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Precision truss structures from concept to hardware reality:application to the Micro-Precision Interferometer Testbed

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ABSTRACT

This paper describes the development of the truss structure at the Jet Propulsion Laboratory that forms the backbone of JPL's Micro-Precision Interferometer (MPI) Testbed. The Micro-Precision Interferometer (MPI) Testbed is the third generation of Control Structure Interaction (CSI) Testbeds constructed by JPL aimed at developing and validating control concepts . The MPI testbed is essentially a space-based Michelson interferometer suspended in a ground-based laboratory.This instrument, mounted to the flexible truss, requires nanometer level precision alignment and positioning of its optical elements to achieve science objectives. A layered control architecture, utilizing isolation, structural control, and active optical control technologies, allow the system to meet its vibration attenuation goals. Success of the structural control design, which involves replacement of truss struts with active and/or passive elements, depends heavily on high fidelity models of the structure to evaluate strut placement locations. The first step in obtaining an accurate structure model is to build a structure which is linear.

Experience with the two previous testbeds (Phase 0 and Phase B) has led JPL design engineers to develop a design methodology for creating large, linear, flexible, lightweight, and lightly damped structures to be used for CSI research. Primary factors that contribute to the fabrication of a linear truss include: truss material selection, truss assembly procedures, and truss joint design. This paper describes this methodology applied to the development of the Micro-Precision Interferometer Testbed truss. The paper concludes by presenting data which demonstrates that the truss is in fact linear.

INTRODUCTION

An attempt will be made in this paper to share with the reader the "recipe" which was used at JPL to build the linear structure known as the MPI Testbed. This testbed was designed to bridge the gap between the analysts ideal world of linear structures and that of hardware reality. The focus will be on commonly overlooked details that when dealt with in the development phase of a testbed will save time, frustration and money as the research matures. Details such as maintaining node to node distances within a specified tolerance (in this case 200 micrometers), truss elements which really do carry axial loads only, and connecting hardware ,which behaves as a true pin joint without non-linearities, will be covered.

Appreciation of the design methodology adopted for the MPI Testbed requires the reader to have a basic understanding of JPL's Phase 0 and Phase B testbed experience.The reader is encouraged to obtain copies of References 1 thru 7.The structure comprising the Phase B Testbed (see Fig #1) consists of a vertical tower standing 2.5 m high with two horizontal arms attached to the top of the tower and oriented at right angles to one another. The tower is rigidly mounted on a massive block of steel (1500kg) which provides rigidity and a measure of isolation of the structure from vibrations emanating from the ground. The basic unit for the assembly of the Phase B Testbed tower and arms is a "bay", which consists of a 40.6 X 40.6 X 28.7 cm truss structure constructed from 1.27 cm aluminum tubes or "struts", with a wall thickness of 1.5 mm. The struts are attached to aluminum "nodes" manufactured by Starnet Structures Inc. ,which have threaded holes at the correct angles.

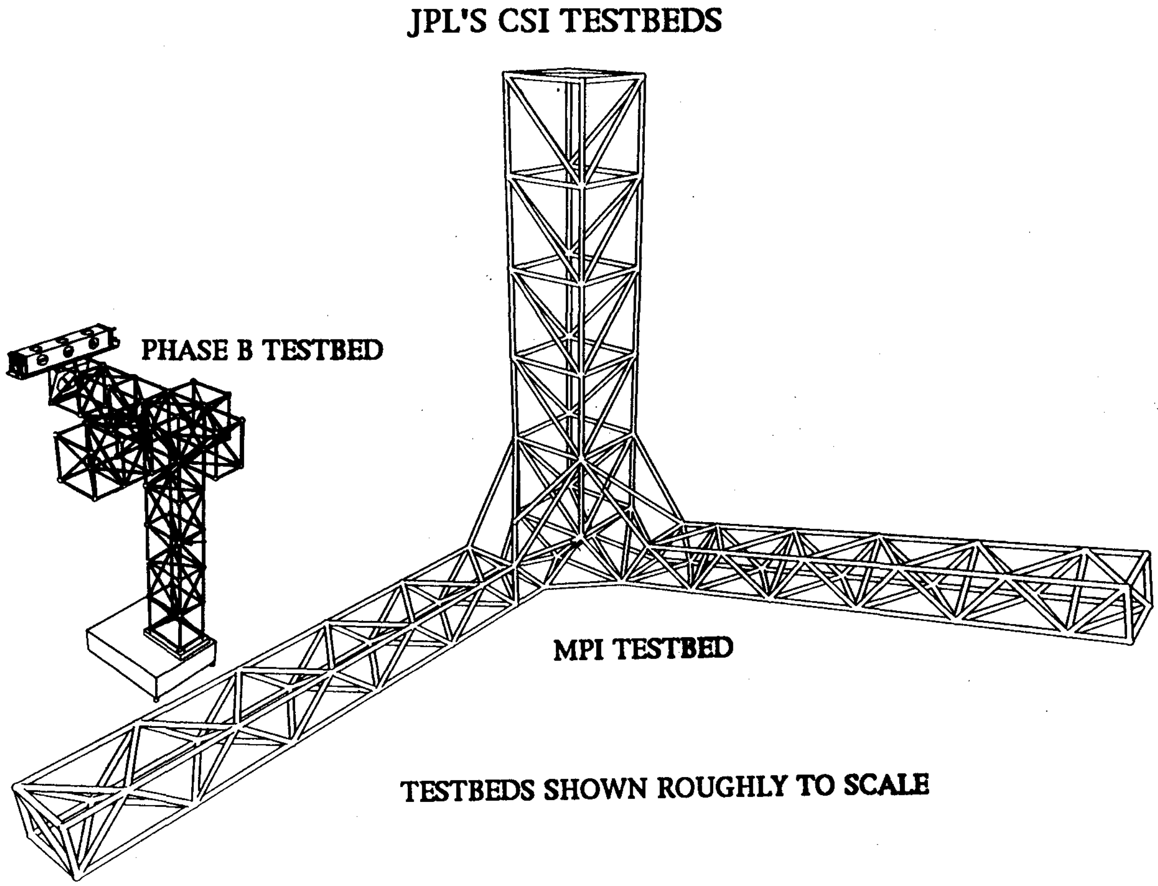

FIGURE 1 MPI & PHASE B TESTBEDS

The next generation of JPL's CSI Testbeds (The Micro-Precision Interferometer Testbed) was designed to have a primary tower a full 6 meters above the ground comprised of 1 meter cubic bays (Coincident with the Z axis,origin at the base of the tower), and two booms .707m X .5m X 6m (one coincident with the X axis , the other 15 degrees above the Y axis) connected to the base of the tower. Additionally, this testbed is suspended from overhead I-beams at three points emulating the "free-free" conditions of a structure in space.

1.TRUSS MATERIAL SELECTION

Choice of materials has a direct impact on the predictability of structural behavior. In a truss structure, elements are assumed to carry axial loads only and most FEM (Finite Element Model) normally assume perfectly straight struts with uniform cross sectional area and material properties. Unfortunately, in the "real" world we live in, materials are produced with "allowable" deviations from straight and uniform.

Composites, aluminum and titanium are the three logical material choices for struts on a space based truss structure. Composite material, although the best choice with respect to strength / weight ratio, is unacceptable for this application due to its geometric inconsistency, and unpredictable lay of fibers that make accurate computer modeling of its behavior difficult. Drawn thin walled 6061-T6 aluminum tubing was chosen for this application due to its geometric consistency and homogeneous make-up which results in predictable behavior. titanium tubing would be a preferred material choice, having the same advantages as aluminum tubing with an even higher strength / weight ratio , but was not chosen for this application due to prohibitive cost.

This modelable tube must now interface with a node point through some ideal "pin joint". In order to avoid modeling problems due to thermal expansion and contractions end fittings and node points are fabricated from the same aluminum alloy used for the struts. A small segment of threaded stainless steel hardware is used as the "pin joint" to connect the end fittings with the node points (see "Truss Joint design").

2.PRECISION STRUT ASSEMBLY

Drawn Aluminum tubing purchased from any approved metal supply source must satisfy standards set forth in ANSI H 35.2. For most applications, this tubing would be considered "straight", however for long lengths (in excess of 1 meter) requiring linearity, the allowable deviation from straight may cause significant offset of the line of action between the two ends (FIGURE #2). This offset may create undesirable moments (difficult to model) when subjected to an "axial" load.

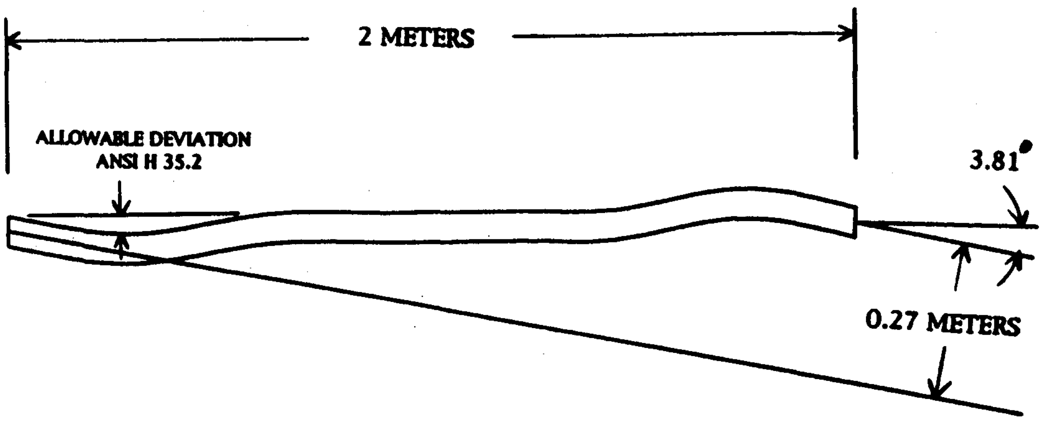

FIGURE 2 A "STRAIGHT" TUBE : ACCORDING TO ANSI H 35.2

JPL's Phase 0 and Phase B testbeds were designed with struts short enough not to experience this phenomenon, however the MPI testbed includes struts in excess of 1.65 meters. In order to assure collinearity of the line of action between end fittings, a method was developed which secures the end fittings in the proper orientation (collinear), and allows the tube to "float" (maintaining a bond line thickness between .003" and .008") while adhesive (EA9394) is injected and cured(FIGURE 3). This procedure yields a strut whose behavior can be reliably modeled even in the "micro-dynamic" range.

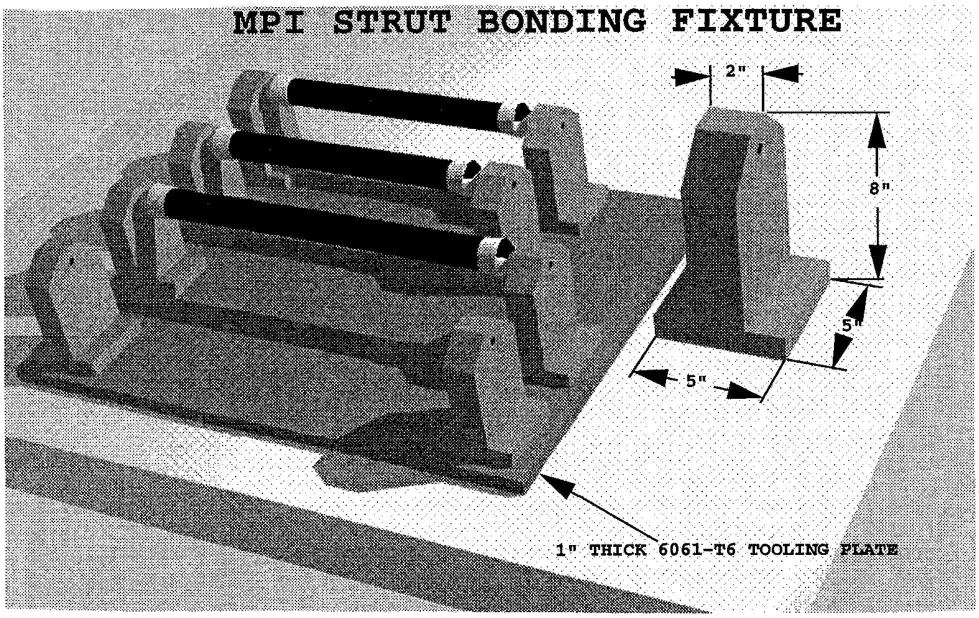

FIGURE 3 BONDING FIXTURE

3.TRUSS ASSEMBLY

Truss assembly on previous JPL testbeds (Phase 0 & Phase B) involved securing the node balls in the proper orientation to a reference plate, and then installing the struts between them. Experience has shown that tensile and compressive stresses (created by inaccurate strut length adjustments) cause the truss to distort when the node balls are released from the reference plate. These distortions now result in a structure that is slightly different than what the design engineer had intended or the analyst had modeled. Predicting the behavior of this "new" structure is quite difficult without accurately characterizing the distortions.

ALIGNMENT PIN

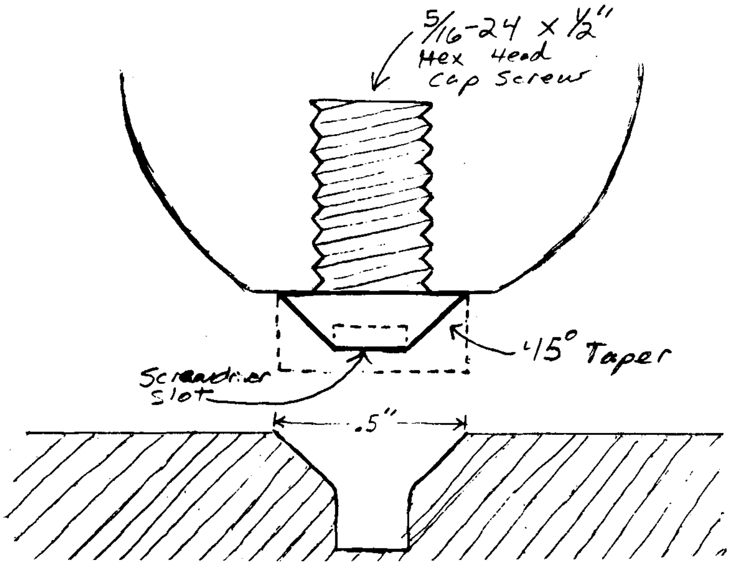

FIGURE 4 ALIGNMENT DEVICE

A new approach to truss assembly was applied to the MPI testbed which eliminates the difficult to characterize distortions and results in a truss structure that matches the engineers intended design as well as the analysts model. Rather than secure the node balls to a reference plate, the new method relies on gravity loading of a tapered pin attached to the node ball into a corresponding tapered hole in the reference plate (FIGURE 4). It has been shown by experiment that linear adjustment errors in excess of .13 mm result in a visible mismatch between pin and hole. Planar faces of the truss were assembled with the reference plates attached to a standard "optics" table to assure planarity, while more difficult linear adjustments were made with the aid of a portable & adjustable alignment device equipped with the same type of tapered hole.

4.TRUSS JOINT DESIGN

Ask the design teams from ten different truss based testbeds to describe the best joint, and you are likely to hear ten different joints described. At JPL, both the Phase 0 and the Phase B testbeds employed a version of the adjustable "B-nut" joint. This joint design has proven itself to be reliable and predictable. Truss elements are easy to replace and adjust, and when installed properly (high enough torque to create initial preload), exhibit linear behavior that is easily modelable. This same joint design has been applied to the MPI testbed with very satisfactory results (FIGURE 5).

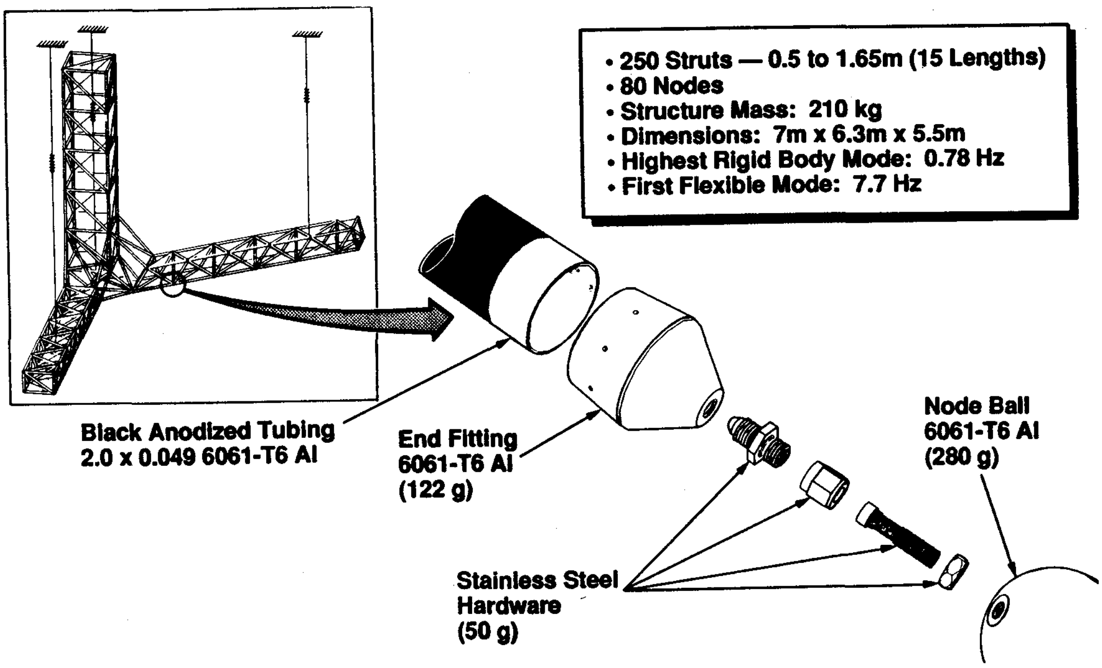

FIGURE 5 JOINT HARDWARE

5.TRUSS SUSPENSION

Choices made in designing the suspension system for a ground based testbed can have a dramatic impact on the success and usefulness of the testbed. The testbeds suspension system has the responsibility of isolating the testbed from mechanical vibrations in the laboratory facility, as well as emulating the "free-free" conditions of a structure in space. Because the MPI testbed will experience dramatic changes in mass over the first few years, the first suspension system installed was inexpensive, consisting of linear extension springs, steel aircraft cable and large turnbuckles for adjustability. The design goal for the springs was a fundamental frequency of 0.6 Hz, with experimentally measured results of 0.598 Hz (a full order of magnitude lower than the first elastic mode of the structure).

6. TESTING

Many different tests are planned for the MPI to evaluate various aspects of its design including the optical system, control systems, and the structural design. An experimental modal analysis was first of these tests, with the objective to confirm or update the analytical finite element model of the MPI structure. However, the test also provided an excellent opportunity to evaluate the linearity of the MPI design and fabrication.

To perform the modal test, the MPI was supported in the laboratory to simulate the free boundary conditions which would best mimic its operational environment. Three soft coil springs were used to support the MPI from overhead beams, producing rigid-body modes with frequencies less than one-tenth of the first elastic mode. The MPI was instrumented using a tri-axial accelerometer at each of its eighty node balls for 240 channels. In addition, accelerometers were added to a number of the long struts at their mid-spans and at various support locations producing a total of 272 accelerometer measurements in the modal test. Two fifty-pound shakers excited the structure simultaneously and were attached to the structure at optimal locations in order to excite all the modes below sixty Hertz. Frequency response functions (FRFs) were measured for each accelerometer due to input from each shaker using burst random excitation. These FRFs were the test data used to estimate the modal frequencies, mode shapes, and modal damping. Reference 8 described the modal testing procedures and results in more detail.

In addition to measuring FRFs, a number of structural dynamic tests were performed to specifically evaluate the linearity of the assembled MPI structure. Figure 6 shows a representative decayed response after removing excitation from the MPI for an accelerometer signal at the end of the optics boom. The response direction was chosen so that we would obtain primarily only one of the lower modes, then the signal was low-pass filtered to remove the contributions due to the higher modes. This particular signal is dominated by the third mode at 12.67 Hertz. The response decays by approximately a factor of ten, causing the amplitude of the modal vibration to vary by a factor of ten within this window of data. To evaluate the linearity of the structure, this response is divided into a number of segments, and then each segment is used in a separate modal analysis to determine the modal frequency as a function of time and correspondingly as a function of vibration amplitude. The computed modal frequencies are plotted versus time in Figure 7. One can clearly see that there is no trend in the data, showing that the frequencies are constant and not dependent on vibration amplitude. The random variation in the frequencies is due to the estimation procedure, and is quite small (the frequency axis is very expanded).

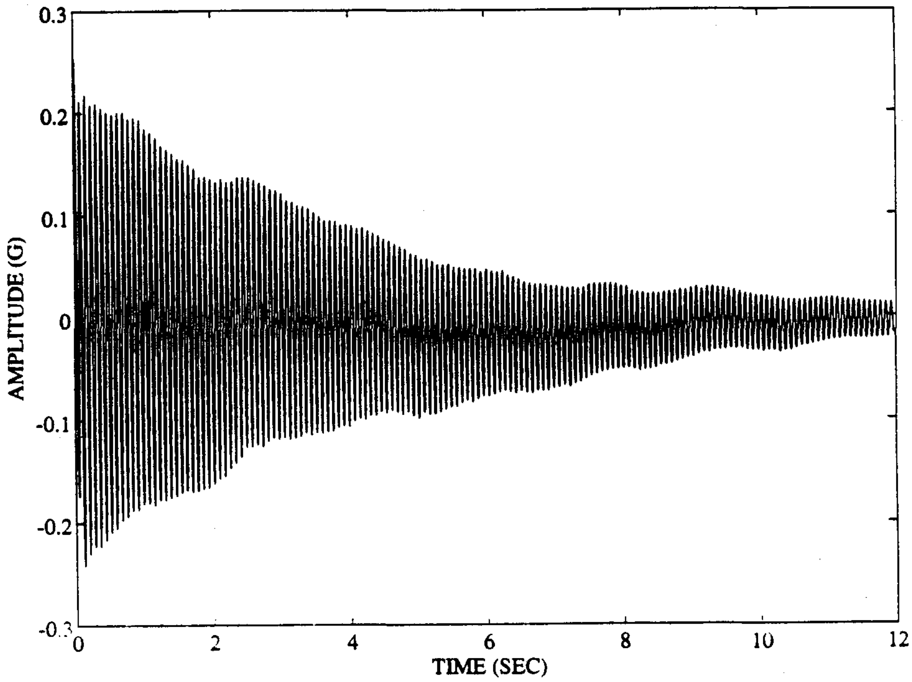

FIGURE 6 DECAYING TIME-HISTORY OF A RESPONSE ACCELERATION

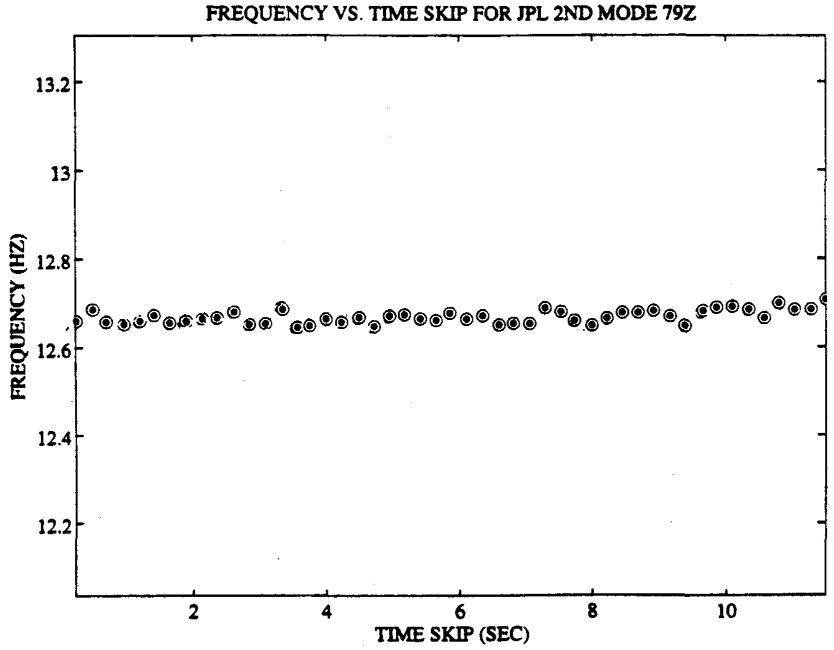

FIGURE 7 MODAL FREQUENCIES COMPUTED FROM DECAYING RESPONSE

Another test which is very useful to evaluate the linearity of a structure is to compare the reciprocity FRFs. A reciprocity FRF is the response at one shaker location due to force input from another shaker. Since we used two shakers to perform the modal test, we can compare the two reciprocity functions. A linear, elastic structure is a requirement for these two reciprocity functions to be equal. Figure 8 shows these acceleration-to-force reciprocity FRFs. The overlay shown in Figure 8 is excellent, far superior than that seen on typical structures during tests. This result shows again that the structure is quite linear and repeatable, and that a linear finite element model should be capable of predicting its structural response.

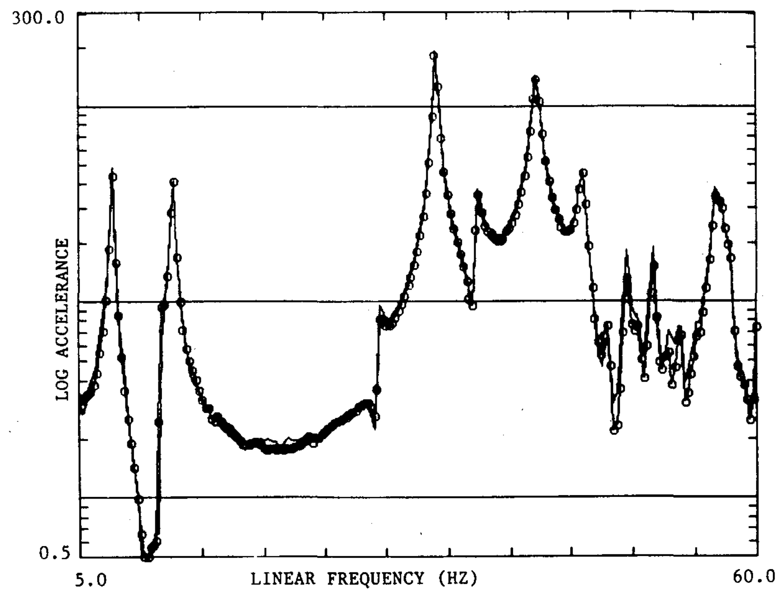

FIGURE 8 OVERLAY OF THE TWO RECIPROCITY FREQUENCY-RESPONSE-FUNCTIONS

As was mentioned earlier, the main objective of the modal test was to measure the modal parameters (frequencies, shapes, and dampings) for comparison with the analytical finite element model, [9]. After the modal parameters have been estimated using the set of FRFs as input data, then new FRFs can be synthesized, using these estimated parameter and linear modal analysis theory for comparison with the raw test data. Figure 9 shows the first six mode shapes from the nineteen that were measured below sixty Hertz. The deformed shape is overlaid upon the undeformed shape. The first three modes are scissoring type modes between the booms and/or the tower. The next three modes all have a strong twisting deformation, either a boom or the tower. The subsequent mode shapes become more complex as the frequency increases.

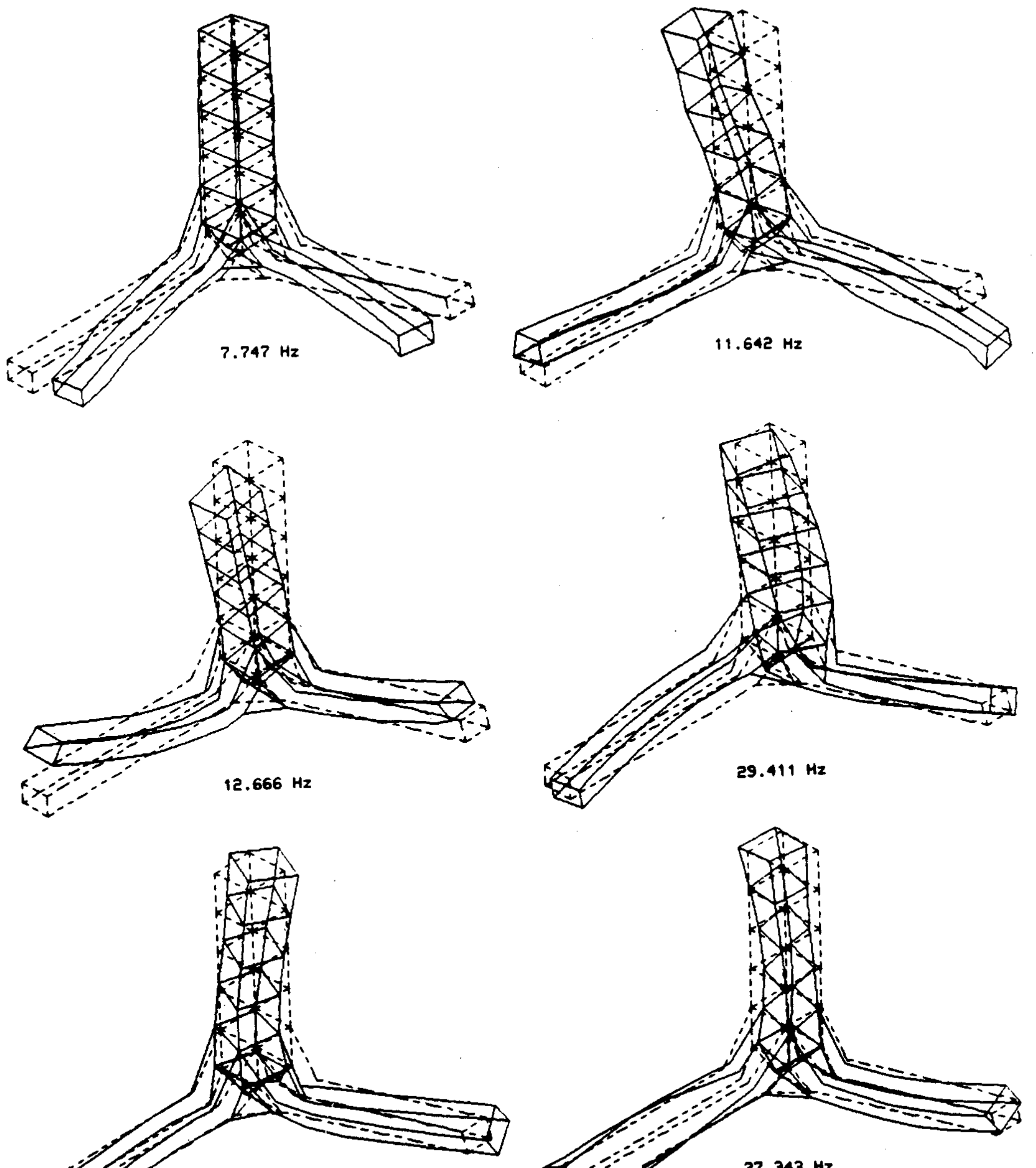

FIGURE 9 : MODE SHAPES FROM THE EXPERIMENTAL MODAL ANALYSIS
- - - - - - Undeformed Shape, ----------- Deformed Shape

As the last step in the analysis of the estimated modal parameters, FRFs are synthesized using these modal parameters and assuming linear theory. These are compared to the original measured FRFs to evaluate how closely the synthesis compares to measured FRF. Figures 10 and 11 both show a comparison of an original measured FRF with a synthesis. If the synthesis matches the original measured function well, then that indicates that the extracted modal parameters are correct and that the measured data behaves as the assumed linear model. Figure 10 shows an overlay for the cross-driving point measurement, and Figure 11 shows the overlay for a response measurement from the top of the tower. Both figures show an extremely fine reproduction of the experimental data, verifying the accuracy of the estimated modal parameters and the adequacy of the underlying linear model for the response of the structure.

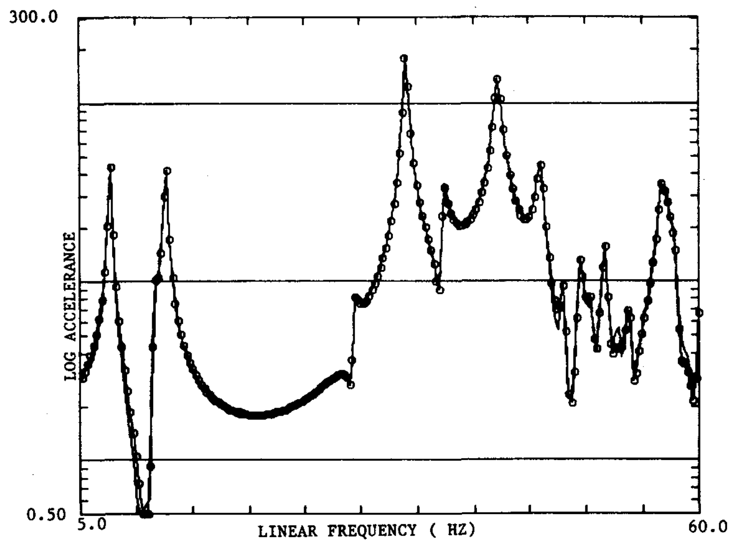

FIGURE 10 SYNTHESIS OF CROSS-DRIVING POINT FRF FROM EXPERIMENTAL MODAL PARAMETERS OVERLAID ON MEASURED FRF

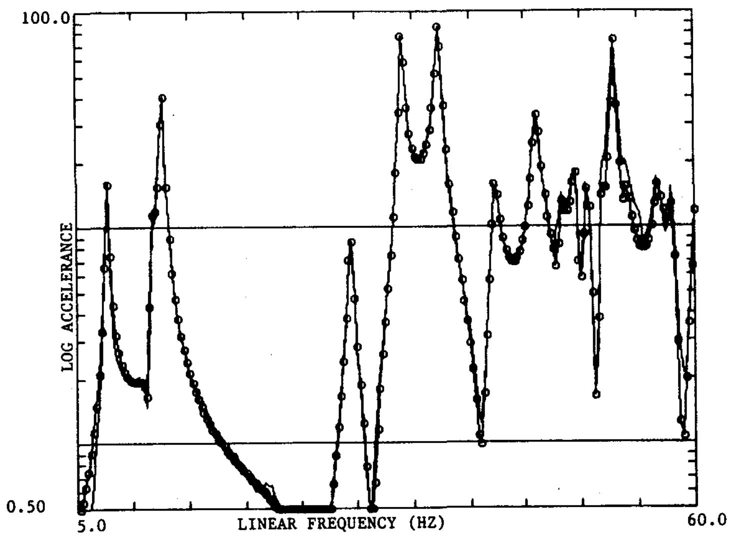

FIGURE 11 SYNTHESIS OF A TOWER FRF FROM EXPERIMENTAL MODAL PARAMETERS OVERLAID ON MEASURED FRF

In this section a number of test results have been discussed which relate to the linear behavior of the MPI structure. These tests were: Modal frequency as a function of amplitude from a decayed response, the comparison of the reciprocity functions from the two shaker inputs, and the comparison of synthesized FRFs with the measured FRFs. All of these test results reveal that the MPI is indeed a very linear structure for the level of input forces used during these tests.

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