MODELING AND MODAL IDENTIFICATION OF JOINTED SPACE STRUCTURES IN ONE- AND ZERO-GRAVITY ENVIRONMENTS

by

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Abstract

High authority control of space structures requires the existence of a high fidelity structural model. However, analytical models created based on drawings and material property tables are usually inaccurate and should be corrected based on the experimental results. Ground test results that are available before the flight are corrupted by gravity and suspension effects and cannot be used directly to refine a zero-gravity finite element model. This report studies an approach which uses ground test data for the development of precise zero-gravity structural models.

The developed approach is applied to models of four test articles in the Middeck 0-Gravity Dynamics Experiment (MODE). These test articles are assembled using a set of modules with different levels of inherent nonlinearity. The structures were tested on the ground using a suspension system with 1 Hz plunge fundamental frequency, and one-gravity models are updated based on the test results. Then suspension and gravity effects are removed to yield zero-gravity models. Predictions of these updated models are compared with the results of the orbital tests collected during the STS 62 shuttle flight mission. This comparison indicates the validity of the approach and specifies the accuracy that can be achieved for the prediction of the modal behavior in a different environment. Finally, the effects of nonlinear joints and gravity on the structural dynamics are also investigated by comparing ground and orbital test results. The repeatability of the orbital test results is also studied by comparing current results with the data collected during the first MODE flight experiment.

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Chapter 1.
Introduction

The high per-pound launch cost of space systems and the precision pointing requirements of space missions are conflicting goals for the design of space structures. Cost drives the design to lighter but more flexible structures, while pointing requirements lead the design to more rigid structures. Active structural control provides a solution to this conflicting design requirement. With active control, a flexible structure can be controlled to meet the desired pointing requirements. However, for stability and robustness, active control requires a high fidelity structural model which must be both accurate and available prior to flight.

Mathematical modeling is a common method for predicting the dynamic properties of structures. However, to create a mathematical model of a complex structure, many assumptions and simplifications are necessary; unfortunately, they introduce errors into the model. For example, modeling errors for the finite-element method, one of the most common methods, come from the following sources:

- imprecise knowledge of the physical parameters and dimensions of the real structure,
- discretization errors appearing because continuous elements are modeled with discrete representations,
- nonmodeling of damping mechanisms and nonlinear elements in the structure,
- mismodeling of boundary conditions.

The magnitude and importance of these errors are often not known *a priori*. Often, ground modal experiments are used to validate and update the first generation structural model. In normal engineering practice, a first generation model, typically developed using blueprints and manufacturer's material tables before the real hardware exists, is fine-tuned using data from dynamic tests.
In the update process, an attempt is made to identify how the model can be improved to match the ground experimental results. This process can, for example:

- provide better estimates of physical parameters,
- indicate where the model must be refined to minimize discretization errors,
- indicate how boundary conditions can be modified to better match the experimental boundary conditions.

This updating process, based on ground experiments, can provide very accurate structural models, as demonstrated by the MIT Middeck Active Control Experiment (MACE) [15]. However, these models are only valid for one-gravity conditions and extrapolation of these models to zero-gravity (space) is unfortunately not straightforward. The main problem is the presence of gravity. Gravity requires suspension systems, which results in the structures to be tested on earth having different boundary conditions than those in space. Gravity also leads to: the deformation (sagging) of the test structure, the stiffening (pre-tensioning) or de-stiffening of structural elements, and changes in the operating point of nonlinearities.

For the purpose of studying the effects of gravity on the linear and nonlinear modal characteristics of space structures, a research program was established at Massachusetts Institute of Technology (MIT) in the Space Engineering Research Center (SERC). When traditional zero-gravity facilities, such as drop towers and the KC-135, failed to provide the benchmark quality data necessary to evaluate and validate structural dynamic models, the Middeck 0-gravity Dynamics Experiment (MODE) program was proposed to NASA. NASA funded MODE in 1988 under the INSTEP program. An extensive MODE ground test program, which investigated the modal characteristics of structural configurations assembled from prototypical space structure building elements, was followed by the first MODE space experiment onboard STS-48 in September 1991. Astronauts Jim Buchli and Mark Brown were the mission specialists responsible for this experiment (referred to as MODE-1).

Although MODE-1 provided a wealth of data that allowed researchers to quantify the effects of gravity on the modal characteristics of space structures, the scope of the MODE-1 test matrix was limited by the short STS-48 on-orbit testing time. The results
indicated that modal behavior was far more nonlinear in space than expected or observed on earth. Also, in some cases the removal of gravity resulted in resonance frequency shifts so severe they fell outside the pre-flight selected frequency windows. These observations, the limited MODE-1 test matrix, and the fact that MODE was always proposed as a two flight experiment motivated a second flight. The second MODE experiment (MODE-R), also funded by the INSTEP program, was conducted under the watchful eye of astronaut Sam Gemar onboard STS-62 in March 1994. The research presented in this document reports both the results obtained from this flight and the results of the supporting ground experiments. The results of MODE-1 were previously reported by Barlow [1].

Specific objectives of the research were: 1) to establish a systematic modeling approach that will provide engineers with high fidelity structural models, valid for zero-gravity, for the purpose of design and active structural control; 2) to validate and update this approach by comparing predictions obtained from such models with actual on-orbit test data.

The approach to achieving these objectives was: 1) to conduct a set of one-gravity tests on four different configurations of structures; 2) to predict modal characteristics of the structures in space using a model updated with the ground experimental results; 3) to perform the same experiments in the zero-gravity environment of the Space Shuttle Middeck; 4) to make a comparison between the predicted and measured dynamic characteristics, and thereby to verify the ability of the approach to establish an accurate mathematical model also valid for space conditions.

In this approach, first generation finite element models, which include suspension system and gravity effects of the structures, are fine-tuned or updated based on the results from ground modal experiments. A model valid for space zero-gravity conditions is obtained by removing the effects of suspension and gravity forces. The models and thus the modeling approach are then validated by comparing the results predicted by this "space" model with the measured results obtained from an orbital experiment.

The remainder of this chapter describes the MODE Structural Test Article (STA) hardware, the sensors and sensor locations, the actuator, the test procedures, and the data reduction techniques. It also reviews the results obtained in the first part of the MODE
program [1]. The second and third chapters describe the results of the ground and orbital experiments of the MODE-Reflight program. These results, for completeness, are also compared with the corresponding MODE-1 results. The fourth chapter deals with the finite-element models of the STA configurations. It also describes the update procedure and its results. Predictions obtained using this procedure are compared with experimental results. Finally, the fifth chapter discusses the overall performance of the modeling approach in predicting space structural behavior.
1.1 Description of Hardware Configurations

Modules

A set of hardware that are representative of real space hardware was designed for the MODE experiment. Using the building blocks in the MODE Structural Test Article (STA) set, configurations of different complexity were assembled. The set includes two deployable truss modules, a set of erectable elements, two rotary joints, and two rigid appendages.

The STA modules were scaled to mirror the common structural forms used in space constructions. In the MODE-1 program the modules were assembled into three configurations: straight, straight with rotary joint, and an L-shaped. The only MODE-R hardware change to the MODE-1 program was that a new rotary joint (see Figure 1.1) was added to the MODE-1 set of modules. It is described in detail later in this chapter. Compared to the MODE-1 frictional-alpha-joint, the force/torque transfer mechanisms in this joint better modeled the mechanisms present in the International Space Station's Alpha-Joint. A straight configuration with this new torsional-alpha-joint was added to the test configurations. The four configurations tested in the MODE-R program are depicted in Figure 1.1.

Each of the two deployable truss modules, comprising the bulk of the STA, consists of four bays. The bays are cubes formed by lexan longerons attached to batten frames with each side eight inches long. The longerons have a knee joint at the midpoint that allows them to hinge, so the whole module collapses like an accordion for stowage. Note that when folded, the batten frames stay rigid. Tension in the deployed position is maintained by pre-tensioned steel cables, which run diagonally between the batten frames. In the deployed state, tension on the cables reaches 25 pounds. These cables prevent movement in both the hinges and the knee joints from entering the system dynamics.

One of the cubic bays in one of the two deployable modules includes a mechanism allowing the preload level in the steel cables to be varied. This enables the study of how
Figure 1.1: STA Configurations Tested in MODE-R Program (from top to bottom):
Baseline, Frictional Alpha, Torsional Alpha, and L Configurations.
joints, and consequently system dynamics, are affected by various preload levels. It is possible to use three different preload levels in this bay: high preload of 24 lb., which is further referenced as preload 1 (PL1); medium preload of 13 lb., or preload 2 (PL2); and a low preload of 7 lb., or preload 3 (PL3).

Another part of the STA hardware is the erectable truss, consisting of: spherical nodes with 26 holes where standoffs can be attached, and lexan struts terminating in lugs which slip in and can be securely tightened in those standoffs. The same standoffs are connected to the end batten frames on the deployable modules. This allows the connection of the erectable longerons, diagonals, and batten frames to the deployable elements to form different structural configurations.

The next modules in the building block set are the alpha-joints. Two different alpha-joints were used in MODE-Refight. The first is referred to as the frictional-alpha-joint. It weighs 2.5 pounds and consists of two aluminum disks that are connected at their center by a common axle and stainless steel ball bearings. Lexan struts are attached at 45° angles along the circumferences of both disks. Three neighboring struts are then connected together by an aluminum mounting block to which a hollow aluminum strut is attached. This allows the alpha-joint to be attached to either the deployable modules or to the erectable batten frames that have their own special standoffs. The bearings permit the disks to rotate with respect to each other. Friction between the two disks of the frictional-alpha-joint can be varied by a cam mechanism. A tensioning lever in this mechanism sets the friction at two levels. In the high friction level, rotation of one disk with respect to the other is virtually eliminated. This setting is referred to as the alpha-joint tight setting (AT). In the loose position (AL), the friction is set to a lower value, allowing some relative rotation of the disks. The slip torque was approximately 4 N·m for the alpha joint tight and 0.8 N·m for the alpha joint loose.

The modules in the STA building block set are designed to resemble the hardware elements proposed for the International Space Station Alpha (ISSA). The deployable bays are similar to the ISSA's solar array truss structure. The frictional-alpha-joint was intended to mimic the Solar Array Rotary Joint (SARJ) from the ISSA project. However, the load transfer mechanisms of the frictional-alpha-joint don't correspond well to those
of the ISSA SARJ. In order to capture the dynamics of the SARJ more accurately, a new alpha-joint module was designed, which will be referred to as the torsional-alpha-joint.

The torsional-alpha-joint is very similar in geometry to the frictional-alpha-joint, but better represents the load paths of the SARJ. It consists of two aluminum disk plates connected by roller bearings on the sides. A steel axle, that can be inserted in the square openings in the center of both disks, elastically constrains the two disks from relative rotation. The stiffness of the axle represented the stiffness of the ISSA's alpha-joint drive train. In the STA the torsional rigidity of the joint can be varied by inserting axles of different diameter.

The torsional-alpha-joint can be connected to the rest of the STA modules via standoffs mounted to four mounting plates. These mounting plates are attached to the disks with three aluminum rods, which in turn are mounted at 45 degree angles around each plate.

The new alpha-joint is shown in Figure 1.2. In this joint, the friction in the torsional direction is provided by the bearing-disk frictional surfaces. As it would be in ISSA, the amount of friction is a function of the alignment tolerances between the two disks. The expected friction in the torsional-alpha-joint is much lower compared to the friction in the frictional-alpha-joints.

Rigid appendages are attached to the ends of the deployable modules. Each appendage weighs approximately 16 pounds and can be separated into two pieces for stowage; they lowered the fundamental frequencies of STA configuration to below 10 Hz. The lower natural frequencies were desired to set a proper structure-suspension system frequency ratio and thus ensure that the effects of gravity would be measurable.

**STA Configurations**

The modules described above are assembled for tests into four configurations. The simplest is called the baseline configuration. Two deployable modules are joined through a single bay of erectable hardware to form a straight truss. A rigid appendage is
connected to each end of the truss. See Figure 1.1 for the finite element models of the structural configurations tested in the MODE-Reflight program.

The second and third configurations are similar to the baseline, but instead of erectable hardware, the two deployable modules are joined with a rotary alpha-joint. These are referred to as the frictional-alpha configuration and the torsional-alpha configuration, depending on the type of alpha-joint used. A fourth, more complex configuration contains both erectable hardware and the frictional-alpha-joint. It is a planar or 2-D configuration, and due to its shape, is called the L configuration. This

Figure 1.2: Torsional Alpha Joint
configuration was included to explore how gravity effects a more complex planar or 2-D structure, and to compare the effects with those observed in the more simple 1-D structures.

**Actuation and Data Acquisition**

Excitation of the STA was provided by a proof-mass actuator. It was mounted to a corner of the batten frame of the deployable module which contains the bay with adjustable preload. The actuator spring-mass system was mounted to a load cell that measures the force transmitted into the STA. The actuator weighs 1.82 pounds. It contains a 1 pound throw mass and two interchangeable springs: one for ground testing, and another for space testing. With the spring for ground testing, the spring-mass system has a resonance at 2.3 Hz; with the spring for orbit testing, this resonance occurs at 4.0 Hz. Due to the different springs, the actual force level differed slightly between zero-gravity and one-gravity tests for the same value of command voltage. In order to investigate the nonlinearity of the STA configurations, three force levels of excitation are applied to the structure. The force amplitudes are referred to in the remainder of the report as high, medium and low, but the actual level of force that was measured by the load cell for the different STA configurations in the MODE-1 experiment can be found in Table 1.1, from [2].

| Table 1.1: Typical Observed STA Forcing Levels |
|---|---|---|---|---|---|---|
| Config. | Mode | Type | Approx. Freq. | Low Amplitude | Medium Amp. | High Amplitude |
| | | | | Ground (lbf) | Space (lbf) | Ground (lbf) | Space (lbf) | Ground (lbf) | Space (lbf) |
| Baseline | 1 | Torsion | 7.75 | 0.05 | 0.05 | 0.22 | 0.3 | 0.4 | 0.53 |
| | 2 | Bending | 20 | 0.04 | 0.05 | 0.21 | 0.23 | 0.37 | 0.41 |
| | 3 | Shearing | 29 | 0.04 | 0.05 | 0.2 | 0.22 | 0.36 | 0.4 |
| Frictional Alpha | 1 | Torsion | 7.25 | 0.05 | 0.05 | 0.23 | 0.3 | 0.28 | 0.55 |
| | 2 | Bending | 10.5 | 0.04 | 0.05 | 0.13 | 0.26 | 0.38 | 0.46 |
| L | 1 | Torsion | 7.75 | 0.05 | 0.05 | 0.26 | 0.29 | 0.47 | 0.53 |
| | 2 | Bending | 25.5 | 0.04 | - | 0.23 | 0.22 | 0.4 | - |
| | 3 | Bending | 30.5 | 0.03 | - | 0.22 | 0.22 | 0.4 | - |
The dynamics of the STA are measured using eleven accelerometers located on the structure to best capture the modes of interest for each structural configuration. The accelerometers are located on the end batten frames of the deployable modules. Four strain gauges are also mounted to the cables of the adjustable bay. The locations and directions of sensors for the straight STA configurations and the L configuration can be seen in Figure 1.3. The number in the parentheses near each of the accelerometers indicates the output channel corresponding to this accelerometer. Output channels from the strain gauges has the same number as the strain gauge (Figure 1.3).
A flexible umbilical transfers the signals from the sixteen sensors (the four strain gauges, the load cell, and the eleven accelerometers) to the Experimental Support Module (ESM). The MODE ESM samples the information from the sensors using 12 bit A/D's at 500 Hz frequency and stores it on the WORM disk for future retrieval and analysis. The umbilical also carries the excitation signal, generated by the MODE ESM, to the STA shaker.

**Ground Suspension System**

During the ground testing, four (five for the L configuration) steel wires attached to coil springs suspended the STA from the laboratory ceiling. The suspension wires are attached to the corners of the deployable modules. The nominal length of the spring-wire combination is 120 inches. The stiffness of the coil can be adjusted to yield the desired plunge suspension frequency.

To reduce the influence of the suspension system on the ground test results, it is important to maintain frequency separation between the fundamental frequencies of the test article and the suspension. This goal is usually considered to be achieved when the suspension frequency is at least an order of magnitude (ten times) smaller than that of the test article.

While MODE-1 used four different sets of suspension springs with nominal plunge frequencies of 0.5, 1, 2, and 5 Hz to evaluate the influence of suspension on the experimental results, all the MODE-R ground experiments were conducted with the nominal 1-Hz-plunge-frequency suspension. Note that MODE-1 results indicated that the natural frequencies of the structure increased when the stiffness of the suspension system is increased [1].
Test Procedure and Data Reduction

The test procedure for both ground and orbital tests was essentially the same. The configuration was assembled and, when on the ground, suspended. In the zero-gravity environment of the shuttle middeck, it was attached to the middeck interior by elastic tethers with the fundamental frequency 0.25 Hz to prevent drift during shuttle maneuvers. On the ground, the structure was also leveled to ensure that gravity distribution matched the even distribution used in the finite element models. Leveling also provided the vertical position of the actuator necessary for its proper functioning. The umbilical was attached to the ESM that performed sensor conditioning, balancing and automatic execution of the test protocols written on the WORM disk. The protocols stored on the WORM disk determined the sensor gain settings, the level of excitation and the frequency ranges of excitation.

Excitation of the article was done by sine sweeping over a pre-selected range of frequencies. For each of these frequencies, the ESM recorded the time histories of the measured channels on the WORM disk. This data was retrieved later using a program developed by Payload Systems, Inc., a MODE subcontractor, and converted into the frequency domain by extracting only the harmonic content in the signal.

1.2 Results of the MODE-1 Program

The rest of this chapter summarizes the results of the MODE-1 experiments and the conclusions that were derived from these results. The reader is referred to References 1 and 16 for a more detailed presentation and discussion.

Modeling Results

In order to obtain the estimates of the modal frequencies of the STA and to compare analytical models with experimental results, Barlow [1] developed finite-element
models of the MODE STA configurations. Two different finite-element modeling packages were used: ADINA (Automatic Dynamic Incremental Nonlinear Analysis) [3], which allows nonlinear static and dynamic analysis to be performed; and NASTRAN (NASA STRuctural ANalysis) [4], which has more limited nonlinear analysis capabilities. However, NASTRAN can automatically calculate sensitivity coefficients, necessary for model updating. Barlow developed three STA ADINA models: 1) high order evaluation models for zero-gravity environment, 2) reduced order development models of the structure for zero-gravity obtained by element level Guyan reduction of the evaluation model, and 3) development models for the suspended structure in the gravity field. Barlow used NASTRAN primarily to obtain sensitivity coefficients for the model update procedure.

The evaluation models were more detailed. In these models the structure was represented by the assembly of rod and beam elements. The tensioning cables were modeled as a single rod element. The elements of the deployable modules and of the erectable hardware were modeled as a combination of beam elements.

The so-called development models of the STA were obtained from the evaluation models by reducing the internal degrees of freedom. Several internal degrees-of-freedom were eliminated by reducing the beam elements, used to model the longerons and the diagonals, to one equivalent beam element using the Guyan reduction technique [5]. Since the reduction process introduced errors into the models, the eigenvalues of the reduced models differed slightly from the those of the evaluation models.

These ADINA reduced-order development models were used to model the MODE STA configurations in one-gravity environment. The suspension system springs and wires were modeled as rods without bending stiffness. Gravity loading was also added to the model. The modal characteristics of the structures in one-gravity were determined with a two step process. In the first step, a nonlinear static analysis of the structure was performed until the structure reached an equilibrium under the applied gravity load. In the second step, an eigensolution was found using the geometry obtained from the static analysis.
This two step process allowed the finite element model to capture gravity induced behavior such as: pendulum modes of the structure, pitch and roll modes, axial modes of the springs, violin spring modes, and spring/wire transverse modes. However, the models failed to model gravity induced joint stiffening. The modal frequencies predicted by these "first generation" finite element models are compared with the MODE-1 orbital and ground modal test results in Tables 1.2 and 1.3.

Table 1.2: Comparison of Modal Frequencies from FEM Models and Orbital Test Results

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mode</th>
<th>Space Modal Data (Hz)</th>
<th>Evaluation Model (Hz)</th>
<th>% Difference</th>
<th>Guyan Equivalent Model (Hz)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>7.63</td>
<td>7.68</td>
<td>0.7</td>
<td>8.04</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>20.27</td>
<td>19.26</td>
<td>-5.0</td>
<td>19.31</td>
<td>-4.7</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.22</td>
<td>28.27</td>
<td>-3.3</td>
<td>28.68</td>
<td>-1.8</td>
</tr>
<tr>
<td>Alpha</td>
<td>Torsion</td>
<td>7.35</td>
<td>7.69</td>
<td>4.6</td>
<td>7.70</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>11.00</td>
<td>11.78</td>
<td>7.1</td>
<td>11.58</td>
<td>5.3</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>7.34</td>
<td>8.12</td>
<td>10.6</td>
<td>8.00</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>-</td>
<td>25.29</td>
<td>-</td>
<td>25.28</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>-</td>
<td>31.3</td>
<td>-</td>
<td>31.15</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1.3: Comparison of Frequencies from 1 Hz Suspended Ground Test Results and ADINA Development Models

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mode</th>
<th>Ground Modal Data (Hz)</th>
<th>Development Model (Hz)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>7.74</td>
<td>8.05</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>20.43</td>
<td>19.29</td>
<td>-5.6</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.42</td>
<td>28.68</td>
<td>-2.5</td>
</tr>
<tr>
<td>Alpha</td>
<td>Torsion</td>
<td>7.52</td>
<td>7.66</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>10.85</td>
<td>11.57</td>
<td>6.6</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>7.87</td>
<td>7.90</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>25.84</td>
<td>25.16</td>
<td>-2.6</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>31.69</td>
<td>30.78</td>
<td>-2.9</td>
</tr>
</tbody>
</table>
The MODE-1 Test Matrix

The flexibility of the MODE STA hardware allowed MODE-1 to investigate the effects of different settings, such as tension (preload) of the adjustable deployable bay, and the preload on the frictional alpha-joint, on the modal behavior of the structure. MODE-1 also investigated how the modal behavior varies between nominally identical structures by testing three shipsets of the MODE STA structures. Two of these structures were tested at MIT and the other at MDSSC, the supplier of all the MODE structural hardware. MODE-1 checked test results for repeatability by experimentally determining the modal behavior after multiple disassembly-assembly cycles. The effects of gravity on the nonlinear modal behavior were studied by investigating different modes, excited at multiple force levels. Thus, in summary, there were seven dimensions in the MODE-1 test matrix: 1) number of configurations, 2) preload in the deployable bay and/or the frictional-alpha-joint, 3) suspension system plunge frequency, 4) number of modes tested, 5) number of force levels, 6) shipset number, and 7) assembly/disassembly.

The size of the test matrix was reduced by limiting the number of modes to a select few. The first torsion, bending and shearing modes were selected as the dominant low frequency global modes for the straight configuration. Only the first torsion and bending modes were included in the frictional-alpha-joint test matrix, while the L configuration tests concentrated on the first torsion and first two bending modes. All the modal tests were conducted at low, medium, and high force excitation levels. The space force excitation levels were slightly different from the ground values since the different shaker springs resulted in a shift in shaker resonant frequency.

The ground test matrix was essentially repeated in space (STS-48) to enable researchers to identify and quantify the effects of gravity. However, the limited on-orbit testing time excluded the repeatability (assembly/disassembly) and different shipsets tests from the space test matrix.

Once the data were transferred from the MODE WORM disks to an IBM PC, the results were examined by calculating force-to-acceleration transfer functions, and by considering linear modal parameters, namely, the modal frequency and damping ratio. The
linear modal parameters were obtained with the circle-fit technique. MODE-1 summarized and compared the changes in modal parameters as a function of excitation level, preload setting, and suspension stiffness. The accuracy of first generation finite element models was also determined by comparing experimental and predicted results. These MODE-1 results are briefly summarized in the remaining sections of this chapter.

**Ground Tests Results**

In the ground experiments, the STA showed weak to moderate nonlinear behavior with lightly damped, well separated modes. The damping ratios were between 0.2 and 1.9%. In all experiments, except those with the loose frictional-alpha-joint, only weak nonlinear behavior was observed. The general trend was that modal frequencies were lower and damping ratios were higher with the higher forcing levels or as the bay preload was lowered. There was no indication of strong nonlinear behavior such as jumps, multiple solutions, or chaos in the ground tests.

The repeatability of modal parameters was fairly good for the baseline configuration (i.e., the deployable modules connected by the erectable hardware), but it was poor for the configurations with the frictional-alpha-joint. The standard deviation for reassembly of the structure was 0.54% in frequency and 0.22% in damping ratio.

A comparison between low force test results and suspended FEM models results showed that the maximal difference between frequencies was 6.6%. Note that the finite-element model, due to its nature, could not predict damping ratios. However, ADINA models accurately predicted frequency shifts due to different suspension stiffness. An increase in the modal frequencies was predicted by the models and observed in the test results when the stiffness (frequency) of the suspension system was increased. The modal parameters, as determined by the MODE-1 ground test program, are presented in Table 1.4.
Table 1.4: Modal Data for Ground Tests with Nominal 1 Hz Suspension

<table>
<thead>
<tr>
<th>Config.</th>
<th>Mode</th>
<th>Frict. Alpha Joint</th>
<th>Low Force Freq. (Hz)</th>
<th>Damping Ratio (%)</th>
<th>Medium Force Freq. (Hz)</th>
<th>Damping Ratio (%)</th>
<th>High Force Freq. (Hz)</th>
<th>Damping Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>High</td>
<td>NA</td>
<td>7.74</td>
<td>0.24</td>
<td>7.7</td>
<td>0.4</td>
<td>7.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>NA</td>
<td>7.71</td>
<td>0.27</td>
<td>7.66</td>
<td>0.42</td>
<td>7.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>NA</td>
<td>-</td>
<td>-</td>
<td>7.58</td>
<td>0.67</td>
<td>7.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>High</td>
<td>NA</td>
<td>20.43</td>
<td>0.41</td>
<td>20.37</td>
<td>0.39</td>
<td>20.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>NA</td>
<td>20.48</td>
<td>0.58</td>
<td>20.41</td>
<td>0.48</td>
<td>20.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>NA</td>
<td>20.29</td>
<td>0.55</td>
<td>20.18</td>
<td>0.52</td>
<td>20.12</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>High</td>
<td>NA</td>
<td>29.42</td>
<td>0.25</td>
<td>29.33</td>
<td>0.27</td>
<td>29.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>NA</td>
<td>29.34</td>
<td>0.26</td>
<td>29.26</td>
<td>0.27</td>
<td>29.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>NA</td>
<td>-</td>
<td>-</td>
<td>29.14</td>
<td>0.3</td>
<td>29.1</td>
</tr>
<tr>
<td></td>
<td>Frictional Alpha</td>
<td>Torsion</td>
<td>High Tight</td>
<td>7.52</td>
<td>0.39</td>
<td>7.44</td>
<td>0.71</td>
<td>7.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bending</td>
<td>High Tight</td>
<td>10.85</td>
<td>1.24</td>
<td>10.68</td>
<td>1.16</td>
<td>10.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Torsion</td>
<td>High Loose</td>
<td>7.31</td>
<td>1.58</td>
<td>7.08</td>
<td>3.36</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bending</td>
<td>High Loose</td>
<td>-</td>
<td>-</td>
<td>10.72</td>
<td>1.31</td>
<td>10.68</td>
</tr>
<tr>
<td></td>
<td>Frictional Alpha</td>
<td>Torsion</td>
<td>High</td>
<td>31.69</td>
<td>0.55</td>
<td>31.47</td>
<td>0.73</td>
<td>31.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bending</td>
<td>High</td>
<td>25.84</td>
<td>0.4</td>
<td>25.74</td>
<td>0.34</td>
<td>25.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Torsion</td>
<td>High Loose</td>
<td>7.76</td>
<td>0.51</td>
<td>7.63</td>
<td>0.77</td>
<td>7.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bending</td>
<td>High Loose</td>
<td>25.83</td>
<td>0.37</td>
<td>25.76</td>
<td>0.32</td>
<td>25.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bending</td>
<td>High Loose</td>
<td>31.77</td>
<td>0.45</td>
<td>31.58</td>
<td>0.84</td>
<td>31.59</td>
</tr>
</tbody>
</table>

Orbital Test Results

For the straight configuration, the results obtained on-orbit showed well-defined, almost linear resonant behavior for the low level of actuation force. However, with higher force levels, the modal behavior became significantly more nonlinear. The extracted parameters (Table 1.5) of the linear approximation to the nonlinear transfer functions showed the same trend that was observed in the ground tests. As the actuation force increased, the modal frequencies became lower and the damping ratios increased. Essentially the same trends observed on the ground were also apparent on-orbit when the
preload of the adjustable bay was decreased from the PL1 position to the PL2 and PL3 positions.

The space modal frequencies were lower than the modal frequencies of the same modes in the ground experiments, and the damping ratios were higher. The straight-configuration's MODE-1 zero-gravity modal characteristics are summarized in Table 1.5.

Tests of the frictional-alpha configuration with the alpha-joint in the tight position showed tendencies similar to those observed in the straight configuration tests. However, in the tests with alpha-joint set in the loose position, the torsion mode exhibited jump phenomenon at the medium and high actuation forces. For low excitation levels, the frictional force in the alpha-joint was high enough to keep it locked so that fairly linear behavior was observed. However, as the actuation force increased, the frictional-joint began to slip. This sudden change in torsional rigidity of the alpha-joint produced the discontinuity (jump) in the transfer functions. This phenomenon was not observed in the ground tests, mostly likely because the additional gravity loading on the alpha-joint kept it locked.

Unfortunately, in space the resonance frequencies of some the modes of the frictional-alpha configuration, and all the modes of the L configurations, shifted more than was predicted. The narrow frequency windows of MODE-1, dictated by the limited on-orbit testing time, failed to capture the modal behavior of these modes.

A comparison of the FEM predictions and zero-gravity results concluded that the models poorly predicted the space modal frequencies (Table 1.2). The maximum difference between analytical predictions and tests results was 5% for the straight configuration, 7.1% for the frictional-alpha-configuration, and 10.6 % for the L configuration.
Table 1.5: STA Modal Data for Orbital Tests

<table>
<thead>
<tr>
<th>Config. Mode</th>
<th>Frict. Alpha Joint</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Freq. (Hz)</td>
<td>Damping Ratio (%)</td>
<td>Freq. (Hz)</td>
</tr>
<tr>
<td>Torsion</td>
<td>High</td>
<td>7.63</td>
<td>0.4</td>
<td>7.59</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>7.61</td>
<td>0.34</td>
<td>7.57</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>NA</td>
<td>-</td>
<td>7.52</td>
</tr>
<tr>
<td>Baseline Bending</td>
<td>High</td>
<td>20.24</td>
<td>0.51</td>
<td>20.23</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>20.24</td>
<td>0.46</td>
<td>20.21</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>NA</td>
<td>-</td>
<td>29.08</td>
</tr>
<tr>
<td>Shearing</td>
<td>High</td>
<td>29.22</td>
<td>0.22</td>
<td>29.18</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>29.18</td>
<td>0.23</td>
<td>29.14</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>NA</td>
<td>-</td>
<td>29.14</td>
</tr>
<tr>
<td>Frictional Alpha</td>
<td>Torsion</td>
<td>7.35</td>
<td>0.51</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>10.62</td>
<td>2</td>
<td>10.59</td>
</tr>
<tr>
<td></td>
<td>Torsion</td>
<td>7.21</td>
<td>1.21</td>
<td>6.74</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>10.4</td>
<td>2.7</td>
<td>10.15</td>
</tr>
</tbody>
</table>

1.3 MODE-1 Conclusions

The first part of the MODE program (MODE-1) established a significant and valuable database of space structures' modal behavior. MODE-1 also demonstrated that the shirt-sleeve environment of the middeck can be used to obtain benchmark quality data at relatively low cost. Generally the STA exhibited weak and moderate nonlinear behavior in both one- and zero-gravity. The joints of the deployable modules, the frictional-alpha-joint, the joints of the erectable hardware, and the tensioning cables contribute to the nonlinearity of the structure. In the most tests the modal frequencies shifted lower and the damping ratios increased with the increase of the excitation force. These phenomena can be explained as follows. A low excitation force cannot overcome the stiction forces in the joints and the joints stay locked. This is more true when gravity adds an additional preload. As the actuation force increases, it exceeds the stiction forces.
in the joints. The joints are able to move more freely, and thus decrease the global stiffness of the structure. Also, with larger joint movement, more energy is dissipated in friction and through impacts, explaining the higher observed modal damping ratios. This also explains why in both one- and zero-gravity environments the nonlinear behavior of the structures becomes more pronounced as the preload in the adjustable bay decreases. With less tension in the cables, the preloads on the joints are lower.

Another possible explanation of the more nonlinear behavior of the STA in space, especially at higher amplitudes of the actuation force, is given in [6]. It was observed that the joints used to connect erectable hardware and the frictional-alpha-joint to the deployable modules had a tendency to loosen during tests, especially when they were not properly tightened. One would expect the nonlinear behavior to increase with time as the joints loosen. Since the excitation force was always increased, the nonlinear behavior would also increase with force as the joints loosen with time. Special measures were taken in the MODE-Reflight experiment to ensure the tightness of the joints.

As expected, first generation finite-element models did a poor job in predicting the modal behavior of the STA. Generally the differences between the modal frequencies in one- and zero-gravity were less than the differences between the finite-element predictions and measured results. The modeling of the suspension and of the influence of gravity was only partially successful since the influence of gravity on the nonlinear elements could not be modeled. However, the models correctly predicted the trends in modal behavior of the STA on different suspensions.

The inaccuracy of these first generation finite element models is a clear motivation for model updating. Chapter 4 of this reports describes the success of using ground experimental results to obtain higher fidelity mathematical models.
Chapter 2.

Ground Test Results

This chapter describes the results of the STA ground tests conducted during the MODE-Reflight program. The ground test matrix repeated some of the protocols of the MODE-1 program. It allowed comparison of results to be made and also to check the repeatability of ground dynamic behavior.

Four different structural configurations were tested in the one-gravity environment. The torsional alpha configuration was added to the baseline, frictional alpha, and L configurations previously tested. Only a nominal 1 Hz suspension system was used for the ground experiments, since the MODE-1 program thoroughly investigated the influence of suspension system stiffness on modal behavior. Furthermore, no assembly/reassembly tests were conducted during the MODE-R program.

The same combinations of bay preload, frictional alpha joint settings, and modes as in the MODE-1 program were tested for the baseline, frictional alpha, and L configurations. In addition, the L configuration was tested with the alpha joint in the loose position and also with a medium bay preload and the alpha joint tight. The torsional alpha configuration was tested with the low, medium, and high levels of the bay preload. The three lowest global modes of the torsional alpha configuration were investigated: the torsion, bending, and shearing modes. Table 2.1 indicates the modes that were tested for each of the configurations.

Each of the modes were tested at three excitation force levels. The levels of force slightly differed from those used during MODE-1 program (see Table 1.1). For each level the same voltage was applied to the actuator, but due to small differences in friction between the moving mass and the shaker walls, slight variations in the applied forces were observed. The observed actuation force levels for each mode are given in Table 2.1.

Two different kinds of tests were performed for each of the STA configurations. First, they were tested over a wide frequency interval (6 Hz to 42 Hz). These wide sweep tests were performed at three excitation force levels to provide an overall picture of the
system dynamics. These tests, where the spacing between the excitation frequencies was coarse, did not allow accurate identification of modal parameters, especially damping ratios. Unfortunately, it was impossible to perform high resolution tests, at closer spaced excitation frequencies, for the whole range due to time restrictions. However, it was possible to choose particular modes of interest for each STA configuration that were afterwards investigated with high resolution frequency sweeps over a narrow frequency window. The same modes of those configurations that were tested during MODE-1 were investigated in the MODE-R program. However, wider frequency windows were used to ensure that the modal behavior of all modes is captured.

Table 2.1: Observed Levels of STA Actuation Forces for the MODE-R Tests

<table>
<thead>
<tr>
<th>Config</th>
<th>Mode Type</th>
<th>Approx. Freq.</th>
<th>Low Amplitude</th>
<th>Medium Amp.</th>
<th>High Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ground (lbf)</td>
<td>Space (lbf)</td>
<td>Ground (lbf)</td>
</tr>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>7.7</td>
<td>0.052</td>
<td>0.056</td>
<td>0.213</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>20.5</td>
<td>0.05</td>
<td>0.055</td>
<td>0.198</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.2</td>
<td>0.051</td>
<td>0.055</td>
<td>0.198</td>
</tr>
<tr>
<td></td>
<td>Wide</td>
<td></td>
<td>0.051</td>
<td>0.055</td>
<td>0.199</td>
</tr>
<tr>
<td>Frictional Alpha</td>
<td>Torsion</td>
<td>7.25</td>
<td>0.051</td>
<td>0.056</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>12</td>
<td>0.051</td>
<td>0.055</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Wide</td>
<td>0.049</td>
<td>0.192</td>
<td>-</td>
<td>0.285</td>
</tr>
<tr>
<td>Torsional Alpha</td>
<td>Torsion</td>
<td>7</td>
<td>0.062</td>
<td>0.057</td>
<td>0.225</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>14</td>
<td>0.054</td>
<td>0.055</td>
<td>0.207</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.7</td>
<td>0.053</td>
<td>0.055</td>
<td>0.201</td>
</tr>
<tr>
<td></td>
<td>Wide</td>
<td>0.055</td>
<td>0.055</td>
<td>0.209</td>
<td>0.219</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>7.75</td>
<td>0.051</td>
<td>0.057</td>
<td>0.205</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>25.1</td>
<td>0.048</td>
<td>0.056</td>
<td>0.191</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>30.5</td>
<td>0.048</td>
<td>0.055</td>
<td>0.189</td>
</tr>
<tr>
<td></td>
<td>Wide</td>
<td>0.049</td>
<td>0.055</td>
<td>0.193</td>
<td>0.22</td>
</tr>
</tbody>
</table>

The beginning of this chapter describes a technique used to obtain estimates of modal frequencies and damping ratios from the experimental transfer functions. The following sections present ground test data for the baseline, frictional alpha, L, and torsional alpha configurations. For each of the STA configurations, wide frequency sweep
data are shown first, then selected modes are studied for different combinations of bay and alpha joint preloads. The results of the ground tests are also compared with the corresponding results from the MODE-1 program.

2.1 Modal Identification Procedure

A new method was employed for the identification of modal parameters from the experimental transfer functions. The circle fit method used in the MODE-1 program extracts modal parameters from an experimental force-acceleration transfer function. However, MODE measured data included experimental transfer functions from the actuator to eleven accelerometers. To concurrently incorporate all this transfer function information, a single-input/multiple-output (SIMO) or, more generally, the multiple-input/multiple-output (MIMO) system identification technique was used.

A software package for MIMO system identification developed at MIT SERC by Jacques [7] was used for the modal parameter estimation. This software uses the following steps to generate the state-space model from the multi-channel experimental data. First, the Eigensystem Realization Algorithm is used to generate a high order model, then the model is reduced, and finally curve-fitted to match experimental data using non-linear least squares algorithms. Afterwards, modal parameters are extracted from the obtained SIMO state-space models.

Figure 2.1 is an example of how a four-state system fit to the experimental transfer functions of the torsion mode of the L STA configuration. As can be seen, the software finds the best possible fit over all transfer functions. Differences between the fitted and measured transfer functions can be due to nonlinearities in the dynamic behavior of the real structure that cannot be approximated by the linear system.
Figure 2.1: Selected Transfer Functions of a Four State System Fitted to the Experimental Torsion Mode Transfer Functions of the 1Hz Ground Suspended L Configuration (AT, PL1).
2.2 Baseline Configuration Results

First, the baseline configuration was investigated over a wide frequency range (6-42 Hz). Figure 2.2 shows transfer functions from the actuator to selected accelerometers for the structure excited at the low and high forcing levels. The preload in the adjustable bay was set to the most linear position, high (PL1). The full set of transfer functions for the tests performed on this configuration is presented in Appendix A. Phase jumps of 360 degrees noticed in some of these plots occur due to inconsistency in phase unwrapping and should be ignored.

Three modes were chosen to be investigated in greater detail: the torsion mode (7.7 Hz), the bending mode at 20.5 Hz, and the shearing mode at 29.2 Hz. The modeshapes for these modes, as predicted by the finite element analysis, are shown in Figure 2.3. The same three global modes were also investigated during the MODE-1 program. This enable MODE-R to investigate repeatability issues.

Next, narrow frequency window tests were performed for each of the chosen modes. All three modes were tested with the high (PL1) and low (PL3) bay preload settings, and the shearing mode was also tested with the medium preload setting (PL2). Table 2.2 contains estimates of modal parameters obtained using narrow frequency sweeps data for these modes for different excitation levels and for different preloads. Each of these modes will be discussed in greater detail later in this section.

Selected transfer functions for the torsion mode in tests with high and low bay preload are presented in Figure 2.4. Each of the presented plots contains transfer functions corresponding to the three levels of actuation force. It is obvious that the system is nonlinear since for a linear system all three curves would coincide. As the excitation force increases, the transfer function becomes less symmetric, modal frequencies decrease, and damping ratios increase. This is a general trend that was also observed in the MODE-1 ground tests.
Figure 2.2: Selected Wide Sweep Transfer Function of the 1Hz Ground Suspended Baseline Configuration (PL1).
a) b) c)

Figure 2.3: Predicted Modeshapes of the Baseline Configuration: (a) Torsion, (b) Bending, and (c) Shearing.

Table 2.2: Estimated Modal Parameters of the Baseline Configuration - 1 Hz Ground Suspended Test Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Type</th>
<th>Bay Preload</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Freq. (Hz)</td>
<td>ζ (%)</td>
<td>Freq. (Hz)</td>
</tr>
<tr>
<td>1</td>
<td>Torsion</td>
<td>PL1</td>
<td>7.71</td>
<td>0.19</td>
<td>7.68</td>
</tr>
<tr>
<td>2</td>
<td>Bending</td>
<td>PL3</td>
<td>20.62</td>
<td>0.37</td>
<td>20.67</td>
</tr>
<tr>
<td>3</td>
<td>Shearing</td>
<td>PL2</td>
<td>29.21</td>
<td>0.19</td>
<td>29.13</td>
</tr>
<tr>
<td>3</td>
<td>Shearing</td>
<td>PL2</td>
<td>29.17</td>
<td>0.22</td>
<td>29.06</td>
</tr>
</tbody>
</table>

Comparing the modal parameters for this torsional mode with the corresponding parameters obtained in the MODE-1 ground tests (see Table 1.4), one can see that modal frequencies are slightly lower in the current experiment. This can be explained by either changes in the material properties of the structure with time, by the slackening of the tensioning cables in the deployable modules, by joint loosening, or by variations due to
assembly/reassembly. The damping ratios in the current tests were also slightly lower than in the MODE-1 program.

Figure 2.5 compares the medium excitation transfer functions for the low and high bay preload settings. Medium excitation transfer functions were chosen for this
Figure 2.6 Selected Transfer Functions for the Bending Mode of the 1Hz Ground Suspended Baseline Configuration (a - PL1, b - PL3).

Figure 2.7: Comparison of Selected Bending Mode Transfer Functions of the Baseline Configuration at the High (PL1) and Low (PL3) Bay Preloads.
appears to be softer, more nonlinear, and more damped. The same effects were also observed in the MODE-1 ground tests.

Figure 2.6 shows selected transfer functions for the bending mode of the baseline configuration tested at the high and low bay preloads. The modal parameters for this mode are given in Table 2.2. In comparison with the MODE-1 test results, the modal frequencies became slightly higher, while the damping ratios were approximately the same. This mode does not follow the trend of modal softening as the forcing increases. Modal frequencies for different excitation levels were very close to each other. However, the damping ratios increased slightly as the forcing level increases.
A comparison between transfer functions for the high and low preload settings is shown in Figure 2.7. It can be seen that the mode became softer and more damped for the low preload setting (PL3).

Finally, the transfer functions for the shearing mode of the baseline configuration with high, medium, and low preload settings are shown in Figure 2.8. The estimates for its modal parameters can be found in Table 2.2. This mode follows the general trend noticed for other modes: the modal frequency decreases and the damping ratio increases as the excitation force increases. In comparison with the results of the MODE-1 ground tests, the modal frequency is slightly lower in the current tests, and the damping ratios stayed approximately the same.

Figure 2.9 compares the transfer functions for the different preload settings at the same excitation level. The frequency of the mode decreases and the damping ratio increases as the preload changes from high to medium, and to low.

Figure 2.9: Comparison of Selected Shearing Mode Transfer Functions of the Baseline Configuration at the High (PL1), Medium (PL2), and Low (PL3) Bay Preloads.
2.3 Frictional Alpha Configuration Results

The alpha configuration with a frictional alpha joint was investigated next. Figure 2.10 presents selected wide frequency sweep transfer functions for this configuration with the alpha joint tight and the bay preload high. For this configuration two modes were chosen for a more detailed investigation: the torsion and the first bending modes. These are the same modes that were studied in the MODE-1 tests. The frequency of the torsion mode is approximately 7.6 Hz, while the bending mode is located at 12.7 Hz. The modeshapes predicted by the finite element model for these modes are shown in Figure 2.11.

The chosen modes were tested for both tight (AT) and loose (AL) alpha joint. This allowed the effects of the alpha joint preload on the dynamics of the structure to be investigated. In both cases the preload in the adjustable bay was set at high (PL1).

Selected transfer functions for the torsion mode of the frictional alpha configuration with the alpha joint in the tight and loose positions are shown in Figure 2.12. Table 2.3 contains estimates of the modal parameters obtained from the experimental narrow frequency window transfer functions.

The transfer functions show the same pattern that was observed for the torsion mode of the baseline configuration. As the actuation force increases, the mode becomes softer, more nonlinear, and the damping ratio increases. In comparison with the MODE-1 program the modal frequency is slightly higher in the current test, and the damping ratio is slightly lower. One possible explanation for these effects is that the standoffs of the frictional alpha joint were changed during the MODE-R program to accommodate the new torsional-alpha-joint.
Figure 2.10: Selected Wide Sweep Transfer Functions of the 1Hz Ground Suspended Frictional Alpha Configuration (AT, PL1).
Figure 2.11: Predicted Modeshapes of the Frictional Alpha Configuration: (a) Torsion and (b) Bending.

Figure 2.12 compares the transfer functions for the frictional alpha configurations with the alpha joint tight and loose. It can be seen that with the alpha joint in the loose position, the mode is more nonlinear, softer, and the damping ratio almost doubled from that of the structure with the tight alpha joint.

The bending mode was investigated next. Figure 2.14 contains transfer functions for the bending mode of the frictional alpha configuration with the alpha joint in the tight and loose positions. The bending mode for the tests with tight alpha joint coincides with some local modes, making modal parameter identification difficult.

Figure 2.12: Selected Torsion Mode Transfer Functions of the 1Hz Ground Suspended Frictional Alpha Configuration (a - AT, b - AL).
Table 2.3: Estimated Modal Parameters of the 1Hz Ground Suspended Frictional Alpha Configuration

<table>
<thead>
<tr>
<th>Mode</th>
<th>Type</th>
<th>Alpha Joint Preload</th>
<th>Bay Preload</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Freq. (Hz)</td>
<td>ζ (%)</td>
<td>Freq. (Hz)</td>
</tr>
<tr>
<td>1</td>
<td>Torsion</td>
<td>AT</td>
<td>PL1</td>
<td>7.6</td>
<td>0.29</td>
<td>7.54</td>
</tr>
<tr>
<td>2</td>
<td>Bending</td>
<td></td>
<td></td>
<td>12.67</td>
<td>0.41</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Torsion</td>
<td>AL</td>
<td>PL1</td>
<td>7.59</td>
<td>0.43</td>
<td>7.503</td>
</tr>
<tr>
<td>2</td>
<td>Bending</td>
<td></td>
<td></td>
<td>11.25</td>
<td>1.3</td>
<td>11.102</td>
</tr>
</tbody>
</table>

However, for the configuration with alpha joint in loose position, it can be seen that the mode is well defined at the low excitation force but becomes highly nonlinear for medium and high force levels. The modal frequency is lower for higher excitation levels and the damping ratios increase.

Figure 2.13: Comparison of Selected Torsion Mode Transfer Functions of the Frictional Alpha Configuration at the Tight (AT) and Loose (AL) Alpha Joint Preloads.
Figure 2.14: Selected Bending Mode Transfer Functions of the 1Hz Ground Suspended Frictional Alpha Configuration (a - AT, b - AL).

Finally, Figure 2.15 compares the bending mode transfer functions for tests with the tight and loose alpha joint. It can be seen that the modal frequency dropped considerably in the test with the loose alpha joint.

Figure 2.14: Comparison of Selected Bending Transfer Functions of the Frictional Alpha Configuration at the Tight (AT) and Loose (AL) Alpha Joint Preloads.
2.4 L Configuration Results

Next, the L configuration was investigated with the frictional-alpha-joint in both the tight and loose settings with the bay preload high (PL1). Also, in order to investigate effects of the changes in preload on structural dynamics, it was tested with a medium bay preload and a tight alpha joint. Wide sweep tests for the L configuration with the alpha joint in the tight position and the high preload were performed first. The low and high excitation force transfer functions for these tests can be found in Figure 2.16.

Four modes were chosen for more detailed testing: the two torsion modes near 7 and 8 Hz, the bending mode of the long leg of L configuration at 25.5 Hz, and the bending mode of the short leg at 31 Hz. Modeshapes of these modes, predicted by the finite element model, are shown in Figure 2.15.

Figure 2.15: Predicted Modeshapes of the L Configuration: (a,b) Two Torsion, (c) Long Leg Bending, and (d) Short Leg Bending.
Figure 2.16: Selected Wide Sweep Transfer Functions of the 1Hz Ground Suspended L Configuration (AT, PL1).
Figure 2.17: Selected Torsion Mode Transfer Functions of the 1Hz Ground Suspended L Configuration (a - AT, PL1, b - AL, PL1, c - AT, PL2).

The MODE-1 program considered only the second of the two torsional modes. In the first, the ends of the structure rotate out of phase, while in the second the ends are rotating in phase. Since two torsion modes occur near each other, it was possible to choose a wider frequency window, thereby catching both modes. Selected transfer functions for these torsion modes can be found in Figure 2.17. Table 2.4 contains modal parameter estimates for these modes.

It appears that these modes follow the general trend observed in the other STA configurations. As the excitation level increases, the modal frequency decreases and the damping ratio increases.
Comparing the MODE-R modal data with the MODE-1 test results (see Table 1.4), one can see that the modal frequency is slightly higher in the current tests. Current damping ratios are within the limits of deviations noticed in the MODE-1 repeatability studies (for the torsion mode that was tested in the MODE-1 ground tests).

Comparing the test results for the alpha joint in the tight and loose settings (see Figure 2.18a), it can be seen that the modal frequency of the second torsion mode decreased in the loose alpha joint tests, while the modal frequency of the first mode stayed approximately the same. The damping ratios of both modes slightly increased in the loose alpha joint tests.
Figure 2.18: Comparison of Selected Transfer Functions for the 1Hz Suspended L Configuration (a - AT, PL1 vs. AL, PL1; b - AT, PL1 vs. AT, PL1)

Figure 2.18b compares the (AT, PL1) L configuration torsion mode test results with those at medium preload setting (AT, PL2). Both modes became slightly softer; the damping ratio stayed approximately the same for the first mode while it increased for the second one.

The long leg bending mode is considered next. Selected transfer functions for this mode can be found in Figure 2.19, and modal parameter estimates are summarized in Table 2.4. Modal frequency estimates for this mode are very close to the corresponding values obtained in the MODE-1 ground tests. Estimates for the damping ratios, however, are higher in the current tests. This mode also follows the general trend of softening as the excitation level increases but the damping ratio does not exactly follow the tendency observed for other modes. For both tests with changed alpha joint settings and bay preload, the maximum value of damping ratio is observed for the medium excitation force level. This behavior was not noticed in the MODE-1 tests.

Figure 2.20 compares selected transfer functions of the long leg bending mode (AT, PL1) with the transfer functions for the same configuration with a loose alpha joint (AL, PL1), and for the same configuration with a medium bay preload (AT, PL2). In both cases the mode of the configuration with lower preload is slightly softer and more damped.
Figure 2.19: Selected Long Leg Bending Transfer Functions of the 1Hz Ground Suspended L Configuration (a - AT, PL1, b - AL, PL1, c - AT, PL2).

Figure 2.20: Comparison of the Selected Transfer Functions of the 1Hz Suspended L Configuration (a - AT, PL1 vs. AL, PL1; b - AT, PL1 vs. AT, PL2).
The last mode that was tested for the L configuration was the short leg bending mode. Figure 2.21 depicts selected transfer functions for this mode. Estimated modal parameters can be found in Table 2.4. This mode is almost linear but becomes progressively nonlinear as the excitation force increases. The mode also follows the common trend of decrease in modal frequency and increase in damping ratio. The modal frequency in the current test is considerably lower (-3.05 %) than in MODE-1 tests (see Table 1.4), and the damping ratios are nearly 100% higher.

In Figure 2.22 selected (AT, PL1) transfer functions for this mode are compared with the transfer functions of the configuration with the alpha joint loose (AL, PL1) and with the bay preload set at medium (AT, PL2). It is interesting to notice that at the higher
forcing the modal frequencies for the configuration with the loose alpha joint are slightly higher, and the damping ratios are lower than in the tight alpha joint tests. This contradicts the trend that was observed in the other modes. The modal frequencies in the tests with medium bay preload are lower, and the damping ratios are higher than in the tests with the nominally "linear" structure.

### 2.5 Torsional Alpha Configuration Results

The STA configuration with the new torsional-alpha-joint was investigated next. In addition to the nominally "linear" tests with the bay preload set at high (PL1), this configuration was also tested for medium (PL2) and low (PL3) preload levels.

Wide frequency sweeps were performed first to locate and choose modes for more detailed testing. Figure 2.23 presents selected transfer functions for these tests. Three modes were chosen for testing: the torsion mode near 7 Hz, the bending in the appendage plane mode near 15 Hz, and the shearing mode at 29.6 Hz. Figure 2.24 shows the predicted modeshapes for these modes, obtained from the finite element model.

Selected torsion mode transfer functions for this configuration at different bay preloads are shown in Figure 2.25. Table 2.5 summarizes the estimates for the modal
Figure 2.23: Selected Wide Sweep Transfer Function of the 1Hz Ground Suspended Torsional Alpha Configuration (PL1).
Figure 2.24: Predicted Modeshapes of the Torsional Alpha Configuration: (a) Torsion, (b) Bending, and (c) Shearing.

Figure 2.25: Selected Torsion Mode Transfer Functions of the 1Hz Ground Suspended Torsional Alpha Configuration (a - PL1, b - PL2, c - PL3).
parameters extracted from the transfer functions.

As can be seen, the torsion mode for the low force was strongly nonlinear, and its frequency was much higher than for the medium and high excitation levels. An explanation for this phenomenon might be that friction in the roller bearings initially locks the joints and that the low force cannot overcome these locking forces. As a higher force is applied, it overcomes the locking force of the bearings, and the torsional stiffness of the alpha joint drops considerably. Consequently, the modal frequency drops. Since the bearings influence mostly torsional motion, it will be seen that this locking phenomenon is only observed in the torsional mode of this configuration.

Table 2.5: Estimated Modal Parameters for the 1 Hz Ground Suspended Torsional Alpha Configuration.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Type</th>
<th>Bay Preload</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Freq. (Hz)</td>
<td>Freq. (Hz)</td>
<td>Freq. (Hz)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ζ (%)</td>
<td>ζ (%)</td>
<td>ζ (%)</td>
</tr>
<tr>
<td>1</td>
<td>Torsion</td>
<td>PL1</td>
<td>7.51 0.67</td>
<td>7.06 0.62</td>
<td>7.02 0.57</td>
</tr>
<tr>
<td>2</td>
<td>Bending</td>
<td>PL1</td>
<td>15.03 0.68</td>
<td>14.98 1.44</td>
<td>14.91 1.9</td>
</tr>
<tr>
<td>3</td>
<td>Shearing</td>
<td>PL1</td>
<td>29.66 0.16</td>
<td>29.58 0.32</td>
<td>29.54 0.26</td>
</tr>
<tr>
<td>1</td>
<td>Torsion</td>
<td>PL2</td>
<td>7.09 0.53</td>
<td>7.01 0.63</td>
<td>7 0.68</td>
</tr>
<tr>
<td>2</td>
<td>Bending</td>
<td>PL2</td>
<td>15.03 0.57</td>
<td>14.96 1.44</td>
<td>14.95 1.72</td>
</tr>
<tr>
<td>3</td>
<td>Shearing</td>
<td>PL2</td>
<td>29.56 0.24</td>
<td>29.49 0.27</td>
<td>29.44 0.29</td>
</tr>
<tr>
<td>1</td>
<td>Torsion</td>
<td>PL3</td>
<td>7.09 0.51</td>
<td>6.97 0.82</td>
<td>6.94 0.96</td>
</tr>
<tr>
<td>2</td>
<td>Bending</td>
<td>PL3</td>
<td>15 1.16</td>
<td>15.02 1.4</td>
<td>14.91 1.9</td>
</tr>
<tr>
<td>3</td>
<td>Shearing</td>
<td>PL3</td>
<td>29.49 0.24</td>
<td>29.43 0.27</td>
<td>29.39 0.33</td>
</tr>
</tbody>
</table>
Figure 2.26: Comparison of Selected Torsion Mode Transfer Functions of the 1Hz Ground Suspended Torsional Alpha Configuration.

Other than the effect described above, modal dynamics for this configuration fits into the pattern observed in the other MODE STA configurations. Again the modes become softer and more damped as the excitation level increases.

Figure 2.26 compares torsion mode transfer functions for high, medium, and low bay preloads at the medium excitation force levels. As the preload changes to a lower value, the modal frequency decreases and the damping ratio increases.

The bending mode was tested next. Figure 2.27 depicts selected transfer functions for this mode at the different bay preload settings. The test window also captured another bending mode of the structure (bending in the plane perpendicular to the appendage plane). As can be seen from the modal parameters (Table 2.5), this mode also fits in the general pattern noticed for most other modes: it becomes softer, more nonlinear, and more damped as the excitation level increases. Figure 2.28 compares bending mode transfer functions for the high (PL1), medium (PL2), and low (PL3) preload settings. The general trend that the modes become softer and more damped as the preload setting decreases is not as clear for this mode. There is a possibility that the frequency resolution was not high enough to observe the trend.
Figure 2.27: Selected Bending Mode Transfer Functions of the 1Hz Ground Suspended Torsional Alpha Configuration (a - PL1, b - PL2, c - PL3).

The shearing mode of the torsional alpha configuration was tested last. Transfer functions for this mode can be found in Figure 2.29, and modal parameters in Table 2.5. The shearing mode at 29.65 Hz is accompanied by another mode with a slightly lower frequency that becomes more pronounced as the excitation level increases or bay preload decreases. Other than that, the shearing mode follows the trends observed in the other modes. Modal frequency decreases and damping ratio increases as the excitation increases or as the bay preload decreases (see Figure 2.29 for a comparison of the transfer functions of different preload settings).

The bending and shearing mode of the torsional alpha configuration did not show "locked bearings" effects at the low excitation force such as were described for the torsion
Figure 2.28: Comparison of Selected Bending Mode Transfer Functions of the 1Hz Ground Suspended Torsional Alpha Configuration.

Figure 2.29: Comparison of the Shearing Mode Transfer Functions of the 1Hz Ground Suspended Torsional Alpha Configuration.
mode. Clearly the locking and unlocking of the bearings mostly influence the torsional dynamics of the joint.

Figure 2.30: Selected Shearing Mode Transfer Functions of the 1Hz Ground Suspended Torsional Alpha Configuration (a - PL1, b - PL2, c - PL3).
Chapter 3.
Orbital Test Results

This chapter describes the results of the orbital experiments performed during the STS 62 shuttle flight mission and compares them with the ground experimental results. These results are also compared with those obtained in the space experiments of the MODE-1 program.

The same set of tests was performed in space as on the ground, except for the wide frequency window tests for the frictional alpha joint configuration that were not performed in space. Excitation force levels differ slightly from the levels in ground test since a different actuator spring was used in space. The force levels registered by the load cell are shown in Table 2.1 where they are also compared with ground force levels. Unfortunately, in some of the experiments low actuation force level was not sufficient to overcome the stiction in the actuator. Thus, there was no structural response recorded for these experiments.

Orbital test results are presented in this chapter in the following order. First, wide frequency sweep transfer functions are shown in order to highlight the changes in modal characteristics between earth and space. The selected modes are then investigated in more detail by using high resolution windows. These tests were performed for the nominal state of each configuration (usually the most linear configuration with high bay preload level and frictional alpha joint in the tight position) and also for some variations in adjustable parameters such as bay preload level or frictional alpha joint state. The results of these tests are presented using selected transfer function plots (a complete set of all orbital test transfer functions can be found in Appendix B). Modal parameters estimated by applying the identification technique described in Section 2.1. Test results are presented starting from the baseline configuration that is followed by the frictional alpha, L, and, finally, torsional alpha configuration results.
3.1 Baseline Configuration Results

Selected transfer functions for the wide frequency tests on the baseline configuration at medium and high excitation levels are presented in Figures 3.1 and 3.2. In these figures they are also compared with corresponding ground test transfer functions. It can be seen that the global structural modes at 7.7 Hz, 20.7 Hz, and 29.2 Hz that were tested in detail in ground experiments are still present in the orbital tests. Torsion, bending, and shearing modes were investigated on orbit using narrow frequency windows for high (PL1) and low (PL3) preload settings. In addition, the shearing mode was also tested for the medium bay preload (PL2).

Selected torsion mode transfer functions for the baseline configuration with high and low bay preload settings are shown in Figure 3.3. Estimates of the modal parameters obtained from experimental data are given in Table 3.1 where they are compared with corresponding ground test parameters. The transfer functions are almost linear for the low excitation level but become progressively nonlinear as the excitation increase to the medium and high levels. In comparison with the ground test results (see Figure 3.4) the modes in orbital tests appear to be much more nonlinear and more damped. The modal frequencies are slightly lower in the orbital tests for high bay preload case but slightly higher for low preload.

<table>
<thead>
<tr>
<th>Preload</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\omega$ (Hz)</td>
<td>$\Delta \omega$ (%)</td>
<td>$\zeta$ (%)</td>
</tr>
<tr>
<td>PL1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PL3</td>
<td>7.65 0.55</td>
<td>0.25 -0.03</td>
<td>7.59 0.36</td>
</tr>
</tbody>
</table>

Table 3.1: Torsion Mode Modal Parameters of the Baseline Configuration in Space (shifts are with respect to the results of the ground tests of the same configuration)
Figure 3.1: Comparison of the Selected Orbital and Ground Transfer Functions of the Baseline Configuration (PL1) for Medium (a) and High (b) Excitation Levels.
Figure 3.2: Comparison of the Selected Orbital and Ground Transfer Functions of the Baseline Configuration (PL1) for Medium (a) and High (b) Excitation Levels.
Comparing the STS-62 orbital test results with those obtained in the MODE-1 program (Figure 3.5) one can see essentially similar modal behavior. The "erosion" of the torsion mode as the excitation level increases was also observed in MODE-1 orbital tests. The explanation in Section 1.3 that the loosening of the erectable hardware joints during STS-48 mission caused this phenomenon is not confirmed since in the current tests special precautions were taken to ensure that the joints are not loose. Astronauts that were conducting the on-orbit experiments tightened the joint before each test with a specially designed tool. Thus, the effects observed for the torsion mode can only be explained by

Figure 3.3: Selected Torsion Mode Transfer Functions of the Baseline Configuration in Orbit (a - PL1, b - PL3)

Figure 3.4: Comparison of the Selected Orbital and Ground Torsion Mode Transfer Functions of the Baseline Configuration (a - PL1, b - PL3)
the inherent nonlinear behavior of the structure in space. In space the structure is more nonlinear since joints are not locked by gravity loads and more energy is dissipated in friction.

The bending mode of the baseline configuration was investigated next. Selected transfer functions for this mode can be found in Figure 3.6, and Table 3.2 contains estimates of frequencies and damping ratios for this mode. The modal frequencies and damping ratios appear to be significantly higher than in the ground tests (see Figure 3.7). The bending mode for the configuration with high preload (PL1) contradicts the trend
observed for other modes since the modal frequency increased and the damping ratio decreased as the excitation level increased.

Table 3.2: Bending Mode Modal Parameters of the Baseline Configuration in Space
(shifts are with respect to the results of the ground tests of the same configuration)

| Preload | Medium Force | | High Force | | |
|---------|--------------| | | | |
|         | $\omega$ (Hz) | $\Delta \omega$ (%) | $\zeta$ (%) | $\Delta \zeta$ (Hz) | $\Delta \omega$ (%) | $\zeta$ (%) | $\Delta \zeta$ (%) |
| PL1     | 21.14        | 2.28 | 2.97 | 2.37 | 21.17        | 2.49 | 1.399 | 0.98 |
| PL3     | 20.77        | 1.21 | 0.61 | 0    | 20.73        | 0.94 | 0.92  | 0.08 |

Figure 3.8 compares the bending mode transfer functions for the orbital tests in MODE-1 and MODE-R programs. The modal frequencies in the current test are higher and the modes are more damped than in the MODE-1 orbital experiments.

The discussion is now turned to the shearing mode's modal behavior in space. Figure 3.9 present selected transfer functions of this mode for the baseline configuration with high (PL1), medium (PL2), and low (PL3) bay preloads. Modal parameter estimates for this mode can be found in Table 3.3. The shearing mode dynamics is similar in ground

Figure 3.7: Comparison of the Selected Orbital and Ground Bending Mode Transfer Functions of the Baseline Configuration (a - PL1, b - PL3)
Figure 3.8: Comparison of the Selected Orbital Torsion Mode Transfer Functions of the Baseline Configuration Tests in MODE-1 and MODE-R Programs (a - PL1, b - PL3).

Figure 3.9: Selected Shearing Mode Transfer Functions of the Baseline Configuration in Orbit (a - PL1, b - PL2, c - PL3)
and orbital tests (see Figure 3.10). Though, the mode appears to have higher modal frequencies than in the ground tests, and the damping ratios are slightly higher. This is inconsistent with the results obtained in MODE-1 program where the orbital modes were softer than the ground ones.

Table 3.3: Shearing Mode Modal Parameters of the Baseline Configuration in Space
(shifts are with respect to the results of the ground tests of the same configuration)

<table>
<thead>
<tr>
<th>Preload</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ω</td>
<td>Δω</td>
</tr>
<tr>
<td>PL1</td>
<td>29.47</td>
<td>1.16</td>
</tr>
<tr>
<td>PL2</td>
<td>29.47</td>
<td>1.38</td>
</tr>
<tr>
<td>PL3</td>
<td>29.29</td>
<td>1.02</td>
</tr>
</tbody>
</table>

In the ground tests it was possible to notice another mode in close vicinity (28.8 Hz) of the shearing mode (29.2 Hz). It was especially evident in the low preload tests. This mode can not be seen in the high preload orbital tests, however it does appear in the

Figure 3.10: Comparison of the Selected Orbital and Ground Shearing Mode Transfer Functions of the Baseline Configuration (a - PL1, b - PL3)
lower preload test. In orbital tests it seems to be located at 27.8 Hz, further than in the ground experiments from the shearing mode (29.5 Hz).

In comparison with the orbital test results obtained in the MODE-1 program (see Figure 3.11 for this comparison), the baseline configuration shearing mode is stiffer and the damping ratios are lower. But, overall, very similar modal behavior is observed for this mode.

### 3.2 Frictional Alpha Configuration Results

The frictional alpha configuration was tested in the nominal state with the alpha joint in the tight (AT) position and high bay preload setting, and also with alpha joint loose (AL). Due to lack of time, wide frequency sweeps, that were performed for this configuration in the ground tests, were not performed on orbit. The torsion and bending modes that were tested in one-gravity environment were also studied in space.

Figure 3.12 contains selected torsion mode transfer functions of the frictional alpha configuration. Modal parameters for these tests are presented in Table 3.4 where they are also compared with the modal parameters obtained in the ground experiments.
The torsion mode is distinct and almost linear for the low actuation force test. However, it becomes highly nonlinear for the medium and, especially, high actuation force. The modal frequency of the torsion mode is considerably lower in the orbital experiments than on the ground and the damping ratio is much higher (Figure 3.13). The torsion mode follows the general trend observed in the other modes, that is, as the actuation force increases the mode softens, becomes more nonlinear, and more damped.

Table 3.4: Torsion Mode Modal Parameters of the Frictional Alpha Configuration in Space (shifts are with respect to the results of the ground tests of the same configuration)

<table>
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<tr>
<th>Alpha Joint Position</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ω (Hz)</td>
<td>Δω (%)</td>
<td>ζ (%)</td>
</tr>
<tr>
<td>1 Tight</td>
<td>7.147</td>
<td>-6.36</td>
<td>0.713</td>
</tr>
<tr>
<td>2 Loose</td>
<td>7.146</td>
<td>-5.8</td>
<td>1.06</td>
</tr>
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</table>

Figure 3.12: Selected Torsion Mode Transfer Functions of the Frictional Alpha Configuration in Orbit (a - AT, PL1; b - AL, PL1).
Figure 3.13: Comparison of the Selected Orbital and Ground Torsion Mode Transfer Functions of the Frictional Alpha Configuration (a - AT, PL1, b - AL, PL1).

Figure 3.14: Comparison of the Selected Orbital Torsion Mode Transfer Functions of the Frictional Alpha Configuration Tests in MODE-1 and MODE-R Programs (a - AT, PL1, b - AL, PL1).

Figure 3.14 compares the MODE-1 and MODE-R transfer functions for the torsion mode. In the tight alpha joint tests the structure exhibited similar behavior in both programs, though the mode is softer and more nonlinear in the current tests. For the tests with alpha joint loose, the modal dynamics was substantially different in MODE-R. The jump phenomenon that was observed in MODE-1 program does not occur. Though the transfer function for the high excitation force is strongly nonlinear there is no discontinuity seen in the MODE-R tests. It can be explained by the fact that in the repeated
assembly/disassembly cycles during the ground testing the frictional-alpha-joint screw was loosened and it required tightening. Evidently, when it was tightened the friction between the two halves of the joint became different from what it was in the MODE-1 program.

The bending mode of the frictional alpha configuration was investigated next. Figure 3.15 plots selected transfer functions of this mode, and the estimates of the modal parameters are given in Table 3.5.

Table 3.5: Bending Mode Modal Parameters of the Frictional Alpha Configuration in Space (shifts are with respect to the results of the ground tests of the same configuration)

<table>
<thead>
<tr>
<th>Alpha Joint Position</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\omega$ (Hz)</td>
<td>$\Delta \omega$ (%)</td>
<td>$\zeta$ (%)</td>
</tr>
<tr>
<td>1 Tight</td>
<td>13.04</td>
<td>2.92</td>
<td>2.197</td>
</tr>
<tr>
<td>2 Loose</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
This mode appears to be very nonlinear even for the most linear configuration, and in the loose alpha joint tests it shows almost chaotic behavior. In these tests it was impossible to determine modal parameters. The modal frequency in the tight alpha joint tests (13 Hz) is higher than in the ground tests (12.6 Hz), and the damping ratios are significantly higher (see Figure 3.16 for comparison). Note, also, that lightly damped modes of the suspension system that are present in the ground test data is missing in the orbital results (Fig. 3.16a).

Overall strongly nonlinear behavior of the frictional-alpha-joint in the MODE-R flight was caused by the problems revealed during the after flight inspection. It was noticed that joint's bearings occasionally locked and the bearings' seat participated in the motion causing much higher than nominal friction in the joint. This can explain abnormalities of the torsion mode dynamics but bending frequency shift awaits additional investigation.
3.3 L Configuration Results

This section investigates the on-orbit modal characteristics of the L configuration. The ground test matrix was repeated in space by testing the configuration with the frictional-alpha-joint in the tight position (AT) with the high (PL1) and medium (PL2) bay preload settings, and with the alpha joint in the loose position (AL) with a high bay preload. Also, wide frequency sweeps were performed for the most linear L configuration (alpha joint tight and high bay preload). The results of the orbital tests are compared to the results of the corresponding ground tests. Unfortunately, in the MODE-1 orbital tests the frequency windows failed to captured the modal behavior of the L configuration so a comparison between the two sets of the orbital test results is not possible.

Figures 3.17 and 3.18 present selected wide sweep transfer functions obtained from the tests of the nominal (most linear) L configuration compared with the corresponding ground transfer functions. It can be seen from these plots that the modes’ modal frequencies changed considerably. Narrow frequency windows are used to investigate the torsion and bending modes of the three L configurations in more detail.

Selected transfer functions for the two torsion modes of the L configuration tested in the most linear state (AT, PL1), and also for the alpha joint loose (AL, PL1), and with tight alpha joint and medium preload level (AT, PL2) can be found in Figure 3.19. Tables 3.6 and 3.7 contain modal parameter estimates for these modes.

It can be seen from the data that the torsion modes are well defined for the low actuation force. Modal frequencies for this test are lower than in the ground tests and the damping ratios are higher. In fact, the frequency of the first torsion mode dropped by so much that the frequency window barely managed to capture it. As excitation level increases the modal frequencies decrease and the damping ratio increases until the modes disappear at the high force level. Comparing the tight and loose alpha joint tests, one can see that the damping ratio for the configuration with the loose alpha joint is higher.
Figure 3.17: Comparison of the Selected Orbital and Ground Transfer Functions of the L Configuration (AT, PL1) for Medium (a) and High (b) Excitation Levels.
Figure 3.18: Comparison of the Selected Orbital and Ground Transfer Functions of the L Configuration (AT, PL1) for Medium (a) and High (b) Excitation Levels.
Figure 3.19: Selected Torsion Mode Transfer Functions of the L Configuration in Orbit
(a - AT, PL1; b - AL, PL1; c - AT, PL2).

Table 3.6: First Torsion Mode Modal Parameters of the L Configuration in Space
(shifts are with respect to the results of the ground tests of the same configuration)

| Config. | Low Force | | | Medium Force | | |
|---------|-----------|---|---|-------------|---|
|         | $\omega$ (Hz) | $\Delta \omega$ (%) | $\zeta$ (%) | $\Delta \zeta$ (Hz) | $\Delta \omega$ (%) | $\zeta$ (%) | $\Delta \zeta$ |
| AT, PL1 | 6.73      | -5.85 | 1.24 | 0.76       | 6.45 | -8.83 | 1.96 | 1.37 |
| AL, PL1 | 6.74      | -5.81 | 2.22 | 1.73       | -    | -    | -    | -    |
| AT, PL2 | -         | -    | -    | -          | 6.55 | -    | 4.14 | -    |
Table 3.7: Second Torsion Mode Modal Parameters of the L Configuration in Space (shifts are with respect to the results of the ground tests of the same configuration)

<table>
<thead>
<tr>
<th>Config.</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\omega) (Hz)</td>
<td>(\Delta\omega) (%)</td>
<td>(\zeta) (%)</td>
</tr>
<tr>
<td>AT, PL1</td>
<td>7.72</td>
<td>-2.52</td>
<td>0.69</td>
</tr>
<tr>
<td>AL, PL1</td>
<td>7.75</td>
<td>-1.86</td>
<td>1.06</td>
</tr>
<tr>
<td>AT, PL2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3.20: Comparison of the Selected Orbital and Ground Torsion Mode Transfer Functions of the L Configuration (a - AT, PL1; b - AL, PL1; c - AT, PL2).
Collected data show unexpected results for the tests with alpha joint tight and medium preload setting (AT, PL2). The modes in these tests are well defined even at a high excitation level. Additionally, the modal frequencies in these modes are higher than in the nominal configuration (AT, PL1) test, that contradicts the results for other configurations. There are two possible explanations for this phenomenon. First, it is possible that the settings were accidentally switched in these tests. Second, the astronauts experienced some problems with structure assembly, so there is a possibility that some of the joints were left loose in some of the tests.

Long leg bending mode of the L configuration (Figure 2.15) was investigated next. Selected transfer functions for this mode are presented in Figure 3.21, and estimated

Figure 3.21: Selected Long Leg Bending Mode Transfer Functions of the L Configuration in Orbit (a - AT, PL1; b - AL, PL1; c - AT, PL2).
modal parameters for these tests are summarized in Table 3.8. The modal frequencies for these tests fit the previously observed pattern. As excitation level increases, the transfer functions become more nonlinear, the damping increases, and the modal frequency decreases. However, again the test with medium preload level is more linear, and the modal frequencies are higher than those observed in the high preload case, confirming the existence of the problem discussed above.

Table 3.7: Long Leg Bending Mode Modal Parameters of the L Configuration in Space (shifts are with respect to the results of the ground tests of the same configuration)

<table>
<thead>
<tr>
<th>Config</th>
<th>Low Force</th>
<th></th>
<th></th>
<th></th>
<th>Medium Force</th>
<th></th>
<th></th>
<th></th>
<th>High Force</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \omega ) (Hz)</td>
<td>( \Delta \omega ) (%)</td>
<td>( \zeta ) (%)</td>
<td>( \Delta \zeta )</td>
<td>( \omega ) (Hz)</td>
<td>( \Delta \omega ) (%)</td>
<td>( \zeta ) (%)</td>
<td>( \Delta \zeta )</td>
<td>( \omega ) (Hz)</td>
<td>( \Delta \omega ) (%)</td>
<td>( \zeta ) (%)</td>
</tr>
<tr>
<td>AT, PL1</td>
<td>24.17</td>
<td>-6.82</td>
<td>0.77</td>
<td>0.23</td>
<td>23.95</td>
<td>-7.42</td>
<td>1.56</td>
<td>0.87</td>
<td>23.91</td>
<td>-7.45</td>
<td>3.097</td>
</tr>
<tr>
<td>AL, PL1</td>
<td>24.23</td>
<td>-6.49</td>
<td>1.37</td>
<td>0.715</td>
<td>24.06</td>
<td>-7.06</td>
<td>1.703</td>
<td>0.87</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AT, PL2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>25.05</td>
<td>-2.89</td>
<td>1.79</td>
<td>0.81</td>
<td>25.01</td>
<td>-3.02</td>
<td>1.72</td>
</tr>
</tbody>
</table>

Table 3.8: Short Leg Bending Mode Modal Parameters of the L Configuration in Space (shifts are with respect to the results of the ground tests of the same configuration)

<table>
<thead>
<tr>
<th>Config</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \omega ) (Hz)</td>
<td>( \Delta \omega ) (%)</td>
<td>( \zeta ) (%)</td>
</tr>
<tr>
<td>1 AT, PL1</td>
<td>32.17</td>
<td>4.71</td>
<td>0.93</td>
</tr>
<tr>
<td>2 AL, PL1</td>
<td>31.6</td>
<td>2.955</td>
<td>0.93</td>
</tr>
<tr>
<td>3 AT, PL2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 3.23 presents selected transfer functions for the short leg bending mode of the L configuration, and Table 3.8 contains estimates of the modal parameters obtained from the experimental transfer functions.

The short leg bending mode of the L configuration exhibits a jump phenomenon (at 31.88 Hz) for the highest forcing amplitude. For the lower two forcing amplitude levels this mode seems to occur at a higher frequency than in the ground tests (Figure 3.24). The jump for the high force indicates strongly nonlinear behavior of the structural configuration. It can be explained by the nonlinearities in the joints of the structure. It is possible, that the frictional alpha joint begin to slip as the force level increases causing the discontinuity in the transfer functions. However, the fact that the jump phenomenon is

Figure 3.22: Comparison of the Selected Orbital and Ground Long Leg Bending Mode Transfer Functions of the L Configuration (a - AT, PL1; b - AL, PL1; c - AT, PL2).
Figure 3.23: Selected Short Leg Bending Mode Transfer Functions of the L Configuration in Orbit (a - AT, PL1; b - AL, PL1; c - AT, PL2).

Figure 3.24: Comparison of the Selected Orbital and Ground Short Leg Bending Mode Transfer Functions of the L Configuration (a - AT, PL1; b - AT, PL2).
observed for the nominal case that is supposed to be most linear, and there are no indications of this behavior in the transfer functions of other tests confirms the possibility that there were problems with the tight-alpha-joint high preload test. When the test with medium preload is considered, one can see that the mode is well defined even for high excitation level and that the modal frequencies are lower than in the ground tests (see Figure 3.24). The behavior of this configuration follows the general trend observed in the other modes in both the MODE-R and MODE-1 programs.

### 3.4 Torsional Alpha Configuration Results

The last configuration to be investigated was the torsional alpha configuration. This configuration was not available during the MODE-1 program. The configuration was tested with high (PL1), medium (PL2), and low (PL3) bay preload settings.

Wide frequency sweeps were performed with the bay preload at high. Selected transfer functions for these tests are shown in Figures 3.25 and 3.26. Three modes that were tested in one-gravity, namely torsion (7.4 Hz), bending (14 Hz), and shearing (29 Hz) modes, also can be seen in the space data and were investigated in more detail.

The torsion mode was tested first. Selected transfer functions for this mode can be found in Figure 3.27, and the modal parameters are given in Table 3.9.

**Table 3.9: Torsion Mode Modal Parameters of the Torsional Alpha Configuration in Space (shifts are with respect to the results of the ground tests of the same configuration)**

<table>
<thead>
<tr>
<th>Preload</th>
<th>Low Force</th>
<th></th>
<th>Medium Force</th>
<th></th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\omega$ (Hz)</td>
<td>$\Delta \omega$ (%)</td>
<td>$\zeta$ (%)</td>
<td>$\Delta \zeta$ (%)</td>
<td>$\omega$ (Hz)</td>
</tr>
<tr>
<td>1</td>
<td>PL1</td>
<td>7.41</td>
<td>-1.29</td>
<td>1.12</td>
<td>0.45</td>
</tr>
<tr>
<td>2</td>
<td>PL2</td>
<td>7.3</td>
<td>2.95</td>
<td>1.12</td>
<td>0.59</td>
</tr>
<tr>
<td>3</td>
<td>PL3</td>
<td>7.41</td>
<td>4.53</td>
<td>1.82</td>
<td>1.31</td>
</tr>
</tbody>
</table>
Figure 3.25: Comparison of the Selected Orbital and Ground Transfer Functions of the Torsional Alpha Configuration (PL1) for Medium (a) and High (b) Excitation Levels.
Figure 3.26: Comparison of the Selected Orbital and Ground Transfer Functions of the Torsional Alpha Configuration (PL1) for Medium (a) and High (b) Excitation Levels.
Orbital tests of the torsion mode show the same roller bearing locking effects that were observed in the ground tests. At the low amplitude the resonance frequencies are much higher than those observed at the higher excitation levels. As the excitation level increases, the bearings unlock and participate in the torsional motion, dropping the torsion mode's frequency. It can also be noticed that at higher amplitudes the torsion mode becomes increasingly nonlinear. The same "erosion" of the torsion mode was observed in the zero-gravity tests of the baseline configuration.

The mode follows the trend that was seen for most of the other modes, it becomes softer and more damped at higher excitation force levels. However, when modal parameters for different preload levels are examined, no apparent pattern is clear. It can be explained by the fact that the strongly nonlinear dynamic behavior of the mode prohibits good estimates of the modal parameters.

Figure 3.28 compares orbital and ground transfer functions of this mode. Generally, the modes are slightly softer, more damped, and more nonlinear in the orbital tests.

The modal behavior of the bending mode is investigated next. The transfer functions for this mode can be found in Figure 3.29, and the estimates of modal parameters are given in Table 3.10. The mode appears to be fairly linear, but it shows no apparent pattern in the modal parameter changes. In the orbital tests the mode is softer than in corresponding ground experiments (see Figure 3.30 for comparison between orbital and ground transfer function plots).
Figure 3.27: Selected Torsion Mode Transfer Functions of the Torsional Alpha Configuration in Orbit (a - PL1; b - PL2; c - PL3).

Table 3.10: Bending Mode Modal Parameters of the Torsional Alpha Configuration in Space (shifts are with respect to the results of the ground tests of the same configuration)

<table>
<thead>
<tr>
<th>Preload</th>
<th>Medium Force</th>
<th></th>
<th>High Force</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\omega$ (Hz)</td>
<td>$\Delta \omega$ (%)</td>
<td>$\zeta$ (%)</td>
<td>$\Delta \zeta$ (Hz)</td>
</tr>
<tr>
<td>PL1</td>
<td>14.14</td>
<td>-5.6</td>
<td>2.105</td>
<td>0.665</td>
</tr>
<tr>
<td>PL2</td>
<td>14.02</td>
<td>-6.28</td>
<td>1.44</td>
<td>0.002</td>
</tr>
<tr>
<td>PL3</td>
<td>14.35</td>
<td>-4.48</td>
<td>1.54</td>
<td>0.14</td>
</tr>
</tbody>
</table>
Finally, selected transfer functions of the shearing mode are presented in Figure 3.31, and modal parameter estimates obtained from the transfer functions are given in Table 3.11. The transfer functions for this mode appear to be strongly nonlinear for all configurations except for those taken at the medium preload setting.

The shearing mode was separating into two modes located around the "linear" frequency of the high force ground tests. This trend continued in the orbital tests as these two modes separated further from each other. The strong nonlinear behavior also prohibits good estimation of the modal parameters of these modes.
Figure 3.29: Selected Bending Mode Transfer Functions of the Torsional Alpha Configuration in Orbit (a - PL1; b - PL2; c - PL3).

Table 3.10: Shearing Mode Modal Parameters of the Torsional Alpha Configuration in Space (shifts are with respect to the results of the ground tests of the same configuration)

<table>
<thead>
<tr>
<th>Preload</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ω (Hz)</td>
<td>Δω (%)</td>
</tr>
<tr>
<td>PL1</td>
<td>30.41</td>
<td>2.81</td>
</tr>
<tr>
<td>PL2</td>
<td>29.79</td>
<td>1.03</td>
</tr>
<tr>
<td>PL3</td>
<td>30.00</td>
<td>1.93</td>
</tr>
</tbody>
</table>
The modes for the configuration with medium preload level appear to be almost linear in comparison with high and low preload tests. This may be explained by two reasons. Firstly, it can indicate that astronauts performing the experiments with the high and medium preloads accidentally interchanged them. Secondly, it is possible that this mode is sensitive to the position the roller bearings have locked in after the torsion mode tests. In this case the modal behavior will be unpredictable.

Figure 3.32 compares ground and orbital test results for the high and medium preload cases. The modal frequencies in the orbital tests are higher both preloads. This contradicts the general trend noticed in the most other experiments.
Figure 3.31: Selected Shearing Mode Transfer Functions of the Torsional Alpha Configuration in Orbit (a - PL1; b - PL2; c - PL3).

Figure 3.32: Comparison of the Selected Orbital and Ground Shearing Mode Transfer Functions of the Torsional Alpha Configuration (a - PL1; b - PL2).
3.5 MODE-1 and MODE-R Test Results Comparison

This section compares the modal parameters obtained in the MODE-R ground and orbital tests with the corresponding parameters from the MODE-1 tests. These comparisons were already done for individual modes and the tables presented in this section summarize this information. The tables present only the data for the configurations and modes that were tested in both programs.

Table 3.11 shows estimated modal frequencies for 1 Hz suspended ground test in MODE-1 and MODE-R programs, and Table 3.12 compares the estimates of damping ratios for these tests.

<table>
<thead>
<tr>
<th>Config.</th>
<th>Mode</th>
<th>Bay Preload</th>
<th>FRICT. Alpha Joint</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MODE-1 Freq. (Hz)</td>
<td>MODE-R Freq. (Hz)</td>
<td>MODE-1 Freq. (Hz)</td>
</tr>
<tr>
<td>Torsion</td>
<td>High</td>
<td>NA</td>
<td></td>
<td>7.74</td>
<td>7.71</td>
<td>7.70</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>NA</td>
<td></td>
<td>-</td>
<td>7.61</td>
<td>7.58</td>
</tr>
<tr>
<td>Bending</td>
<td>High</td>
<td>NA</td>
<td></td>
<td>20.43</td>
<td>20.62</td>
<td>20.37</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>NA</td>
<td></td>
<td>20.29</td>
<td>20.56</td>
<td>20.18</td>
</tr>
<tr>
<td>Shearing</td>
<td>High</td>
<td>NA</td>
<td></td>
<td>29.42</td>
<td>29.21</td>
<td>29.33</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>NA</td>
<td></td>
<td>29.34</td>
<td>29.17</td>
<td>29.26</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>NA</td>
<td></td>
<td>-</td>
<td>29.06</td>
<td>29.14</td>
</tr>
</tbody>
</table>

Table 3.11: Comparison between 1 Hz Suspended Ground Test Results in MODE-1 and MODE-R programs - Estimated Modal Frequencies
Table 3.12: Comparison between 1 Hz Suspended Ground Test Results in MODE-1 and MODE-R programs - Estimated Damping Ratios.

<table>
<thead>
<tr>
<th>Config. Mode</th>
<th>Frict. Alpha Joint</th>
<th>Low Force</th>
<th>Medium Force</th>
<th>High Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsion</td>
<td>High NA</td>
<td>0.24</td>
<td>0.4</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Low NA</td>
<td>-</td>
<td>0.67</td>
<td>0.86</td>
</tr>
<tr>
<td>Bending</td>
<td>High NA</td>
<td>0.55</td>
<td>0.61</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>Low NA</td>
<td>0.19</td>
<td>0.49</td>
<td>0.64</td>
</tr>
<tr>
<td>Baseline</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torsion</td>
<td>High NA</td>
<td>0.41</td>
<td>0.61</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>Low NA</td>
<td>0.37</td>
<td>0.61</td>
<td>0.42</td>
</tr>
<tr>
<td>Shearing</td>
<td>High NA</td>
<td>0.25</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>Low NA</td>
<td>0.22</td>
<td>0.27</td>
<td>0.30</td>
</tr>
<tr>
<td>Frictional Alpha</td>
<td>High Tight</td>
<td>0.39</td>
<td>0.71</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>High Loose</td>
<td>1.58</td>
<td>3.36</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>High Loose</td>
<td>1.3</td>
<td>1.31</td>
<td>1.52</td>
</tr>
<tr>
<td>L</td>
<td>High Tight</td>
<td>0.42</td>
<td>0.78</td>
<td>1.32</td>
</tr>
<tr>
<td>Bending</td>
<td>High Tight</td>
<td>0.54</td>
<td>0.72</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>High Loose</td>
<td>0.37</td>
<td>0.83</td>
<td>0.37</td>
</tr>
<tr>
<td>Torsion</td>
<td>High Loose</td>
<td>0.51</td>
<td>0.77</td>
<td>0.71</td>
</tr>
<tr>
<td>Bending</td>
<td>High Loose</td>
<td>0.37</td>
<td>0.83</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>High Loose</td>
<td>0.45</td>
<td>0.84</td>
<td>1.27</td>
</tr>
</tbody>
</table>

The higher differences in the damping ratios between two sets of tests can be explained by the new method that was used to obtain the estimates using simultaneously the transfer functions from the load cell to all eleven accelerometers (see Section 2.1) along with some minor changes in the structure (new frictional-alpha-joint standoffs, changed tightness of joints). This new approach provides better estimates of the modal parameters from the available test data.

Tables 3.13 and 3.14 compare estimated modal frequencies and damping ratios for the zero-gravity tests in the MODE-1 and MODE-R programs. The comparison is made for the configurations and modes that were tested in both programs.
The biggest differences in modal frequencies between two tests are observed for the bending mode of the frictional alpha joint configuration. This can be explained by the changes in the frictional-alpha-joint that occurred in the time between two experiments (see Section 3.2).
Table 3.14: Comparison between Orbital Test Results in MODE-1 and MODE-R programs - Estimated Damping Ratios.

<table>
<thead>
<tr>
<th>Config.</th>
<th>Mode</th>
<th>Bay Preload</th>
<th>FRICT. Alpha</th>
<th>Low Force MODE-1</th>
<th>MODE-R</th>
<th>Medium Force MODE-1</th>
<th>MODE-R</th>
<th>High Force MODE-1</th>
<th>MODE-R</th>
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<tr>
<td></td>
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<td>Joint</td>
<td>Damping Ratio (%)</td>
<td>Damping Ratio (%)</td>
<td>Damping Ratio (%)</td>
<td>Damping Ratio (%)</td>
<td>Damping Ratio (%)</td>
<td>Damping Ratio (%)</td>
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<tr>
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<td>-</td>
<td>0.92</td>
<td>1.03</td>
<td>2.3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>NA</td>
<td></td>
<td>0.25</td>
<td>1.6</td>
<td>0.81</td>
<td>2.7</td>
<td>-</td>
<td>-</td>
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<tr>
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<td></td>
<td>0.47</td>
<td>-</td>
<td>0.98</td>
<td>2.97</td>
<td>1.18</td>
<td>1.40</td>
</tr>
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<td></td>
<td>Low</td>
<td>NA</td>
<td></td>
<td>0.51</td>
<td>-</td>
<td>0.85</td>
<td>0.61</td>
<td>1.12</td>
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</tr>
<tr>
<td>Shearing</td>
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<td></td>
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<td>-</td>
<td>0.24</td>
<td>0.22</td>
<td>0.28</td>
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</tr>
<tr>
<td></td>
<td>Medium</td>
<td>NA</td>
<td></td>
<td>0.23</td>
<td>-</td>
<td>0.23</td>
<td>0.24</td>
<td>0.27</td>
<td>0.31</td>
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<td></td>
<td>Low</td>
<td>NA</td>
<td></td>
<td>-</td>
<td>-</td>
<td>0.24</td>
<td>0.23</td>
<td>0.28</td>
<td>0.25</td>
</tr>
<tr>
<td>Frictional Alpha</td>
<td>Torsion</td>
<td>High</td>
<td>Tight</td>
<td>0.51</td>
<td>0.71</td>
<td>1.05</td>
<td>1.67</td>
<td>2.1</td>
<td>3.09</td>
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<tr>
<td></td>
<td>Bending</td>
<td>High</td>
<td>Tight</td>
<td>-</td>
<td>2.20</td>
<td>2</td>
<td>2.79</td>
<td>1.8</td>
<td>3.83</td>
</tr>
<tr>
<td></td>
<td>Torsion</td>
<td>High</td>
<td>Loose</td>
<td>1.21</td>
<td>1.06</td>
<td>NDR</td>
<td>1.54</td>
<td>NDR</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>High</td>
<td>Loose</td>
<td>-</td>
<td>-</td>
<td>2.7</td>
<td>-</td>
<td>2.44</td>
<td>-</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>High</td>
<td>Tight</td>
<td>0.42</td>
<td>-</td>
<td>0.78</td>
<td>0.76</td>
<td>1.32</td>
<td>1.28</td>
</tr>
</tbody>
</table>
Chapter 4.

Finite Element Modeling and Model Updating

The finite element method is a common tool for the mathematical modeling of structures. Unfortunately, finite element models constructed directly from design drawings have a number of drawbacks. In so called "first generation" models, engineers are forced to use material data from manufacturer's tables and to "smooth" complex geometry to bound the finite element model size. In general, nonlinear and dissipative effects are also not included in "first generation" models. This explains why first generation models poorly predict the modal characteristics of real structures.

An accepted practice is to use results from modal experiments to refine first generation models [8,9,10]. The experimental results are used to update selected model parameters to yield a verified model that can be used with confidence. The procedure of how experimental results are used to update the models is outlined in the next section.

The chapter then describes the two sets of models that were developed for the different STA configurations: 1) the "ground" models for the suspended structure under gravity loading, and 2) the "space" models for STA configurations in the free-free environment of zero-gravity. These are first generation models developed from design drawings, material constants, manufacturers tables, and mass measurements of actual components.

The chapter continues by discussing how physical parameters in the MODE ground models were updated using results from the ground modal tests (Chapter 2). Update results from both the MODE-1 and MODE-R programs are presented. Corresponding parameters of the space models were then changed to the updated values to predict the dynamic behavior of the MODE structures in space. Finally, the accuracy of these updated models was determined by comparing the predicted space modal frequencies with the on-orbit experimental data.
### 4.1 Finite Element Model Update Technique

In general, any update procedure uses test data to adjust parameters in an analytical model so that the model's predictions match the measured results. In finite element model updating, it is necessary to solve an optimization problem. There are many variations of the update procedure but they only differ in two major aspects: with respect to the criterion used to compare the model with experimental data, and with respect to the number and types of parameters allowed to be updated.

In the updating of structural dynamic models, the update procedure attempts to match the dynamics predicted by the model to the dynamics of the real structure. In
general, depending on the size and nature of the experimental data, the update procedure can only attempt to minimize the differences between the output of the model and the measurements. Furthermore, the procedure can try to minimize the output-measured differences for all, or a sub-set of the measured parameters. The minimization criterion can be expressed in general form as [13]:

\[ J(P) = \left[F^x - F'(P)\right]^T W_F \left[F^x - F'(P)\right] \]. \hspace{1cm} (4.1)

In this expression, \( F^x \) is a vector of function values measured in the test, \( F' \) is a vector of the function values predicted by the model that is also referred to as design constraints, \( W_F \) is a weighting matrix expressing relative confidence in the obtained measurements of \( F^x \), and \( P \) is a vector of variable parameters in the theoretical model (sometimes referred to as design variables). For example, \( F^x \) can be a measured output time trace vector, a vector of modal frequencies, or a vector of measured normal modes at grid points.

Parameters in the vector \( P \) can either represent individual elements of the global mass and stiffness matrices of the structure, or real physical parameters of structural elements. Examples of real physical parameters of a structure are: material and section properties, moments of inertia, nodal geometry, and boundary conditions. A comparison of advantages and disadvantages of these two approaches is done in [9].

An approach that uses structural matrix elements as variable parameters simplifies calculation of the function \( F^x \) in most cases since stiffness and mass matrix re-calculation is not required. However, a matrix element solution gives very little or no insight on what is incorrectly modeled in the finite element model. Another drawback of this approach is a difficulty in applying engineering insight and physical constraints during the update process. Usually, it is possible to determine the physical properties that are most likely to be mismodeled but it is difficult to incorporate this knowledge into the constrains that are imposed on the elements of the global mass and stiffness matrices.

An alternative approach that uses physical parameters of the model as variables usually requires far more computational time to estimate \( F^x \) for each parameter change. However, this method allows a researcher to use his engineering judgment in choosing the
parameters to be optimized. Thus, only parameters that are likely to be mismodeled are included as "optimization" variables. This significantly reduces the size of the optimization problem. Another advantage is high interpretability of the obtained solution since optimization variables correspond directly to physical characteristics of the structure. This feature is even more important when the structure is analyzed in different configurations and under different environments. Thus, since the purpose of this research is to use ground modal information to predict dynamics in a different environment, physical structural parameters were chosen to be variables in the update procedure.

The model is updated by changing the values of the selected physical parameters until a minimum of the criterion (4.1) is found. The simplest solution to this optimization problem is found using a well-known technique called design sensitivity analysis. It is based on calculation of the sensitivity coefficients:

\[ s_{ij} = \frac{\Delta f_i}{\Delta p_j} \]  

(4.2)

where \( \Delta p_j = p_j - p_{0j} \) is a deviation in design variable \( j \), and \( \Delta f_i = f(p_{01}, p_{02}, \ldots, p_{0r}) - f(p_{01}, p_{02}, \ldots, p_{0r}) \) is a deviation in \( i \)-th constraint due to change in design variable \( j \). In this case, the nonlinear dependence of design constraints on design variables is linearized. This reduces the optimization problem to the solution of a system of linear equations:

\[ \Delta F = S \Delta P \]  

(4.3)

with respect to \( \Delta P \), where \( \Delta F \) is a vector of differences between the design constraints in the experiment and in the finite element model, \( \Delta P \) is a vector of changes in the parameters, and matrix \( S \) is a matrix of sensitivity coefficients (4.2). In a general case, when matrix \( S \) is not square, the solution for (4.3) is obtained using the least-squares method. Thus, the updated parameters of a finite element model are \( P^* = P_0 + \Delta P^* \), where \( \Delta P^* \) is a least squares solution for system (4.3).

However, this procedure gives only an approximate solution since the real dependence \( F(P) \) is not linear. The procedure can be modified to give better results. For example, the sensitivity coefficients can be calculated again at \( P^* \), and a more precise solution for a linear system (4.3) may be found. This multi-step procedure can be time consuming since it is necessary to calculate the matrix of sensitivities (4.2) at each step.
Another alternative is to use some nonlinear optimization technique for minimizing the criterion (4.1) directly.

In this research, the finite element models of different STA configurations were updated using the multi-step sensitivity analysis technique. Since modal frequencies were considered to be best identified by the MODE experiments, they were chosen as the update design constrains.

The next step in the update process was to decide on a set of update variables. The densities of the STA materials were excluded from the set, since mass measurements of individual STA components were used to determine accurate densities for the first generation finite element models. However, Young's moduli of the materials in the STA were considered to be least known. After initial sensitivity analyses showed that the natural frequencies were sensitive to the Young's moduli, the moduli were selected to form the set of physical parameters to be updated. Since all the STA configurations are assembled from the same set of modules, it is desirable to simultaneously update the characteristics of the elements of these modules across all configurations.

The specific criterion chosen for the update procedure was the summation of weighted differences between natural frequencies of interest of a finite element model and in an experimental results for all four STA configurations

\[
J(P) = \sum_{\text{Configurations}} \sum_j \alpha_j \left| f_{j}^{\text{FEM}}(P) - f_{j}^{\text{Experimental}} \right| + \sum_i \beta_i \left| p_i - p_{0i} \right|. \tag{4.4}
\]

In this formula, \(\alpha_j\) is weighting coefficients that indicate the precision of our knowledge of the value of \(j\)-th modal frequency \(f_{j}^{\text{Experimental}}\) obtained from the experiments, \(f_{j}^{\text{FEM}}\) is the value of corresponding frequency predicted by the finite element method, \(p_{0i}\) is an initial value of the model parameter, \(\beta_i\) is a weighting coefficient that indicates the precision in our knowledge of the \(i\)-th parameter in the model. The second part in the formula (4.4) restricts the parameters from changing beyond the sensible limits.

The criterion (4.4) was minimized in the following iterative procedure:

1) calculate sensitivity coefficients (4.2) for the frequencies of interest with respect to the chosen parameters \(p_i\) from the parameter set \(P\);
2) minimize the criterion (4.4) using linear approximation for the frequencies,
\[ f_i = f_{0i} + \sum s_{ij}(p_j - p_{0j}), \]
where \( f_{0i} \) is the value of i-th frequency for initial parameters \( P_0 \).

3) use the parameter set \( P \) obtained on the previous step as an initial step for the next iteration;

4) repeat from step 1 until convergence.

Since sets of data from two environments, ground and space, were available, it was possible to use the above procedure in two directions. First, it was possible to update the finite element models using the ground modal test results. The space behavior could then be predicted by removing the suspension system. Second, it was also possible to use the results from orbital tests to update the free-free "space" models, and then to transfer the updated physical parameters to the ground "suspended" models. Typically, the second direction is not possible for space structures, but given that the structure in space is a less complex problem (there are no gravity or suspension system effects that can be miss-modeled) it can be expected that this direction's updating would provide more reliable parameters for the MODE STAs. By using the space data, which are normally not available before flight, it is possible to highlight/identify gravity and suspension effects. Figure 4.1 graphically shows how the finite element model is modified to predict the zero-gravity structural dynamics.

### 4.2 MODE STA Finite Element Models

The Automatic Dynamic Incremental Nonlinear Analysis (ADINA) finite element package [3] was used to model all the STA configurations for both ground and space environments. The models used in this research are essentially the evaluation models used in MODE-1. The MODE-1 program developed two sets of models for each structural configuration: 1) detailed evaluation models with high degree of discretization, and 2) simplified reduced-order models obtained through Guyan reduction of the evaluation models. Since the purpose of this research was to investigate the effectiveness of the update procedures in modal behavior prediction, only the more accurate evaluation models were used. For zero-gravity analysis of the baseline, frictional-alpha-joint, and L
configurations, the free-free models developed of the MODE-1 program were used. A summary of the element properties for these models is given in Table 4.1. Assembled models for these configurations are shown in Figures 4.2, 4.3, and 4.4.

Table 4.1: Element Properties for STA Models

<table>
<thead>
<tr>
<th>Element</th>
<th>Material</th>
<th>E (x10^6 slugs/in sec^2)</th>
<th>v</th>
<th>ρ (x10^3 slugs/in^3)</th>
<th>A (x10^3 in^2)</th>
<th>I (x10^4 in^4)</th>
<th>J (x10^4 in^4)</th>
</tr>
</thead>
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<tr>
<td>Deployable Longeron Lexan Part</td>
<td>Lexan</td>
<td>5.4</td>
<td>0.49</td>
<td>1.4038</td>
<td>7.6699</td>
<td>4.6813</td>
<td>9.3627</td>
</tr>
<tr>
<td>Deployable Longeron Joint at Node</td>
<td>T-6 Al</td>
<td>120</td>
<td>0.33</td>
<td>3.1081</td>
<td>7.3631</td>
<td>13.302</td>
<td>26.605</td>
</tr>
<tr>
<td>Deployable Longeron Center Part</td>
<td>T-6 Al</td>
<td>120</td>
<td>0.33</td>
<td>3.1081</td>
<td>19.141</td>
<td>30.53</td>
<td>61.061</td>
</tr>
<tr>
<td>Deployable Batten Frame Lexan Part</td>
<td>Lexan</td>
<td>5.4</td>
<td>0.49</td>
<td>1.4038</td>
<td>7.6699</td>
<td>4.6813</td>
<td>9.3627</td>
</tr>
<tr>
<td>Deployable Batten Frame Corners</td>
<td>T-6 Al</td>
<td>120</td>
<td>0.33</td>
<td>3.1081</td>
<td>16.504</td>
<td>22.698</td>
<td>45.396</td>
</tr>
<tr>
<td>Tensioning Cables</td>
<td>Steel</td>
<td>78.23</td>
<td>0.33</td>
<td>8.2548</td>
<td>0.1726</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Erectable Strut Lexan Part</td>
<td>Lexan</td>
<td>5.4</td>
<td>0.49</td>
<td>1.4038</td>
<td>7.6699</td>
<td>4.6813</td>
<td>9.3627</td>
</tr>
<tr>
<td>Erectable Strut Assembly Elements</td>
<td>T-6 Al</td>
<td>120</td>
<td>0.33</td>
<td>3.1081</td>
<td>5.2922</td>
<td>8.689</td>
<td>17.378</td>
</tr>
<tr>
<td>Lexan Parts of Frictional Alpha</td>
<td>Lexan</td>
<td>5.4</td>
<td>0.49</td>
<td>1.4038</td>
<td>7.6699</td>
<td>4.6813</td>
<td>9.3627</td>
</tr>
<tr>
<td>Rigid Structural Parts of Frictional Alpha</td>
<td>Rigid</td>
<td>10,000</td>
<td>0.33</td>
<td>0</td>
<td>36</td>
<td>108</td>
<td>216</td>
</tr>
<tr>
<td>Standoffs of Frictional Alpha</td>
<td>T-6 Al</td>
<td>120</td>
<td>0.33</td>
<td>3.1081</td>
<td>5.2922</td>
<td>8.689</td>
<td>17.378</td>
</tr>
<tr>
<td>Rigid Appendage</td>
<td>Steel</td>
<td>360</td>
<td>0.33</td>
<td>8.7959</td>
<td>36</td>
<td>108</td>
<td>216</td>
</tr>
</tbody>
</table>

A detailed model of the torsional-alpha-joint was required for this research (Figure 4.5). Each of the two aluminum disks of the alpha-joint were modeled using 16 triangular plate elements. However, plate elements do not have stiffness in the out of plate direction. Thus, the central axis was connected to the plates using eight massless beam elements per
Figure 4.2: Finite Element Model of the Baseline Configuration

Figure 4.3: Finite Element Model of the Frictional Alpha Configuration
Figure 4.4: Finite Element Model of the L Configuration

disk to assure torsional rigidity. The central axis steel rod was modeled with a steel beam element. The roller bearing units that were evenly distributed at 45 degree angles around the circumference of two disks were modeled by rod elements. These rod elements still allow the disks to freely rotate about the torsional axis. This was achieved by assigning very soft bending stiffness to these connecting elements.

Each of the disks had twelve aluminum mounting struts attached to the eight points distributed at 90 degree angles along the circumference of the disk. These mounting struts were connected in groups of three by aluminum bars, modeling the plate holding the four standoffs. The four standoffs connected the alpha-joint to the deployable modules. All these parts were modeled using beam elements. Properties of the elements of the torsional-alpha-joint finite element model are summarized in the Table 4.2. The numbers under the heading "Type" in the table correspond to the element numbers in Figure 4.5.
### Table 4.2: Element Properties for the Parts of the Torsional Alpha Joint

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>$E$ ($10^6$ slugs/in sec$^2$)</th>
<th>$\nu$</th>
<th>$\rho$ ($10^3$ slugs/in$^3$)</th>
<th>$h$ (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T-6 Al</td>
<td>120</td>
<td>0.33</td>
<td>3.1081</td>
<td>0.188</td>
</tr>
<tr>
<td>2</td>
<td>Steel</td>
<td>360</td>
<td>0.33</td>
<td>8.7959</td>
<td>17.113</td>
</tr>
<tr>
<td>3</td>
<td>T-6 Al</td>
<td>120</td>
<td>0.33</td>
<td>3.1081</td>
<td>7.6699</td>
</tr>
<tr>
<td>4</td>
<td>T-6 Al</td>
<td>120</td>
<td>0.33</td>
<td>3.1081</td>
<td>28.13</td>
</tr>
<tr>
<td>5</td>
<td>Soft Rods</td>
<td>0.1</td>
<td>0.33</td>
<td>3.1081</td>
<td>42.9</td>
</tr>
<tr>
<td>6</td>
<td>T-6 Al</td>
<td>120</td>
<td>0.33</td>
<td>3.1081</td>
<td>5.269</td>
</tr>
<tr>
<td>7</td>
<td>T-6 Al</td>
<td>120</td>
<td>0.33</td>
<td>3.1081</td>
<td>5.2922</td>
</tr>
</tbody>
</table>

### Figure 4.5: Finite Element Model of the Torsional Alpha Joint

Figure 4.5: Finite Element Model of the Torsional Alpha Joint

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Total measured mass of the torsional-alpha-joint was 98.38\times 10^{-3} slugs compared to 99.4\times 10^{-3} slugs predicted by the finite element model of the alpha-joint.

The finite element model of the torsional-alpha configuration was obtained by replacing the frictional-alpha-joint in the frictional-alpha configuration with this model. The assembled evaluation model for this configuration contains 395 nodal points and is shown in Figure 4.6.

![Finite Element Model of the Torsional Alpha Joint Configuration](image)

Figure 4.6: Finite Element Model of the Torsional Alpha Joint Configuration

The one-gravity behavior of the STA was modeled by adding the suspension system to the "space" free-free models. The coil springs and steel wires of the suspension system were modeled as rod elements, allowing large deformations. Static gravity loading was also added to model the pre-tensioning in the springs. Suspended evaluation models for straight and L configurations are shown in Figures 4.7 and 4.8. Table 4.3 summarizes the element properties of the suspension system.
Table 4.3: Element properties for the parts of the suspension system

<table>
<thead>
<tr>
<th>Element</th>
<th>Material</th>
<th>E (x10^6 slugs/in sec^2)</th>
<th>ν</th>
<th>ρ (x10^3 slugs/in^3)</th>
<th>A (x10^2 in^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension System</td>
<td>Steel</td>
<td>360</td>
<td>0.33</td>
<td>3.01226 x10^6</td>
<td>3.8317 x10^-5</td>
</tr>
<tr>
<td>Coil Springs</td>
<td>Steel</td>
<td>360</td>
<td>0.33</td>
<td>8.7959</td>
<td>0.066052</td>
</tr>
<tr>
<td>Suspension Wires</td>
<td>Steel</td>
<td>360</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.7: Finite-element Model of the Suspended Straight Configurations
In the MODE-1 program, the modeling of the suspended structure was performed in two steps. In the first step, the structure was allowed to settle on the suspension under the influence of gravity. The stiffness matrix of the system was recalculated at each step of this static solution. Then, in the second step, a eigen-solution was performed using the stiffness matrix obtained from the first step.

Although this technique required a large number of computations, it still did not capture the stiffening of the joints due to the gravity preload. Due to the high number of iterations it was almost impossible to apply this two step scheme to the evaluation models of configurations other than the baseline. Thus, in this research the eigen-solutions were found for the suspended structure without including the initial nonlinear geometric deformations resulting from the gravity load. The difference between predicted modal frequencies of this simplified model and those predicted by the correct gravity deformed model was less than 0.3% for the baseline configuration.
4.3 First Generation Model Update Results

Tables 1.2 and 1.3 show predictions of "first-generation" models for space and ground modal frequencies. Note that, since none of the finite element models included any nonlinear material or joint effects, only the low excitation force, high adjustable bay preload and tight alpha-joint results were used in the update procedure. It can be seen that the discrepancies between the predictions and the experimental frequencies are generally about 5% for the orbital tests, and around 3% for the ground tests. An attempt is made to update the models and thus to improve their fidelity.

The following parameters were chosen as update variables: Young's moduli of the 1) aluminum alloy components, 2) lexan components in the deployable modules, 3) steel in appendage elements, 4) tensioning cables in the deployable modules, 5) lexan elements in the parts of the frictional-alpha-joint, 6) lexan parts of the erectable hardware, 7) suspension springs, 8) density of the suspension springs, and 9) Young's modulus of the suspension wires.

First, the upgrade procedure (outlined in section 4.1) was performed on the ground suspended finite element models using the MODE-1 ground experimental results. Table 4.4 contains the initial and updated values of the update variables.

Table 4.5 compares the natural frequencies of the updated ground finite element models and ground test results. As can be expected, the difference became much smaller (compare with Table 1.3). There is still some difference due to unmodeled nonlinear effects, and possibly due to limited set of design variables. As can be seen from Table 4.5, the differences are larger for the alpha and the L configurations. This can be explained by the presence of the nonlinear frictional-alpha-joint in these configurations. The frictional-alpha-joint has a very nonlinear torsional force transfer mechanism. This observation may also explain the large, unjustified change in the Young modulus of the lexan in the alpha-joint. The optimization process only partially succeeded when it tried to compensate for the nonlinear slip in the alpha-joint by softening the lexan.
Table 4.4: Results of the Update Procedure (one-gravity models updated using the MODE-1 one-gravity experimental results)

<table>
<thead>
<tr>
<th>Young's modulus of</th>
<th>Value Before Update (x10^6 slug/in sec^2)</th>
<th>Value After Update (x10^6 slug/in sec^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminum</td>
<td>120</td>
<td>123.77</td>
</tr>
<tr>
<td>lexan in deployable elements</td>
<td>5.4</td>
<td>6.2144</td>
</tr>
<tr>
<td>tensioning cables</td>
<td>78.23</td>
<td>78.7</td>
</tr>
<tr>
<td>steel in rigid appendage</td>
<td>360</td>
<td>388</td>
</tr>
<tr>
<td>lexan in erectable truss</td>
<td>5.4</td>
<td>5.89</td>
</tr>
<tr>
<td>lexan in elements of alpha joint</td>
<td>5.4</td>
<td>2.97</td>
</tr>
<tr>
<td>suspension springs</td>
<td>360</td>
<td>448.6</td>
</tr>
<tr>
<td>density of the suspension springs</td>
<td>3.01226x10^3 slugs/in^3</td>
<td>5.345x10^3 slugs/in^3</td>
</tr>
<tr>
<td>suspension wires</td>
<td>360</td>
<td>360</td>
</tr>
</tbody>
</table>

Table 4.5: Comparison between Modal Frequencies of the Updated Finite Element Models and Experimental Results for the One-Gravity Environment (MODE-1 program).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mode</th>
<th>Ground Modal Frequency Hz</th>
<th>FEM Predicted Frequency Hz</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>7.74</td>
<td>7.744</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>20.43</td>
<td>20.45</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.42</td>
<td>29.52</td>
<td>0.34</td>
</tr>
<tr>
<td>Alpha</td>
<td>Torsion</td>
<td>7.52</td>
<td>7.55</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>10.85</td>
<td>10.76</td>
<td>-0.83</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>7.87</td>
<td>7.93</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>25.84</td>
<td>25.63</td>
<td>-0.81</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>31.69</td>
<td>32</td>
<td>0.98</td>
</tr>
<tr>
<td>Difference Mean</td>
<td></td>
<td></td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td>Difference Standard Deviation</td>
<td></td>
<td></td>
<td></td>
<td>0.71</td>
</tr>
</tbody>
</table>
The updated parameters were then transferred to the "space" finite element models. Natural frequencies of the finite element models and MODE-1 experimental results are compared in Table 4.6. As can be seen, there is a significant improvement in comparison with the first generation models (Table 1.2).

Table 4.6: Comparison Between Modal Frequencies Predicted by the Finite Element Models (Parameters Updated Using One-Gravity Test Results) and Orbital Test Results from the MODE-1 program.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mode</th>
<th>Orbital Modal Frequency Hz</th>
<th>FEM Predicted Frequency Hz</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>7.63</td>
<td>7.75</td>
<td>1.57</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>20.26</td>
<td>20.47</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.22</td>
<td>29.52</td>
<td>1.03</td>
</tr>
<tr>
<td>Alpha</td>
<td>Torsion</td>
<td>7.35</td>
<td>7.622</td>
<td>3.67</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>11.01</td>
<td>10.79</td>
<td>-1.91</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>7.34</td>
<td>7.123</td>
<td>-2.95</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>-</td>
<td>25.67</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>-</td>
<td>31.73</td>
<td>-</td>
</tr>
<tr>
<td>Difference Mean</td>
<td></td>
<td></td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Difference Standard Deviation</td>
<td></td>
<td></td>
<td></td>
<td>2.42</td>
</tr>
</tbody>
</table>

Next, in an attempt to quantify the effects of gravity and suspension, the modal frequencies from the orbital tests were used to update the "space" finite element models. Table 4.7 contains initial and updated values of the selected variable parameters. When these updated parameters from Table 4.7 are compared with those from Table 4.4, it can be seen that corresponding updated parameters are close in value. For example, in both cases the Young's moduli of lexan in deployable and erectable elements increased, Young's modulus of lexan in the frictional-alpha-joint decreased, and Young's modulus of the steel in the appendage parts increased. This confirms that updated parameters reflect material properties of the real structure, and that the effects of gravity and suspensions are correctly modeled in the "ground" finite element models.
Table 4.7: Parameters Obtained from the Update Procedure (Zero-Gravity Models Updated Using the Zero-Gravity Test Results - MODE-1 Program)

<table>
<thead>
<tr>
<th>Young's modulus of</th>
<th>Value Before Update (x10^6 slug/in sec^2)</th>
<th>Value After Update (x10^6 slug/in sec^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminum</td>
<td>120</td>
<td>120.34</td>
</tr>
<tr>
<td>lexan in deployable elements</td>
<td>5.4</td>
<td>6.01</td>
</tr>
<tr>
<td>tensioning cables</td>
<td>78.23</td>
<td>76</td>
</tr>
<tr>
<td>steel in rigid appendage</td>
<td>360</td>
<td>392.96</td>
</tr>
<tr>
<td>lexan in erectable truss</td>
<td>5.4</td>
<td>6.07</td>
</tr>
<tr>
<td>lexan in elements of alpha joint</td>
<td>5.4</td>
<td>3.37</td>
</tr>
</tbody>
</table>

Table 4.8 and 4.9 compare the predictions of the "orbital-results" updated finite element models with the experimental results of the MODE-1 orbital and ground results. Although it is clear from these tables that the finite element models cannot exactly match the experiments, the models that were updated using the on-orbit results matched the ground experimental results to within 1.3%. This is a significant improvement over the accuracy of the "first-generation" models.

For the torsional mode of the alpha-joint configuration in space, it can be seen that in both cases (ground-to-space and space-to-ground updating) the model predicts modal frequencies higher than the experimental measured values. In the absence of gravity, the disks of the frictional-alpha-joint begin to move relative to each other, with a resultant decrease in torsional stiffness. Since the finite element models cannot capture these nonlinear decreases in stiffness, the predicted modal frequencies are higher.

A comparison in performance between updated and the "first-generation" models made for the MODE-1 program shows that updated models did well in predicting modal frequencies for different STA configurations in different environments. The discrepancies between predicted and test modal frequencies were less than 4%, in comparison with 9% for the "first-generation" models. If translated to a physical structural property, such as mass or stiffness, this an improvement of 11% (from 19% to 8%).

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Table 4.8: Comparison between modal frequencies of the updated finite element models and experimental results from zero-gravity (MODE-1 program).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mode</th>
<th>Orbital Modal Frequency Hz</th>
<th>FEM Predicted Frequency Hz</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>7.63</td>
<td>7.64</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>20.26</td>
<td>20.26</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.22</td>
<td>29.22</td>
<td>0.00</td>
</tr>
<tr>
<td>Alpha</td>
<td>Torsion</td>
<td>7.35</td>
<td>7.54</td>
<td>2.53</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>11.01</td>
<td>11.01</td>
<td>0.00</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>7.34</td>
<td>7.08</td>
<td>-3.54</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>-</td>
<td>25.64</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>-</td>
<td>31.65</td>
<td>-</td>
</tr>
<tr>
<td>Difference Mean</td>
<td></td>
<td></td>
<td></td>
<td>-0.15</td>
</tr>
<tr>
<td>Difference Standard Deviation</td>
<td></td>
<td></td>
<td></td>
<td>1.94</td>
</tr>
</tbody>
</table>
Although the updated models show a significant improvement in the prediction of the modal frequencies, they failed to exactly match the experimental results for two reasons: the number of variable (free) parameters in the update procedure was too limited, and nonlinearities of the real structures were not included. Given the MODE STA design, greater model accuracy will require detail modeling of all nonlinear and dissipative elements.

### 4.4 Model Update Based on MODE-R Results

The models updated with the MODE-1 results were used to predict the modal frequencies expected for the MODE-Reflight tests. The predicted frequencies were used to determine the frequency windows for the MODE-R space experiments and they also served as a reality check of the ability of the finite element models to predict space modal behavior prior to flight.

Table 4.10 compares the modal frequencies predicted by the "suspended" updated MODE-1 ground finite element models with the MODE-R ground experimental results, while Table 4.11 compares the frequencies predicted by the MODE-1 ground updated "space" finite element models with the MODE-R orbital test results. Again, since none of the MODE-1 finite element models included any nonlinear material or joint effects, only the MODE-R low excitation force, high adjustable bay preload and tight alpha-joint experimental results are used in the comparison.

It can be seen from Table 4.10 and 4.11 that the maximum differences between predictions and test results were around 10% for the orbital tests and 15% for the ground tests. Possible explanations for these differences, which are higher than those of MODE-1, are: firstly, that the material properties of the structural elements changed with time, and secondly, that some of the joints and tensioning cables in the structure loosened with time. A third possible explanation is that, in order to accommodate the new torsional-alpha-joint, the standoffs of the frictional-alpha-joint had to be modified. Also, the torsional alpha configuration model was not updated yet since it was not tested in
MODE-1 program. Thus, essentially the "first generation" model was used for this configuration.

Table 4.10 Comparison between Modal Frequencies of the Suspended Finite Element Models and the MODE-R Ground Test Results.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mode</th>
<th>Ground Modal Frequency Hz</th>
<th>FEM Predicted Frequency Hz</th>
<th>Δ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>7.71</td>
<td>7.74</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>20.62</td>
<td>20.45</td>
<td>-0.82</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.21</td>
<td>29.52</td>
<td>1.06</td>
</tr>
<tr>
<td>Frictional Alpha</td>
<td>Torsion</td>
<td>7.60</td>
<td>7.55</td>
<td>-0.66</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>12.67</td>
<td>10.76</td>
<td>-15.07</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>7.15</td>
<td>7.111</td>
<td>-0.55</td>
</tr>
<tr>
<td></td>
<td>Torsion</td>
<td>7.92</td>
<td>7.93</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>25.94</td>
<td>25.63</td>
<td>-1.19</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>30.72</td>
<td>32.00</td>
<td>4.17</td>
</tr>
<tr>
<td>Torsional Alpha</td>
<td>Torsion</td>
<td>7.061</td>
<td>7.2</td>
<td>1.99</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>15.03</td>
<td>17.75</td>
<td>18.09</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.65</td>
<td>29.1</td>
<td>-1.85</td>
</tr>
<tr>
<td>Difference Mean</td>
<td></td>
<td></td>
<td></td>
<td>0.48</td>
</tr>
<tr>
<td>Difference SD</td>
<td></td>
<td></td>
<td></td>
<td>7.26</td>
</tr>
</tbody>
</table>

Given the inaccuracy of the MODE-1 models in predicting the modal behavior of STA structures on the ground, the next obvious step was to use MODE-R ground modal results to update the finite element models. The same update procedure that was previously used to update the models with the MODE-1 results was used to obtain updated models from the MODE-R ground results. Since the MODE-R configuration set included an additional torsional-alpha configuration, the set of variable parameters used in the update procedure for the MODE-1 program was extended to include the parameters of the torsional-alpha-joint. These parameters were Young's moduli of the following
elements: 1) aluminum mounting struts and disks of the alpha-joint, 2) steel central rod connecting the two disks of the joint, and 3) side rods connecting the sides of the disks.

Table 4.11 Comparison between the Natural Frequencies Predicted by the Finite Element Models and Space Experimental Results (MODE-R Program).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mode</th>
<th>Orbital Modal Frequency Hz</th>
<th>FEM Predicted Frequency Hz</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>7.67</td>
<td>7.75</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>21.14</td>
<td>20.47</td>
<td>-3.16</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.47</td>
<td>29.52</td>
<td>0.17</td>
</tr>
<tr>
<td>Frictional Alpha</td>
<td>Torsion</td>
<td>7.15</td>
<td>7.62</td>
<td>6.60</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>13.02</td>
<td>10.79</td>
<td>-17.13</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>6.73</td>
<td>7.12</td>
<td>5.84</td>
</tr>
<tr>
<td></td>
<td>Torsion</td>
<td>7.72</td>
<td>8.00</td>
<td>3.65</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>24.17</td>
<td>25.67</td>
<td>6.20</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>32.17</td>
<td>31.73</td>
<td>-1.37</td>
</tr>
<tr>
<td>Torsional Alpha</td>
<td>Torsion</td>
<td>7.02</td>
<td>7.21</td>
<td>2.68</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>14.14</td>
<td>15.09</td>
<td>6.71</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.79</td>
<td>30.10</td>
<td>1.04</td>
</tr>
<tr>
<td>Difference Mean</td>
<td></td>
<td></td>
<td></td>
<td>1.02</td>
</tr>
<tr>
<td>Difference Standard Deviation</td>
<td></td>
<td></td>
<td></td>
<td>6.58</td>
</tr>
</tbody>
</table>

Table 4.12 shows initial values of the variable parameters of the update procedure (those obtained by MODE-1) and their values after the update was performed. Note that the parameters changed similarly to the corresponding parameters in the MODE-1 updated models; for example: Young's modulus of lexan elements increased except for the lexan in the parts of the frictional-alpha-joint, Young's modulus of steel in the appendage elements decreased, Young's modulus of the tensioning cables decreased, etc.

Parameters \( \alpha \) (see Formula 4.4) were chosen for each modal frequency to reflect the confidence in this value. These values were chosen higher for the modal frequencies of the well defined modes and lower for the cases when nonlinear behavior or multiple
local modes prevented precise identification of the modal parameters. For example, the values $\alpha_i$ were chosen lower for the bending modes of the frictional alpha and torsional alpha configurations. The physical parameter changes were restricted using coefficients $\beta_i$ that were chosen approximately one tenth of $\alpha_i$ that allowed variation in these parameters but prevented excessive variations.

The updated model predictions for the modal frequencies of the STA configurations are presented in Table 4.13. Although the update failed to correctly model the bending modal characteristics of the alpha-joint-configurations, it can be seen that newly updated models yield better predictions of the modal frequencies.

Table 4.12: Parameters Obtained from the Update Procedure (One-Gravity Models Updated Using the One-Gravity Test Results - MODE-R Program)

<table>
<thead>
<tr>
<th>Young's modulus of</th>
<th>Value Before Update</th>
<th>Value After Update</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(x10^6 \text{ slug/in sec}^2)$</td>
<td>$(x10^6 \text{ slug/in sec}^2)$</td>
</tr>
<tr>
<td>aluminum</td>
<td>123.77</td>
<td>116.38</td>
</tr>
<tr>
<td>lexan in deployable elements</td>
<td>6.2144</td>
<td>6.17</td>
</tr>
<tr>
<td>tensioning cables</td>
<td>78.7</td>
<td>76.8</td>
</tr>
<tr>
<td>steel in rigid appendage</td>
<td>388</td>
<td>375.56</td>
</tr>
<tr>
<td>lexan in erectable truss</td>
<td>5.89</td>
<td>6.62</td>
</tr>
<tr>
<td>lexan in elements of alpha joint</td>
<td>2.97</td>
<td>3.68</td>
</tr>
<tr>
<td>suspension springs</td>
<td>448.6</td>
<td>296.29</td>
</tr>
<tr>
<td>density of the suspension springs</td>
<td>$5.345 \times 10^3 \text{ slugs/in}^3$</td>
<td>$3.56 \times 10^3 \text{ slugs/in}^3$</td>
</tr>
<tr>
<td>suspension wires</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>mounting struts (torsional alpha joint)</td>
<td>120</td>
<td>22</td>
</tr>
<tr>
<td>center beam (torsional alpha joint)</td>
<td>360</td>
<td>800</td>
</tr>
<tr>
<td>side rods (torsional alpha joint)</td>
<td>0.1</td>
<td>0.086</td>
</tr>
</tbody>
</table>
The new updated physical parameters were then transferred to the zero-gravity STA models. Table 4.14 compares the predictions made by these zero-gravity models and results from the orbital tests. When compared with the predictions of the "first-generation" models (Table 4.2), it can be seen that considerable improvement is observed for the baseline and torsional-alpha configurations, but there is almost no improvement for frictional-alpha and L configurations. This can again be explained by the presence of the frictional-alpha-joint. Obviously, models including nonlinear effects, will be needed if these structural configurations are to be modeled more accurately.

Table 4.13: Comparison between Modal Frequencies of the Newly Updated Finite Element Models and the MODE-1 Ground Test Results.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mode</th>
<th>Ground Results (Hz)</th>
<th>Updated FEM Results (Hz)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>7.71</td>
<td>7.69</td>
<td>-0.26</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>20.62</td>
<td>20.47</td>
<td>-0.73</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.21</td>
<td>29.27</td>
<td>0.21</td>
</tr>
<tr>
<td>Frictional Alpha</td>
<td>Torsion</td>
<td>7.60</td>
<td>7.52</td>
<td>-1.02</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>12.67</td>
<td>11.51</td>
<td>-9.15</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>7.15</td>
<td>7.146</td>
<td>-0.06</td>
</tr>
<tr>
<td></td>
<td>Torsion</td>
<td>7.92</td>
<td>8.032</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>25.94</td>
<td>24.83</td>
<td>-4.28</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>30.72</td>
<td>31.83</td>
<td>3.61</td>
</tr>
<tr>
<td>Torsional Alpha</td>
<td>Torsion</td>
<td>7.06</td>
<td>6.96</td>
<td>-1.46</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>15.03</td>
<td>15.05</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.65</td>
<td>29.62</td>
<td>-0.10</td>
</tr>
<tr>
<td>Difference Mean</td>
<td></td>
<td></td>
<td></td>
<td>-0.98</td>
</tr>
<tr>
<td>Difference Standard Deviation</td>
<td></td>
<td></td>
<td></td>
<td>3.15</td>
</tr>
</tbody>
</table>
Table 4.14. Comparison between Modal Frequencies of the "New" Finite Element Models (Parameters Updated with MODE-R Ground Results) and the MODE-R Orbital Test Results.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mode</th>
<th>Orbital Modal Frequency Hz</th>
<th>FEM Predicted Frequency Hz</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Torsion</td>
<td>7.67</td>
<td>7.69</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>21.14</td>
<td>20.49</td>
<td>-3.07</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.47</td>
<td>29.28</td>
<td>-0.64</td>
</tr>
<tr>
<td>Frictional Alpha</td>
<td>Torsion</td>
<td>7.15</td>
<td>7.58</td>
<td>6.01</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>13.02</td>
<td>11.26</td>
<td>13.51</td>
</tr>
<tr>
<td>L</td>
<td>Torsion</td>
<td>6.73</td>
<td>7.16</td>
<td>6.33</td>
</tr>
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<td></td>
<td>Torsion</td>
<td>7.72</td>
<td>8.08</td>
<td>4.66</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>24.17</td>
<td>25.87</td>
<td>7.03</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>32.17</td>
<td>31.83</td>
<td>-1.05</td>
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<td>Torsional Alpha</td>
<td>Torsion</td>
<td>7.02</td>
<td>6.96</td>
<td>-0.85</td>
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<tr>
<td></td>
<td>Bending</td>
<td>14.14</td>
<td>14.14</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Shearing</td>
<td>29.79</td>
<td>29.64</td>
<td>-0.50</td>
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<tr>
<td>Difference Mean</td>
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<td></td>
<td></td>
<td>2.63</td>
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<tr>
<td>Difference Standard Deviation</td>
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<td></td>
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</table>
Chapter 5
Conclusions

The 5 GByte of data on the dynamic behavior of the MODE STA in zero-gravity, obtained during STS-62 mission, significantly expanded our knowledge on how gravity changes the modal behavior of space structures and it also extended our database on such behavior. With the MODE Reflight results, a check on the repeatability of on-orbit (zero-gravity) modal response was possible, and by capturing the modal response of the L configuration, the MODE Reflight data also enabled the determination of the effects of gravity on the dynamics of a two dimensional structure. MODE Reflight confirmed the highly nonlinear behavior of the frictional alpha joint. It also investigated and added to the modal-behavior-database the dynamics of another alpha joint, with load transfer paths similar to that of the proposed ISSA Alpha-joint.

MODE-R Ground Test Results

The STA configurations exhibited weakly and moderately nonlinear behavior in the ground tests. The nonlinear behavior is mainly due to the presence of nonlinear STA joints. Generally, the MODE-R ground results confirm the findings of the MODE-1 program. The modes become softer, more nonlinear, and more damped when the excitation is increased. As the excitation force was increased from low to high, the observed frequency shifts were approximately: -0.5% for the torsion and shearing baseline configuration modes, -2% for the modes of the frictional alpha configuration, and -1% for the torsion and bending modes of the L configuration. The bending mode of the baseline configuration was the only mode that did not follow this trend, its frequency remained constant. The modal damping ratios typically double as the excitation is changed from low to high.
The torsion mode of the torsional alpha configuration exhibited strongly nonlinear behavior in the ground tests. The modal frequency dramatically decreased (6.5%) as the excitation increased from low to medium. This is most likely due to the locking and unlocking of the roller bearings of the joint. The bearings, initially locked by the gravity induced stiction forces, unlock as the excitation increase.

The results concluded that a decrease in adjustable bay preload makes the modes softer, more nonlinear, and more damped. The same modal tendency was observed when the preload in the frictional-alpha-joint was decreased from tight to loose. A drop of 11% was observed in the bending mode frequency of the frictional alpha configuration when the preload was changed from tight to loose. These observations confirm MODE-1 results.

The modal parameters of the MODE-R program are somewhat different from the MODE-1 results. In MODE-R the modal frequencies are slightly higher (except for the L configuration short leg bending mode that was 3% lower in the current tests), and the damping ratios, in general, slightly increased. These differences can be explained by either aging of the STA materials, by slackening of the tensioning cables and tightening/loosening of the joints, or normal assembly/reassembly variations. The differences may also be explained by the fact that MODE-1 and MODE-R used different techniques to determine the modal parameters. In MODE-R a SIMO complex transfer function curve fitting technique was used while MODE-1 used the circle-fit technique.

MODE-R Orbital Test Results

In the MODE-R orbital tests, the STAs exhibited stronger nonlinear behavior than was observed in the ground tests. The nonlinear resonance "erosion", that was seen in the MODE-1 orbital results, was also observed in the MODE-R baseline, frictional alpha, and torsional alpha configuration results. Given that MODE-R ensured proper tensioning of the STA joints throughout the modal tests, it can be concluded that this behavior is due to inherent nonlinearities in the structure and not due to loosening of the joints. The jumps in the MODE-1 alpha configuration tests were not seen in the MODE-R data, but jumps in the force-acceleration transfer functions were observed in the L configuration results.
Most of the on-orbit modes were softer and more damped than in the ground tests. The best explanation for this behavior is that, in the absence of gravity, the preloads on the joints are lower, and thus, the stiction forces in the joint are lower too. Lower excitation forces are necessary to overcome the stiction forces and "looser" joints decrease the global stiffness of the structure. However, this was not true for all the modes. The frequencies of the bending and shearing modes of the baseline, the bending mode of the frictional alpha, and the shearing mode of the torsional alpha configuration all increased slightly in zero-gravity. Currently there is no clear explanation for this behavior. The largest frequency shift between ground and space was approximately 9%. Generally, due to the strong nonlinear behavior of the frictional alpha joint, configurations with this joint exhibited larger shifts.

Comparing current zero-gravity results with those from the MODE-1 program, it can be concluded that the modal frequencies are higher in the current program for all the modes except the torsion mode of the frictional alpha configuration. The largest change was as much as 18% for the bending mode of the frictional alpha configuration. These shifts can be possibly explained by both the hardware modifications between MODE-1 and MODE-R and by the aging of the STA materials. In MODE-R the standoffs of the frictional alpha joint were changed and the joint was also torsionally re-tightened after it was disassembled during the change-out of the standoffs.

The trend that was observed in the ground tests and in the MODE-1 program was also evident in the orbital experiments. Modes became softer, more nonlinear, and more damped as excitation level increased, or as the bay preload or tightness of the frictional-alpha-joint, decreased. This confirms the observations of the MODE-1 program.

**Modeling Results**

Poor performance of the models in modal parameter prediction required fine-tuning the models using experimental data. In order to improve the poor performance of the "first generation" finite element models, a sensitivity analysis update technique was used to update the model parameters. The objective of the update procedure was to find
updated physical parameters that will yield a finite element model which modal frequencies match those experimentally measured on the ground. Prediction of the zero-gravity behavior of the MODE STA configurations were obtained by removing gravity effects and suspension effects from the models. The accuracy of the finite element models was determined by comparing these predictions with the STS-62 on-orbit measured modal behavior.

The first step was to update the "first generation" MODE-1 STA models, created from the drawings and material property tables, using the MODE-1 ground test results. The zero-gravity predictions from these models were then compared with the STS-48 results. The difference between the predictions and the on-orbit results decreased to less than 4%, in comparison with the 9% difference obtained with the "first generation" models. Since the MODE-1 zero-gravity test results were also available, it was also possible to update the zero-gravity models using the zero-gravity results. These updated models showed a similar improvement, but, more importantly, the updated parameters closely matched the parameters obtained from the "ground-data" update. This indicates that the updated parameters represents real values of the STAs structural properties.

The one-gravity predictions of the updated "second generation" models were then compared with the MODE-R ground results. The differences between predicted and measured modal frequencies were as high as 15%. This is most likely due to the structural modifications performed on the MODE structure. In order to improve the accuracy of the models, the models were updated again using MODE-R preflight ground test results. This update reduced differences between the predicted and measured frequencies to less than 9%. The updated models were then used to predict the in space modal behavior of the STA configurations. Comparison of these predictions with the STS-62 results shows a maximum difference of less than 13%. For the baseline and torsional alpha configurations, however, the discrepancy is less than 3%. The results were better for these two configurations since the other two configurations use more nonlinear frictional alpha joint.

MODE-1 and MODE-R clearly showed that better zero-gravity modeling accuracy can only be achieved if all the nonlinear stiffness and dissipative effects of nonlinear structural elements are included in a nonlinear dynamic model. This is an important
conclusion when active control of structures are considered. MODE bracketed the accuracy that can be expected from "first" and "second" generation linear mathematical models. Control engineers must consider not only the expected "first" generation model errors but also errors arising from nonlinear and gravity effects.
References


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Appendix A

Ground Test Data

Baseline Configuration - PL1

Channel 6/Load Cell - Baseline - PL1 - Ground Test

Channel 7/Load Cell - Baseline - PL1 - Ground Test

Channel 8/Load Cell - Baseline - PL1 - Ground Test

Channel 9/Load Cell - Baseline - PL1 - Ground Test

Channel 10/Load Cell - Baseline - PL1 - Ground Test

Channel 11/Load Cell - Baseline - PL1 - Ground Test

- Low Force; + = Medium Force; x = High Force
Channel 12/Load Cell - Baseline - PL1 - Ground Test

Channel 13/Load Cell - Baseline - PL1 - Ground Test

Channel 14/Load Cell - Baseline - PL1 - Ground Test

Channel 15/Load Cell - Baseline - PL1 - Ground Test

Channel 16/Load Cell - Baseline - PL1 - Ground Test

\( \circ \) = Low Force, \( + \) = Medium Force, \( \times \) = High Force.
Channel 12/Load Cell - Baseline - PL1 - Ground Test

- Frequency (Hz)

- o = Low Force, + = Medium Force, x = High Force.

Channel 13/Load Cell - Baseline - PL1 - Ground Test

- Frequency (Hz)

- o = Low Force, + = Medium Force, x = High Force.

Channel 14/Load Cell - Baseline - PL1 - Ground Test

- Frequency (Hz)

- o = Low Force, + = Medium Force, x = High Force.

Channel 15/Load Cell - Baseline - PL1 - Ground Test

- Frequency (Hz)

- o = Low Force, + = Medium Force, x = High Force.

Channel 16/Load Cell - Baseline - PL1 - Ground Test

- Frequency (Hz)

- o = Low Force, + = Medium Force, x = High Force.
Baseline Configuration - PL2

Channel 6/Load Cell - Baseline - PL2 - Ground Test

Channel 7/Load Cell - Baseline - PL2 - Ground Test

Channel 8/Load Cell - Baseline - PL2 - Ground Test

Channel 9/Load Cell - Baseline - PL2 - Ground Test

Channel 10/Load Cell - Baseline - PL2 - Ground Test

Channel 11/Load Cell - Baseline - PL2 - Ground Test

Symbols:
- o = Low Force
- + = Medium Force
- x = High Force

Frequency (Hz)

Transfer Function Magnitude (g/Hz)
Baseline Configuration - PL3

Channel 6/Load Cell - Baseline - PL3 - Ground Test

Channel 7/Load Cell - Baseline - PL3 - Ground Test

Channel 8/Load Cell - Baseline - PL3 - Ground Test

Channel 9/Load Cell - Baseline - PL3 - Ground Test

Channel 10/Load Cell - Baseline - PL3 - Ground Test

Channel 11/Load Cell - Baseline - PL3 - Ground Test
Channel 12/Load Cell - Baseline - PL3 - Ground Test

Channel 14/Load Cell - Baseline - PL3 - Ground Test

Channel 15/Load Cell - Baseline - PL3 - Ground Test

Channel 16/Load Cell - Baseline - PL3 - Ground Test

\( o = \) Low Force, \( + = \) Medium Force, \( x = \) High Force,
\( o = \text{Low Force}; + = \text{Medium Force}; x = \text{High Force} \)
Baseline Configuration - PL1 - Low Force

Channel 6/Load Cell - Baseline - PL1 - Low Force - Ground Test

Channel 7/Load Cell - Baseline - PL1 - Low Force - Ground Test
Channel 10/Load Cell - Baseline - PL1 - Low Force - Ground Test

Magnitude

Phase (deg)

Channel 11/Load Cell - Baseline - PL1 - Low Force - Ground Test

Magnitude

Phase (deg)
Baseline Configuration - PL1 - Medium Force
Baseline Configuration - PL1 - High Force

Channel 6/Load Cell - Baseline - PL1 - High Force - Ground Test

Channel 7/Load Cell - Baseline - PL1 - High Force - Ground Test

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Frictional Alpha Configuration - AT, PL1

Channel 6/Load Cell - Frictional Alpha - AT, PL1 - Ground Test

Channel 7/Load Cell - Frictional Alpha - AT, PL1 - Ground Test

Channel 8/Load Cell - Frictional Alpha - AT, PL1 - Ground Test

Channel 9/Load Cell - Frictional Alpha - AT, PL1 - Ground Test

Channel 10/Load Cell - Frictional Alpha - AT, PL1 - Ground Test

Channel 11/Load Cell - Frictional Alpha - AT, PL1 - Ground Test

\( \circ \) = Low Force, \( + \) = Medium Force, \( x \) = High Force,

Frequency (Hz)
Frictional Alpha Configuration - AL, PL1

Channel 6/Load Cell - Frictional Alpha - AL, PL1 - Ground Test

Channel 7/Load Cell - Frictional Alpha - AL, PL1 - Ground Test

Channel 8/Load Cell - Frictional Alpha - AL, PL1 - Ground Test

Channel 9/Load Cell - Frictional Alpha - AL, PL1 - Ground Test

Channel 10/Load Cell - Frictional Alpha - AL, PL1 - Ground Test

Channel 11/Load Cell - Frictional Alpha - AL, PL1 - Ground Test

- Low Force, + Medium Force

Frequency (Hz)
Frictional Alpha Configuration - AT, PL1 - Low Force

Channel 6/Load Cell - Frictional Alpha - AT, PL1 - Low Force - Ground Test

Channel 7/Load Cell - Frictional Alpha - AT, PL1 - Low Force - Ground Test
Channel 12/Load Cell - Frictional Alpha - AT, PL1 - Low Force - Ground Test

Magnitude

Frequency (Hz)

Channel 13/Load Cell - Frictional Alpha - AT, PL1 - Low Force - Ground Test

Magnitude

Frequency (Hz)

Phase (deg)

Frequency (Hz)
Channel 14/Load Cell - Frictional Alpha - AT, PL1 - Low Force - Ground Test

Magnitude

Frequency (Hz)

Phase(°)

Frequency (Hz)

Channel 15/Load Cell - Frictional Alpha - AT, PL1 - Low Force - Ground Test

Magnitude

Frequency (Hz)

Phase(°)

Frequency (Hz)
Frictional Alpha Configuration - AT, PL1 - Medium Force

Channel 6/Load Cell - Frictional Alpha - AT, PL1 - Med. Force - Ground Test

Channel 7/Load Cell - Frictional Alpha - AT, PL1 - Med. Force - Ground Test
Channel 10/Load Cell - Frictional Alpha - AT, PL1 - Med. Force - Ground Test

Magnitude

Phase(deg)

Channel 11/Load Cell - Frictional Alpha - AT, PL1 - Med. Force - Ground Test

Magnitude

Phase(deg)
Channel 16/Load Cell - Frictional Alpha - AT, PL1 - Med. Force - Ground Test

Magnitude

Phase(deg)

Frequency (Hz)

Frequency (Hz)
Frictional Alpha Configuration - AT, PL1 - High Force

Channel 6/Load Cell - Frictional Alpha - AT, PL1 - High Force - Ground Test

Channel 7/Load Cell - Frictional Alpha - AT, PL1 - High Force - Ground Test
L Configuration - AT, PL1

Channel 6/L-AT, PL1 - Ground Test

Channel 7/L-AT, PL1 - Ground Test

Channel 8/L-AT, PL1 - Ground Test

Channel 9/L-AT, PL1 - Ground Test

Channel 10/L-AT, PL1 - Ground Test

Channel 11/L-AT, PL1 - Ground Test

- Low Force, + = Medium Force, x = High Force.

Frequency (Hz)
\( o = \text{Low Force}; + = \text{Medium Force}; x = \text{High Force}, \)
Channel 6/Load Cell - L, AT, PLI - Ground Test

Channel 7/Load Cell - L, AT, PLI - Ground Test

Channel 8/Load Cell - L, AT, PLI - Ground Test

Channel 9/Load Cell - L, AT, PLI - Ground Test

Channel 10/Load Cell - L, AT, PLI - Ground Test

Channel 11/Load Cell - L, AT, PLI - Ground Test

- o = Low Force, + = Medium Force, x = High Force.
- Frequency (Hz) range: 22 to 26.5
L STA Configuration - AT, PL2

Channel 6/Load Cell - L - AT, PL2 - Ground Test

Channel 7/Load Cell - L - AT, PL2 - Ground Test

Channel 8/Load Cell - L - AT, PL2 - Ground Test

Channel 9/Load Cell - L - AT, PL2 - Ground Test

Channel 10/Load Cell - L - AT, PL2 - Ground Test

Channel 11/Load Cell - L - AT, PL2 - Ground Test

- o = Low Force, + = Medium Force, x = High Force;
- Frequency (Hz)
Channel 12/Load Cell - L - AT, PL2 - Ground Test

Transfer Function Magnitude (dB)

Frequency (Hz)

100 o = Low Force, + = Medium Force, x = High Force;

Channel 13/Load Cell - L - AT, PL2 - Ground Test

Transfer Function Magnitude (dB)

Frequency (Hz)

100 o = Low Force, + = Medium Force, x = High Force;

Channel 14/Load Cell - L - AT, PL2 - Ground Test

Transfer Function Magnitude (dB)

Frequency (Hz)

100 o = Low Force, + = Medium Force, x = High Force;

Channel 15/Load Cell - L - AT, PL2 - Ground Test

Transfer Function Magnitude (dB)

Frequency (Hz)

100 o = Low Force, + = Medium Force, x = High Force;

Channel 16/Load Cell - L - AT, PL2 - Ground Test

Transfer Function Magnitude (dB)

Frequency (Hz)

100 o = Low Force, + = Medium Force, x = High Force;
L Configuration - AL, PL1

Channel 6/Load Cell - L - AL, PL1 - Ground Test

Channel 7/Load Cell - L - AL, PL1 - Ground Test

Channel 8/Load Cell - L - AL, PL1 - Ground Test

Channel 9/Load Cell - L - AL, PL1 - Ground Test

Channel 10/Load Cell - L - AL, PL1 - Ground Test

Channel 11/Load Cell - L - AL, PL1 - Ground Test
Channel 12/Load Cell - L - AL, PL1 - Ground Test

Transfer Function Magnitude (g/Hz)

- Low Force, + = Medium Force, x = High Force.

Frequency (Hz)

Channel 13/Load Cell - L - AL, PL1 - Ground Test

Transfer Function Magnitude (g/Hz)

- Low Force, + = Medium Force, x = High Force.

Frequency (Hz)

Channel 14/Load Cell - L - AL, PL1 - Ground Test

Transfer Function Magnitude (g/Hz)

- Low Force, + = Medium Force, x = High Force.

Frequency (Hz)

Channel 15/Load Cell - L - AL, PL1 - Ground Test

Transfer Function Magnitude (g/Hz)

- Low Force, + = Medium Force, x = High Force.

Frequency (Hz)

Channel 16/Load Cell - L - AL, PL1 - Ground Test

Transfer Function Magnitude (g/Hz)

- Low Force, + = Medium Force, x = High Force.

Frequency (Hz)
Channel 12/Load Cell - L - AL, PL1 - Ground Test

Channel 13/Load Cell - L - AL, PL1 - Ground Test

Channel 14/Load Cell - L - AL, PL1 - Ground Test

Channel 15/Load Cell - L - AL, PL1 - Ground Test

Channel 16/Load Cell - L - AL, PL1 - Ground Test

\( \alpha \) = Low Force, \( + \) = Medium Force, \( \times \) = High Force.
Channel 6/Load Cell - L, AL, PL1 - Ground Test

○ = Low Force; + = Medium Force; x = High Force,

27 28 29 30 31 32 33
Frequency (Hz)

Channel 7/Load Cell - L, AL, PL1 - Ground Test

○ = Low Force; + = Medium Force; x = High Force,

28 29 30 31 32
Frequency (Hz)

Channel 8/Load Cell - L, AL, PL1 - Ground Test

○ = Low Force; + = Medium Force; x = High Force,

28 29 30 31 32
Frequency (Hz)

Channel 9/Load Cell - L, AL, PL1 - Ground Test

○ = Low Force; + = Medium Force; x = High Force,

28 29 30 31 32
Frequency (Hz)

Channel 10/Load Cell - L, AL, PL1 - Ground Test

○ = Low Force; + = Medium Force; x = High Force,

27 28 29 30 31 32 33
Frequency (Hz)

Channel 11/Load Cell - L, AL, PL1 - Ground Test

○ = Low Force; + = Medium Force; x = High Force,

28 29 30 31 32
Frequency (Hz)
L Configuration - AT, PL1 - Low Force

Channel 6/Load Cell - L - AT, PL1 - Low Force - Ground Test

Frequency (Hz)

Magnitude

10^-3

10^-1

10^0

10^1

10^2

10^3

Phase(deg)

-600

-400

-200

0

200

400

600

Frequency (Hz)

Channel 7/Load Cell - L - AT, PL1 - Low Force - Ground Test

Magnitude

Frequency (Hz)

10^-3

10^-1

10^0

10^1

10^2

Phase(deg)

-600

-400

-200

0

200

400

600

Frequency (Hz)
Channel 8/Load Cell - L - AT, PL1 - Low Force - Ground Test

Magnitude

10^1
10^-1
10^-2
10^-3

Frequency (Hz)

10 15 20 25 30 35 40

Channel 9/Load Cell - L - AT, PL1 - Low Force - Ground Test

Magnitude

10^1
10^-1
10^-2
10^-3

Frequency (Hz)

10 15 20 25 30 35 40

Phase (deg)

-200
-400
-600

Frequency (Hz)
L Configuration - AT, PL1 - Medium Force

Channel 6/Load Cell - L - AT, PL1 - Medium Force - Ground Test

Channel 7/Load Cell - L - AT, PL1 - Medium Force - Ground Test
L Configuration - AT, PL1 - High Force

Channel 6/Load Cell - L - AT, PL1 - High Force - Ground Test

Channel 7/Load Cell - L - AT, PL1 - High Force - Ground Test
Torsional Alpha Configuration - PL1

Channel 6/Load Cell - Torsional Alpha - PL1 - Ground Test

Channel 7/Load Cell - Torsional Alpha - PL1 - Ground Test

Channel 8/Load Cell - Torsional Alpha - PL1 - Ground Test

Channel 9/Load Cell - Torsional Alpha - PL1 - Ground Test

Channel 10/Load Cell - Torsional Alpha - PL1 - Ground Test

Channel 11/Load Cell - Torsional Alpha - PL1 - Ground Test

Transfer Function Magnitude (g/Hz)

Frequency (Hz)

Low Force, + = Medium Force, x = High Force;
Channel 6/Load Cell - Torsional Alpha - PLI - Ground Test

Channel 7/Load Cell - Torsional Alpha - PLI - Ground Test

Channel 8/Load Cell - Torsional Alpha - PLI - Ground Test

Channel 9/Load Cell - Torsional Alpha - PLI - Ground Test

Channel 10/Load Cell - Torsional Alpha - PLI - Ground Test

Channel 11/Load Cell - Torsional Alpha - PLI - Ground Test

Frequency (Hz)

Transfer Function Magnitude (g/Hz)

- o = Low Force; + = Medium Force; x = High Force;

26 27 28 29 30 31 32

10^-1

10^0

10^1

10^2

27 28 29 30 31

Frequency (Hz)

Transfer Function Magnitude (g/Hz)

- o = Low Force; + = Medium Force; x = High Force,

26 27 28 29 30 31 32

10^-1

10^0

10^1

10^2

27 28 29 30 31

Frequency (Hz)

Transfer Function Magnitude (g/Hz)

- o = Low Force; + = Medium Force; x = High Force,

26 27 28 29 30 31 32

10^-1

10^0

10^1

10^2

27 28 29 30 31

Frequency (Hz)

Transfer Function Magnitude (g/Hz)

- o = Low Force; + = Medium Force; x = High Force,
Torsional Alpha Configuration - PL2

Channel 6/Load Cell - Torsional Alpha - PL2 - Ground Test

Channel 7/Load Cell - Torsional Alpha - PL2 - Ground Test

Channel 8/Load Cell - Torsional Alpha - PL2 - Ground Test

Channel 9/Load Cell - Torsional Alpha - PL2 - Ground Test

Channel 10/Load Cell - Torsional Alpha - PL2 - Ground Test

Channel 11/Load Cell - Torsional Alpha - PL2 - Ground Test
Torsional Alpha Configuration - PL3

Channel 6/Load Cell - Torsional Alpha - PL3 - Ground Test

Channel 7/Load Cell - Torsional Alpha - PL3 - Ground Test

Channel 8/Load Cell - Torsional Alpha - PL3 - Ground Test

Channel 9/Load Cell - Torsional Alpha - PL3 - Ground Test

Channel 10/Load Cell - Torsional Alpha - PL3 - Ground Test

Channel 11/Load Cell - Torsional Alpha - PL3 - Ground Test

\[ \text{o = Low Force; + = Medium Force; x = High Force,} \]

Frequency (Hz)

Transfer Function Magnitude (g/Hz)

6.8 7 7.2 7.4 7.6 7.8

10^{-1} 10^{0} 10^{1} 10^{2}
Channel 12/Load Cell - Torsional Alpha - PL3 - Ground Test

- Low Force, + = Medium Force, x = High Force,

Frequency (Hz)

Channel 13/Load Cell - Torsional Alpha - PL3 - Ground Test

- Low Force, + = Medium Force, x = High Force,

Frequency (Hz)

Channel 14/Load Cell - Torsional Alpha - PL3 - Ground Test

- Low Force, + = Medium Force, x = High Force,

Frequency (Hz)

Channel 15/Load Cell - Torsional Alpha - PL3 - Ground Test

- Low Force, + = Medium Force, x = High Force,

Frequency (Hz)

Channel 16/Load Cell - Torsional Alpha - PL3 - Ground Test

- Low Force, + = Medium Force, x = High Force,

Frequency (Hz)
Torsional Alpha Configuration - PL1 - Low Force

Channel 6/Load Cell - Torsional Alpha - PL1 - Low Force - Ground Test

Frequency (Hz)

Magnitude

Phase (deg)

Channel 7/Load Cell - Torsional Alpha - PL1 - Low Force - Ground Test

Frequency (Hz)

Magnitude

Phase (deg)
Frictional Alpha Configuration - AT, PL1 - Medium Force

Channel 6/Load Cell - Torsional Alpha - PL1 - Medium Force - Ground Test

Channel 7/Load Cell - Torsional Alpha - PL1 - Medium Force - Ground Test
Channel 16/Load Cell - Torsional Alpha - PL1 - Medium Force - Ground Test

Magnitude vs. Frequency (Hz)

Phase vs. Frequency (Hz)
Frictional Alpha Configuration - AT, PL1 - High Force

Channel 6/Load Cell - Torsional Alpha - PL1 - High Force - Ground Test

Channel 7/Load Cell - Torsional Alpha - PL1 - High Force - Ground Test
Channel 14/Load Cell - Torsional Alpha - PL1 - High Force - Ground Test

Channel 15/Load Cell - Torsional Alpha - PL1 - High Force - Ground Test
Appendix B

Orbital Test Data

Baseline Configuration - PL1

Channel 6\Load Cell - Baseline - PL1 - Space Test

Channel 7\Load Cell - Baseline - PL1 - Space Test

Channel 8\Load Cell - Baseline - PL1 - Space Test

Channel 9\Load Cell - Baseline - PL1 - Space Test

Channel 10\Load Cell - Baseline - PL1 - Space Test

Channel 11\Load Cell - Baseline - PL1 - Space Test

Frequency (Hz)

Transfer Function Magnitude (g/Hz)

- Low Force, + = Medium Force, x = High Force,

-2 72 74 76 7.8 8 8.2

259
Channel 6/Load Cell - Baseline - PL1 - Space Test

Channel 7/Load Cell - Baseline - PL1 - Space Test

Channel 8/Load Cell - Baseline - PL1 - Space Test

Channel 9/Load Cell - Baseline - PL1 - Space Test

Channel 10/Load Cell - Baseline - PL1 - Space Test

Channel 11/Load Cell - Baseline - PL1 - Space Test

$\circ = \text{Low Force, } + = \text{Medium Force, } x = \text{High Force,}$

$\log_{10}$ magnitudes are plotted against frequency in Hz.
Channel 12/Load Cell - Baseline - PLI - Space Test

Channel 13/Load Cell - Baseline - PLI - Space Test

Channel 14/Load Cell - Baseline - PLI - Space Test

Channel 15/Load Cell - Baseline - PLI - Space Test

Channel 16/Load Cell - Baseline - PLI - Space Test

Symbols:
- o = Low Force
- + = Medium Force
- x = High Force

Frequency (Hz): 27, 27.5, 28, 28.5, 29, 29.5, 30, 30.5

Magnitude (g/Hz): 10^1, 10^2

264
Baseline Configuration - PL2

Channel 6/Load Cell - Baseline - PL2 - Space Test

Channel 7/Load Cell - Baseline - PL2 - Space Test

Channel 8/Load Cell - Baseline - PL2 - Space Test

Channel 9/Load Cell - Baseline - PL2 - Space Test

Channel 10/Load Cell - Baseline - PL2 - Space Test

Channel 11/Load Cell - Baseline - PL2 - Space Test

Legend: ○ = Low Force, + = Medium Force; x = High Force;
Baseline Configuration - PL3

Channel 6/Load Cell - Baseline - PL3 - Space Test

Channel 7/Load Cell - Baseline - PL3 - Space Test

Channel 8/Load Cell - Baseline - PL3 - Space Test

Channel 9/Load Cell - Baseline - PL3 - Space Test

Channel 10/Load Cell - Baseline - PL3 - Space Test

Channel 11/Load Cell - Baseline - PL3 - Space Test
Channel 12/Load Cell - Baseline - PL3 - Space Test

Channel 13/Load Cell - Baseline - PL3 - Space Test

Channel 14/Load Cell - Baseline - PL3 - Space Test

Channel 15/Load Cell - Baseline - PL3 - Space Test

Channel 16/Load Cell - Baseline - PL3 - Space Test

Legend:
- o = Low Force, + = Medium Force, x = High Force.
Channel 6/Load Cell - Baseline - PL3 - Space Test

Channel 7/Load Cell - Baseline - PL3 - Space Test

Channel 8/Load Cell - Baseline - PL3 - Space Test

Channel 9/Load Cell - Baseline - PL3 - Space Test

Channel 10/Load Cell - Baseline - PL3 - Space Test

Channel 11/Load Cell - Baseline - PL3 - Space Test

Legend:
- o = Low Force
- + = Medium Force
- x = High Force
Channel 12/Load Cell - Baseline - PL3 - Space Test

Channel 13/Load Cell - Baseline - PL3 - Space Test

Channel 14/Load Cell - Baseline - PL3 - Space Test

Channel 15/Load Cell - Baseline - PL3 - Space Test

Channel 16/Load Cell - Baseline - PL3 - Space Test

10^{-1} \quad 10^{-2}

27 27.5 28 28.5 29 29.5 30 30.5

Frequency (Hz)

\( \circ \) Low Force, \( + \) Medium Force, \( \times \) High Force,

27 27.5 28 28.5 29 29.5 30 30.5

Frequency (Hz)

27 27.5 28 28.5 29 29.5 30 30.5

Frequency (Hz)

27 27.5 28 28.5 29 29.5 30 30.5

Frequency (Hz)

27 27.5 28 28.5 29 29.5 30 30.5

Frequency (Hz)
Baseline Configuration - PL1 - Low Force

Channel 6/Load Cell - Baseline - PL1 - Low Force - Space Test

- Space Test; -- Ground Test;

Frequency (Hz)

Magnitude

Phase (deg)

Channel 7/Load Cell - Baseline - PL1 - Low Force - Space Test

- Space Test; -- Ground Test;

Frequency (Hz)

Magnitude

Phase (deg)
Channel 16/Load Cell - Baseline - PL1 - Low Force - Space Test

- Space Test; Ground Test;

Magnitude

Frequency (Hz)

Phase (deg)

Frequency (Hz)
Baseline Configuration - PL1 - Medium Force

Channel 6/Load Cell - Baseline - PL1 - Med. Force - Space Test

Channel 7/Load Cell - Baseline - PL1 - Med. Force - Space Test
Baseline Configuration - PL1 - High Force

Channel 6/Load Cell - Baseline - PL1 - High Force - Space Test

- Space Test; -.- Ground Test;

10 15 20 25 30 35 40
Frequency (Hz)

Magnitude

Phase (deg)

- Space Test; -.- Ground Test;

10 15 20 25 30 35 40
Frequency (Hz)

Channel 7/Load Cell - Baseline - PL1 - High Force - Space Test

- Space Test; -.- Ground Test;

10 15 20 25 30 35 40
Frequency (Hz)

Magnitude

Phase (deg)

- Space Test; -.- Ground Test;

10 15 20 25 30 35 40
Frequency (Hz)

285
Channel 14/Load Cell - Baseline - PL1 - High Force - Space Test

- Space Test; -- Ground Test;

Magnitude

Frequency (Hz)

Channel 15/Load Cell - Baseline - PL1 - High Force - Space Test

- Space Test; -- Ground Test;

Magnitude

Frequency (Hz)

Phase(deg)

- Space Test; -- Ground Test;

Phase(deg)

Frequency (Hz)
Frictional Alpha Configuration - AT, PL1

Channel 6/Load Cell - Frictional Alpha - AT, PL1 - Space Test

Channel 7/Load Cell - Frictional Alpha - AT, PL1 - Space Test

Channel 8/Load Cell - Frictional Alpha - AT, PL1 - Space Test

Channel 9/Load Cell - Frictional Alpha - AT, PL1 - Space Test

Channel 10/Load Cell - Frictional Alpha - AT, PL1 - Space Test

Channel 11/Load Cell - Frictional Alpha - AT, PL1 - Space Test

- Low Force; + Medium Force; x High Force;
Channel 12/Load Cell - Frictional Alpha - AT, PLI - Space Test

Channel 13/Load Cell - Frictional Alpha - AT, PLI - Space Test

Channel 14/Load Cell - Frictional Alpha - AT, PLI - Space Test

Channel 15/Load Cell - Frictional Alpha - AT, PLI - Space Test

Channel 16/Load Cell - Frictional Alpha - AT, PLI - Space Test

Frequency (Hz)

Transfer Function Magnitude (dB)
Frictional Alpha Configuration - AL, PL1

Channel 6/Load Cell - Frictional Alpha - AL, PL1 - Space Test

Channel 7/Load Cell - Frictional Alpha - AL, PL1 - Space Test

Channel 8/Load Cell - Frictional Alpha - AL, PL1 - Space Test

Channel 9/Load Cell - Frictional Alpha - AL, PL1 - Space Test

Channel 10/Load Cell - Frictional Alpha - AL, PL1 - Space Test

Channel 11/Load Cell - Frictional Alpha - AL, PL1 - Space Test

Frequency (Hz)
Channel 12/Load Cell - Frictional Alpha - AL, PLI - Space Test

Channel 13/Load Cell - Frictional Alpha - AL, PLI - Space Test

Channel 14/Load Cell - Frictional Alpha - AL, PLI - Space Test

Channel 15/Load Cell - Frictional Alpha - AL, PLI - Space Test

Channel 16/Load Cell - Frictional Alpha - AL, PLI - Space Test

Transfer Function Magnitude (g/Hz)

Frequency (Hz)

o = Low Force; + = Medium Force; x = High Force;
L Configuration - AT, PL1

Channel 6/Load Cell - L - AT, PL1 - Space Test

Channel 7/Load Cell - L - AT, PL1 - Space Test

Channel 8/Load Cell - L - AT, PL1 - Space Test

Channel 9/Load Cell - L - AT, PL1 - Space Test

Channel 10/Load Cell - L - AT, PL1 - Space Test

Channel 11/Load Cell - L - AT, PL1 - Space Test

& = Low Force; + = Medium Force; x = High Force;
Channel 12/Load Cell - L - AT, PLI - Space Test

Channel 13/Load Cell - L - AT, PLI - Space Test

Channel 14/Load Cell - L - AT, PLI - Space Test

Channel 15/Load Cell - L - AT, PLI - Space Test

Channel 16/Load Cell - L - AT, PLI - Space Test

- $\circ$ = Low Force, $+$ = Medium Force, $x$ = High Force,
- $\circ$ = Low Force, $+$ = Medium Force, $x$ = High Force,
Channel 6/Load Cell - AT, PLI - Space Test

Transfer Function Magnitude (g/Hz)

Frequency (Hz)

- Low Force; + = Medium Force; x = High Force,

Channel 7/Load Cell - AT, PLI - Space Test

Transfer Function Magnitude (g/Hz)

Frequency (Hz)

- Low Force; + = Medium Force; x = High Force,

Channel 8/Load Cell - AT, PLI - Space Test

Transfer Function Magnitude (g/Hz)

Frequency (Hz)

- Low Force; + = Medium Force; x = High Force,

Channel 9/Load Cell - AT, PLI - Space Test

Transfer Function Magnitude (g/Hz)

Frequency (Hz)

- Low Force; + = Medium Force; x = High Force,

Channel 10/Load Cell - AT, PLI - Space Test

Transfer Function Magnitude (g/Hz)

Frequency (Hz)

- Low Force; + = Medium Force; x = High Force,

Channel 11/Load Cell - AT, PLI - Space Test

Transfer Function Magnitude (g/Hz)

Frequency (Hz)

- Low Force; + = Medium Force; x = High Force,
Channel 12/Load Cell - L- AT, PLI - Space Test

Channel 13/Load Cell - L- AT, PLI - Space Test

Channel 14/Load Cell - L- AT, PLI - Space Test

Channel 15/Load Cell - L- AT, PLI - Space Test

Channel 16/Load Cell - L- AT, PLI - Space Test

\( \circ \) = Low Force, \( + \) = Medium Force, \( x \) = High Force.

Frequency (Hz)
Channel 12/Load Cell - L - AT, PL1 - Space Test

- Frequency (Hz)

Channel 13/Load Cell - L - AT, PL1 - Space Test

- Frequency (Hz)

Channel 14/Load Cell - L - AT, PL1 - Space Test

- Frequency (Hz)

Channel 15/Load Cell - L - AT, PL1 - Space Test

- Frequency (Hz)

Channel 16/Load Cell - L - AT, PL1 - Space Test

- Frequency (Hz)
L Configuration - AL, PL1

Channel 6/Load Cell - L - AT, PL1 - Space Test

Channel 8/Load Cell - L - AT, PL1 - Space Test

Channel 7/Load Cell - L - AT, PL1 - Space Test

Channel 9/Load Cell - L - AT, PL1 - Space Test

Channel 10/Load Cell - L - AT, PL1 - Space Test

Channel 11/Load Cell - L - AT, PL1 - Space Test

Frequency (Hz)

6.8 7 7.2 7.4 7.6 7.8

Frequency (Hz)

6.8 7 7.2 7.4 7.6 7.8
Channel 6/Load Cell - L, AL, PLI - Space Test

Channel 7/Load Cell - L, AL, PLI - Space Test

Channel 8/Load Cell - L, AL, PLI - Space Test

Channel 9/Load Cell - L, AL, PLI - Space Test

Channel 10/Load Cell - L, AL, PLI - Space Test

Channel 11/Load Cell - L, AL, PLI - Space Test
o = Low Force, + = Medium Force, x = High Force.
Channel 12/Load Cell - L. AL, PLI - Space Test

Channel 13/Load Cell - L. AL, PLI - Space Test

Channel 14/Load Cell - L. AL, PLI - Space Test

Channel 15/Load Cell - L. AL, PLI - Space Test

Channel 16/Load Cell - L. AL, PLI - Space Test

\( o = \text{Low Force}, + = \text{Medium Force}, x = \text{High Force} \)

Frequency (Hz)
L Configuration - AT, PL2

Channel 6/Load Cell - L - AT, PL2 - Space Test

Channel 7/Load Cell - L - AT, PL2 - Space Test

Channel 8/Load Cell - L - AT, PL2 - Space Test

Channel 9/Load Cell - L - AT, PL2 - Space Test

Channel 10/Load Cell - L - AT, PL2 - Space Test

Channel 11/Load Cell - L - AT, PL2 - Space Test

\[ \text{o = Low Force, + = Medium Force, x = High Force,} \]

Frequency (Hz)
Channel 6/Load Cell - L - AT, PL2 - Space Test

Channel 7/Load Cell - L - AT, PL2 - Space Test

Channel 8/Load Cell - L - AT, PL2 - Space Test

Channel 9/Load Cell - L - AT, PL2 - Space Test

Channel 10/Load Cell - L - AT, PL2 - Space Test

Channel 11/Load Cell - L - AT, PL2 - Space Test

- Low Force; + Medium Force, x High Force;

Frequency (Hz)

- Low Force, + Medium Force, x High Force;

Frequency (Hz)

- Low Force, + Medium Force, x High Force;

Frequency (Hz)

- Low Force, + Medium Force, x High Force;

Frequency (Hz)
\( \Delta = \text{Low Force}; + = \text{Medium Force}; \times = \text{High Force} \)
Channel 12/Load Cell - L - AT, PL2 - Space Test

Channel 13/Load Cell - L - AT, PL2 - Space Test

Channel 14/Load Cell - L - AT, PL2 - Space Test

Channel 15/Load Cell - L - AT, PL2 - Space Test

Channel 16/Load Cell - L - AT, PL2 - Space Test

\[ \text{o = Low Force, + = Medium Force, x = High Force,} \]

Frequency (Hz)
L Configuration - AT, PL1 - Medium Force

Channel 6/Load Cell - L - AT, PL1 - Med. Force - Space Test
- Space Test; -- Ground Test;

Channel 7/Load Cell - L - AT, PL1 - Med. Force - Space Test
- Space Test; -- Ground Test;
Channel 10/Load Cell - L - AT, PL1 - Med. Force - Space Test

- Space Test; -- Ground Test;

Frequency (Hz)

Magnitude

10^0
10^-1
10^-2
10^-3
10^-4

10
20
25
30
35
40

Phase(deg)

-500
-1000

Frequency (Hz)

319
L Configuration - AT, PL1 - High Force

Channel 6/Load Cell - L - AT, PL1 - High Force - Space Test

Magnitude

Frequency (Hz)

100
10
1
-2
-3
-4

Phase (deg)

Frequency (Hz)

-200
-400
-600

Channel 7/Load Cell - L - AT, PL1 - High Force - Space Test

Magnitude

Frequency (Hz)

100
10
1
-2
-3
-4

Phase (deg)

Frequency (Hz)

-200
-400
-600
Channel 10/Load Cell - L - AT, PL1 - High Force - Space Test

- Space Test; -- Ground Test;

Magnitude

Frequency (Hz)

Channel 11/Load Cell - L - AT, PL1 - High Force - Space Test

- Space Test; -- Ground Test;

Magnitude

Frequency (Hz)

Phase (deg)

Frequency (Hz)

325
Channel 12/Load Cell - L - AT, PL1 - High Force - Space Test

- Space Test; -- Ground Test;

Channel 13/Load Cell - L - AT, PL1 - High Force - Space Test

- Space Test; -- Ground Test;
Channel 16/Load Cell - L - AT, PL1 - High Force - Space Test

- Space Test; -- Ground Test;

Magnitude

Frequency (Hz)

Phase (deg)

Frequency (Hz)
$o = \text{Low Force}, + = \text{Medium Force}, x = \text{High Force.}$
Torsional Alpha Configuration - PL2

Channel 6/Load Cell - Torsional Alpha - PL2 - Space Test

Channel 7/Load Cell - Torsional Alpha - PL2 - Space Test

Channel 8/Load Cell - Torsional Alpha - PL2 - Space Test

Channel 9/Load Cell - Torsional Alpha - PL2 - Space Test

Channel 10/Load Cell - Torsional Alpha - PL2 - Space Test

Channel 11/Load Cell - Torsional Alpha - PL2 - Space Test

\( \circ = \) Low Force, \( + = \) Medium Force, \( x = \) High Force;

\( a = \) Low Force, \( b = \) Medium Force; \( c = \) High Force,
Channel 6/Load Cell - Torsional Alpha - PL2 - Space Test

Channel 7/Load Cell - Torsional Alpha - PL2 - Space Test

Channel 8/Load Cell - Torsional Alpha - PL2 - Space Test

Channel 9/Load Cell - Torsional Alpha - PL2 - Space Test

Channel 10/Load Cell - Torsional Alpha - PL2 - Space Test

Channel 11/Load Cell - Torsional Alpha - PL2 - Space Test

Transfer Function Magnitude (g/Hz)

Frequency (Hz)

$\omega$ = Low Force, + = Medium Force, x = High Force.
Channel 12/Load Cell - Torsional Alpha - PL3 - Space Test

Channel 13/Load Cell - Torsional Alpha - PL3 - Space Test

Channel 14/Load Cell - Torsional Alpha - PL3 - Space Test

Channel 15/Load Cell - Torsional Alpha - PL3 - Space Test

Channel 16/Load Cell - Torsional Alpha - PL3 - Space Test

Frequency (Hz)
Channel 12/Load Cell - Torsional Alpha - PL3 - Space Test

Channel 13/Load Cell - Torsional Alpha - PL3 - Space Test

Channel 14/Load Cell - Torsional Alpha - PL3 - Space Test

Channel 15/Load Cell - Torsional Alpha - PL3 - Space Test

Channel 16/Load Cell - Torsional Alpha - PL3 - Space Test

Frequency (Hz)

Transfer Function Magnitude (g/Hz)

- Low Force, + = Medium Force; x = High Force,
Torsional Alpha Configuration - PL1 - Low Force

Channel 6/Load Cell - Torsional Alpha - PL1 - Low Force - Space Test

- Space Test; -- Ground Test;

Frequency (Hz)

Magnitude

Channel 7/Load Cell - Torsional Alpha - PL1 - Low Force - Space Test

- Space Test; -- Ground Test;

Frequency (Hz)

Magnitude

Phase (deg)
Torsional Alpha Configuration - PL1 - Medium Force

Channel 6/Load Cell - Torsional Alpha - PL1 - Med. Force - Space Test

Channel 7/Load Cell - Torsional Alpha - PL1 - Med. Force - Space Test
Channel 12/Load Cell - Torsional Alpha - PL1 - Med. Force - Space Test

- Space Test; -- Ground Test;

Magnitude

Frequency (Hz)

Phase(deg)

Frequency (Hz)

Channel 13/Load Cell - Torsional Alpha - PL1 - Med. Force - Space Test

- Space Test; -- Ground Test;

Magnitude

Frequency (Hz)

Phase(deg)

Frequency (Hz)
Channel 16/Load Cell - Torsional Alpha - PL1 - Med. Force - Space Test

- Space Test; - Ground Test;

Magnitudes

Frequency (Hz)

Phase (deg)

Frequency (Hz)
Torsional Alpha Configuration - PL1 - High Force

Channel 6/Load Cell - Torsional Alpha - PL1 - High Force - Space Test

Magnitude

Frequency (Hz)

Phase(deg)

Frequency (Hz)

Channel 7/Load Cell - Torsional Alpha - PL1 - High Force - Space Test

Magnitude

Frequency (Hz)

Phase(deg)

Frequency (Hz)
Channel 14/Load Cell - Torsional Alpha - PL1 - High Force - Space Test

- Space Test; -- Ground Test;

Channel 15/Load Cell - Torsional Alpha - PL1 - High Force - Space Test

- Space Test; -- Ground Test;