MODAL TESTING OF SEVEN SHUTTLE CARGO ELEMENTS FOR SPACE STATION

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ABSTRACT

From December 1996 to May 2001, the Modal and Control Dynamics Team at NASA's Marshall Space Flight Center (MSFC) conducted modal tests on seven large elements of the International Space Station. Each of these elements has been or will be launched as a Space Shuttle payload for transport to the International Space Station (ISS). Like other Shuttle payloads, modal testing of these elements was required for verification of the finite element models used in coupled loads analyses for launch and landing. The seven modal tests included three modules – Node, Laboratory, and Airlock, and four truss segments – P6, P3/P4, S1/P1, and P5. Each element was installed and tested in the Shuttle Payload Modal Test Bed at MSFC. This unique facility can accommodate any Shuttle cargo element for modal test qualification. Flexure assemblies were utilized at each Shuttle-to-payload interface to simulate a constrained boundary in the load carrying degrees of freedom. For each element, multiple-input, multiple-output burst random modal testing was the primary approach with controlled input sine sweeps for linearity assessments. The accelerometer channel counts ranged from 252 channels to 1251 channels. An overview of these tests, as well as some lessons learned, will be provided in this paper.

BACKGROUND

During the early development phases of the International Space Station (ISS), a Space Shuttle Payload Modal Test Bed was designed and built by Boeing at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama. The modal test fixture was developed to provide a rigid test bed with interfaces that would provide a laboratory simulation of the flight boundary constraints of the ISS modules in the Space Shuttle cargo bay.

The test bed is a steel welded structure consisting of 10"x10" box beams supporting one-foot thick steel plates. The test bed was designed to be "universal" so that the interface locations could be adjusted to accommodate any payload that could be integrated into the Shuttle cargo bay. A modal test of the basic fixture, or strongbacks, showed the fundamental mode is approximately 50 Hz. Figure 1 shows the strongbacks of the test bed.

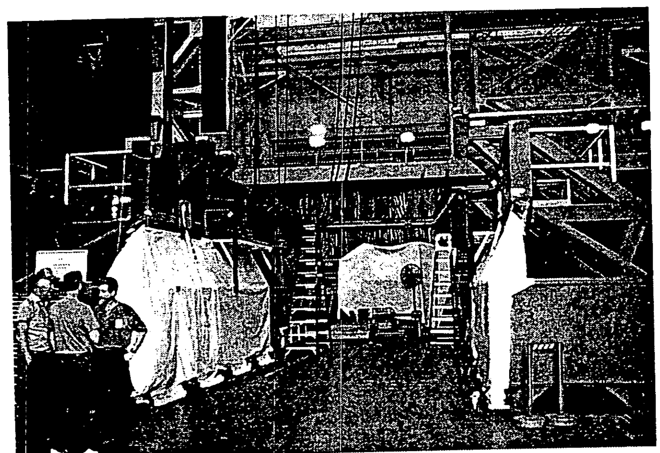

FIGURE 1. TEST BED STRONGBACKS

The initial design of the modal test bed involved the use of large bearings to provide the stiff trunnion constraint degrees of freedom (DOF), as well as the free DOF's that are designed to slide and rotate. In 1991, a test of the Common Module Prototype, a 40-foot long module, was conducted in the modal test bed with the original bearing design. The boundaries in this original configuration proved highly non-inear due to the inherent gapping between the trunnions and bearing interfaces. Further details regarding the Common Module Prototype Test can be found in Reference [1]. Subsequently, the fixture interfaces went through a very thorough redesign, modification, and characterization. The interfaces between the test bed and the test article were redesigned to use flexure assemblies. The flexures are designed to provide a high axial stiffness while having relatively low lateral and rotational stiffnesses. Two flexures are used at each primary trunnion interface to transfer loads in the Orbiter X- and Z-axes. One flexure is located at each secondary trunnion location in the Orbiter Z-axis and at each keel interface in the Orbiter Y-axis.

Following the redesign of the fixture's trunnion interface hardware, an extensive program was implemented to characterize the behavior of the fixture. This characterization involved both static and dynamic testing to fully understand the stiffness of the fixture and to ensure finite element models of the fixture and its components were accurate. As part of this characterization, modal tests of two pathfinder structures were conducted. In 1995, a test was conducted on a "calibration beam" which spanned the two primary trunnion interfaces. A photograph of this test article in the modal test bed is shown in Figure 2. The following year, a second structure was installed and tested in the modal test bed. This test article, which weighed approximately 27,000 lb, had interfaces identical to the Node. A photograph of this mass simulator in the test bed is shown in Figure 3.

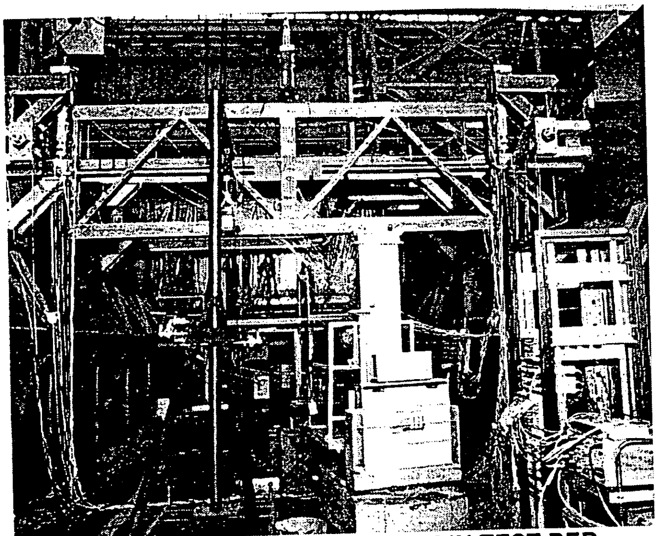

FIGURE 2. CALIBRATION BEAM IN TEST BED

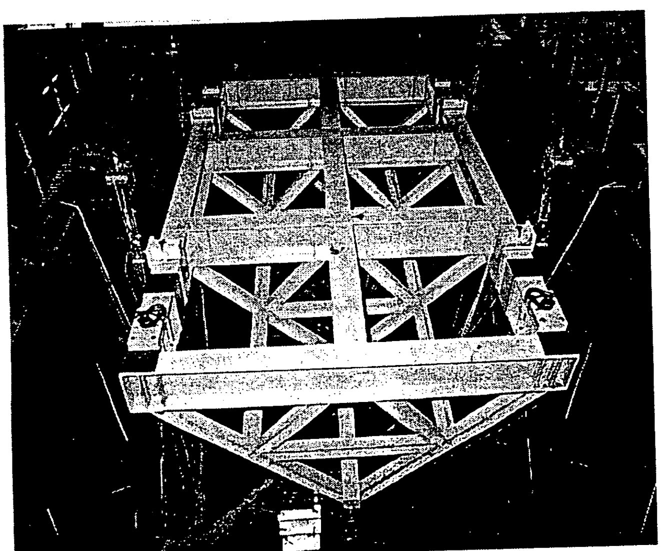

FIGURE 3. NODE SIMULATOR IN TEST BED

In December 1996, the first Space Station hardware, the Resource Node "Unity", was tested in the MSFC modal test bed. From that time through the spring of 2001, a total of seven major elements of the International Space Station were tested by MSFC in the test bed. Table 1 summarizes the elements tested as well as some information regarding each test.

For each test, Boeing was the hardware developer and customer. Boeing organizations from Huntsville, Canoga Park, and Huntington Beach were involved in different tests and provided the analysts for the pretest analysis and model correlation. For the Node, Common Module, and Airlock, multiple configurations were tested. Photographs of each test setup are shown in Figures 4 through 10.

TABLE 1. SUMMARY OF TESTS

Test Article	Test Dates	Approx. No. of Response Channels	Total No. Drive Pts.	No. of Con-strained DOF's
Node	12/21/96-1/14/97	1248	3	7
Common Module	7/14/97-8/21/97	1047	3	7
P6	11/25/97-12/16/97	1185	6	8
Airlock	4/10/98-4/22/98	1095	3	6
S1/P1	4/12/99-4/27/99	843	3	8
P3/P4	8/9/99-8/30/99	957	3	8
P5	4/26/01-5/1/01	258	3	7

TEST EQUIPMENT

Accelerometer instrumentation for the modal tests was primarily PCB 333 ICP accelerometers, although some PCB 330A Structcels were used in the earlier tests. A calibration database is generated annually, which relates the calibration constant of the accelerometers in inventory to the serial number bar-coded on the accelerometers. Shakers included APS Model 113, as well as Unholtz-Dickie Model 1 and Model 4 shakers. PCB load cells or impedance head transducers were used during these series of tests to measure the input forces. For the first six modal tests, the data acquisition system was a 224-channel Hewlett Packard 35650 with PCB Data Harvester signal conditioning (Figure 11). A 256-channel DIFA Scadas III system (Figure 12) was used for signal conditioning and as the front-end for the P5 test. In each case, Leuven Measurement Systems (LMS) CADA-X software was used for data acquisition and analysis.

TEST APPROACH

Multi-point burst random was the primary approach for modal testing of these seven test articles. All instrumentation was calibrated and installed prior to test start. Accelerometers were typically mounted to the test articles using hot glue. Kapton tape was placed at each measurement point on the hardware to identify the measurement locations and aid in post-test instrumentation removal. Due to the large number of accelerometers

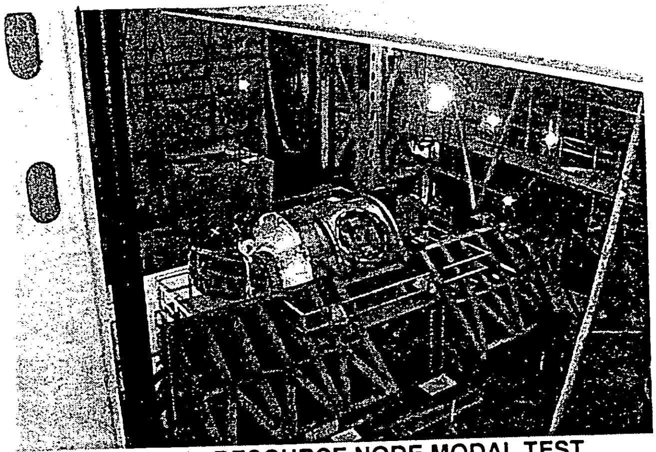

FIGURE 4. RESOURCE NODE MODAL TEST

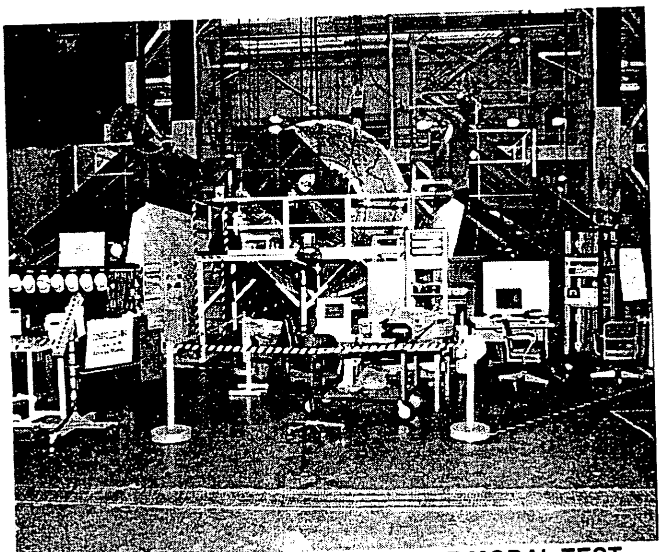

FIGURE 5. LABORATORY MODULE MODAL TEST

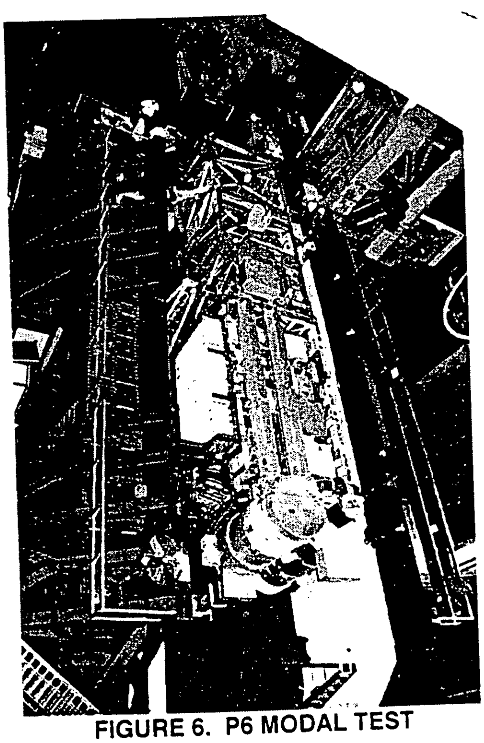

FIGURE 6. P6 MODAL TEST

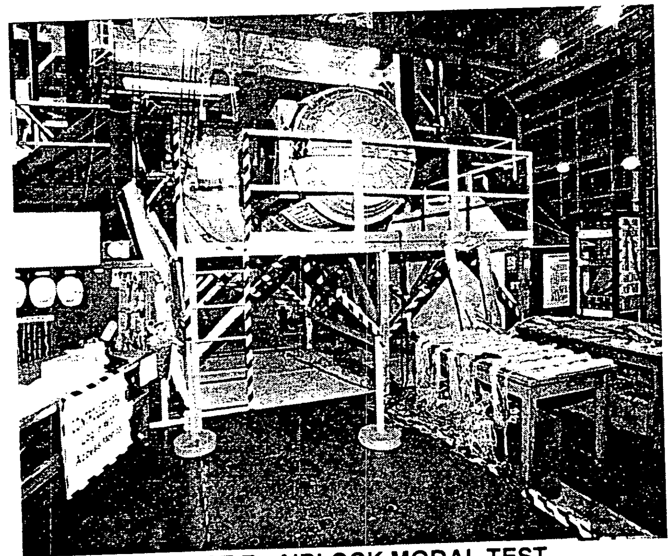

FIGURE 7. AIRLOCK MODAL TEST

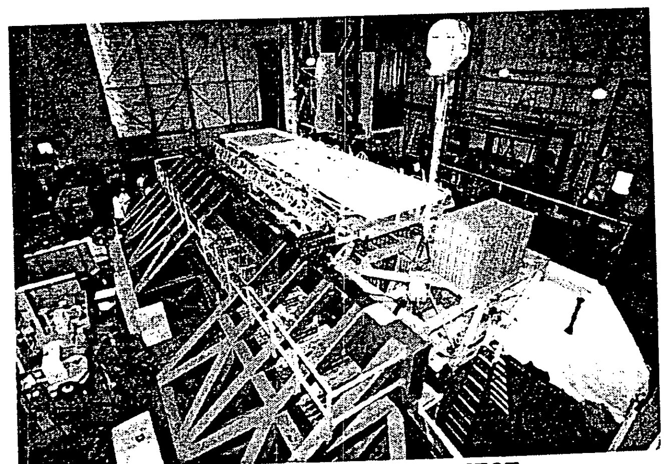

FIGURE 8. S1/P1 MODAL TEST

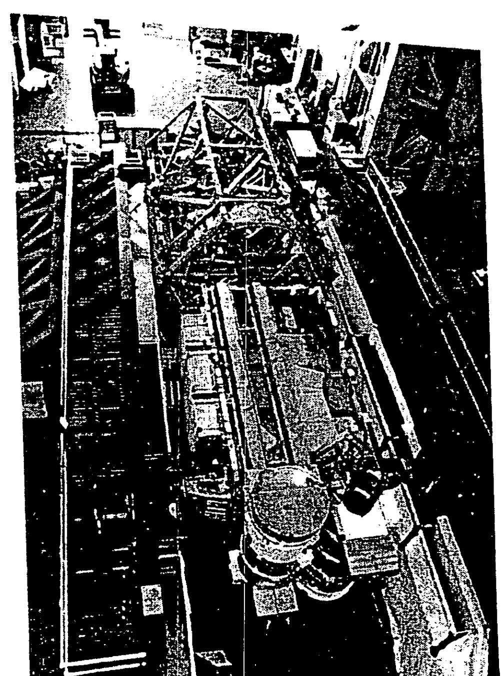

FIGURE 9. P3/P4 MODAL TEST

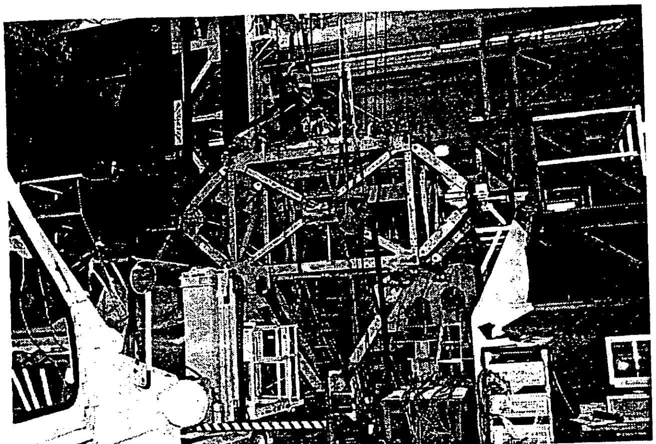

FIGURE 10. P5 MODAL TEST

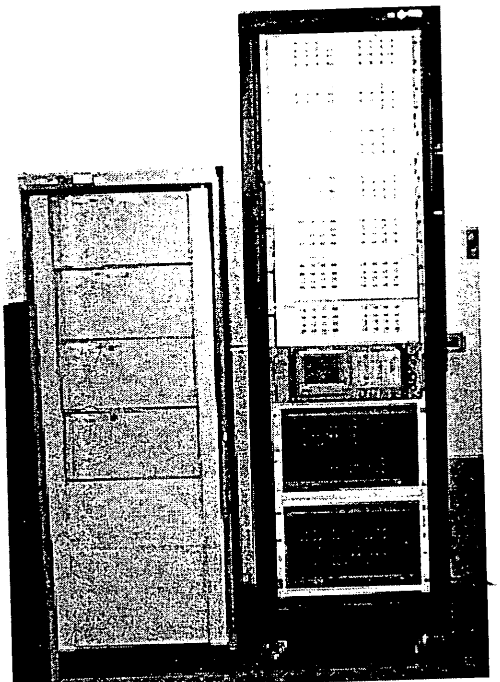

FIGURE 11. HP35650 FRONT END

required, several "sets" or patches of data were acquired during each acquisition until all channels were measured. The transducer calibration values were imported to LMS software from the database for the appropriate channels in each set. Shakers were installed at the selected locations by either mounting them to a shaker support stand or by suspending them from bungee cord. The load cells were attached to the test article through an Aluminum pad that was dental cemented to the test article. Input forces from the burst random tests were typically 15-20 lbs rms.

A burst-random "checkout run" was typically conducted first to identify and correct any instrumentation problems observed. During the checkout run, all measurements were acquired, but only with a relatively small number of averages. Once any necessary corrections were made, a complete test was run by acquiring measurements from each data set. The typical frequency bandwidth was 0-64 Hz and normally 100 averages were acquired. Following the multi-point burst random data acquisition, preliminary modal parameters were estimated. The Complex Mode Indicator Function (CMIF) was the primary tool for preliminary analysis. Additionally, force-controlled sine sweeps were acquired at each drive point to characterize any force dependent non-linear behavior of the structure. Sine sweep force levels were typically 3-15 lbs pk, but went as high as 80 lbs pk on the P6 element. Final analysis primarily used CMIF and time domain parameter estimation.

For some of the tests, impact measurements to evaluate residual flexibility were acquired at interface locations that would be important for on-orbit dynamics. These drive point frequency response function measurements were acquired at locations that would ultimately transfer on-orbit dynamic loads to other modules or components of the Space Station.

LESSONS LEARNED

Several good practices were learned through the course of the testing. Many of these were suggestions by the analysts. One of these was to establish a "common set" of important measurements that would be acquired during the acquisition of every patch, or set. This common set was initially used to evaluate optimum force levels and frequency resolution. The common set was also used during the tests to investigate any variations that may have occurred between the sets of data.

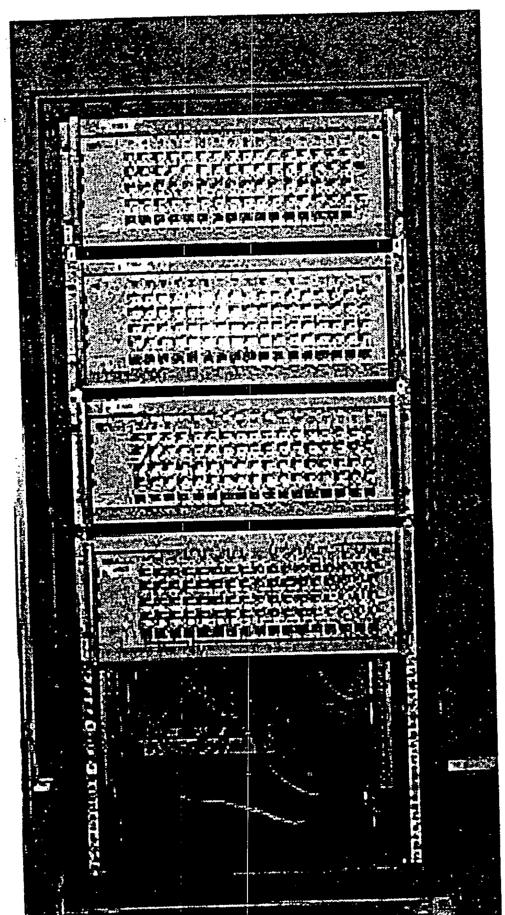

FIGURE 12. SCADAS III FRONT END

FREQUENCY RESOLUTION ISSUE

A particular observation of interest regarding frequency resolution was highlighted during the Resource Node modal test, as noted also in Reference [2]. A high modal density was anticipated for the Node test. As a result, a very high frequency resolution was selected. For the 0-64 Hz bandwidth, 2048 frequency lines were used, resulting in a resolution of 0.03125 Hz. Following the initial acquisition of all the accelerometer patches, some suspect measurements were corrected and were uniquely reacquired the following day under the assumption that the frequencies had not changed. However, a lightly damped lower-frequency mode shifted approximately two delta f or six hundredths of a Hertz between the initial acquisition and the reacquisition. With a larger delta f, this shift would not even be observed. However, because of the high frequency resolution and the light damping, the mode shape coefficients appeared inaccurate for the reacquired measurement points. This resulted in an initial conclusion that the earlier attempts at correcting the measurement instrumentation were unsuccessful. Upon realization of the small two delta f variance in the frequency of this first mode in the newly acquired data, a "band fit" method was successfully utilized for estimation of this mode shape. The length of time to acquire all of the data should be minimized and should be considered when determining the frequency resolution. For large channel count modal survey tests that require multiple patches, very small frequency shifts should be evaluated as a possible source of mode shape contamination for high frequency resolution data.

NON-LINEAR BEHAVIOR

In several of the elements, significant non-linearities were encountered due to gapping or looseness at the keel trunnion. Some of the keel trunnions were designed to be rotated on orbit by the astronauts to alleviate payload deployment interference. This on-orbit task had to be relatively easy to accomplish. The loose interface present in this and other keel hardware configurations resulted in a softening spring effect. As the input force level was increased, the frequency decreased and the damping increased. For each test article, modal data was acquired in the actual flight-like boundary configuration. Shimming was attempted in some instances but only introduced an additional unknown. Following the acquisition of the modal data, force-controlled sine sweeps at the drive points were conducted to characterize the non-linear behavior. The mode shapes remained constant even though the frequency was shifting. The sinusoidal input force levels were increased until the frequency reached an "asymptotic" value. For example, on the P6 element, 80 pounds of sine was required to reach this "lowest" frequency. For the P6, the fundamental mode (Y-axis) shifted 7-8%, from approximately 7 Hz to about 6.5 Hz. Other modes of the P6 also shifted slightly, but were within the 5% frequency correlation range required. A sample of a typical narrow-band sine sweep from the P6 test is shown in Figure 13.

NON-REPEATABILITY ISSUE

An unusual occurrence was encountered on the last element, the P5 Cargo Truss Element (Figure 10). Multiple

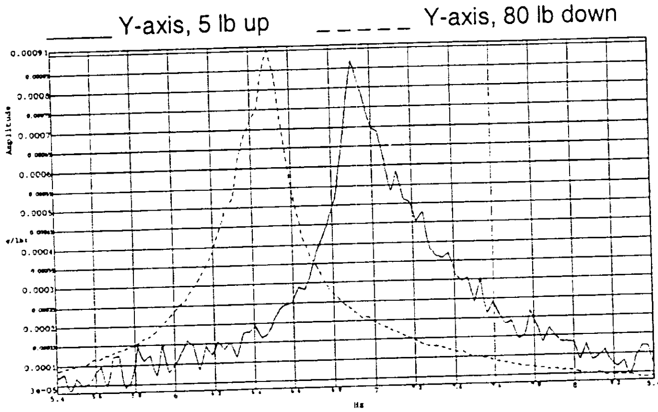

FIGURE 13. SAMPLE SINE SWEEP FROM P6

acquisitions of the same data set resulted in different modal parameters, even if acquired in a relatively short amount of time. This non-repeatability was neither force nor temperature dependent. Rather it was due to something in the structure. The fundamental mode varied from 16.17 Hz in initial testing to around 17.68 Hz by the end of the test. In fact, the first two modes actually switched places from the first test (TSS1) to the last test (TSS16) as shown in Table 2.

TABLE 2. COMPARISON OF FUNDAMENTAL MODES FOR P5

Frequency		MAC (%)
TSS16	TSS1	
17.40	17.66	92
17.68	16.17	84

Sensitivity studies during the model correlation phase showed that this non-repeatable behavior was due to some loose struts in the structure. No attempt was made to preload all of the struts prior to test, so there was no assurance that all struts were providing a load path. During high-level sine sweeps, various struts were observed to have a notable rattle. Post-test analysis also showed that the loose struts could cause the first two modes to swap, as was observed during the test. Further information can be obtained in Reference [3].

SUMMARY AND CONCLUSIONS

The NASA/Marshall Space Flight Center Modal and Control Dynamics Team conducted highly successful tests of these seven Space Station elements in the Shuttle Payload Modal Test Bed at MSFC. These test articles ranged in weight from approximately 10,000 to 30,000 pounds. The fixture also accommodated a wide range of interfaces for the trunnion-constrained test articles. The Modal Test Bed provided a very stiff boundary support at constraint DOF's, a weak boundary for free DOF's and an good overall simulation of the desired flight boundary. These tests were generally conducted in a matter of two to three weeks including installation of the instrumentation, shaker setup, test conduct, and test teardown. A very efficient, process-oriented test approach allowed all of these large channel count modal tests to be completed on or ahead of schedule.

ACKNOWLEDGEMENTS

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