clamped at the discretion of the engineer. The objective was to constrain the hardware to alleviate the adverse terrestrial conditions and yet obtain good meaningful data. A large number of different boundary conditions were imposed, and excellent data were readily obtained; in fact, the extremely low stiffness of the overall structure helped in the constrained tests. The lowest resonant frequencies with the restraints were approximately 10 Hz., and meaningful static displacements were measured. Within a 2-day period, up to 30 different restraint conditions were tested for the first two modes. The accuracy of the experimental data appeared to be good. The test indicated the ease by which a limited number of modes could be obtained for a large number of conditions with various restraints. Our experience validated the ability to obtain good reliable test data for the MBCT approach.



SAMPLE PROBLEM

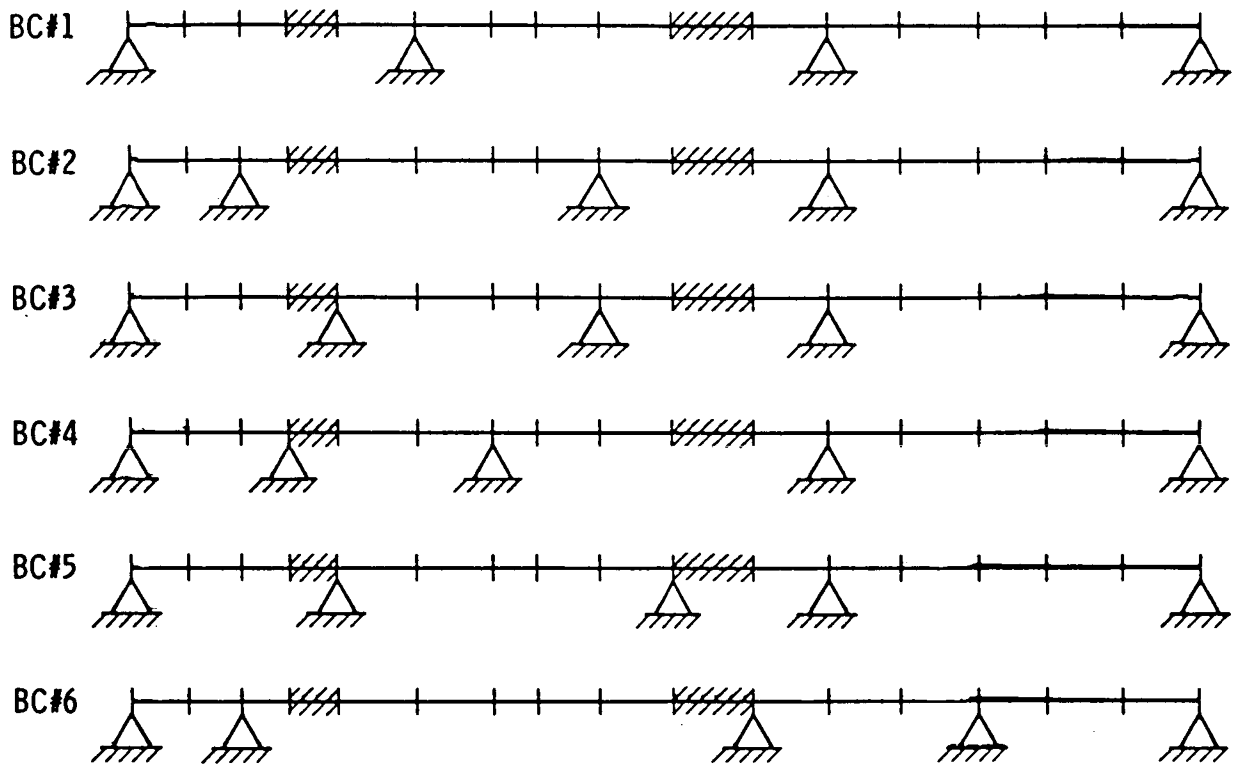
A numerical simulation of the MBCT approach was performed to validate the approach. The beam consists of 16 beam elements and is simply supported at both ends. The objective is to find the 10-percent error in element 4 and the 20-percent error in element 10 using the MBCT approach.

CURRENT APPROACH



MBCT CONDITIONS

In the simulation study, the following arbitrary restraints were selected. Although six different boundary conditions are shown, only two will be used in this paper.



C-4

SIMULATION RESULTS

This chart shows that if a conventional modal test could be performed, then the errors in the mathematical model could be corrected to within 96 percent in two test/analysis update iterations. However using the MBCT approach of using 2 to 5 frequencies from each of the first two MBCT configurations, the mathematical model could be corrected to within 99 percent with the same amount of effort.

ESTIMATED PARAMETERS, ITERATIONS 1 AND 2 ΔI_4 AND ΔI_{10} (THEORETICAL VALUES $\Delta I_4 = 0.00834$, $\Delta I_{10} = 0$)

(CASE 2)

CASE	ITERATION 1		ITERATION 2		CONFIGURATION
a ΔI_4	0.005897	71%	0.007971	96%	CONVENTIONAL MODAL TEST
ΔI_{10}	0.000657		0.000523		10 FREQUENCIES TOTAL
b ΔI_4	0.007031	84%	0.008166	98%	MBCT CONFIGURATION 1-2
ΔI_{10}	0.000323		0.000034		10 FREQUENCIES TOTAL
c ΔI_4	0.007690	92%	0.008268	99%	MBCT CONFIGURATION 1-2
ΔI_{10}	0.000028		-0.000006		8 FREQUENCIES TOTAL
d ΔI_4	0.006322	76%	0.008273	99%	MBCT CONFIGURATION 1-2
ΔI_{10}	0.000881		-0.000030		6 FREQUENCIES TOTAL
e ΔI_4	0.005358	64%	0.008255	99%	MBCT CONFIGURATION 1-2
ΔI_{10}	0.000678		-0.000012		4 FREQUENCIES TOTAL

INFLUENCE OF TERRESTRIAL ENVIRONMENT ON THE DYNAMICS OF STRUCTURES

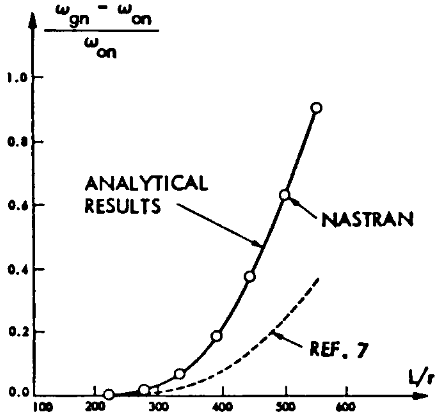
Another important consideration in the ground validation of structures is to establish the ground test conditions under which the terrestrial environment can adversely affect the test results. These data are of value in establishing the artificial boundary conditions in the MBCT approach or in subsystem testing.

The efforts are to investigate the influence of the forces in the structure and structural displacement due to gravitational forces and their impact on the dynamics of structures. This figure shows the influence of the gravitational field on the frequencies of a beam for the various types of modes.

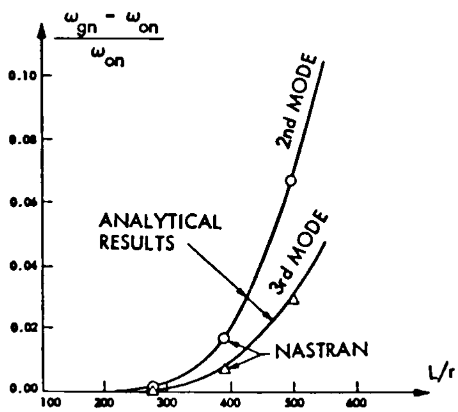
- LINEARIZED FREQUENCY EQUATION

$$\frac{\omega_{gn}}{\omega_{on}} = \left[1 + \frac{NL^2}{n^2\pi^2 EI} + \frac{AW_i^2}{2I}\right]^{1/2} ; n = i = 1,3,5,\ldots$$

$$\frac{\omega_{gn}}{\omega_{on}} = \left[1 + \frac{NL^2}{n^2\pi^2 EI}\right]^{1/2} ; \text{FOR } n = 2,4,6,\ldots$$



(a) n = 1

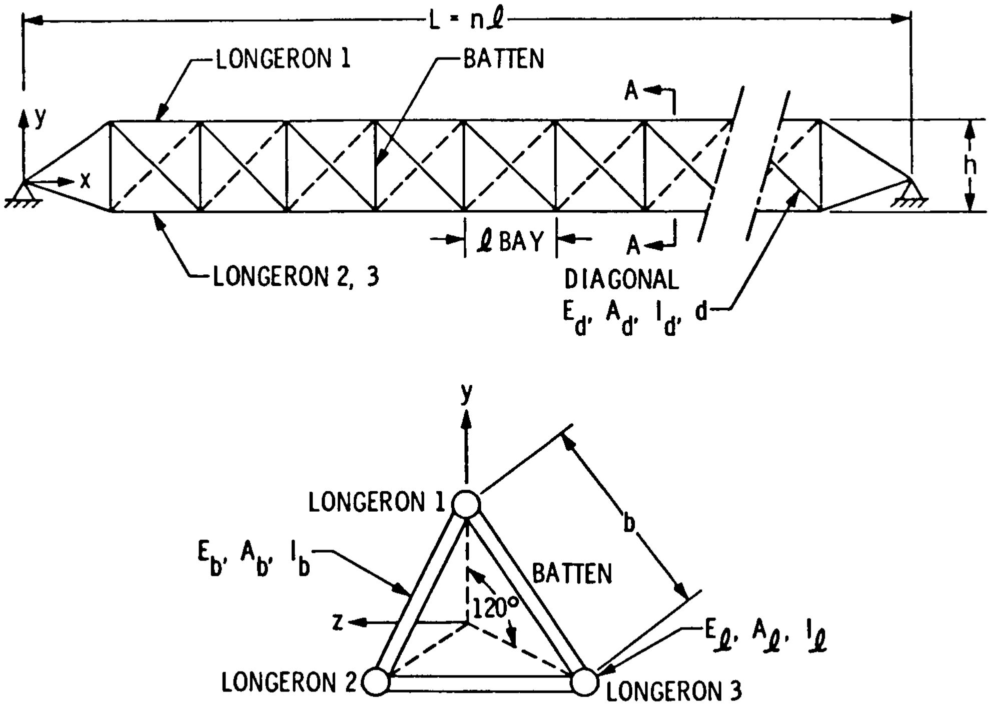


(b) n = 2 AND n = 3

EXAMPLE USED TO CORRECT FOR THE
INFLUENCE OF GRAVITY

A truss-type structure was selected to illustrate the extension of the ideas developed in the previous figure.

TRUSS-COLUMN TYPE STRUCTURE



A-A CROSS SECTION

PREDICTION OF THE DYNAMIC BEHAVIOR
OF A MAST-TYPE BEAM

This figure depicts other aspects of the research performed to predict the dynamics of large space structures utilizing ground test data and analyses. Step number one is to perform a buckling analysis to determine the number of bays which can physically maintain its geometry and retain its basic stiffness characteristics. Step number two is to select the number of bays for the ground test. Step number three is to correct the results of the test data from step number two for a zero gravity condition. Step number four is to extrapolate the results of steps number three to the full beam in a zero gravity condition. Step number five compares the test/analysis approach to the results of the total beam if an accurate test on the beam could have been performed; the comparison is within .003 Hz.

VERIFYING THE NATURAL FREQUENCY OF A LARGE TRUSS-COLUMN (60-BAY)

PROCESS

1. BUCKLING ANALYSIS FOR A 60-BAY TRUSS-COLUMN
(RESULTS: BUCKLED IF $n > 53$)

2. GROUND TESTS FOR A 40-BAY STRUCTURE
(RESULTS: N, W_0, ω_g ARE MEASURED)

3. NATURAL FREQUENCY OF A 40-BAY TRUSS-COLUMN IN 0-g FIELD CAN BE PREDICTED BY USING LINEARIZED FREQUENCY EQUATION

4. NATURAL FREQUENCY OF A 60-BAY TRUSS-COLUMN IN 0-g FIELD CAN BE EXTRAPOLATED BY USING SCALING LAW

5. NUMERICAL DEMONSTRATION:

NASTRAN:

ω_0(60-BAY) = 0.415 Hz

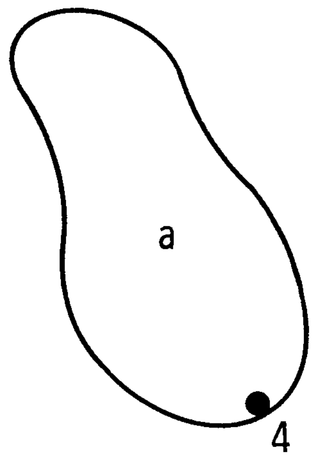
$$\begin{cases} \omega_g(\text{40-BAY}) = 0.953 \text{ Hz} \\ \omega_0(\text{40-BAY}) = 0.905 \text{ Hz} \\ \omega_0(\text{60-BAY}) = \underline{0.418 \text{ Hz}} \end{cases}$$

ERRORS IN SUBSYSTEM TESTING

In many structures, the entire system may not be assembled on the ground prior to assembly in space. An example may possibly be the Space Station. In these situations, testing of subsystems or groups of subsystems may have to be performed to validate and update its analytical model; then the analytical model of the subsystems may be combined to predict the dynamics of the total system.

History has shown that subsystem testing and validation have concentrated on those elements which are loaded during the subsystem test and not loaded through the interconnection of the subsystems.

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}$$



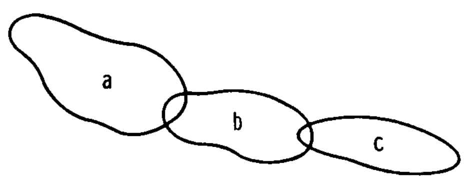
USE OF THE MBCT APPROACH TO
SYSTEMATIC SUBSYSTEM TESTING

An evaluation of a comparison between the analytical model generated by test verified subsystem models and the final system modal test indicates that most often the discrepancies occur because of the errors in the analytical model at the subsystem interconnection points.

In order to test for these important parameters at the interconnection points during the subsystem testing, concepts developed for the MBCT have been adapted. The initial step is to a priori determine the terms in the overall system which are important to the dynamic characteristics which affect the overall system performance. This can be accomplished in many ways; an approach used is to evaluate the elements with large strain energy distribution in the important system modes. The second step is to determine the elements validated by the standard subsystem modal test methods to evaluate the elements which require additional test verification. In most cases these elements can be verified by a large number of tests which load the interface at the subsystem interconnection points. The type and number of tests are selected such that all the important elements, not previously validated, are loaded a sufficient number of times to obtain a good statistical estimate.

SYSTEM

$$
\begin{bmatrix}
a_{11} & a_{12} & a_{13} & a_{14} & & & & & & \\
a_{21} & a_{22} & a_{23} & a_{24} & & & & & & \\
a_{31} & a_{32} & a_{33} & a_{34} & & & & & & \\
a_{41} & a_{42} & a_{43} & \begin{pmatrix} a_{44} \\ b_{11} \end{pmatrix} & b_{12} & b_{13} & b_{14} & & & \\
 & & & b_{21} & b_{22} & b_{23} & b_{24} & & & \\
 & & & b_{31} & b_{32} & b_{33} & b_{34} & & & \\
 & & & b_{41} & b_{42} & b_{43} & \begin{pmatrix} b_{44} \\ c_{11} \end{pmatrix} & c_{12} & c_{13} & c_{14} \\
 & & & & & & c_{21} & c_{22} & c_{23} & c_{24} \\
 & & & & & & c_{31} & c_{32} & c_{33} & c_{34} \\
 & & & & & & c_{41} & c_{42} & c_{43} & c_{44}
\end{bmatrix}
$$



SUMMARY

The basic ideas behind the research being performed at JPL in the area of ground test of large flexible structures for validation of its mathematical model are presented. The goal is to validate the techniques developed at JPL as a part of the MAST effort which is part of the COFS Program. The objective will be to ground test the MAST hardware, predict its dynamic characteristics by analysis using the ground test data, and to verify the predictions by using the flight measured data.

- **GROUND TEST OF LARGE SPACE STRUCTURES ENABLES USE OF STRUCTURES REQUIRED FOR FUTURE MISSIONS**
- **PRESENTED CONCEPTS PURSUED IN JPL R&AD**
  - **INFLUENCE OF TERRESTRIAL ENVIRONMENT ON TESTING**
  - **SUBSYSTEM TEST/ANALYSIS ----> SYSTEM**
  - **MULTIPLE BOUNDARY CONDITION TESTS**
- **PARTICIPATE IN COFS**