NASA Technical Memorandum 102752

THE NASA CONTROLS-STRUCTURES INTERACTION TECHNOLOGY PROGRAM

Jerry R. Newsom
W. E. Layman
H. B. Waites
R. J. Hayduk

(NASA-TM-102752) THE NASA CONTROLS-STRUCTURES INTERACTION TECHNOLOGY PROGRAM (NASA) 19 p CSCL 22B N91-16057

Unclas

G3/18 0326553

OCTOBER 1990

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665-5225

THE NASA CONTROLS-STRUCTURES INTERACTION TECHNOLOGY PROGRAM

Jerry R. Newsom
NASA Langley Research Center
Hampton, VA 23665

W. E. Layman
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

H. B. Waites
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

R. J. Hayduk
NASA Headquarters
Washington, DC 20546

Abstract

The interaction between a flexible spacecraft structure and its control system is commonly referred to as controls-structures interaction (CSI). The CSI technology program is developing the capability and confidence to integrate the structure and control system, so as to avoid interactions that cause problems and to exploit interactions to increase spacecraft capability. A NASA program has been initiated to advance CSI technology to a point where it can be used in spacecraft design for future missions. The CSI technology program is a multicenter program utilizing the resources of the NASA Langley Research Center (LaRC), the NASA Marshall Space Flight Center (MSFC), and the NASA Jet Propulsion Laboratory (JPL). The purpose of this paper is to describe the current activities, results to date, and future activities of the NASA CSI technology program.

Introduction

Spacecraft design is conducted conventionally by estimating sizes and masses of mission-related components, designing a structure to maintain desired component relationships during operations, and then designing a control system to orient, guide and/or move the spacecraft to obtain the required performance. This approach works well in cases where a relatively high-stiffness structure is attainable and where non-structural components are concentrated masses and inertias, or where performance requirements are not stringent.

Frequently, distributed-mass components, such as booms, solar arrays and antennas, are an integral part of the spacecraft. In these spacecraft, unlike concentrated-mass components, a primary design requirement of the structure is to maintain distributed geometric relationships rather than to simply constrain the positions of component centers of gravity relative to the spacecraft center of gravity. Making them structurally stiff is desirable from a geometric control standpoint but costly in terms of operational mass as well as launch packaging and weight. The usual approach is to accept more structural flexibility of these components than is desirable. Because of this flexibility, controls-structures interaction (CSI) can occur which may reduce spacecraft performance or restrict operations (ref. 1).

Designing to avoid CSI generally requires either stiffening the structure (costly in mass and/or fuel consumption) or slowing down the control system response (costly in performance capability). Using the power available in the control system to reduce the interactive motions is theoretically possible and has been suggested in several publications (e.g. refs. 2, 3). However, hardware implementation of these approaches has not been accomplished, except on a few simple laboratory models. The techniques generally require analytical representations of the system within the control loop. The fidelity, size, accuracy, and computational speed of these analyses are integrally related to and affect the performance of the combined structure-control system. The structural hardware, the control hardware, and the analytical models cannot be separated in the process of verifying that the system performs as required. Furthermore, if improperly designed, the closed-loop system is subject not only to inadequate performance, but also to potentially destructive dynamic instability.

Future NASA missions are likely to increase the need for CSI technology because of increased size of distributed-mass components, greater requirements for surface and pointing precision, increased use of articulated components, and increased use of multi-payload platforms (with multiple control systems on board). Because of this projected increased need, NASA has initiated a program to advance CSI technology to a point where it can be used in spacecraft design for future missions. Because of the close interrelationships between the structure, the control hardware/software, and the analysis and design approach, a highly interdisciplinary activity is required. Methods are being developed which allow the control and structure analysis and design functions to use the same mathematical models. Verification of methods in hardware applications and tests is emphasized and requires development of hardware concepts and test methods for implementation.

This paper describes the NASA CSI Program including the goals and approach employed to meet the goals, current activities, results to date, and some future plans. Emphasis is placed on current activities and results to date.

CSI Program Description

The CSI Program is a focused technology element of NASA's Civilian Space Technology Initiative. The CSI Program is managed from the Office of Aeronautics, Exploration, and Technology (OAET) by the Materials and Structures Division. OAET is specifically focusing CSI technology to enable or enhance classes of missions which are supported by the Office of Space Science and Applications (OSSA).

Goals

The overall objective of the CSI program is to develop and validate the technology needed to design, verify, and operate spacecraft in which the structure and the control system interact beneficially to meet the requirements of 21st-century NASA missions. Long term goals of the effort are as follows:

(1) To provide spacecraft dynamic response amplitude reductions of 50 percent, for any input or maneuver, with minimum increase in system mass.

(2) To enable the use of wide-bandwidth CSI control systems to achieve several orders of magnitude improvement in control and pointing capabilities.

(3) To predict the on-orbit performance of CSI systems within 10 percent of all amplitude, frequency, time and stability requirements based on the results of integrated analyses tuned/corrected by closed-loop ground and/or flight test data.

(4) To develop unified controls-structures modeling, analysis and design methods which allow a complete iteration on all critical design variables in a single integrated computational framework.

(5) To develop the capability to validate the performance of flight systems by analysis/ground tests.

To meet these long term goals, the program is divided into four interactive focused technical areas and a Guest Investigator (GI) program to tap the unique ideas and expertise in industry and academia. The four technical areas are: 1) Configurations and Concepts; 2) Integrated Analysis and Design Methodology; 3) Ground Test Methodology; and 4) In-Space Flight Experiments.

Approach

NASA mission needs are used to set and update requirements on the four technical area activities. Specific mission configurations are used as guides or drivers for methods development and design studies, but the total scope of the effort spans several missions with different characteristics. The complexity and degree of specialization of problems attacked will be increased as technical progress is made on general problems.

The approach for meeting the objectives of the Configurations and Concepts task is to evaluate overall NASA mission requirements and benefits at the systems level on a continuing basis in order to guide the emphasis of technical activities, and to define an initial set of configuration and concept development tasks which will likely evolve as CSI activities progress.

The approach for meeting the objectives of the Integrated Analysis and Design Methodology task is to define analytical efforts and the development of necessary computer programs. All activities will be approached within a unified controls-structures framework. Major efforts include modeling, unified design and optimization methods, and methodology validation.

The approach for meeting the objectives of the Ground Test Methodology task is to: 1) establish requirements for advanced ground test methods and/or facilities and testing needs specifically related to interfaces with the integrated analysis/design activity, flight test activity, and the CSI technical community; 2) develop advanced ground test methods to meet these requirements; 3) develop facilities, test beds, computer and data acquisition systems, and excitation and sensing systems needed to meet the ground test requirements; and 4) conduct tests to obtain data for validation of analysis and design methods.

The approach for meeting the objectives of the In-Space Flight Experiments task is to: 1) define the technical needs/benefits of in-space flight experiments to CSI technology development; 2) determine the required maturity level of ground development necessary for productive flight testing; and 3) define and select cost effective on-orbit experiment opportunities.

A Guest Investigator (GI) Program is being conducted to involve the university and industry technical community in CSI research. Selected guest investigators are provided resources and technical support in adapting their research to the program applications and hardware. Selection is by response to formal solicitation at significant junctures in the program.

Current Activities, Results to Date, and Future Activities

The Langley Research Center (LaRC), the Jet Propulsion Laboratory (JPL), and the Marshall Space Flight Center (MSFC) are the field centers cooperatively developing NASA's CSI technology. The LaRC CSI task emphasizes multiple payload platforms (MPP) and global control of large antennas. MPP CSI technology is needed by large flexible systems carrying many separately controlled payloads and appendages, such as Earth Observing System (EOS) and advanced Space Station. The JPL task emphasizes development of CSI design technology for micro-precision controlled structures (μ-PCS). μ-PCS technology is needed for large optical systems such as large (20 to 100m) optical interferometers, large (8m to 16m) telescopes, and some high surface accuracy (micron level) microwave antennas. The MSFC CSI task emphasizes CSI technology for astrophysics missions such as the advanced pinhole occulter facility. The specific mission selected by each field center to focus the CSI technology development is shown in figure 1. The LaRC has chosen a large geostationary Earth observation platform (fig. 1a), the JPL has chosen a large space-based interferometer (fig. 1b), and the MSFC has chosen a Shuttle attached astrophysics x-ray imaging system (fig. 1c).

As stated previously, the CSI Program is divided into five major areas: Configuration and Concepts; Integrated Analysis and Design Methodology; Ground Test Methodology; Flight Experiments; and the GI Program. The LaRC is the lead center and has program activities in all five elements. The JPL has program activities in Configuration and Concepts, Integrated Analysis and Design Methodology, and Ground Test Methodology. The MSFC has program activities in Ground Test Methodology and Flight Experiments. A brief description of the activities in each element follows.

Configurations and Concepts

The major ongoing activities in the configurations area have been three CSI benefits studies. The major activities in the concepts area have been the development of active structural members and of multi-layered vibration control architectures.

The purpose of the benefits studies is to quantify the specific advantages of employing CSI technology for future missions. The approach is to select a future NASA mission and define the difference in the spacecraft design and/or performance both without and with CSI technology. The LaRC has conducted two benefits studies to date: a study involving the Shuttle remote manipulator system (RMS) arm and a study involving a large geostationary Earth observation platform. The RMS was selected because of the potential operational benefits possible for future missions involving the RMS such as assembly of Space Station Freedom. The geostationary platform was selected since the science requirements are reasonably well defined and can be used to quantitatively define CSI technology benefits. The JPL has conducted a benefit study for a large space interferometer. The optical interferometer was selected to demonstrate the value of CSI technology on advanced large optical missions.

Shuttle RMS - The first benefits study conducted by the LaRC involved the application of CSI technology to the Shuttle RMS and in particular the benefits to be derived during Space Station Freedom assembly operations. The first step in this study was to establish a baseline mission-build scenario to determine the timeline impact of the RMS operation on the Space Station assembly sequence. A timeline analysis was performed and it was determined that the RMS operation time over the first sixteen Shuttle flights is approximately 47 hours. This is a significant portion of the assembly timeline. Based on the RMS timeline, the assembly process sensitivity to the RMS performance was investigated. The CSI improvement studies focused on reducing the RMS settling time portion of the overall RMS timeline. Individual RMS maneuver response data were generated using the Draper RMS Simulator. The data showed that RMS settling times are sensitive to payload weight, but insensitive to distance traveled since maneuvers for a payload were made at a fixed, "safe," limited rate. Settling to within 2 inches and 1 inch were used as settling time measures based on an overall RMS positioning accuracy requirement of ± 2 inches. Simulation data showed representative settling times of ~ 15-80 seconds (fig. 2a). In order to apply the individual maneuver response data to the full assembly sequence, the Station assembly items were first categorized into 8 weight classes. Several "generic" assembly maneuvers were then analyzed in detail. The conclusion was that assembly maneuvers tend to have the same number of starts and stops. Using the individual response, weight class, and generic maneuver data, total RMS settling times were found to range from ~ 20 percent to 30 percent of the cumulative RMS time (see fig. 2b) and 5 percent - 7 percent of the cumulative EVA time. This means that 5 percent - 7 percent of the total timeline is used up waiting for the RMS vibrations to settle out. The individual RMS response data were observed to have damping ratios (as a percentage of critical damping) of ~ 5 percent - 10 percent. Studies have shown that active damping controllers can achieve damping ratios of 20 percent on individual modes. This would be approximately a factor of 2-4 increase in damping. Figure 2c shows the potential CSI benefits of cumulative settling time as a function of damping ratio improvement factor. A factor of 2 increase in damping reduces the cumulative settling time from 10 hours to 4 hours. The study results are conservative in that they do not include additional timeline factors due to unplanned activities, crew skill variability, and/or Orbiter thruster firings. The timeline savings identified here can also be viewed as reducing the total amount of time that the crew is exposed to hazards.

<u>Geostationary Earth Observation Platform</u> - The second CSI technology benefits study conducted by the LaRC was a study involving a large geostationary Earth observation platform. The platform would be used to support the proposed Mission-to-Planet Earth program where among other things a continually updated precipitation map of the Earth would be obtained. In order to provide the needed precipitation maps every 30 minutes, precision pointing and beam scanning are necessary for the large space antennas shown on each end of the geostationary platform in figure 1a. Since the beam scanning will most likely be accomplished mechanically by moving some parts of the antenna, this and other spacecraft disturbances will cause feed mast flexure and antenna distortion resulting in beam pointing jitter. Jitter up to 10 percent of the resolution cell size can be allowed without seriously degrading the quality of the precipitation map. Figure 3 shows the expected pointing capability with and without CSI technology. Beam jitter requirement becomes more stringent as the antenna diameter increases since cell size varies inversely with antenna diameter. Without CSI technology, the uncontrolled behavior is unacceptable for all antennas above 20 meters in diameter. In contrast to that limit, antennas up to 80 meters diameter could be used while still meeting a 10 percent pointing jitter constraint if CSI technology is employed. The CSI technology benefit, for this example case study, is that significantly larger antennas could be used with improved performance for future missions.

<u>Optical Interferometer</u> - The third CSI benefit study, conducted by the JPL, involved a large, 24-meter baseline spaceborne optical interferometer design to: 1) firm up the CSI technology performance requirements needed to support advanced optical missions; and 2) explore the benefits of meeting advanced optical mission requirements with CSI technology versus conventional structural designs. Advanced optical mission performance requirements boil down to a requirement of optical element position stability of one nanometer across large (10m to 100m) structures. The initial JPL optical mission design used CSI technology and produced a reasonable structural weight (≈ 2200Kg). Without CSI technology, figure 4a indicates that the original 2200Kg structure might be stiffened to satisfy a one nanometer stability requirement but the 70 fold increase in weight (to 150,000Kg) would be unreasonable. Lighter non-CSI designs might be possible but it's unlikely that a practical non-CSI design can achieve the one nanometer stability requirement typical of advanced optical missions. Figure 4b shows the stability performances of that design without a CSI control system, with rudimentary CSI technology, and with advanced CSI technology. An advanced CSI technology vibration reduction factor of 1000 is required to satisfy the one nanometer performance requirement.

<u>Concepts Development Effort</u> - In addition to the benefits studies, a concepts development effort has also been mounted. The purpose of the concepts development effort is to develop new design strategies for structural control of future NASA missions. A major JPL concept effort is the development of active members and of strategies for their use in structural control. Active members, inserted in place of conventional truss struts, are used to produce direct control of structural shapes and dynamic responses. Figure 5a shows piezoelectric active members installed in the JPL Precision Truss. The active members have open loop stiffness equivalent to the truss members they replace, and commandable stroke equivalent to the maximum strain allowable in the members they replace. A second concept effort at the JPL is development of multi-layered structural control architecture to achieve extreme amounts

(factor of 1,000 or more) of vibration reduction in which structural control is one of the layers, disturbance isolation is another, and optics motion compensation is a third. Figure 5b displays an example of the multi-layered architecture applied to a large flexible space structure on which a precision pointed telescope is threatened by disturbances coming from on-board rotating machinery (reaction control wheels, tape recorders, and mechanical actuators).

Integrated Analysis and Design Methodology

The objective of integrated design is to enable the interdisciplinary design of a single integrated structure and control system, as a replacement for today's practice of integrating a structural design with a separate control system design. The approach selected to develop integrated structure/control design methodology is an optimization-based procedure employing mathematical programming techniques. The optimization approach allows a large amount of freedom and variety in selecting the potentially large number of design variables. The optimization approach is also the one commonly used in the field of structural design.

There are generally two system design approaches for integrated structure/control design (fig. 6): a combined approach and a system decomposition approach. The combined approach is one in which the structural design and the control system design is combined into a single problem. The system decomposition approach (ref. 4) is one in which the large structure/control system is broken down into a structure and control subsystem that are smaller and more easily managed that the overall system. The overall system is coupled through the use of subsystem sensitivity information.

Four methods, all employing optimization, for integrated structure/control design are presently being investigated. Three of the methods employ the combined approach and one of the methods employs the system decomposition approach. Method I incorporates in-core finite element analysis, control design, and parametric optimization capabilities and is an extension of the work presented in reference 5. Method II employs a homotopy approach involving multi-objective functions and is described in reference 6. Method III employs Boeing's Integrated Analysis Capability (IAC) database management approach in conjunction with the Q-DESIGN controller design techniques and is described in reference 7. Method IV employs the system decomposition approach of reference 4. Initial numerical results using method I will be discussed.

The focus configuration shown in figure 1a was used to generate the numerical results. The configuration, shown in figure 7, is a truss-type structure bus with two flexible antennas having a total initial mass of 1028Kg. The antennas are generically designed to exhibit radial rib and hoop/column-like vibration mode shapes. The bus is approximately 25 meters in length with a 3-meter cross section. It consists of 51mm diameter X 1.59mm wall thickness graphite-epoxy tubes. The antennas are 15 meters and 7.5 meters in diameter and also are made of graphite-epoxy.

The objective of the initial integrated design study was to minimize the RMS pointing error at a point on the 15-meter antenna. In addition, constraints were applied to the total structural mass, frequencies, and damping ratios of the structure. Control was accomplished by three control moment gyros located at the center of gravity of the structure. Collocated sensors were used for feedback. The steady state disturbance was assumed to be sensor noise. The structural design variables were the outside diameters of the truss tubes and the control design variables were the feedback gain matrices on position and rate. Table I shows the results of the integrated design study. The results are shown as controlled performance (RMS pointing error), structural mass, actuator masses, and total mass. Three cases are considered: initial design (open loop), a conventional (control-optimized) design, and an integrated design. All results are normalized with respect to the initial design. Conventional design (control only) shows a controlled performance improvement of 1.41 but with a 9 percent increase in total mass due to actuator mass increase. However, the integrated structure/control design shows a controlled performance improvement of 4.82 with a 3 percent decrease in total mass. Although the actuator mass increases by 97 percent the structural mass decreases by 42 percent. Integrated design shows significant improvements in overall performance over the conventional design approach.

Ground Test Methodology

The objective of the ground test methodology task is to develop advanced techniques for CSI ground testing, provide facilities, test articles, computer and data acquisition systems, and excitation and sensing devices required for the verification and validation of the integrated design methods. The major areas that are currently being worked are suspension system design, system identification algorithms, actuator and sensor hardware development, controller implementation, and testbed development.

The two primary testbeds at the LaRC are the Mini-Mast and CSI evolutionary model (CEM). The primary testbed at the JPL is the Precision Truss. In addition, a CSI interferometer testbed is being designed at the JPL. The primary testbed at the MSFC is the Advanced Control Evaluation for Structures (ACES). In addition, a Control, Astrophysics, Structures Experiment in Space (CASES) testbed is under development at the MSFC. A brief description of the testbeds and some experimental results will be given.

Mini-Mast - The Mini-Mast testbed is shown in figure 8. The Mini-Mast is a 20-meter long generic truss that is deployed vertically and cantilevered from its base on a rigid foundation. The test article is being used to conduct active vibration control experiments on a realistic large space structure. To support these experiments, additional actuators, sensors, and computer hardware have been integrated with the basic truss. The actuators and sensors for control are located on two stiff platforms at the tip and near the mid-point of the truss. The actuators and sensors are connected using fiber-optic cable to a mainframe real-time control computer. Representative experimental and simulation results for the Mini-Mast are shown in figure 9. The closed-loop performance of two guest investigators' controllers are shown. Both controllers are shown to increase the system damping.

CSI Evolutionary Model - The CEM will be the primary test article for future CSI testing at the LaRC. The concept of an evolutionary model is that the model will evolve over time in size, complexity, and experimental capabilities. The Phase-0 CEM, shown schematically in figure 10a and installed in the laboratory in figure 10b, consists of a four-longeron truss, 16.8m in length with 0.25m cubic bays, an eight-rib reflector 4.9m in diameter, and a suspension system using two cables 19.8m long, located to minimize the interaction between the suspension and the structural modes (The first flexible mode is approximately 1.4Hz). Sixteen force actuators (which have variable thrust capability) are distributed on the structure along with eight accelerometers and eight angular rate sensors. In addition, a laser-detector system is incorporated into the testbed. A laser beam, whose source is located at the top of the long vertical truss, is reflected off a mirror, located at the center of the reflector, onto a detector located on the laboratory ceiling. Figure 11 shows some initial numerical results (ref. 8) indicating the suppression of both pendulum (pseudo rigid-body) and vibratory motion. The thrusters are seen to be excellent control devices for suppressing both motions. Experimental studies began in the summer of 1990.

Precision Truss - The JPL Precision Truss is being used to develop structural control methods employing active structural elements and passive damper elements. Figure 12 shows the Precision Truss with active struts and a passive viscous damper strut installed. Also shown are the active strut drive electronics, the networked real-time control computer, and one of the networked Unix work stations used to design and conduct Precision Truss structural control experiments. The Precision Truss is currently being used to explore: 1) optimal placement of active struts; 2) optimal placement of passive damper struts; 3) optimal combinations of passive and active struts; 4) optimal tuning of passive strut stiffness and damping values; 5) improved μ-synthesis global structural control design methods; 6) active impedance-matching local structural control design methods; and 7) blending of global and local controllers.

Local controllers reduce structural vibrations by dissipating energy (active damping). Global controllers can go beyond energy dissipation to actually change mode shapes and "dynamically stiffen" the structure against motion at critical locations. Blending of the local and global controllers will be used later this year to achieve more structural control than either can produce by itself. The first panel of figure 13 displays vibration response reductions achieved by adding discrete passive viscous damping to the Precision Truss. Passive damping will be blended with active controls in the near future to achieve more structural control than otherwise possible. Representative Precision Truss local and global structural control test results are displayed in the second and third panels of figure 13. A limitation on the allowable authority of these controllers is set by the structure's capacity to absorb spillover energy without parasitic mode instability. Passive damping of parasitic modes can reduce response to spillover excitation and permit a dramatic increase in allowable control authority. In addition to increased performance, controllers of passively damped structures exhibit robustness to structural changes, nonlinearities, and modeling errors.

Phase 1 Test Bed - As stated earlier, JPL is developing a multi-layered architecture for extreme vibration response reduction in which structural control is one of the layers, disturbance isolation is another, and optics motion compensation is a third. A new JPL "Phase 1 Test Bed" is being designed in order to develop and validate the multi-layer concept. The Phase 1 Test Bed (fig. 14) integrates disturbance isolation, structural control, and optics motion compensation layers onto a large free-floating structure which also incorporates rigid body attitude control and precision optical pointing systems. The Phase 1 "full system-level" test bed will validate the readiness of CSI technology to support future large optical missions.

Advanced Control Evaluation for Structures Test Article - The ACES (ref. 8) basic test article, a spare Voyager Astromast, is a deployable lightweight, lightly damped beam, which is approximately 13.7m in length. The ACES configuration, shown in figure 15, consists of an antenna and counterweight legs appended to the Astromast tip and pointing gimbal arms at the Astromast base. The baseline set of actuators consists of three torque motors on the advanced gimbal system, four proof-mass actuators, and two image motion compensation torque motors. The control sensors are three-axis rate gyros and accelerometers at the base and tip of the Astromast, accelerometers and linear variable displacement transducer (LVDT's) in each proof-mass actuator, and the image motion compensator position detector (a photo-detector). Disturbances can be introduced into the system through a programmable base excitation table. The computer system consists of an HP-9000 computer with an Analogic Array Processor. A representative experimental result for the ACES is shown in figure 16. The closed-loop performance of one of the guest investigator's controllers is shown. The closed-loop response shows a significant amount of increased system damping.

Control, Astrophysics, Structures Experiment in Space Facility - The CASES Ground Test Facility (GTF) is being developed at the MSFC as one of the first operational test beds designed specifically for CSI investigations (fig. 17). The primary test structure for the baseline CASES GTF is the 32-meter Solar Array Flight Experiment (SAFE) boom which was flown on STS-41D as part of the NASA Office of Aeronautics and Space Technology flight program. The deployment canister of the SAFE boom is inverted and clamped to a mock-up of a Space Transportation System (STS) Multipurpose Experiment Support Structure (MPESS) which, in turn, is attached to an airbearing tripod system that translates freely in the horizontal plane and rotates freely about the boom longitudinal axis. The tripod assembly is driven by a programmable disturbance actuator system which is used to excite the system for modal survey tests, and to simulate disturbances transmitted to the CASES experiment from the STS Orbiter. An articulated, flexible, rectangular plate attached to the SAFE boom tip, with nominal dimensions of 2 X 2 X 0.0005 meters, adds the desired structural complexity to this facility by coupling the boom and plate structural modes. Control sensors for the baseline CASES GTF include linear accelerometers at the boom base, rate gyros at the boom base, tip and an intermediate location, and an optical displacement sensor of the boom tip relative to its base. Control actuators consist of a pair of linear bi-directional cold gas thrusters (BLTs) at the boom tip, and small angular momentum (reaction) wheels located at the boom tip and an intermediate location. To compensate for static deformations of the boom tip plate relative to the base and to introduce parameter variations in the structural model of the CASES assembly, a Parameter Modification System is incorporated on the boom tip to statically translate and rotate the tip plate. A digital control computer capable of handling up to 32 inputs, 32 outputs, controllers with 100 states, and a sample rate of 100 Hertz will be employed in the CASES GTF.

In-Space Flight Experiments

The major activities in the in-space flight experiments area have been the conceptual definition studies of two candidate small-scale CSI flight experiments and the preliminary design of a large-scale CSI flight experiment (fig. 18). The first study, conducted by the Massachusetts Institute of Technology (MIT) for the LaRC, was the conceptual definition of a relatively inexpensive, subscale experiment for the Space Shuttle middeck area (ref. 10). The second study, conducted by the Charles Stark Draper Laboratory (CSDL) for the LaRC, was the conceptual definition of an experiment using the Space Shuttle remote manipulator system (ref. 11). Two preliminary design studies, conducted by Teledyne Brown Engineering and Lockheed Missiles and Space Company for the MSFC, considered the CASES. All of the studies provided preliminary cost estimates of the flight hardware development. Brief descriptions of the experiments will be given.

Middeck Active Control Experiment - The MIT study defined an experiment that has been designated as the Middeck Active Control Experiment (MACE). The small-scale, but very flexible, MACE flight article (fig. 19) is a phenomena model of a multibody platform. This flight article will undergo 1-g dynamic testing using an active ground suspension system. The same flight article (or duplicate) stores in middeck lockers in the Space Shuttle Orbiter and is assembled by the Shuttle crew for 0-g dynamic testing. MACE is similar to a tinker-toy set in that it can be assembled in a variety of configurations to allow progression from relatively simple to relatively complex controller implementations. In the initial, straight configuration, MACE is 1.5m in length. Each MACE configuration is excited and characterized after on-orbit assembly. Characterization data are downlinked and processed by ground-based system identification algorithms. Control system parameters are then derived and uplinked to the MACE experiment computer.

Controller performance is evaluated in various disturbance environments. The gimbaled payloads can be placed in a scanning mode to produce disturbances that excite low frequency MACE modes while proof-mass actuators simultaneously create a high-frequency noise environment. MACE is now in the Phase-B design process and has been selected as a flight experiment in the NASA In-Step program. It is scheduled to fly in late 1993 or early 1994.

Remote Manipulator System Flight Experiment - A conceptual definition study of an RMS-based CSI flight experiment was completed by CSDL in June 1989. This study established the feasibility of implementing a safe and useful experiment using existing Shuttle hardware and other flight qualified/proven hardware. Presently, the LaRC is investigating the feasibility of active damping controller designs. Shuttle system changes are being held to a minimum. The scope of these changes can vary from software changes in the existing Shuttle computers to hardware changes such as additional modal sensors and a separate high speed experiment computer. In the spring of 1991 a joint Johnson Space Center (JSC)/LaRC recommendation will be made whether or not to proceed with a flight demonstration test. If a flight test materializes, JSC will manage any hardware and software development with the LaRC in a principal investigator role.

CASES Flight Experiment - The CASES Flight experiment (see fig. 1c) is an MSFC managed Space Transportation System/Spacelab Mission. The CASES will investigate critical control technology applicable to stabilizing and pointing large flexible structures in space. To fully understand and control large space structures, the ability to identify and characterize system parameters in space must be demonstrated. To perform system identification of the CASES on-orbit, modal tests will be conducted to determine natural frequencies and mode shapes. System parameters will then be used to modify control gains used in closed-loop tests. These tests will verify both CSI controller design methodologies and parameter predictive techniques. Such verification is impossible on the ground because of gravity, seismic, and atmospheric effects. The CASES employs the 32m extendable boom design used in the SAFE program. Control will be performed using small cold gas thrusters with variable thrust for pointing and angular momentum exchange devices for active damping to suppress vibrations. Since the boom is rigidly attached to the orbiter, the orbiter/boom system will be pointed to a predetermined target for periods of at least 30 minutes. In addition, tracking and slewing of the Orbiter at small angular rates by the tip mounted thrusters will be demonstrated. The CASES will provide accommodations for an Astrophysics/Solar Physics Hard X-Ray Imaging experiment. This experiment will address important issues in high energy astronomy. In particular, the identification of the energy source seen at the galactic center and determination of the energy release mechanisms in solar flares. The high energy imaging is made possible by aperture plates mounted on the tip of the boom. They provide both coded aperture and Fourier-transform imaging on position sensitive, proportional counter arrays placed in the cargo bay (at the base of the boom). High spatial resolution is made possible by the large separation between masks and detectors afforded by the boom. The Phase-B studies were completed in May 1990. The future of the CASES is uncertain at this time.

Guest Investigator Program

The GI program, centered around the ground testbeds, is the formal mechanism for integrating the ideas and capabilities of university and industry research programs in meeting the goals and objectives of the CSI program. Table II lists the Phase-I guest investigators that were selected. The primary research thrust of each of the five university and three industry GI's is also given in Table II. The Phase-I GI's have been using both the LaRC Mini-Mast and the MSFC ACES ground testbeds to conduct their experiments. A description of the results of six of the GI's first year's activity is given in references 12-17. A formal solicitation for the Phase-II activity was announced in June 1989. It is anticipated that the selection of the Phase-II GI's will be announced in the Fall of 1990.

Summary

A NASA program has been initiated to advance Controls-Structures Interaction (CSI) technology to a point where it can be used in spacecraft design for future missions. The CSI technology program is a multicenter program utilizing the resources of the NASA Langley Research Center, the NASA Marshall Space Flight Center, and the NASA Jet Propulsion Laboratory. CSI technology is a key technology for future NASA spacecraft and offers the potential for significant improvements in spacecraft capability. Examples of potential improvements using CSI technology shown in this paper include:

(1) An increase of 4 in the maximum antenna diameter for a large geostationary platform that meets pointing jitter requirements.
(2) A decrease of 5 in the amount of settling time for the Shuttle RMS during Space Station Freedom assembly operations.
(3) A decrease by a factor of 1000 in the vibration response of a large optical interferometer.

Integrated structure/control design methods have been shown to simultaneously increase the performance and decrease the mass of spacecraft employing CSI technology. Initial ground experiments indicate significant increases in system modal dampings are possible. In addition, several advanced CSI ground testbeds have been developed or are under development. Finally, several flight experiments have been defined that could provide the in-space demonstration of the technology. However, currently only a small Shuttle middeck experiment has been approved for flight.

References

1. Noll, R. B.; Deyst, J. J.; and Spenny, C. H.: A Survey of Structural Flexibility Effects on Spacecraft Control Systems. AIAA Paper No. 69-116, January 1969.

2. Likins, P. W.; and Bouvier, H. K.: Attitude Control of Nonrigid Spacecraft. Astronautics and Aeronautics, 1971, pp. 64-71.

3. Balas, M. J.: Trends in Large Space Structure Control Theory: Fondest Hopes, Wildest Dreams. IEEE Trans. Auto. Control, Vol. AC-27, No. 3, June 1982.

4. Sobieszczanski-Sobieski, J.: A Linear Decomposition Method for Large Optimization Problems - A Blueprint for Development. NASA TM-83248, Feb. 1982.

5. Belvin, W. K.; and Park, K. C.: Structural Tailoring and Feedback Control Synthesis: An Interdisciplinary Approach. AIAA 88-2206, April 1988.

6. Milman, M.; Scheid, R. E.; Salama, M.; and Bruno, R.: Methods for Combined Control-Structure Optimization. Proceedings of the 7th VPI&SU Symposium on Dynamics and Control of Large Structures, May 1989.

7. Hunziker, K. S.; Kraft, R. H.; Kosut, R. J.; and Armstrong, E. S.: Optimization of Linear, Controlled Structures. Proceedings of the ACC, May 1990, pp. 854-859.

8. Lim, K. B.; and Horta, L. G.: A Line-of-Sight Performance Criterion for Controller Design of a Proposed Laboratory Model. Proceedings of the AIAA SDM Conference, April 1990, pp. 349-359.

9. Waites, H. B.; Jones, V. L.; and Seltzer, S. M.: Cost Effective Development of a National Test Bed. NASA TM-100321, Feb. 1988.

10. Miller, D. W.; de Luis, J.; and Crawley, E. F.: Dynamics and Control of Multipayload Platforms: The Middeck Active Control Experiment (MACE). IAF Paper 90-292, Oct. 1990.

11. Demeo, M. E.: Remote Manipulator System (RMS) - Based Controls-Structures Interaction (CSI) Flight Experiment Feasibility Study. NASA CR-181952, Jan. 1990.

12. Vander Velde, W. E.; and Van Schalkwyk, C. M.: Failure Detection and Isolation Experiments with the Langley Mini-Mast. Proceedings of the ACC, May 1990, pp. 1422-1427.

13. Wie, B.; Horta, L.; and Sulla, J.: Active Structural Control Design and Experiment for the Mini-Mast. Proceedings of the ACC, May 1990, pp.1428-1434.

14. Hsieh, C.; Kim, J.; and Skelton, R. E.: Closed Loop Lab Tests of NASA's Mini-Mast. Proceedings of the ACC, May 1990, pp. 1435-1440.

15. Allemang, R. J.; Shelley, S.; Brown, D. L.; and Zhang, Q.: Practical Experience with Identification of Large Flexible Structures. Proceedings of the ACC, May 1990, pp. 1441-1444.

16. Slater, G.; Bosse, A.; and Zhang, Q.: Practical Experience with Multivariable Positivity Controllers. Proceedings of the ACC, May 1990, pp. 1445-1448.

17. Collins, E. G.; Phillips, D. J.; and Hyland, D. C.: Design and Implementation of Robust Decentralized Control Laws for the ACES Structure at Marshall Space Flight Center. Proceedings of the ACC, May 1990, pp. 1449-1454.

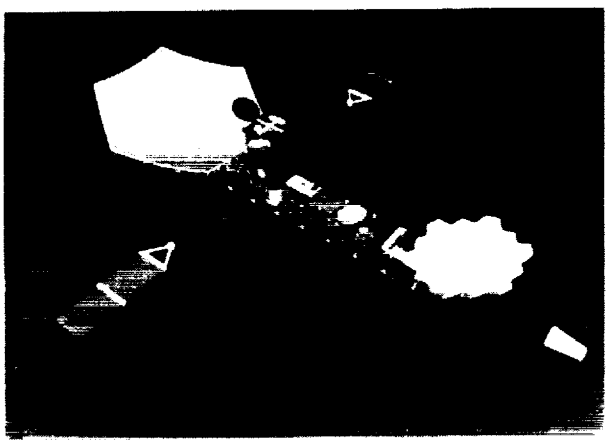
	Controlled Performance	Structural Mass	Actuator Mass	Total Mass
Initial Design (No CSI)	1.0	1.0	1.0	1.0
Conventional (Control-optimized) Design	1.41	1.0	1.33	1.09
Integrated Design	4.82	0.58	1.97	0.97

Table I. Integrated Design Results

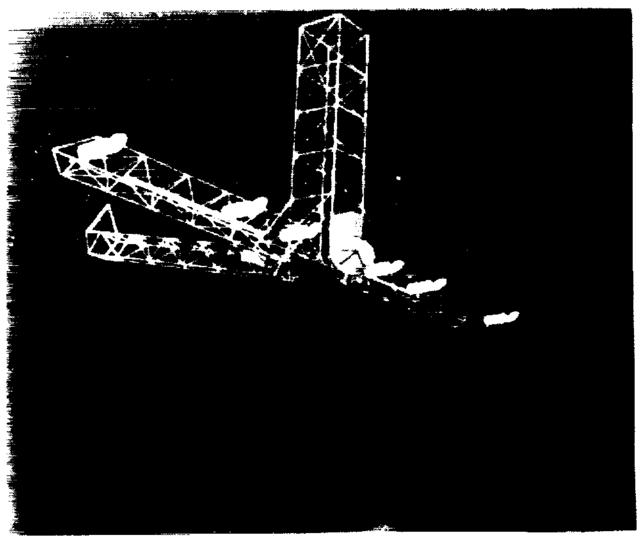
UNIVERSITY INDUSTRY	PRINCIPAL INVESTIGATOR	FACILITY*	PRIMARY THRUST
CAL TECH	Dr John Doyle	MSFC/LaRC	Noncollocated Controller Design
MIT	Dr W Vander Velde	LaRC/MSFC	Off-Line and On-Line Sys. ID Algorithms
PURDUE	Dr Robert Skelton	LaRC/MSFC	Noncollocated Controller Design
U. CINCINNATI	Dr. Randall Allemang	MSFC/LaRC	Off-Line System ID Algorithms
U. TEXAS	Dr. Bong Wie	LaRC/MSFC	Collocated/Noncollocated Controller Design
HARRIS	Dr David Hyland	MSFC/LaRC	Noncollocated Controller Design
BOEING	Dr Michael Chapman	LaRC	Nonlinear Math Modeling
Dynamic Engin /VPI	Wilmer Reed	LaRC	Design of Passive and Active Suspension Systems

* FACILITY
LaRC - Mini-Mast Ground Testbed MSFC - Active Control Evaluation for Spacecraft (ACES)

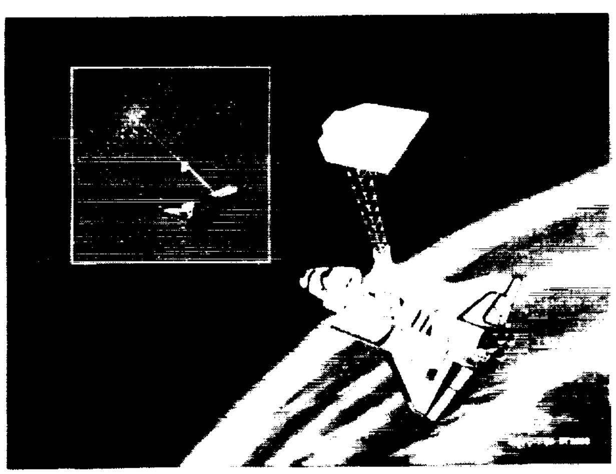
Table II. Phase I Guest Investigators



1a. Earth Observation Platform



1b. Space-based Interferometer



1c. Astrophysics X-ray Imaging System

Figure 1. Focus Missions for CSI Technology Development

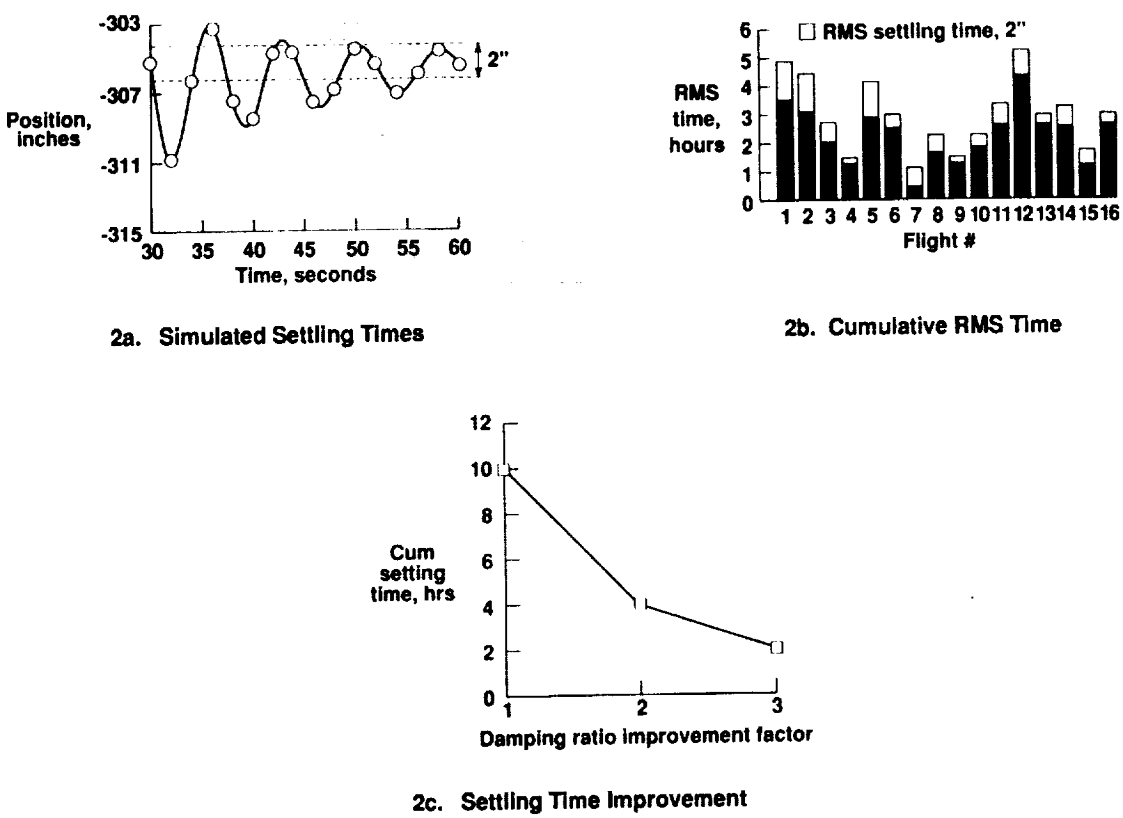


Figure 2. CSI Performance Improvement for Shuttle RMS

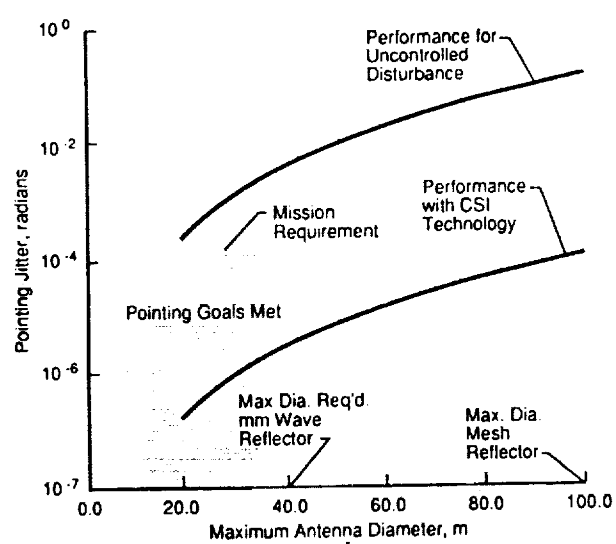
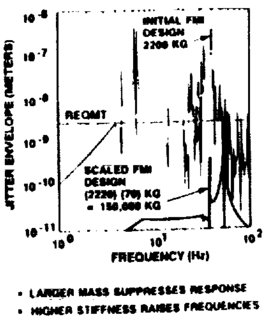
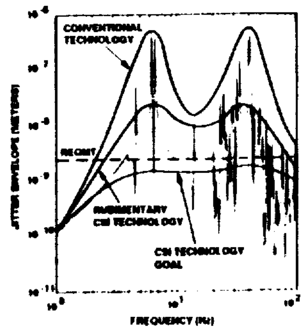


Figure 3. CSI Performance Improvement for Earth Observation Platform



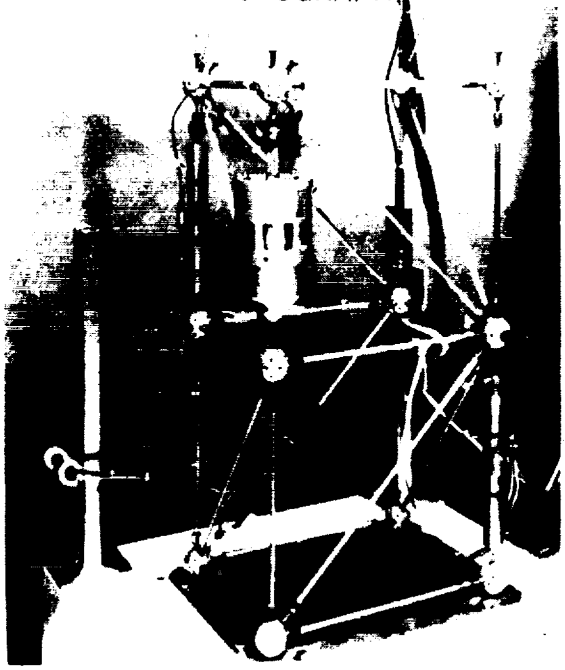


4a. FMI at 70 Times Nominal Mass

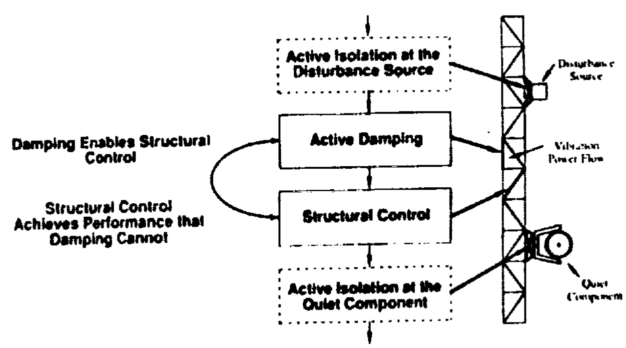
4b. Pathlength Jitter Envelope Due to Reaction Wheel Disturbance

Figure 4. CSI Performance Improvement for Focus Mission Interferometer (FMI)

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



5a. Active Members



5b. Multi-layered Structural Control Architecture

Figure 5. CSI Concepts Development

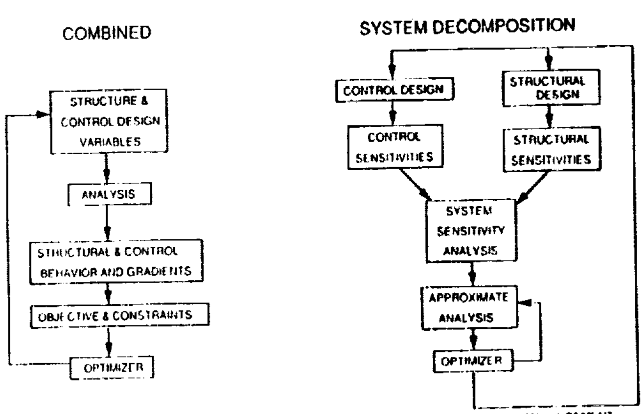


Figure 6. Integrated Design System Design Approaches

ORIGINAL PAGE IS
OF POOR QUALITY

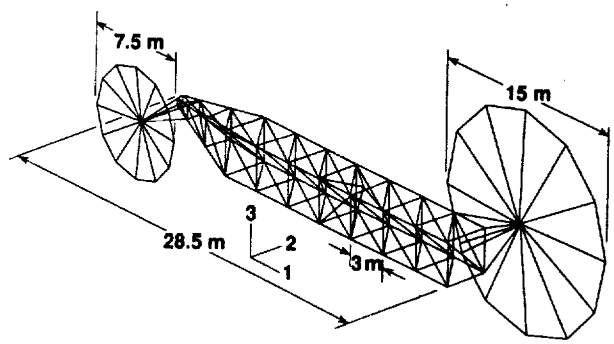
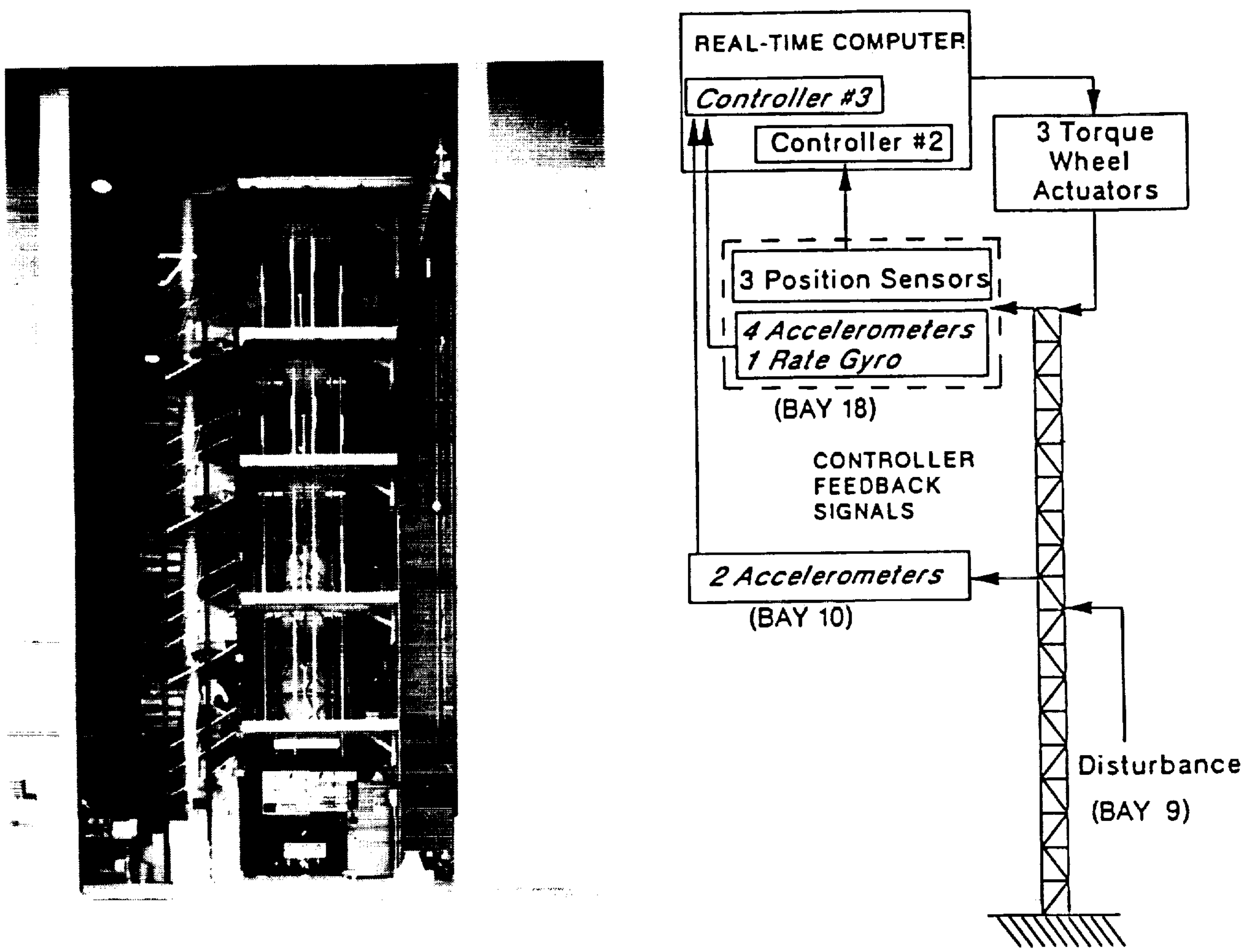


Figure 7. Earth Observation Platform Configuration Used in Integrated Design Study

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 8. Mini-Mast Testbed

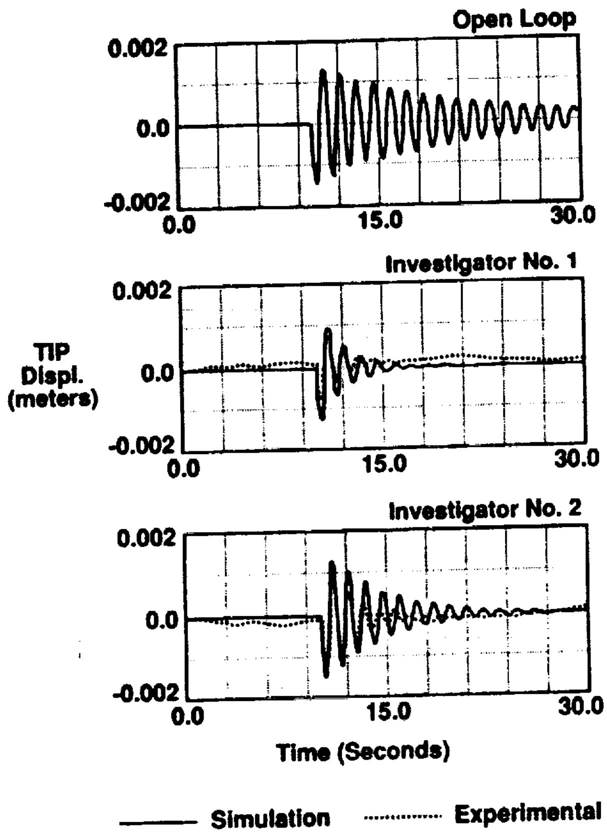
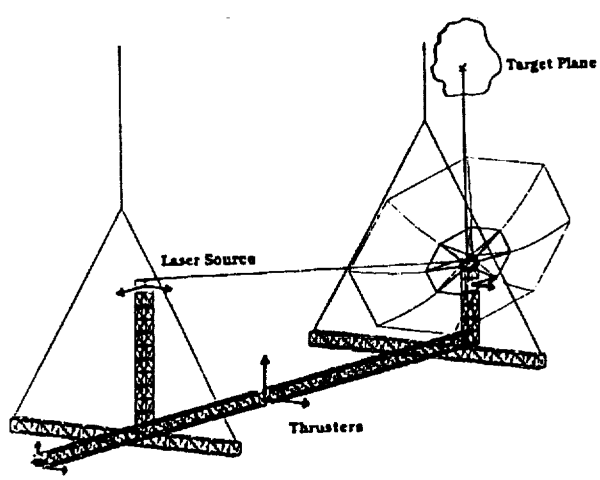
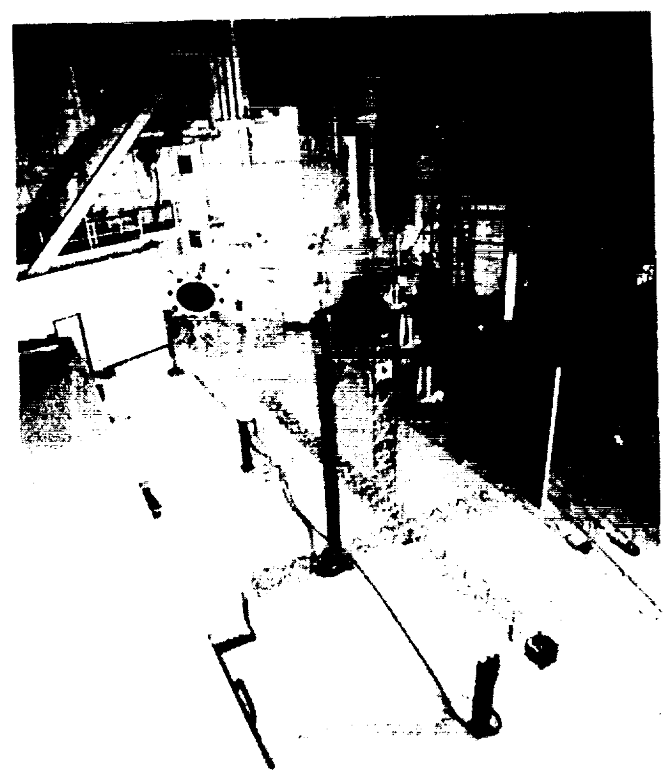


Figure 9. Experimental and Simulation Results for Mini-Mast



10a. CEM Schematic



10b. CEM Installed In Laboratory

Figure 10. Phase-0 CSI Evolutionary Model Testbed

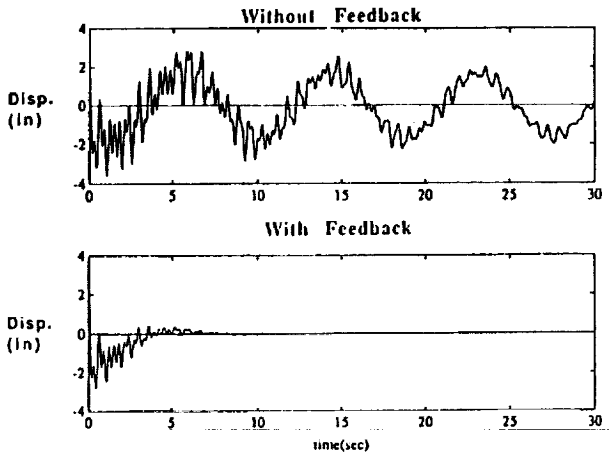


Figure 11. Numerical Results Showing Suppression of Pendulum and Vibratory Motion for CSI Evolutionary Model

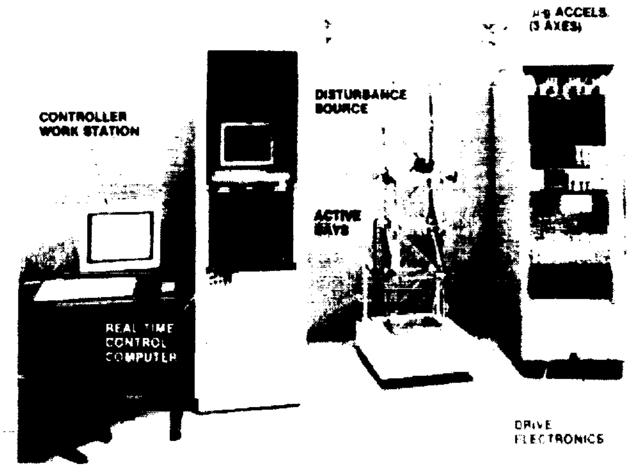


Figure 12. Test Setup Showing Precision Truss, Active Member Electronics, and Digital Computer

ORIGINAL PAGE IS OF POOR QUALITY

ORIGINAL PAGE BLACK AND WHITE PHOTOGRAPH

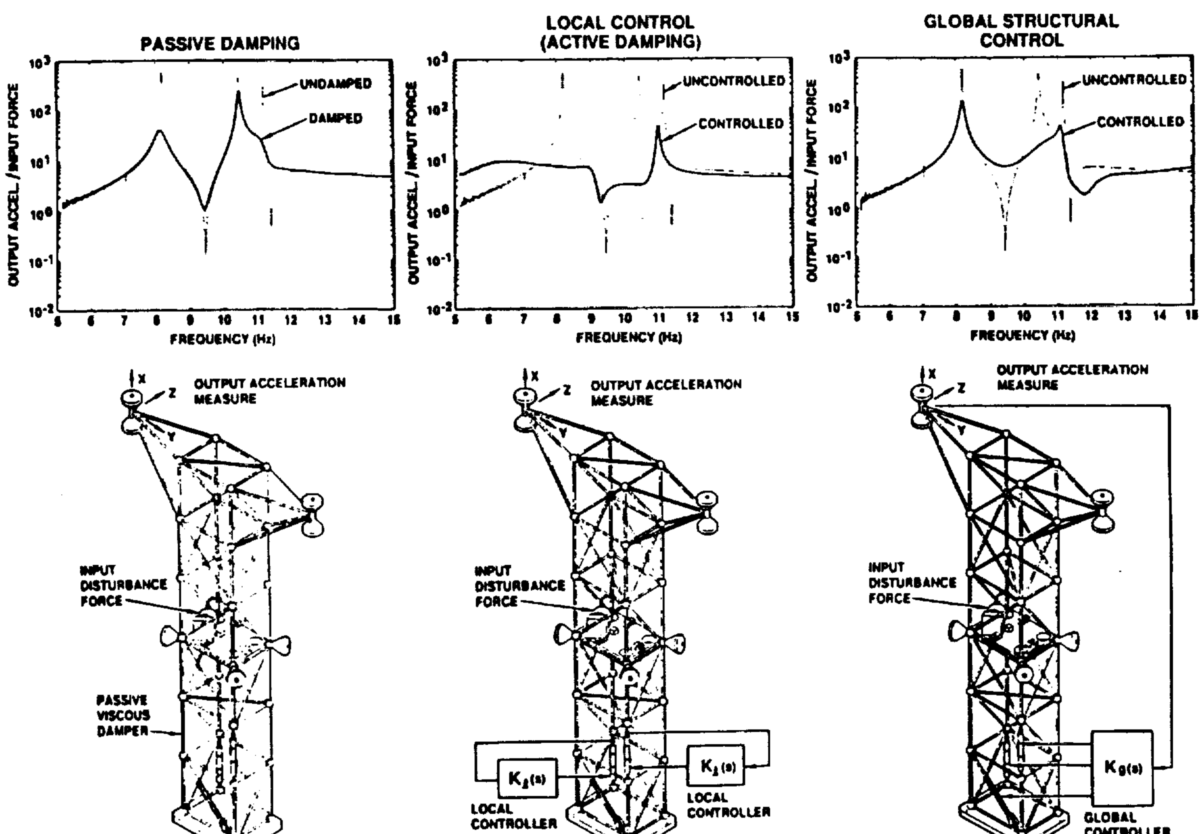


Figure 13. Precision Truss Experimental Results

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

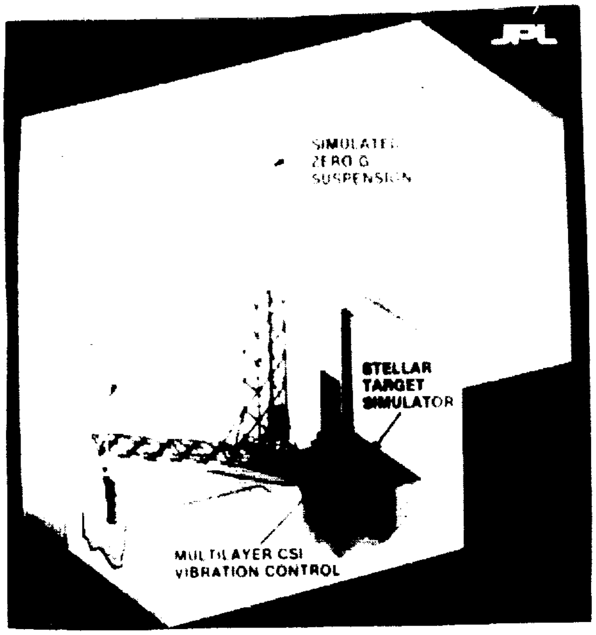


Figure 14. CSI Phase 1 Interferometer Testbed

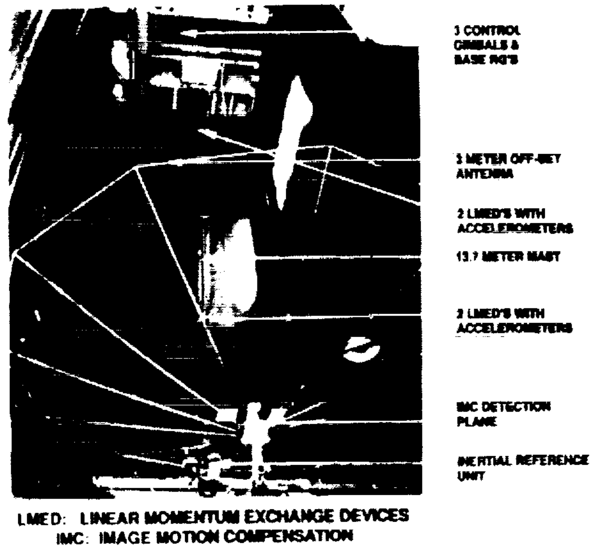


Figure 15. ACES Testbed

ORIGINAL PAGE IS
OF POOR QUALITY

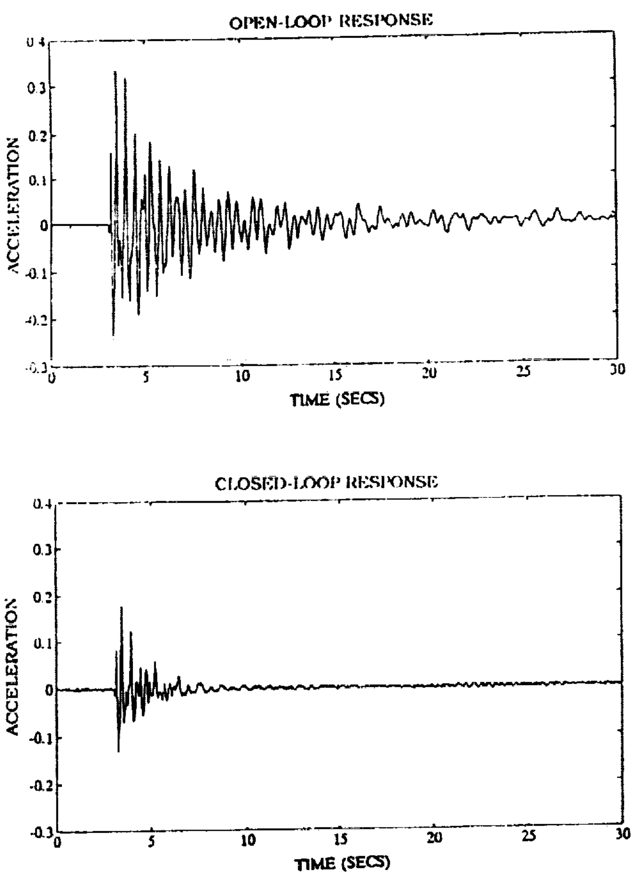


Figure 16. Representative Results for ACES

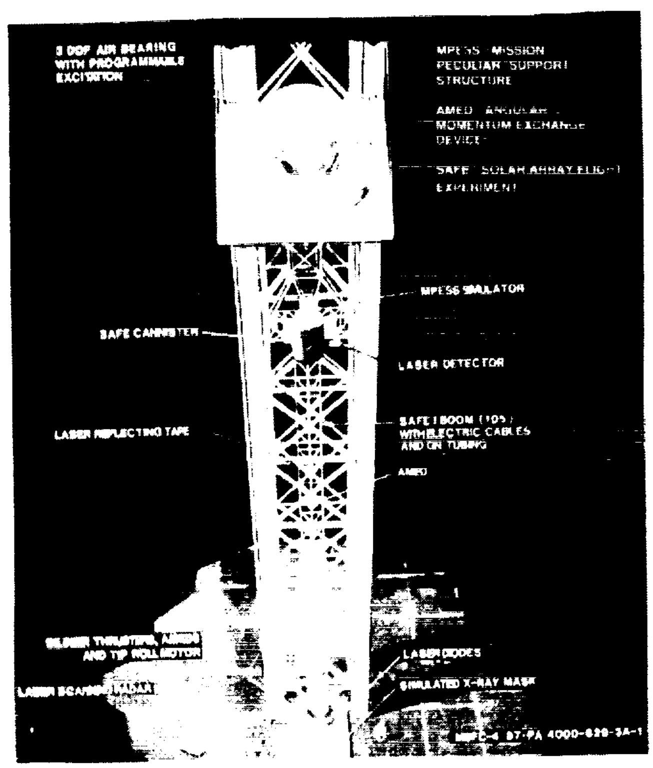


Figure 17. CASES Ground Test Facility

Figure 18. CSI Flight Experiment Studies

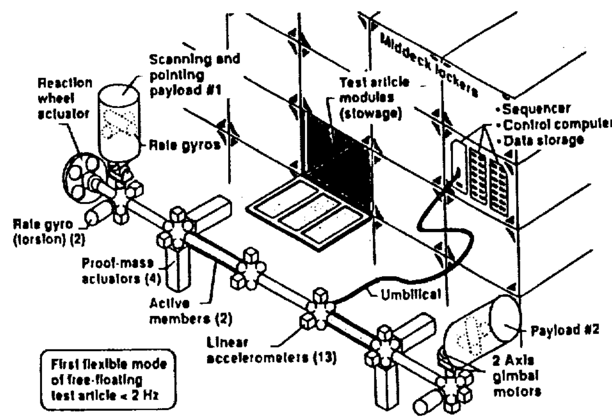


Figure 19. Middeck Active Control Experiment Configuration

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

ORIGINAL PAGE IS
OF POOR QUALITY

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM-102752	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle The NASA Controls-Structures Interaction Technology Program		5. Report Date October 1990
		6. Performing Organization Code
7. Author(s) Jerry R. Newsom, W. E. Layman, H. B. Waites, R. J. Hayduk		8. Performing Organization Report No.
		10. Work Unit No. 590-14-41-02
9. Performing Organization Name and Address National Aeronautics and Space Administration Langley Research Center Hampton, VA 23665-5225		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

Jerry R. Newsom: Langley Research Center, Hampton, Virginia.
W. E. Layman: Jet Propulsion Laboratory, Pasadena, California.
H. B. Waites: George C. Marshall Space Flight Center, Marshall Space Flight Center, AL.
R. J. Hayduk: NASA Headquarters, Washington, DC.
Published as Paper No. IAF-90-290, 41st Congress of the International Astronautical Federation, October 6-12, 1990, Dresden, GDR.

16. Abstract

The interaction between a flexible spacecraft structure and its control system is commonly referred to as controls-structures interaction (CSI). The CSI technology program is developing the capability and confidence to integrate the structure and control system, so as to avoid interactions that cause problems and to exploit interactions to increase spacecraft capability. A NASA program has been initiated to advance CSI technology to a point where it can be used in spacecraft design for future missions. The CSI technology program is a multicenter program utilizing the resources of the NASA Langley Research Center (LaRC), the NASA Marshall Space Flight Center (MSFC), and the NASA Jet Propulsion Laboratory (JPL). The purpose of this paper is to describe the current activities, results to date, and future activities of the NASA CSI technology program.

17. Key Words (Suggested by Author(s)) Controls-Structures Interaction; Structural Dynamics; Large Space Structures; Precision Space Structures	18. Distribution Statement unclassified - unlimited; subject category - 18

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
unclassified	unclassified	18	A03

NASA FORM 1626 OCT 86