Truss Space Structures System Identification Using the Multiple Boundary Condition Test Method

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The Multiple Boundary Condition Test (MBCT) method has proven, through mathematical simulations performed on beam-type structures, to be a valid method for system identification of large space structures. A laboratory test was conducted to validate experimentally and to help establish the limits of the MBCT approach. The results show that the MBCT method is a vital alternate technique for ground testing large flexible structures. A three-dimensional MAST-type truss structure has been successfully simulated and system identified by the MBCT method.

Introduction

A CRITICAL near-future challenge in the field of spacecraft structure system identification will be to develop ground test/analysis approaches that can be utilized for large space structures and that will provide program managers with the confidence needed for committing structures for flight. Historically, spacecraft structures have been validated by full-scale ground testing prior to launch. The size and flexibility of many proposed spacecraft structures for future programs, however, will severely limit the acquisition by ground testing of valid experimental structural dynamics data. This is because of limitations in test facilities and techniques and to the adverse affects of the ground environment. This lack of quality test data will, in turn, limit validation of the analytical models that use current system identification and modal updating methods. Recently a test/analysis approach, the Multiple Boundary Condition Test (MBCT) method, has been proposed by the authors to overcome some of the difficulties in validating large space structures.

The MBCT method, which uses mathematical simulations performed on beam-type structures (as discussed in Refs. 1-3), has been shown to be valid for system identification of large space structures. As detailed in Ref. 4, the system identification process was substantially improved by the introduction of nonlinear sensitivity parameters. To support and substantiate the development of the MBCT approach with experimental data, a laboratory test program was initiated. The initial results of the MBCT method within that program, as applied to experimental hardware, are presented in this paper. Those results include the successful application of MBCT to a numerical simulation of a large three-dimensional (3-D) truss structure, a success that allows us to validate MBCT for use with a MAST truss.

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The MBCT Method

This section presents an overview of the MBCT method. (The history and the developments leading to the MBCT method are presented in Refs. 1-3.) The objective of the tests to date has been to simulate a structure in an operational configuration prior to obtaining the eigencharacteristics. Information obtained would be used in updating the mathematical model. One advantage gained by simulation was that errors introduced through artificial boundary conditions were minimized. The procedure has proven successful despite the frequently encountered difficulties of 1) having to measure a large number of modes and 2) establishing for modifications the select number of coefficients in the large mathematical model.

It was the failure of one simulation test on a long flexible antenna rib with simulated boundary conditions that led to the development of the MBCT method. The Earth's atmosphere and the ground fixtures that supported the structure in a 1-*g* gravity field had completely overwhelmed the test results. To obtain valid ground-test data, we used MBCT to constrain the structure artificially with the full realization that all parameters representing the structure would not be validated—especially those at the artificial restraints. Because the test nevertheless excited portions of the structure, those portions of the mathematical formulation that were tested could be verified and modified as required. The updating procedure was simplified because each constrained test could be related to a small subset of the total mathematical formulation. Another advantage was that by moving the restraints to various locations, an arbitrarily large number of experimental estimates of any given parameter could be obtained. Statistical analysis has shown that by measuring a sufficiently large number of experimental parameters, the final mathematical model, updated to correlate with the test data, was as good if not better than one obtained with a full ground test with simulated boundaries. Still another advantage was that testing was simplified since the number of modes for any restraint condition could be reduced and replaced by more test conditions.

Experimental Results

Since the numerical simulation studies discussed in the preceding section were presented in Refs. 1-3, an effort was undertaken to run further laboratory experiments on similar structures. Previous experience has shown that theoretical studies using numerical simulation often fail when using ex-

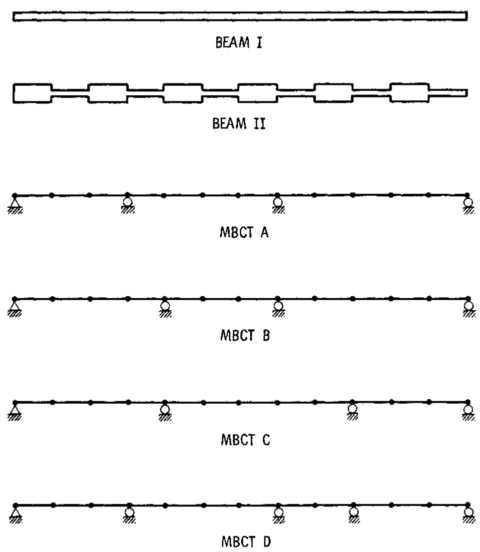

Fig. 1 Test configurations of the beams.

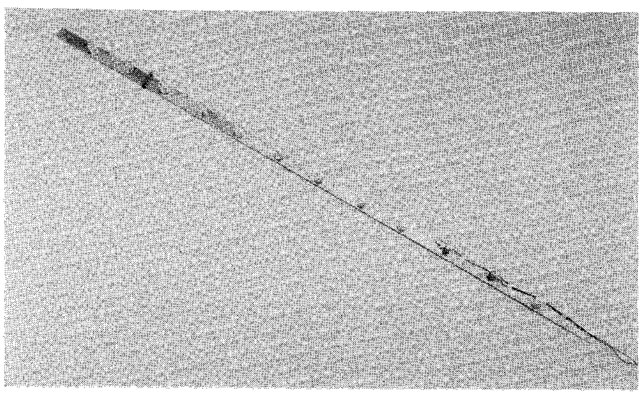

Fig. 2 Picture of test beam I.

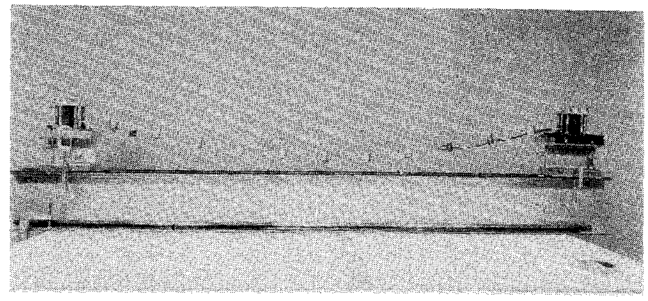

Fig. 3 Simply supported configuration of beam I.

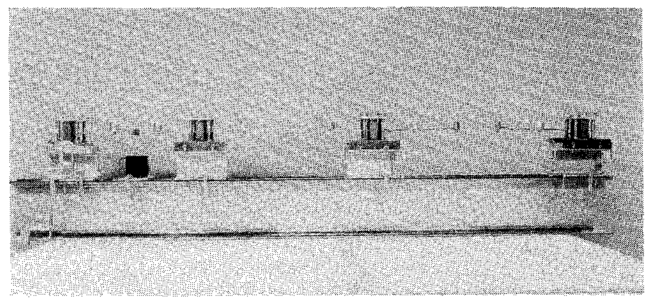

Fig. 4 Test configuration of MBCT A of Fig. 1.

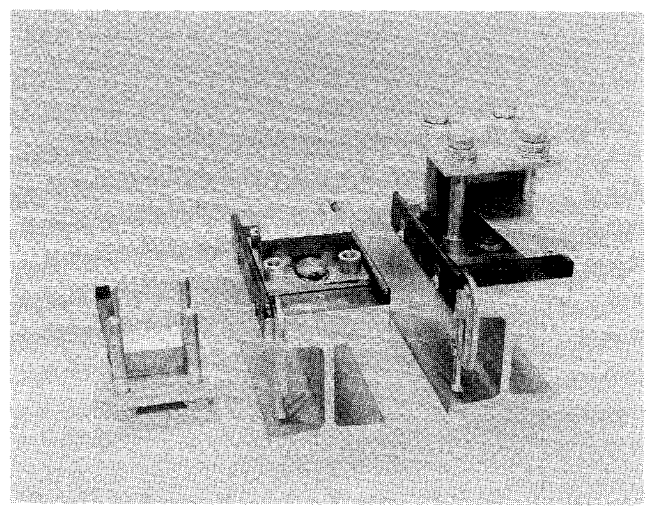

Fig. 5 Details of the support used in the MBCT test.

perimental data because of nonsystematic test-related errors and the incompatibilities between the analytical model and the test data. The initial efforts consisted of testing two beams identified as beam I and beam II (see Fig. 1). The overall dimensions of the two aluminum beams were 1.8288 m long and 4.445 cm wide. Beam I had a uniform cross section, whereas beam II consisted of two different alternating cross sections. The different types of MBCT restraints selected to identify the cross-sectional values of the beams are noted as *A*, *B*, *C*, and *D* in Fig. 1.

Both beams are assumed to be supported simply at both ends and are modeled by 12 beam elements. The concentrated masses and the weights of accelerometers at the nodal points are given and are identical. Beam I is depicted in Fig. 2. The moment of inertia of the beam section for beam I is to be updated. As shown in Fig. 3, the configuration of beam I, when supported simply at both ends, has a distinctly nonlinear deformation shape, and it is difficult to test by conventional methods on the ground. By providing additional intermediate supports, as suggested by the MBCT method, the configuration of MBCT A of Fig. 1 becomes a linear system (see Fig. 4) and can be tested by an available conventional method.

In general, the rigidities of the additional supports should be included in the analyses. The rigidities of the supports used in the laboratory test are designed to be somewhat more stiff than the tested beams and are considered as rigid, simply supported joints in the analyses. The details of the supports are shown in Fig. 5. Two types of excitation, chirp (fast sine sweep) and SWIFT (discrete sine sweep), as discussed in Ref. 5, were used to obtain the eigencharacteristics of the systems. The excitations were limited to a bandwidth between 2 and 40 Hz.

The test on beam I was the simplest that could be performed. The cross-section moment of inertia of the beam in the analysis was assumed to be 6.077E-11 m^4, whereas the moment of inertia of the hardware was 3.997E-11 m^4. As noted in Table 1, the first two modes of each of the four different boundary conditions were experimentally measured using the chirp and SWIFT extraction methods. For the system identification, the experimental results of SWIFT were used as the test data. The analytical modal predictions (see Table 1) of the initially unverified model show that the discrepancies were selected intentionally to be relatively large in order to test the methodology properly.

Table 1 MBCT results of beam I

		Test ($I=39.97\times10^{-12}\text{m}^4$)		Model ($I=60.77\times10^{-12}\text{m}^4$)		
		Frequencies, Hz				I
MBCT	Mode	Chirp	Swift	Frequencies Hz	Sensitivities $\times10^7$	Updated $\times10^{-12}\text{m}^4$
A	1	7.74	7.67	9.28	2.329691	−19.28
	2	14.76	14.61	17.43	8.214478	−18.07
B	1	8.08	8.02	9.71	2.550529	−19.33
	2	12.26	12.01	14.78	5.910168	−20.67
C	1	8.81	8.64	10.40	2.925335	−18.84
	2	12.98	12.79	16.49	7.353325	−24.21
D	1	13.92	13.69	17.06	7.871934	−21.65
	2	20.94	20.91	26.00	18.277518	−21.47

Average updated $I=-20.44\times10^{-12}\text{m}^4$

Table 2 Test and model data of beam II

Test $I_1=188.68\times10^{-12}\text{m}^4$, $I_2=39.97\times10^{-12}\text{m}^4$				Model $I_1=I_2=60.77\times10^{-12}\text{m}^4$		
		Frequencies, Hz			Sensitivities $\times10^6$	
MBCT	Mode	Chirp	Swift	Frequencies, Hz	I_1	I_2
A	1	9.59	9.49	8.34	9.790606	9.012529
	2	16.89	16.67	15.73	32.492158	34.42654
B	1	9.59	9.41	8.73	10.662402	9.935017
	2	14.36	14.05	13.34	24.351492	23.773156
C	1			9.40	11.294390	12.618696
	2	15.74	15.60	14.98	30.019580	29.88785
D	1	15.63	15.45	15.41	30.694616	33.51984
	2	22.42	22.22	23.28	91.365136	55.20166
	3	27.34	27.07	26.04	69.19208	114.19392

Table 3 Updated results of beam II by MBCT method

Identified groups	Moment of inertia (10^{-12}m^4) Test	ANA	Updated by MBCT	Error, %
Beam II Section II	188.68	60.77	171.40	−9.2
Beam II Section I	39.97	60.77	41.54	3.9

The sensitivity coefficients used for the identification are listed in Table 1 to help provide insights on the influence of the various boundary conditions in the identification of the parameters. In future studies, the magnitude of the sensitivity coefficients will be used to select the test data for use in updating specific terms in the analytical model. Although every mode resulted in a good estimate of the error, the average increase in the moment of inertia was $-2.044\text{E-}11\ \text{m}^4$, whereas the actual error was $-2.08\text{E-}11\ \text{m}^4$. The correlation was exceedingly good. One possible explanation for the excellent results may be that the procedure allows for an arbitrarily large number of experimental estimates for any parameter, which will increase the accuracy in a statistical sense.

The results of the test on beam II are presented in Table 2. As in the previous test, large differences between the initially assumed analytical model and the hardware were used to help evaluate the potential limitations. One value of the moment of inertia of the hardware was higher than the analytical estimate, and the other was lower. Again utilizing all the parameters identified by all the test data, the 310% initial error was reduced to a 9.2% error (see Table 3).

The experimental results to date indicate that the MBCT method is valid. Additional effort will be pursued to improve and expand the applicability of the MBCT method by selectively using the sensitivity coefficients and by testing increasingly more complex structural systems.

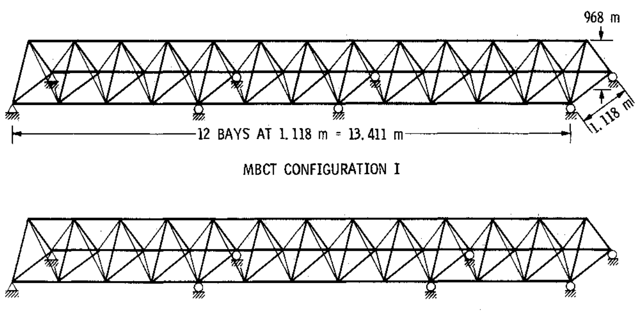

Fig. 6 MAST truss structure test configurations.

Application to a Truss Structure

The MBCT method was applied to an analytical simulation of a 12-bay, MAST-type structure, depicted in Fig. 6. For this example, two different boundary conditions were selected from which test data were obtained to update and modify the analytical model. The analytical model was assumed to have errors in four of the major structural components—the bottom longerons, top longerons, diagonals, and battens. The mass at each nodal point was given and fixed in the simulation.

Table 4 lists both the test and analytical frequencies as well as the sensitivity coefficients of the four structural parameters with respect to all the modes to be used in the system identification. After applying the MBCT method, the cross-section areas of the updated mathematical model were within 4.5% of the true values. The results are summarized in Table 5. The initial results indicate that the MBCT approach can be effectively implemented within the MAST program and used to aid in the identification of structural parameters.

Table 4 MAST truss structure test and model data

MBCT	Mode	Frequencies, Hz Test	Frequencies, Hz ANA	Sensitivities Bottom longerons	Sensitivities Top longerons	Sensitivities Diagonals	Sensitivities Battens
	1	46.33	46.25	−3.5025E4	9.3269E3	4.0962E5	1.0639E5
	2	52.61	51.54	2.3494E5	−1.3534E4	−1.5057E5	−4.2719E4
I	3	64.23	63.94	−5.3649E4	2.0270E4	7.9727E5	1.3397E5
	4	87.51	86.38	−2.1292E5	−6.7967E4	2.2224E6	3.1507E5
	5	101.61	100.82	2.9798E5	−9.1256E4	2.7858E6	7.2455E5
	1	48.01	47.77	−4.36663E4	−5.3307E3	5.0240E5	1.3791E5
	2	52.63	51.59	2.3041E5	−9.8669E3	−1.4713E5	−4.6530E4
II	3	64.35	64.06	−5.6915E4	1.8901E4	8.0774E5	1.4472E5
	4	86.30	85.26	−1.8894E5	−4.9001E4	2.0690E6	2.6509E5
	5	102.00	101.11	−3.0379E5	−9.8783E4	2.8624E6	7.0783E5

Table 5 Updated results of MAST truss structure by MBCT method

Identified groups	Area of cross section, $\times 10^{-4}$m^2 Test	ANA	Updated by MBCT	Error, %
Bottom longerons	1.558810	1.417094	1.628126	4
Top longerons	1.627313	1.808125	1.665545	2.3
Diagonals	0.459102	0.417367	0.480947	4.5
Battens	0.339999	0.377419	0.334148	1.7

Summary

This paper shows the viability of the MBCT method for use in ground testing large flexible space structures that otherwise cannot be tested by conventional methods because of the influence of gravity and other adverse terrestrial environmental conditions. The first attempt to validate the MBCT method by experiment succeeded with excellent results. The initial tests were purposely selected to be simple but meaningful in order to avoid unknown problems that often arise from experimentation with new test approaches. With the success of these tests, the plan is to perform further tests to validate and improve upon the approach.

The application of MBCT on a numerical simulation of the MAST-type beam was also successful. Only by continual application of the MBCT method on test or flight hardware will the MBCT approach become accepted as an alternate ground-test technique that can be used to validate and commit space structures for flight. The successes to date have been very encouraging, and the authors are looking forward to applying the MBCT method to other appropriate structures.

Acknowledgments

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