The Mini-Mast CSI Testbed: Lessons Learned

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Abstract

The Mini-Mast testbed was one of the first large scale Controls-Structure-Interaction (CSI) systems used to evaluate state-of-the-art methodology in flexible structure control.[1] Now that all the testing at Langley Research Center has been completed, a look back is warranted to evaluate the program. This paper describes some of the experiences and technology development studies by NASA, university, and industry investigators. Lessons learned are presented from three categories: the testbed development, control methods, and the operation of a guest investigator program. It is shown how structural safety margins provided a realistic environment to simulate on-orbit CSI research, even though they also reduced the research flexibility afforded to investigators. The limited dynamic coupling between the bending and torsion modes of the cantilevered test article resulted in highly successful SISO and MIMO controllers. However, until accurate models were obtained for the torque wheel actuators, sensors, filters, and the structure itself, most controllers were unstable. Controls research from this testbed should be applicable to cantilevered appendages of future large space structures.

Lessons Learned: Controls Methods

Just as modeling played a key role in readying the testbed for guest investigators' use, it also was the first consideration for controls designers. The finite element model developed by NASA to represent the structural dynamics of the truss structure was found to be adequate for accurately predicting the low- frequency dynamics of the flexible test article. However, the best dynamic representation of the full system was obtained from experimentally identified models. Models based on system identification could include the dynamics of actuators and sensors and the computational delays within the system, in addition to the structural dynamics of the truss. Whether the application was controls implementation or failure detection, identified models were found to be preferable over FEM-based models for capturing system level dynamics.

With its decoupled dynamics, the Mini-Mast testbed could be controlled with classical single-input single-output (SISO) techniques. This success emphasized the potential of controlling some appendages on future space platforms via simple classical techniques. The simplicity of parameterization with the classical methods has the distinct advantage of providing physical insight into the system being controlled.

Modern controls techniques were also successful in providing substantial amounts of damping to the system's response. These multi-input multi-output (MIMO) designs share a common difficulty, however. The parameterization via weighting matrices lacks the physical insight provided by classical SISO techniques, making a priori performance predictions difficult. In fact, while in theory the parameters for modern MIMO controllers would encompass the control-space of any SISO controller, no modern controller was developed that could match the performance of an SISO constant gain feedback controller which was most effective in controlling the Mini-Mast first torsion mode.

Design Models

- **FEM based models proved to be adequate for structural dynamics representation**
- **System ID models provide best dynamic representation of system (actuators/structure/sensors/computational delay)**

Classical

- **SISO design viable for systems with decoupled dynamics**
- **Simplicity of parameterization provides physical insight**

Modern

- **MIMO designs were successful in providing damping**
- **Difficult to prescribe performance a priori with weighting matrices (parameterization)**
- **Torsion mode controlled "best" by SISO constant gain feedback**

Guest Investigator Studies

University and industry researchers applied a wide variety of techniques to the Mini-Mast testbed, as shown in this figure which highlights the methodology applied by each guest investigator who used the facility. A synopsis of the guest investigators' work with Mini-Mast, as well as their work at a second CSI facility, can be found in Ref. 1. In addition, numerous publications have been completed by individual investigators, providing more detailed reporting of their work. A listing of their publications on research with Mini-Mast is provided in the references.[4-19]

Five teams who used the Mini-Mast facility conducted controls experiments and one worked with failure detection and isolation applied to both sensors and actuators. Four groups designed controllers based on the NASTRAN finite element model developed by NASA. Two groups developed their own modal models of the testbed, but only one group used its experimentally derived model for controls design. Both classical and modern control theories were employed in creating SISO and MIMO controllers.

Institution (Principal Investigator)	Methodology
MIT (Wally Vander Velde)	Failure Detection and Isolation Methods
Arizona State University (Bong Wie)	Classical Theory with Disturbance Rejection, using collocated and noncollocated Sensors
Harris Corporation (Dave Hyland)	Maximum Entropy Optimal Projection; and Decentralized Hierarchical Control
CalTech (John Doyle) (Gary Balas)	H_∞ and μ-Synthesis, with Additive and Multiplicative Uncertainties
University of Cincinnati (Randy Allemang) (Gary Slater)	System Identification; and Multivariable Positivity Control Design
Purdue University (Bob Skelton)	System identification using Q-Markov, Modal Cost Analysis, and Multivariable Control Design

Generic Controls Software

To minimize phase distortion, fast controller update commands are needed to digitally implement controllers designed using continuous time synthesis procedures. The "real-time" computer chosen for the Mini-Mast testbed was an existing CYBER-175 used at LaRC for aircraft flight simulation. However, software for this computer was not configured for typical linear state space controllers, so new software was developed for this application. The software was written to accommodate real-time implementation of any linear time invariant controller design; hence the term generic software is used.

The generic software is one of the key benefits derived from the Mini-Mast program. The FORTRAN program permits both system identification and vibration suppression experiments. Various excitation, filtering, controls, bias removal and data file generation software were developed, with the capability of using each function in either an open- or closed-loop mode of testing. A crucial part of the code was the limit-checking software required to prevent excessive response of the structure. This was necessary for the Mini-Mast testbed since relatively small displacements or twist angles could have resulted in buckling of the truss members.

The CYBER-175 could execute the control code at an update rate which was adequate for the research objectives of Mini-Mast. For example, it had an update rate of 80 Hz for a 40-state controller with 6 inputs and 3 outputs.

- **Implemented on existing CYBER-175**
- **Generic software developed to accommodate:**
  - **Any linear time-invariant controller design**
  - **System ID and vibration suppression**
  - **Open- or closed-loop mode of testing**
  - **Excitation, filtering, bias removal, and data file generation**
  - **Limit checking software included**
- **Adequate update rate**

  (80 Hz update rate for a 40-state controller with 6 inputs and 3 outputs)

CSI Pathfinder Testbed

Even as the CSI program was just beginning, it was clear that application of controls theory to realistic hardware would play an essential role in advancing CSI technology. A need was identified for a pathfinder CSI research program for early investigation of flexible space structure control. The rapid development and implementation of the Mini-Mast testbed fulfilled this need during the time period when other more complex testbeds were being developed. Three constraints were imposed by the overall objective: (1) that, wherever possible, the testbed emulate physical characteristics of future space structures or space structure components; (2) that the testbed operation be sufficiently flexible to accommodate multiple researchers with varied experiment objectives; (3) and that the testbed be brought on-line quickly. The last constraint resulted in the use of existing equipment that could be brought together to form the testbed. Existing sensors and actuators were incorporated, and software was developed so that the flight simulation computer at NASA Langley Research Center (LaRC) could be used as a real-time controls computer. Even the test article was an existing space-quality truss, called Mini-Mast, which had been used in a previous program.

Objective

Develop and implement a pathfinder CSI research test program for early investigation of flexible space structure control

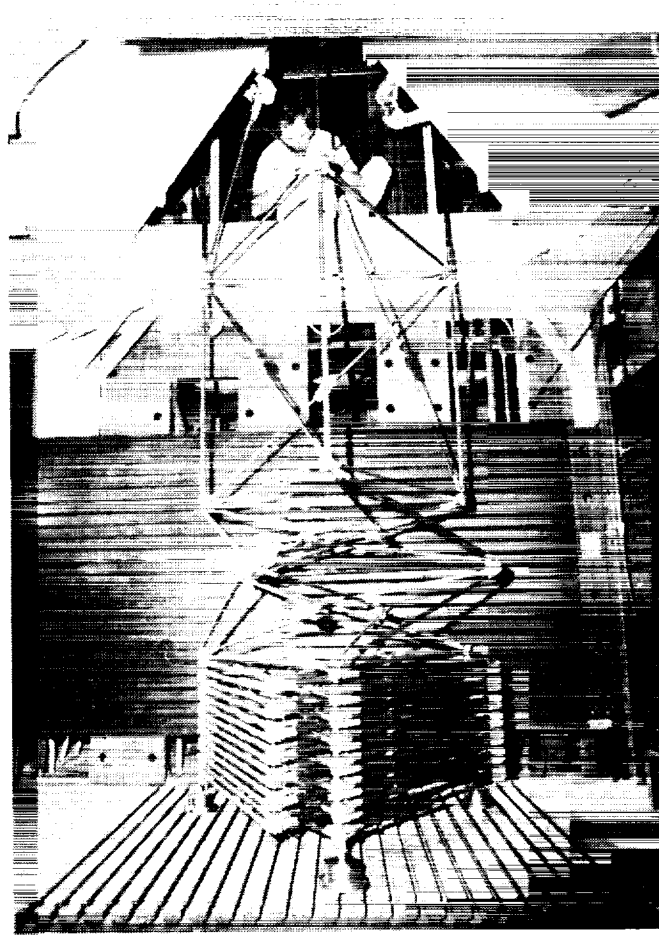
Constraints

- **Emulate space component physical characteristics where possible**
- **Provide for multiple experiment objectives and multiple researchers**
- **Bring the CSI testbed on-line quickly**

Deployable Composite Truss

The truss structure, made of graphite epoxy tubes and titanium joints, extends from approximately 3 feet in a stowed configuration to approximately 65 feet when fully deployed. Both longeron members (parallel to the truss longitudinal axis) and diagonal members (in the face plane) have pinned connections to allow their rotation during deployment. Batten members, forming the triangular cross section, were fixed rigidly to the corner-body joints.

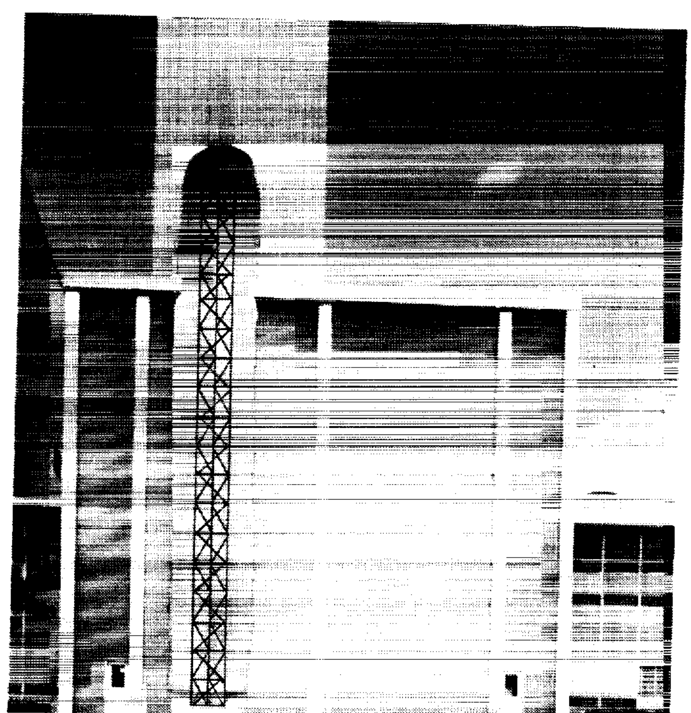
Diagonal members were also hinged to allow their folding during retraction and storage. These heavy hinges create clusters of localized bending modes, with 108 local modes between the system's pair of second bending modes at approximately 6.5 Hz and the second torsion mode at approximately 22 Hz. It is important to note that the diagonal modes do not involve the bending of only a single diagonal, but rather show localized displacements along the entire length of the structure and thus contribute to the testbed's complexity. The problem of clustered local modes is anticipated for future large space structures, such as clusters of solar array modes with Space Station Freedom.



Mini-Mast Structure

Mini-Mast was an existing 65 foot long deployable/retractable truss which was available for research purposes at the time of the testbed development. This prototype structure was one of the first flight-quality deployable space structures ever tested on the ground. In its cantilevered configuration in the tower of Building 1293B at NASA LaRC, the dynamic response of the truss was dominated by low frequency vibrational modes.[2] The pair of first bending modes of the structure was at approximately 0.86 Hz. Five target modes identified for control purposes were all below 10 Hz. They were the pair of first bending modes, the first torsional mode, and the pair of second bending modes. A full discussion of the dynamic characteristics of the structure and the validated finite element model can be found in Reference 3.

The truss was already instrumented with noncontacting displacement sensors mounted to the tower along the truss length. While the truss was used as the flexible-body structure for the pathfinder CSI testbed, external locks were in place on the diagonal truss member hinges to ensure they could not open during testbed operation.



Torque Wheel Actuators

The torque wheels, shown mounted on the tip plate prior to its installation on Mini-Mast, are angular momentum actuators used to impart control (or excitation) moments to the tip of the cantilevered truss. Oriented along three orthogonal axes and weighing approximately 80 pounds each, the actuators provided ample control authority in the frequency range of interest. The actuators are comprised of two sections, the center hub where the motor resides and a 24 in. diameter annular ring connected to the hub. The motor is a permanent magnet motor with a rated 50 ft-lbs peak torque at 50 volts and 9.6 amps. The wheel motor is driven by a high power, high frequency switching amplifier.

Introduction

Future space missions will most likely include large, flexible structures with high precision performance requirements. Control engineers and structural dynamicists will need to work together in an integrated effort to meet these requirements. Toward this purpose, NASA developed the multidisciplinary Controls-Structures-Interaction (CSI) Program to aid in the development and validation of CSI technology. Industry and university researchers are included through the Guest Investigator (GI) Program, providing participants the opportunity to validate experimentally CSI methodology on ground-test hardware and thereby improve the understanding of the practical performance characteristics of promising active-vibration-control techniques which may be applied to future space structures.

The Mini-Mast testbed at NASA Langley Research Center (LaRC) was one of two testbeds used in the first phase of the GI Program. Objectives of the testbed and testbed constraints will be discussed. A brief description of the testbed is presented, highlighting its major components and their modeling. Development of generic controls software, a significant benefit of this program, is discussed.

The structural safety margins and operational procedures created a realistic environment for space flight applications, but one that necessarily limited the research flexibility of guest investigators. Those guest investigators will be identified, together with the major topics they studied. Finally, recommendations will be presented in the form of lessons learned in three categories: the testbed development (including hardware, modeling and simulation) and software development; the control methods, covering design models as well as both classical and modern techniques; and the operation of a guest investigator program.

Outline

- **Objective**
- **Testbed Hardware/Modeling**
- **Generic Controls Software**
- **Operational Procedures**
- **Guest Investigator Studies**
- **Recommendations/Summary**

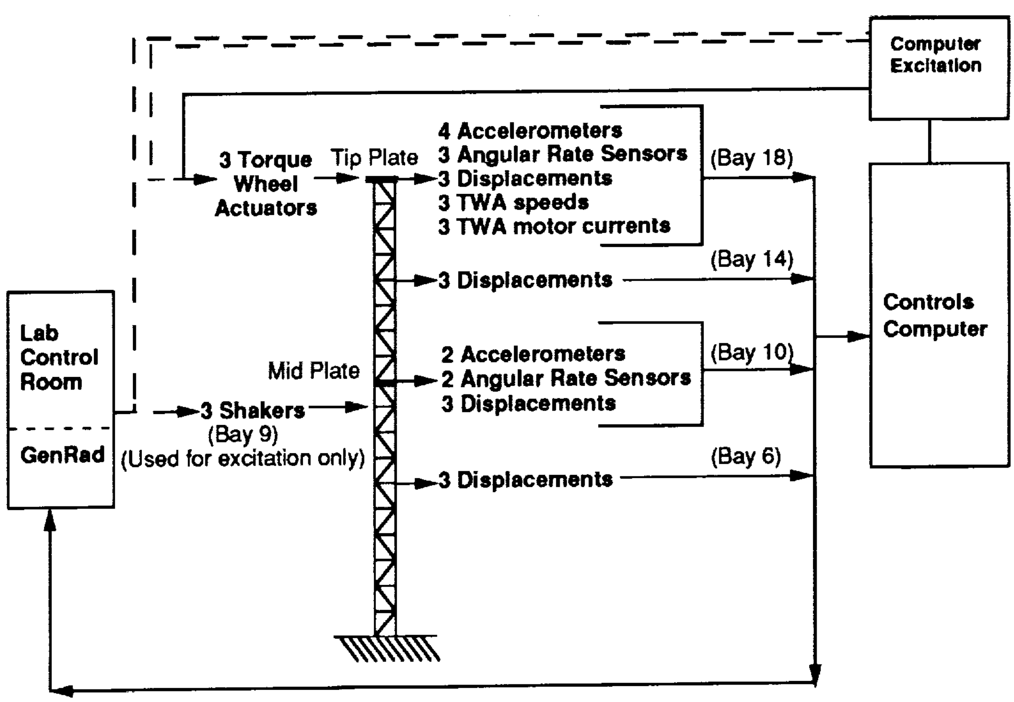
Mini-Mast Testbed Schematic

A schematic of the Mini-Mast testbed shows the integrated cantilevered truss with instrumentation linked via fiber optic cables to a real-time computer for excitation and control. The second computer connected to the system (GenRad) was used for post- processing data. Three torque wheel actuators, mounted on the tip platform, were the only control effectors available through the GI program. Measurement sensors for wheel speed and actuator motor currents were also included. Excitation of the truss structure could be performed with the torque wheels or with shakers that were available at Bay 9 of the 18-bay truss. Shaker excitation could be initiated by either the controls computer or the laboratory computer.

Accelerometers and rate gyros were mounted on two platforms, one at the tip and the other near the mid-span of the truss, at Bay 10. Early in the program, five rate gyros were available--three at the tip-plate and two at the mid-plate. However, equipment failures reduced that number to one before the two year program was completed. At the end of the program, only one rate gyro was available. The surviving rate gyro was located on the tip plate measuring torsion about the longitudinal axis .

Noncontacting displacement sensors were distributed along the length of the truss, at each vertex of the triangular cross-section. These sensors were mounted to the tower along side the truss, thus providing absolute displacement measurements of the truss with respect to the tower. Displacement measurements from Bays 6, 10, 14, and 18 were linked to the computers and thus could be used for controls feedback if selected by guest investigators.

Mini-Mast Testbed



Mini-Mast Testbed Development

The flight quality truss added realism to the Mini-Mast CSI testbed, in line with the constraint that physical characteristics of future space structure components be emulated whenever possible. To ready the structure for use as a CSI testbed, equipment mounting platforms were added together with acceleration and rate sensors. Two equipment mounting platforms were designed, built and installed, one at the tip (Bay 18) and one near the midspan of the truss length (Bay 10). Existing servo accelerometers and rate gyro sensors were installed on the platforms, linked via fiber optic cables to an existing real-time computer. Torque wheel actuators, designed and built under a previous research program, were also included in the new testbed.

Mini-Mast Testbed Overview

- **Used available flight-quality truss**
- **Added equipment mounting platforms**
- **Installed existing actuators and sensors**
- **Linked signals to existing real-time computer**

Torque Wheel Actuators Characteristics

Initially the actuators operated in a current mode, i.e., voltage commands proportional to the current flowing to the motor. In this mode, modeling of the torque wheel dynamics should have reduced to a determination of a torque constant while the wheel was operating without feedback compensation. However, nonlinearities in the actuators made such simple models inaccurate. Proper characterization of the torque wheel dynamics was critical because the actuators were capable of buckling truss members. Ultimately, the nonlinearities led to modifications of the actuators that reduced their nonlinear response.

To minimize nonlinearities and facilitate modeling, feedback was introduced from a friction driven tachometer attached to the wheel. Using rate feedback, nonlinear effects were reduced significantly. In particular, the amplitude dependence of the transfer function was minimized, allowing the same model to be used at different excitation levels. With the local feedback loop in place, a second-order torque wheel model provided good agreement between the analytic predictions and experimentally derived measurements. This model, which was now a representation of the closed-loop torque wheel dynamics, was accurate for most of the test operating conditions.

Torque Wheel Actuators

- **Characteristics:**
  - **Weigh 80 lbs. each**
  - **Provide 50 ft-lbs peak load**
  - **Nonlinear response**
- **Local feedback loop added**
  - **Linearized actuators**
  - **Facilitated modeling**
- **2nd-order model provided good agreement**

Important Considerations of the Truss Structure

Some joint nonlinearities are present in the structure, causing both modal damping and modal frequency to increase with decreasing displacement amplitudes. Such nonlinearities add realism to the controls problem.

Dynamic coupling between torsion and bending modes is anticipated with CSI problems and future large space structures. Mini-Mast has limited coupling between the bending and torsion modes, and thus, research from this testbed is most applicable to beam-like structures such as cantilevered appendages on space platforms. In fact, the significant decoupling of the vibration modes allowed good closed-loop controls performance with single-input, single-output (SISO) controllers.

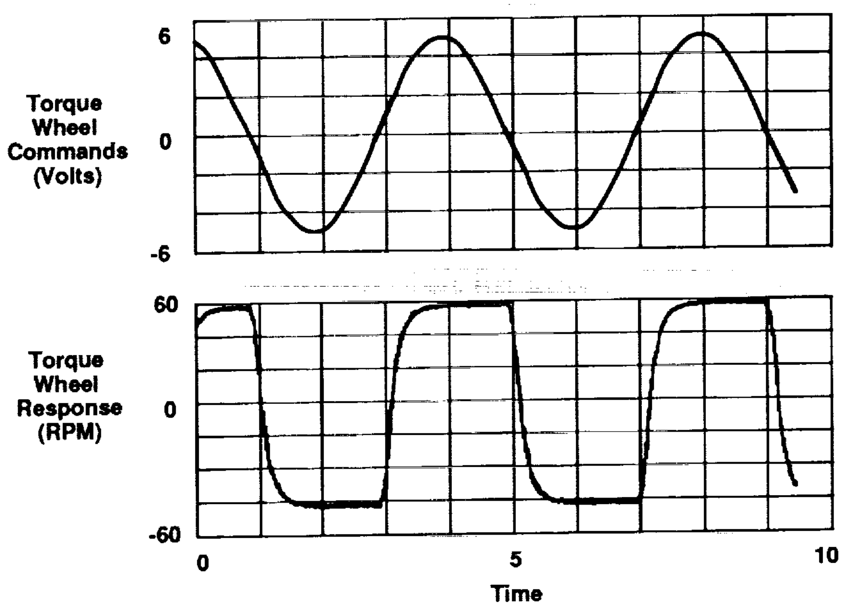
A safety concern resulted from the high compressive stresses at the base of the structure due to the vertical cantilevered configuration. These stresses could break the brittle graphite-epoxy truss members, and no replacement parts were available. Consequently, strict operational limitations were necessary to protect the structure; specifically, tip displacements were limited to 0.3 inches and tip rotations were limited to 0.15 degrees.

- **Realistic joints and nonlinearities**
- **Limited bending/torsion coupling**
- **Stress constraints resulted in strict operational limits on controls**

Torque Wheel Actuator Nonlinearities

Modeling the actuators was very difficult due to nonlinearities such as static/dynamic friction and impedance variations due to temperature changes. In addition, speed and current saturation limits were both frequency dependent. This figure shows the torque wheel actuator input commands in volts and actuator response in rpm during a typical test before any modifications were made to the actuators. The commanded sine wave was not reproduced due both to saturation and to the nonlinearities present in the devices. The amplitude dependence of the frequency response functions is not demonstrated in this figure. Attempts to experimentally determine some of the nonlinear parameters failed to produce an analytical model which would be accurate throughout the operating range of interest.

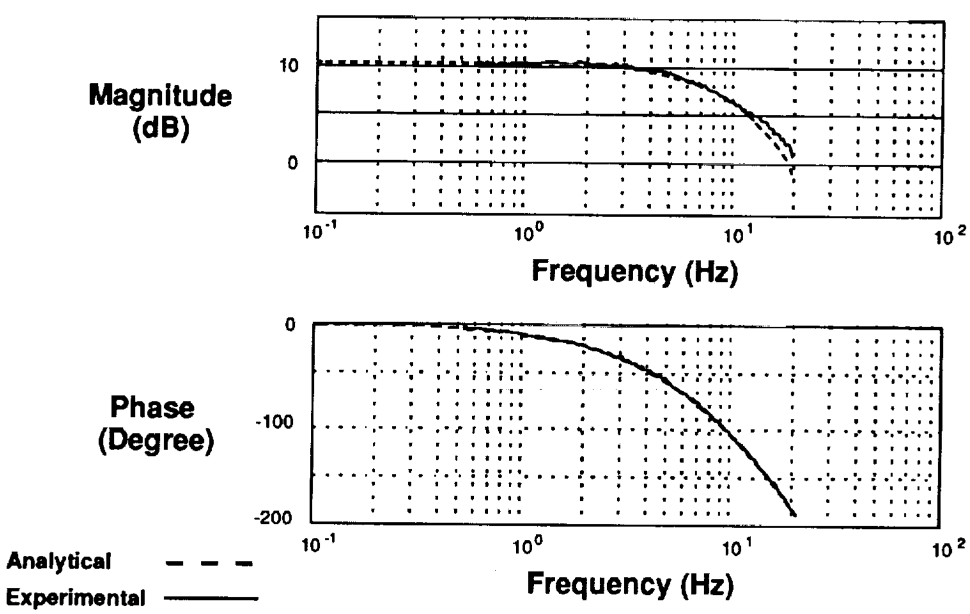
Torque Wheel Actuator Nonlinear Characteristics



Analytical Models of the Torque Wheel Actuators

Once the local feedback loop was created for each of the torque wheel actuators, parameters were experimentally obtained to create a second- order torque wheel model for use in subsequent analyses. This model, now a representation of the closed-loop torque wheel dynamics, was accurate for most of the test operating conditions. This figure compares the experimentally determined transfer function for one of the torque wheels, shown in the solid line, and its second order analytical model developed from experimental parameters, shown in the dashed line. The agreement between the transfer functions is sufficient for control purposes on the Mini-Mast testbed.

Torque Wheel Actuator Dynamics with Local Feedback Loop

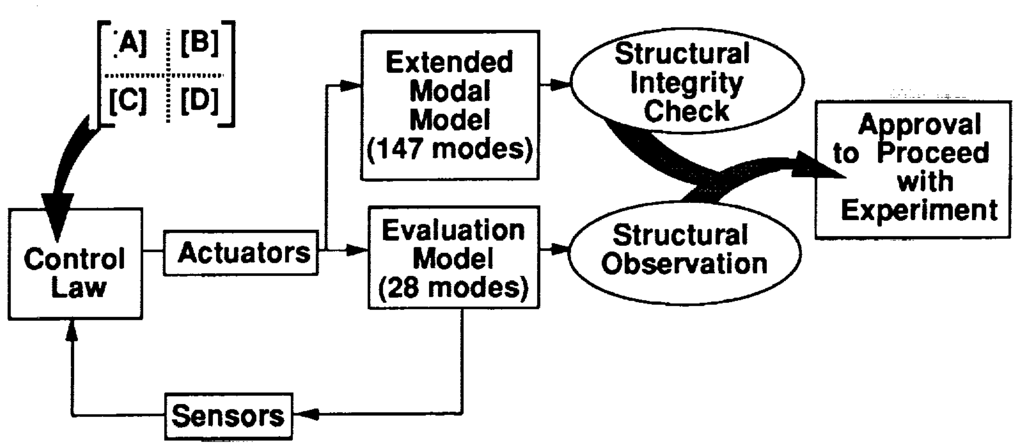


Pre-Test Approval Process

Through analysis, member loads were found to be sensitive not only to the amplitude of excitation and control commands but also to the relative phase between the shaker excitations and the actuator control moments. Therefore, in the absence of a reliable load measurement, a pretest approval process was instigated, as shown in this figure, to estimate the worst case loading on critical longeron and diagonal members.

Actuator and shaker time histories were created during closed-loop simulations, using a 28-mode evaluation model to represent the structural dynamics. Loads verification was accomplished by applying these load time histories in an open-loop transient analysis to a high fidelity finite element structural model comprised of 147 modes between 0 and 100 Hz.[3] The calculation of transient member loads was performed using a modal acceleration technique for improved accuracy. A conservative approach was again used in determining the worst-case single load: the maximum bending moment of any member in the truss was combined with the maximum axial load of any member, and these loads were assumed to act at the same time on a single member.

The time required for the loads calculation meant that each controller had to be submitted to the loads analysis group well before the controller could be implemented in the laboratory. The operational constraints imposed by the high stresses prevented changes to the controller by the researcher during testing, which is realistic for flight applications. Researchers were not able to immediately test the numerous "What if?" questions that arose; the investigation of unpredicted events that occurred while testing had to be delayed until additional loads analysis could be completed for the desired control law changes. However, on occasions during the GI program, small variations in control laws were permitted without additional simulation.



Lessons Learned: Testbed Development

A significant strength of the CSI program lies in the application of theory to actual, realistic hardware, thus eliminating the simplifying assumptions that can be made with purely analytical studies and requiring a certain degree of robustness in any control design. This may be the program's main contribution in advancing the respective control theories.

Operational constraints and requirements for thorough simulation of all control laws prior to implementation on the testbed added realism to the program but also limited the research flexibility afforded to the guest investigators. In addition, such constraints placed a strong emphasis on scheduling work to meet required deadlines.

Other hardware observations include the need for ample spares for key equipment. Specifically with respect to rate gyro sensors, the program experienced high rates of failure. Four of the five rate gyros failed within the two year program. Initially, the rate gyros were considered essential for low frequency control feedback sensors. However, the servo accelerometers proved to be viable feedback sensors in the 0.5-10 Hz frequency range. The high reliability and the inertial measurement available with accelerometers make them suitable for primary flexible-body control sensors.

The analysis and simulation efforts provided additional lessons during the testbed development. First, developing good mathematical models early in any test program is essential. In addition, extensive testing and model verification is an integral part of model development. For example, early torque wheel models were inadequate to cover the full range of actuator operation; ultimately, a local feedback loop was added to the actuators to make the devices more linear. As another example, while early analytical models of Mini-Mast structural dynamics were in good agreement with the preliminary experimental models, a more thorough analysis of the experimental data resulted in frequency shifts of up to 30 percent in higher modes. More extensive early studies might have allowed less stringent safety or operational constraints for protecting the test article.

Adopting a single tool for transferring control laws, dynamics models, or experimental data among program participants proved to be a strong benefit to the program, decreasing the potential for miscommunication. In addition, development of the generic software package for controls implementation has already been noted as a significant accomplishment of the program.

Hardware

- **Application to realistic hardware provides crucial key to full development of CSI technology**
- **Real spacecraft operational constraints**
  - **Affect scheduling**
  - **Limit research flexibility**
  - **Require prioritizing**
- **Ample spares necessary for key equipment**
- **Accelerometers proved to be viable low frequency control sensors**

Analysis & Simulation

- **Develop good mathematical models early**
- **All participants should use a common modeling tool**
- **Generic software format proved valuable**

Lessons Learned: Guest Investigator Program

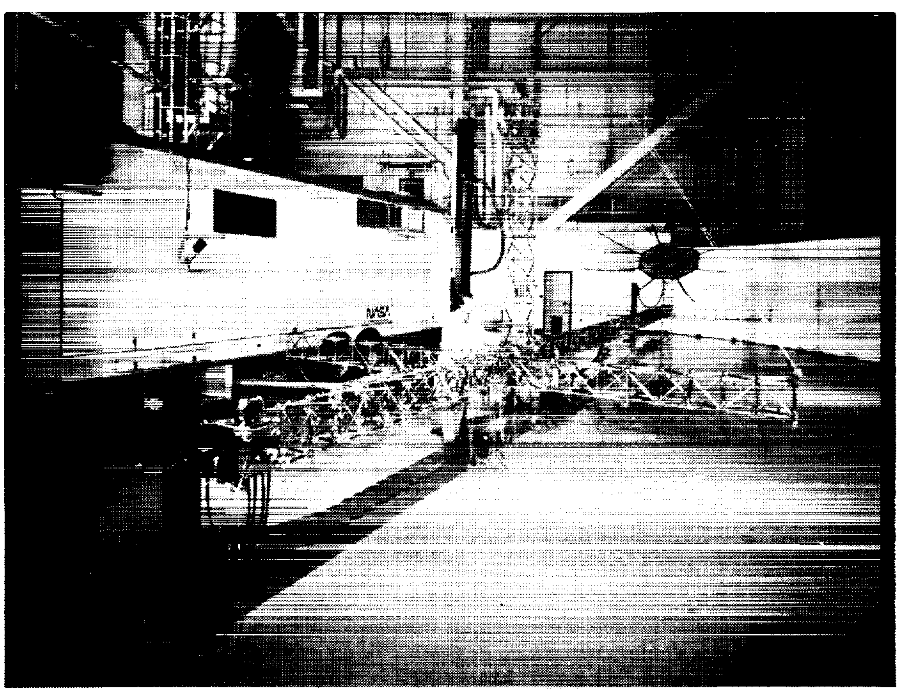
Some general observations can be made for the GI program as a whole. While miscommunications are likely to be a part of any human endeavor, they could be decreased by use of a well-controlled interface document. Rigorously abiding by established naming conventions for sensors, actuators, filters, and analytical models would prevent confusion. Including the date in the names of analytical models would ensure that all program participants were using the latest version of a given model. (This was particularly a problem early in the GI program when the torque wheel actuator models were changing frequently.) A standardized format for test plans could also be defined in such an interface document. Changes to test plans should only be accepted in written format; verbal changes are most likely to cause errors. Finally, the document should identify a single contact person for each outside researcher, a function established in the GI program through NASA technical monitors.

Considerable freedom was given to guest investigators using the Mini-Mast testbed. They determined their own research objectives, selected the method(s) they wished to apply, and determined which sensors and actuators to use. These freedoms, however, formed the basis for several concerns which could be addressed in future programs. First, by not focusing the group on a single objective, the ability was lost to compare the inherent value of various control methodologies. In addition, investigators were more likely to concentrate on controller performance while sacrificing a more generic application of the methodology.

- **Well-controlled interface documentation is critical but it limits experiment freedom**
- **Tendency to demonstrate successful controllers without exploring boundaries of the methodology**
- **Target performance objectives would allow comparison of methodologies**

Summary

The many lessons learned through the Mini-Mast testbed development and the associated guest investigator program have since been applied to new CSI testbeds, such as the CSI Evolutionary Model shown in this photograph. The necessity of applying theory to realistic hardware will continue to be emphasized throughout the CSI programs, advancing the technology to meet future challenges in large space structures.



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