A Synopsis of Test Results and Knowledge Gained From the Phase-0 CSI Evolutionary Model

W. Keith Belvin, Kenny B. Elliott and Lucas G. Horta

Abstract

The Phase-0 CSI Evolutionary Model (CEM) is a testbed for the study of space platform global line-of-sight (LOS) pointing. Now that the tests have been completed, a summary of hardware and closed-loop test experiences is necessary to insure a timely dissemination of the knowledge gained. The testbed is described and modeling experiences are presented followed by a summary of the research performed by various investigators. Some early lessons on implementing the closed-loop controllers are described with particular emphasis on real-time computing requirements. A summary of closed-loop studies and a synopsis of test results are presented. Plans for evolving the CEM from phase 0 to phases 1 and 2 are also described. Subsequently, a summary of knowledge gained from the design and testing of the Phase-0 CEM is made.

Outline

O Testbed Description and Modeling

O Investigators

O Early Lessons

O Real Time Computing

O Closed-Loop Studies

O CEM Plans

O Summary

Introduction

The Phase-0 CSI Evolutionary Model (CEM) testbed design was driven by the interaction of flexible body dynamics and active pointing control systems expected on future space platforms. The testbed structure, shown below, consists of a 55' long aluminum truss with several appendages. A laser, mounted to one appendage, is used to illuminate an optical path from the laser source to a 16' diameter reflector. The optical path continues from the reflector to an LOS scoring detector mounted inertially on the ceiling of the test facility. The structure, instrumentation and data acquisition and control computers are described in detail in Refs. [1-3].

This paper summarizes the types of tests and experimental results obtained using the CEM testbed. Hardware experiences are described in terms of gravity influences and modeling requirements. System identification tests and results are presented to show the accuracy of pre-test and post-test finite element modeling procedures. Results of dissipative controller tests are compared to model based controllers in terms of stability and performance. It is shown with the level of uncertainty that exists in the CEM analytic models, a combination of dissipative and model based controllers give the best performance. The implementation of digital controllers is also discussed in terms of the effects of time delay. Plans for evolving the testbed are also presented.

Phase-0 CSI Evolutionary Model

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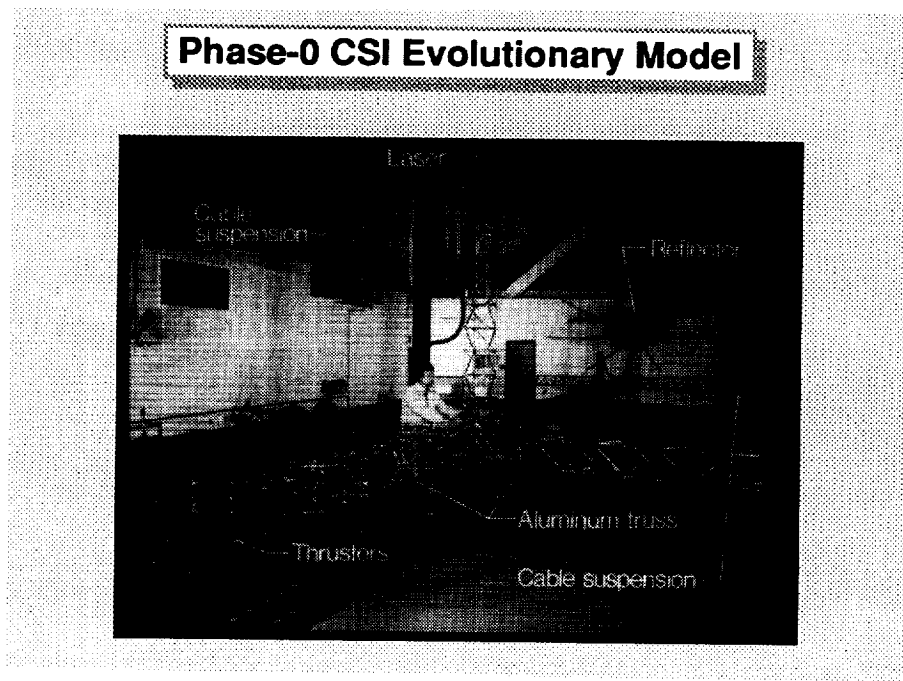
Phase-0 CEM Actuators/Sensor Pairs

Acceleration sensors have been used as the primary control sensor in conjunction with linear bi-directional thrusters. The actuators and sensors were spatially collocated at the 8 locations shown below. The low frequency nature of the testbed requires sensors with a bandwidth down to 0 Hz. As such, the accelerometers detect the acceleration due to gravity. This poses a classic ground-based measurement problem whereby the acceleration of the "pendulum" suspension modes is nearly exactly canceled by the change in the gravity acceleration vector. For the Phase 0 CEM, this phenomenon only occurs in mode 2. Hence the measured acceleration of mode 2 differs significantly from that predicted by linear (small angle) analysis. Another experience with low frequency accelerometers is DC drift and/or biases which require special considerations when integrating the measured acceleration particularly if the controller has a DC gain.

The thrusters [4] have proved to be reliable control effectors with minimal dynamics in the 0 to 10 Hz bandwidth. Eight pairs of thrusters were mounted such that a net force was applied to the model at the 8 locations shown below. Although pure collocation of the sensors and actuators was attempted, results, shown herein, indicate limited success was achieved.
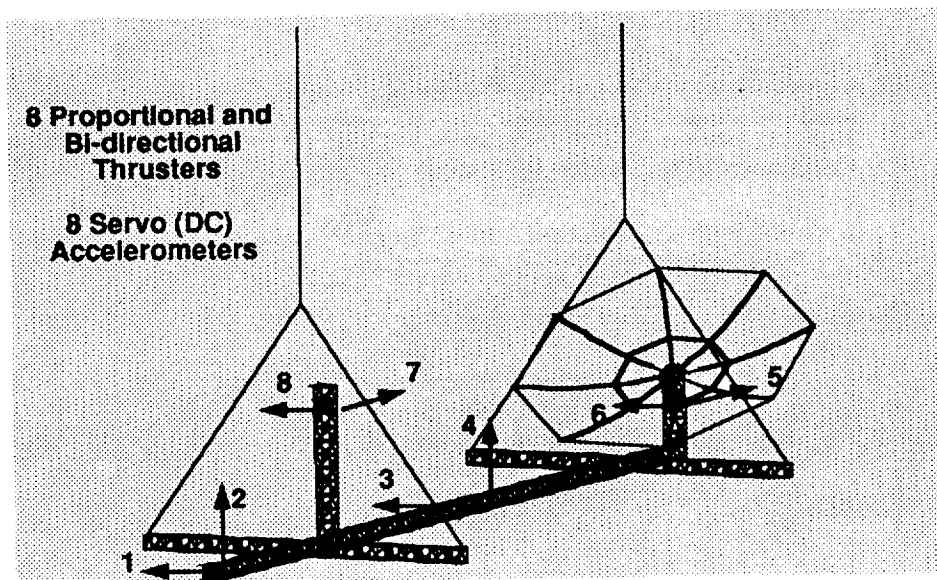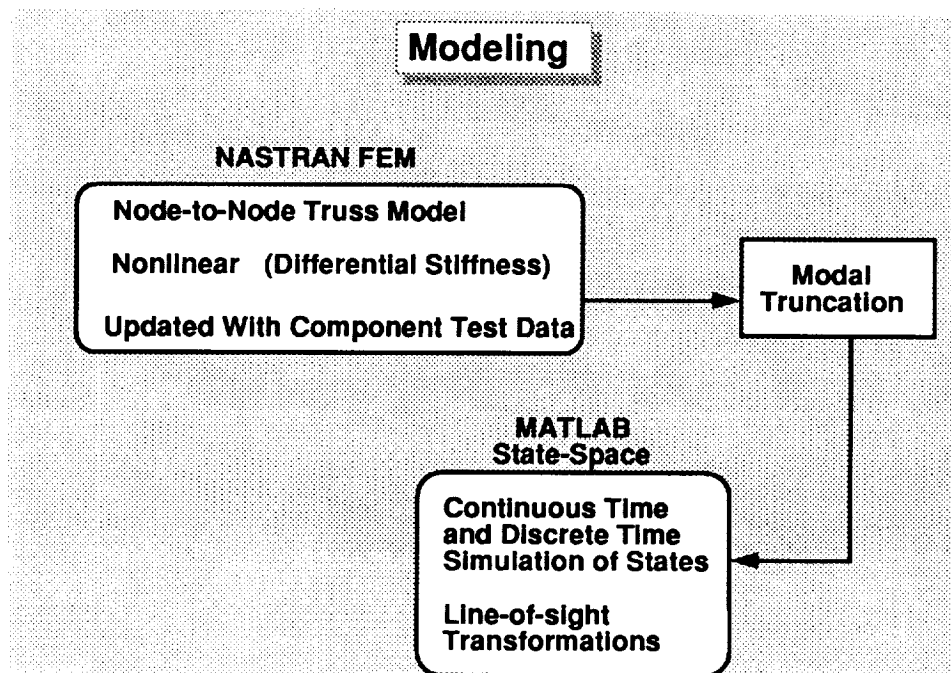
Structural and Line-Of-Sight Modeling

The Phase-0 CEM truss structure was designed to simulate the generic dynamic behavior of space platforms with 1 to 2 Hz global vibration modes coupled with higher-frequency, localized or appendage vibration modes. For ground testing, a structural suspension system was designed to permit all 6 "rigid-body" modes while not overstressing the truss struts due to gravitational preload. The resulting structural system, including the suspension, was modeled by the NASTRAN finite element program. The inclusion of nonlinear differential stiffness was required to predict the "rigid" body modes and the effect of the suspension on the flexible body modes.

As indicated below, the NASTRAN model was used to compute an eigen basis for control design and simulation using the MATLAB program. Various levels of model reduction were performed. Typically a 40 mode "truth" model was used for simulation of the closed-loop response of the Phase-0 testbed.

Once a time history of the modal states was computed, a linear transformation of the response was performed to predict the line-of-sight pointing performance [5].

Modeling

NASTRAN FEM

Node-to-Node Truss Model

Nonlinear (Differential Stiffness)

Updated With Component Test Data

Modal Truncation

MATLAB State-Space

Continuous Time and Discrete Time Simulation of States

Line-of-sight Transformations

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Test and Analysis Frequency Correlation

Modal vibration tests of the CEM have been performed using 24 servo and 195 piezo channels of accelerometer data. Multi-input, multi-output (MIMO) tests were performed to measure the frequency response functions between the acceleration output to the force input from each of the 8 thrusters. The data below show the experimental frequencies as identified from the frequency response functions using the Polyreference method of data reduction. The mode numbers are based on the order of the analytical mode shapes. It is interesting to note the measured damping decreases with increasing mode number.

The frequency error between test and analysis is also shown. Two values of error are shown, one for the original finite element model (FEM) and one for an updated FEM using measured thruster air hose stiffness and component test data from the Phase-0 truss. The refined model was much more accurate in predicting the modes up to 2.5 Hz; however, considerable error still remained in the prediction of modes involving the reflector appendage.
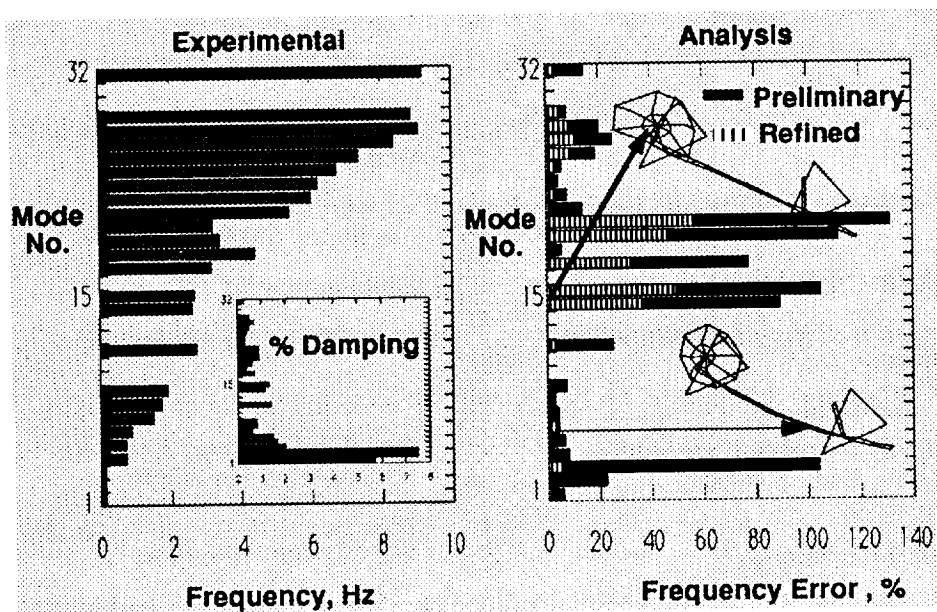
Phase-0 CEM Investigators

A wide variety of research was performed on the Phase-0 CEM. The table below shows the investigators and their major area of research. Two teams at Langley performed most of the system studies. Within the Spacecraft Dynamics Branch, the CSI Ground Test Methods team performed hardware implementation and HAC/LAC control studies. The CSI Analytical Design Methods Team of the Spacecraft Controls Branch performed much research on advanced controllers and integrated controls/structures design.

A number of guest investigators (external to NASA LaRC) pursued CSI technology development using the Phase-0 testbed. The work by JPL is of particular merit and will be described later.

It must be stated that each of the investigators were supported by a large contingent of NASA LaRC and Lockheed Engineering and Sciences Corporation employees. Without this technical support, only a fraction of the studies could have been completed during the Phase-0 CEM operational period (May 21, 1991 to September 5, 1992).

Investigator	Technology
LaRC	
Spacecraft Dynamics Branch,SDyD	System Hardware, High Authority/ Low Authority Control
Spacecraft Controls Branch, GCD	Advanced Controllers, Integrated Design
Electrical Systems Section, SED	SCI/RIU Hardware
Flight Software and Graphics Branch, ACD	SCI Real-Time ADA Software
Guest	
Martin Marietta Corporation Harris Corporation MUSYN JPL IaBG (Germany)	Passive Damping Analyses Proof-Mass Actuators μ-Synthesis Controllers Piezoelectric Struts, D Struts System Identification

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Controller Delay and Non-Collocation Effects

Among the first closed-loop controllers that was executed on the testbed was a dissipative controller with "guaranteed stability" if actuator and sensor collocation was realized. The figure below shows neither spatial nor temporal collocation was realized in the initial experiments.

The time delay introduced by digital implementation of the controllers can result in instabilities. The real-time controller update rate was set to 80 Hz for the first experiment which is more than an order of magnitude greater than the controller bandwidth. Nevertheless, a 7 Hz mode was being destabilized. By simply increasing the controller update rate to 350 Hz, the decrease in time delay stabilized the response. This early lesson indicated that the controller update rates should approach two orders of magnitude higher than the controller bandwidth when trying to implement a continuous time controller with discrete computations.

It was also learned that the original accelerometer mounting violated spatial collocation. The original non-spatial collocation of sensors and actuators involved coupling of bending and torsion vibrations. The figure on the right shows the response with the original accelerometer installation (on the corner of the truss). The accelerometer detected torsional vibration which was fed-back to a thruster pair which could only produce bending. Hence, significant performance degradation was observed. By moving the accelerometers to prevent the torsion/bending coupling, good closed-loop performance was obtained.
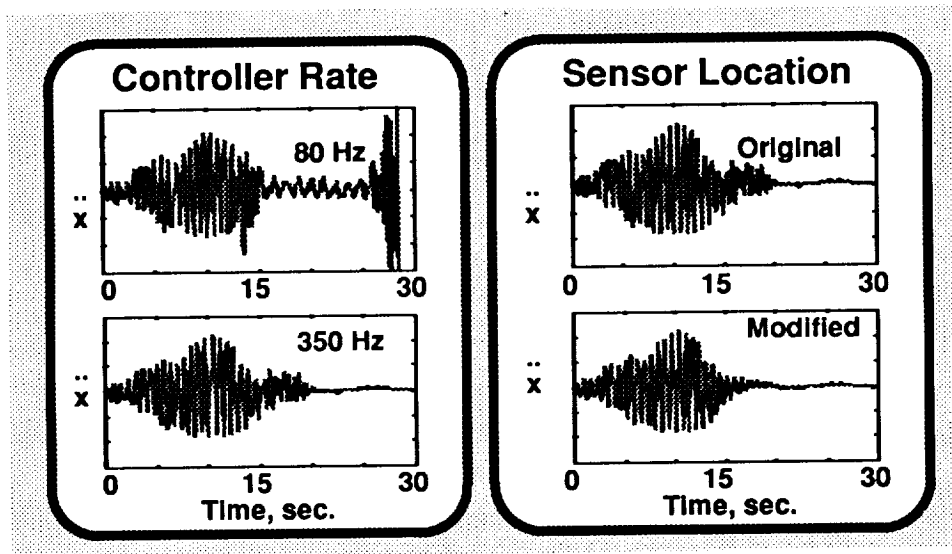
Real-Time Computing

To implement the control laws in digital (discrete) form, several real-time computing systems have been developed. The figure below highlights a flight like SCI computer system, programmed in ADA and implemented using a flight qualified 1553B bus structure. The system software for implementation of general control laws and digital filtering was successfully demonstrated using the Phase 0 testbed.

The controller update rates, which have already been shown to influence stability, are one of the key parameters to assess the adequacy of a real-time computer for closed-loop testing. The data below show the SCI computer can achieve rates exceeding 200 Hz for an 8 input-8 output controller. However, the remote interface unit (RIU) is limited to 200 Hz. This 200 Hz rate proved adequate for most of the Phase-0 experiments. Test results and development documentation for the SCI/RIU system can be found in Ref. [6].

It is noted the primary controller for the Phase-0 testbed was a VAX 3200. The enhanced version of this computer, coupled with tridiagonalization of the controller A matrix could achieve 280 Hz rates for a 40 state controller with 8 inputs and 8 outputs. The VAX based primary control system development is described in Ref. [7].

SCI/RIU Flight Computer System
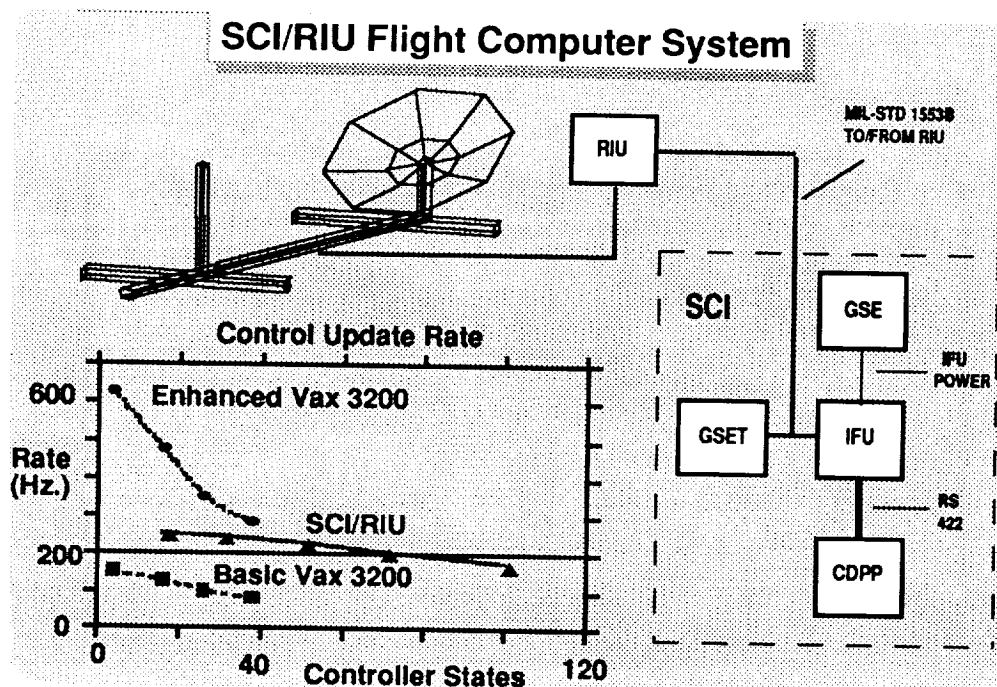
Closed-Loop Studies

A number of controllers have been designed for the Phase-0 CEM using both model independent and model based approaches as indicated below. The performance goals have been to add damping to prescribed modes and to minimize LOS pointing errors due to applied disturbances. Stability determination of the controllers was based on experimental transient response data.

Among the dissipative controllers that were tested, an active vibration absorber (AVA) concept [8, 9] has been used to dissipate energy from the first nine modes of the Phase-0 CEM. The AVA controller is guaranteed to be stable for collocated actuators and sensors. LQG and H-infinity model based controllers have been designed for the Phase-0 CEM. The LQG controllers usually result in instabilities due to controller spillover in higher-frequency, unmodeled modes when high performance is desired. Results from H-infinity controller testing show that to maintain stability with the model error that existed in the FEM, relatively low gain (low performance) controllers were obtained. H-infinity and μ synthesis controller results are also described in Refs. [10, 11].

The AVA controller and a combination LQG/AVA (HAC/LAC) controller will be described and compared in the next few pages. In addition, a novel second-order observer for use with acceleration measurements will be described. Closed-loop LOS pointing results are presented and stability enhancement using strut actuators will be demonstrated.
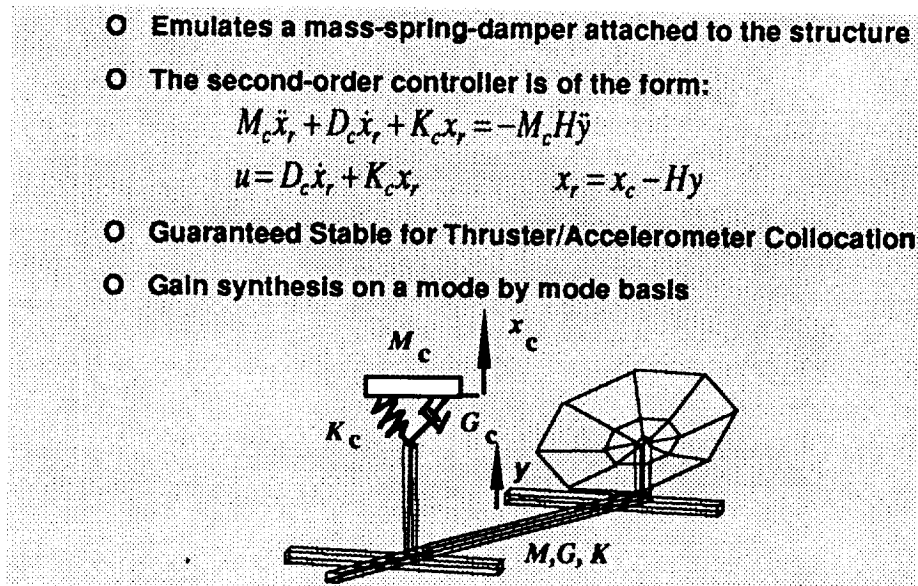
O **Dissipative Controllers**
  - **Active Vibration Absorber (AVA)**

O **Controller Merit Index**
  - **Compare AVA, LQG and HAC/LAC**

O **Model Based Controllers**
  - **HAC/LAC**
  - **Second-Order Observer**

O **Line-Of-Sight Pointing**
  - **Closed-Loop Performance**
  - **Predictive Accuracy**

O **Stability**
  - **HAC/LAC Stability**
  - **Piezoelectric Strut Appendage Control**

Active Vibration Absorber (AVA)

Several collocated controllers have been tested to verify stability and performance. An active vibration absorber (AVA) concept [8, 9] has been used to dissipate energy from the first nine modes of the Phase-0 CEM. The AVA controller is guaranteed stable for collocated actuators and sensors; however, as already shown collocation is only approximated on the Phase-0 testbed.

As shown below, the AVA controller emulates a spring-mass-damper system by using acceleration feedback and a second-order control law. An added advantage of the AVA controller is that the control law gains can be synthesized on a mode by mode basis since the only stability constraint is that positive definite controller mass, damping, and stiffness matrices be used.

Tests of this controller on the Phase-0 testbed have shown good performance and high stability as long as the thruster and accelerometer pairs are "nearly" collocated. The combination of actuator dynamics and computational delay limited the use of the AVA controllers to a bandwidth of 0 to 10 Hz.

O **Emulates a mass-spring-damper attached to the structure**

O **The second-order controller is of the form:**

$$M_c \ddot{x}_r + D_c \dot{x}_r + K_c x_r = -M_c H \ddot{y}$$

$$u = D_c \dot{x}_r + K_c x_r \qquad\qquad x_r = x_c - Hy$$

O **Guaranteed Stable for Thruster/Accelerometer Collocation**

O **Gain synthesis on a mode by mode basis**

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HAC/LAC Control

The HAC/LAC controller developed for the Phase-0 testbed was formed by using the LQG controller for performance (high authority) and designing AVA controllers for stability (low authority); i. e. AVA control of those modes being destabilized by the LQG controller. In the figure below, the HAC and LAC loops are shown to operate in parallel. It is noted that the LAC loop does not appreciably add to the amount of force produced by the thrusters. The low authority "stability" modes require very little energy to control. The HAC/LAC controller, with the first nine modes of the testbed controlled by the LGQ loop and six modes in the AVA loop, was the primary controller used for LOS pointing demonstrations.
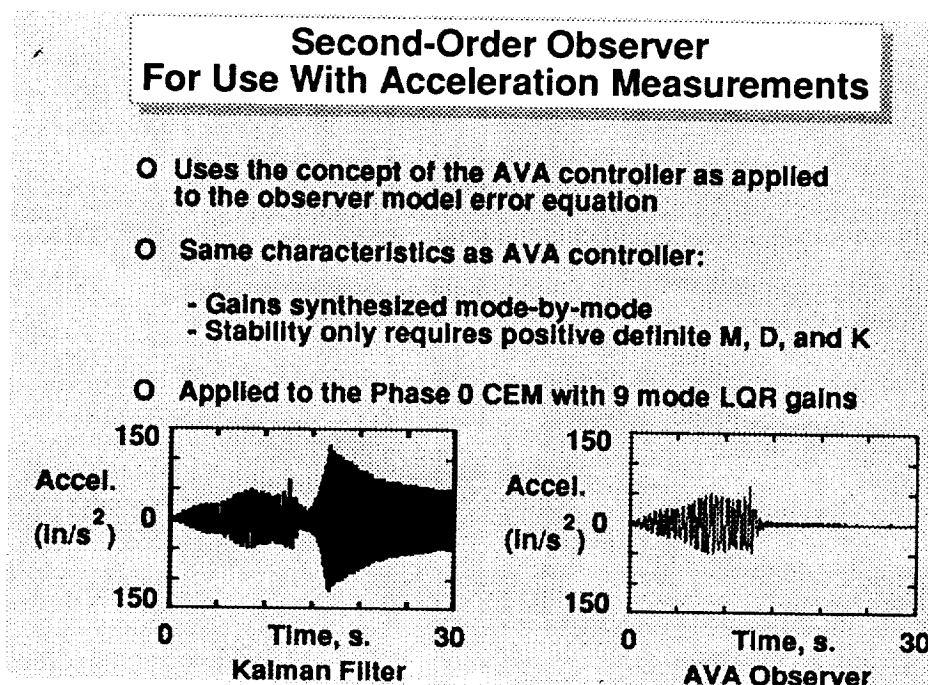
An alternative approach to stabilize the LQG controller, by decreasing the LQG gains for gain stabilization and adding damping with an AVA controller to the same modes to recover performance, was met with limited success. A third approach to improve the stability of implementing LQR (model based) gains was through the use of a second-order observer in place of the Kalman Filter. This new observer is described next.
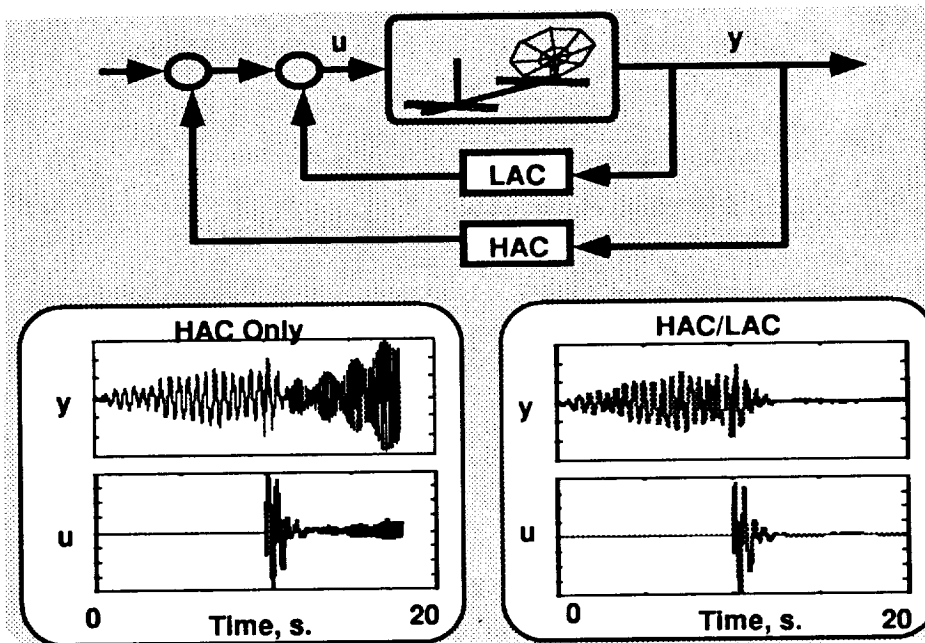
Second-Order State Estimation
Using Acceleration Measurements

A second-order observer has been developed and applied to the Phase-0 testbed for state estimation with direct feedback of acceleration measurements. The observer uses the concept of the AVA controller as applied to the observer model error equation. Hence the model independent stability and mode-by-mode gain synthesis properties of the AVA controller also apply.

To verify the second-order observer performance and stability, LQR gains were synthesized and used with both the Kalman Filter and the second-order (AVA) observer. The figures below show the experimental response of the structure at accelerometer location 2. The data for the LQG shows an instability which required the actuators to be disabled at t=16.6 sec. This instability of a mode near 7 Hz is due to unmodeled dynamics since a nine mode model with frequencies less than 2 Hz was used in the LQR and Kalman filter gain synthesis. Although the AVA observer used the same nine-mode control gain, the AVA observer produced a stable closed-loop response. Hence, the second-order (AVA) observer is useful in reducing observation spillover instabilities. Details of this work are found in Ref. [12].

Second-Order Observer
For Use With Acceleration Measurements

O Uses the concept of the AVA controller as applied
   to the observer model error equation

O Same characteristics as AVA controller:

   - Gains synthesized mode-by-mode
   - Stability only requires positive definite M, D, and K

O Applied to the Phase 0 CEM with 9 mode LQR gains


Kalman Filter   AVA Observer

Line-Of-Sight Pointing Results

Using the HAC/LAC controller described previously, the LOS pointing performance has been measured and simulated using the reduced order state space models. Typical tests consisted of 10 seconds of excitation followed by either free-decay or closed-loop control.

As indicated in the figures below, the test and simulated LOS pointing is qualitatively in very good agreement, although some quantitative differences are apparent. This indicates that control law design for flexible structures using finite element derived design models is quite viable.

The performance of the HAC/LAC controller can be described in terms of the LOS pointing error decay rates. The damping is increased from less than 1% to more than 10% between open- and closed-loop, respectively. While this limitation was partially due to actuator saturation, the stability margin of the high-gain HAC/LAC controller limited performance as described next.

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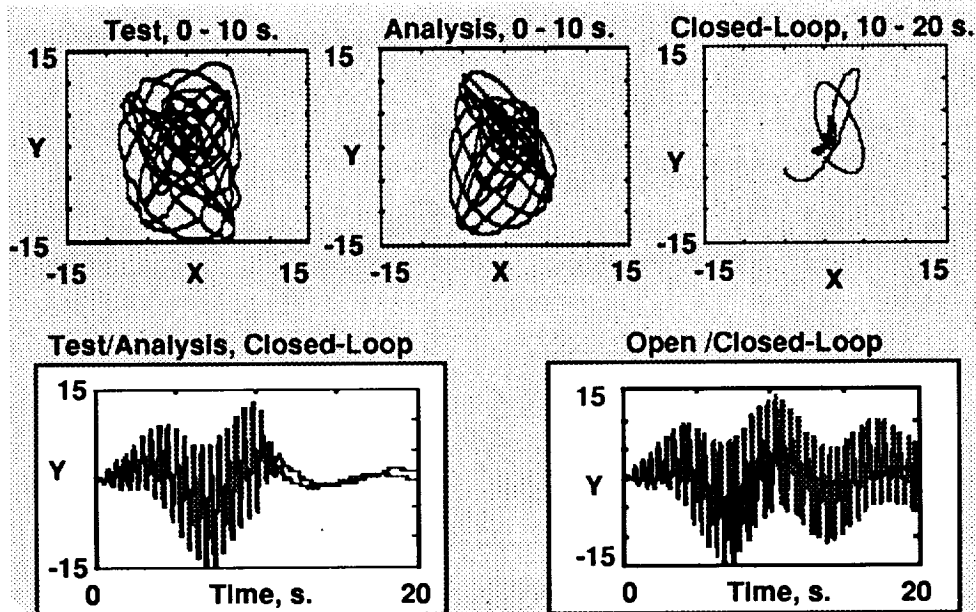
Controller Merit

To assess the performance of various controllers, a merit index was used that measures the RMS LOS error and the RMS energy used by the controller. The lower the merit index, the "better" the controller. As shown below, the HAC/LAC controller merit was among the best tested. The HAC/LAC controller was formed by using the LQG controller for good performance and designing AVA controllers for those modes being destabilized by the LQG control.
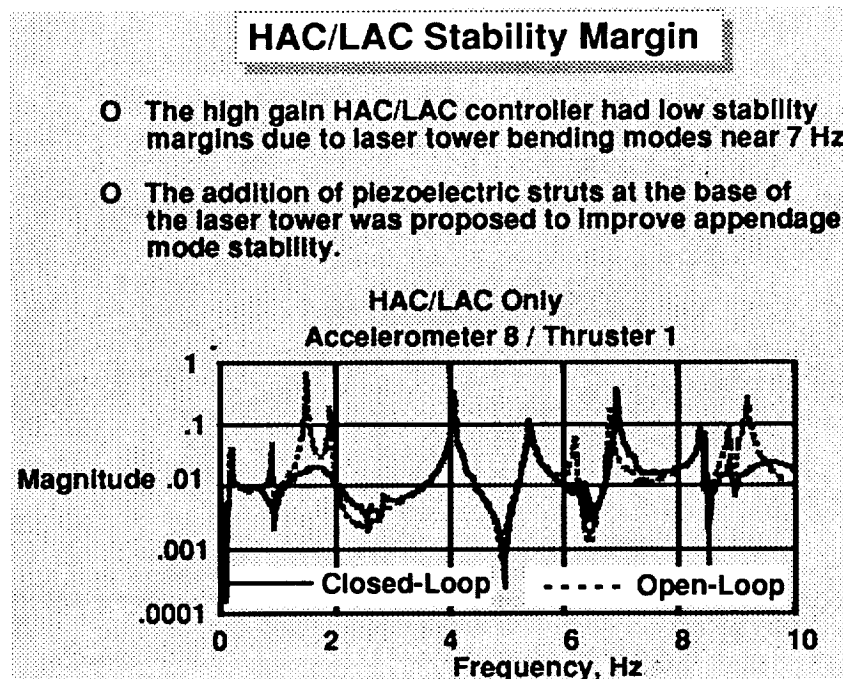
The LQG controller was found to have the best merit index if stability could be maintained. In the data below, a 7 Hz mode is destabilized by the LQG controller as shown in the LOS pointing error. The AVA controller was stable but produced a poor merit index. By combining the two controllers as described above, good stability and a reasonable controller merit index were obtained. The next page further describes the HAC/LAC controller.
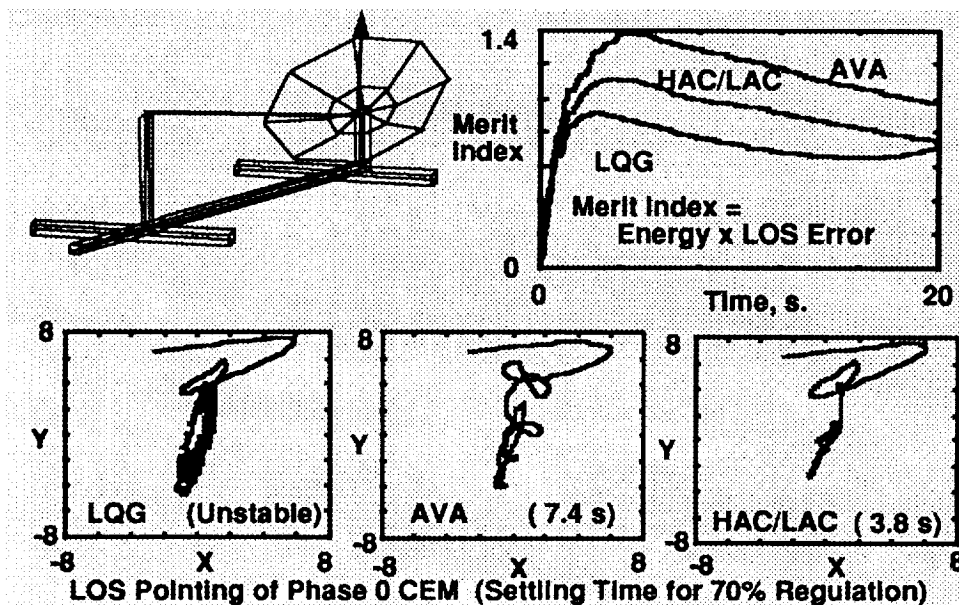
Controller Stability

The high-gain HAC/LAC controller used to produce the closed-loop line-of-sight pointing results shown on the previous page shows lower stability than desired. The figure below shows the open-loop and closed-loop frequency response for the acceleration magnitude at location 8 to a force input at location 1. This particular HAC/LAC controller consisted of an LQG design for the first 9 modes (modes below 2 Hz) and 6 single mode AVA controllers. The AVA controllers were designed to enhance stability of the HAC (LQG) controller in the 6 to 10 Hz frequency range. Nevertheless, there remained a laser tower bending mode which showed very low stability at a frequency near 7 Hz as noted by higher vibration magnitudes in closed-loop than in open-loop!

To enhance the stability of the HAC/LAC controller the use of induced strain actuators at the base of the laser tower was proposed. The next page describes the implementation of two JPL piezoelectric struts and four viscous damped struts to augment the HAC/LAC controller stability.

HAC/LAC Stability Margin

O The high gain HAC/LAC controller had low stability
   margins due to laser tower bending modes near 7 Hz.

O The addition of piezoelectric struts at the base of
   the laser tower was proposed to improve appendage
   mode stability.

HAC/LAC Only
### Accelerometer 8 / Thruster 1

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Appendage Control With Strut Actuators

Two active struts and four passive struts were incorporated in the Phase-0 CEM testbed to augment the damping of modes in the frequency range of 5 to 8 Hz. The active struts, which replaced two longerons at the base of the laser tower, were developed at JPL and are described in Ref. [13]. The passive struts, used to replace four existing diagonal truss members, were jointly developed at Honeywell and JPL as described in Ref [14].

The figures below show the effects of the active and passive struts on the frequency response magnitude function shown previously. Modes in the range of 5 to 8 Hz were successfully attenuated. The figure on the right shows that the combination of the HAC/LAC controller and the decentralized appendage controller using strut actuators. It is shown that the laser tower appendage mode no longer poses a stability concern.

From these results it is shown that the addition of actuators and sensors to control appendage vibrations can be successfully achieved using strut actuators. The ability to implement the appendage controllers in a decentralized manner helps to reduce the complexity of the centralized platform controllers. These results are more fully documented in Ref. [15].
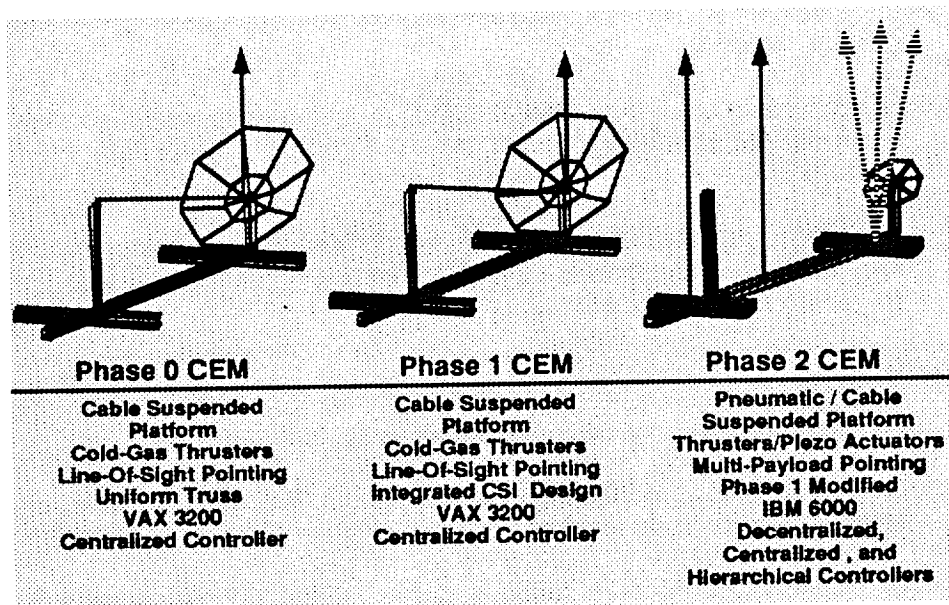

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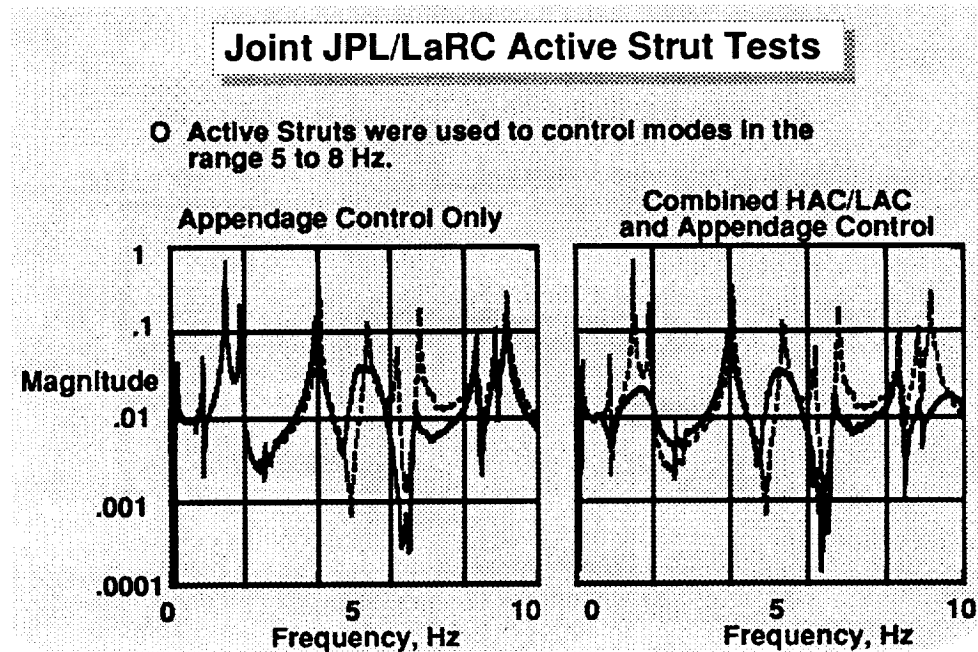
Evolution Of The CEM Testbed

Tests on the Phase-0 CEM were successfully concluded on September 5, 1991.

The Phase-1 testbed will be built based on an integrated design [16] of 21 different strut stiffness/mass properties and a static dissipative controller. The Phase-1 CEM will have the same geometry as the Phase-0 testbed. Tests of the Phase-1 CEM are planned for the spring and summer of 1992.

The Phase-2 CEM will entail a modification of the Phase-1 geometry and suspension. Moreover, Phase-2 will also include three two-axis gimbals and advanced scoring systems to simulate pointing of multiple science instruments. The Phase-2 CEM will permit 2.5 arc-sec pointing using piezo struts for flexible body control. Phase-2 also enables the study of multiple-payload platforms whereby a combination of centralized, hierarchical and/or distributed control schemes may be evaluated. Initial capabilities of the Phase-2 CEM should be operational in the late fall of 1992.

Phase 0 CEM	Phase 1 CEM	Phase 2 CEM
Cable Suspended Platform	Cable Suspended Platform	Pneumatic / Cable Suspended Platform
Cold-Gas Thrusters	Cold-Gas Thrusters	Thrusters/Piezo Actuators
Line-Of-Sight Pointing	Line-Of-Sight Pointing	Multi-Payload Pointing
Uniform Truss	Integrated CSI Design	Phase 1 Modified
VAX 3200	VAX 3200	IBM 6000
Centralized Controller	Centralized Controller	Decentralized, Centralized, and Hierarchical Controllers

Summary

The Phase-0 CEM has been a very fruitful testbed for the study of global LOS pointing and active vibration suppression. The testbed dynamic behavior was sufficiently rich that spillover instabilities were common in model based controllers. The Phase-0 testbed has proved to be very valuable in advancing flexible body control technology, training researchers, and building a knowledge base for future testbeds with similar objectives. Some important findings are offered below:

Design And Modeling

O Integrated suspension and structural design is needed to allow low-frequency dynamic behavior without violating static stress constraints.

O Finite element models should be based on component (and perhaps subassembly) tests to obtain sufficient accuracy for controller design models.

O Although differential stiffness (due to gravity preload) may not significantly affect flexible body vibrations, it must be included in the analysis to predict suspension cable effects.

Hardware

O Truss joints fabricated to carry 1600 lbs of load have typically produced 0.1 - 0.3 % critical damping in the flexible body modes of vibration.

O Linear bi-directional thrusters can be used for laboratory control of flexible structures.

O Servo accelerometers can be used, in conjunction with software bias removal, for feedback control of low frequency (0.15 Hz) structural vibrations.

O Digital implementation of continuous time controllers requires nearly two orders of magnitude faster update rates than the highest mode frequency in the controller design model.

Control

O Dissipative (static and dynamic) controllers are highly stable provided both spatial and temporal collocation can be approximated.

O Model based controllers, when stable, are usually more energy efficient for the same level of performance than dissipative controllers.

O Appendage control, using a decentralized control approach, can enhance stability and simplify the centralized platform controller.

Acknowledgements

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