Precision Slew/Settle Technologies for Flexible Spacecraft

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Abstract

Many spacecraft missions in the next decade will require both a high degree of agility and precision pointing. Agility includes both rotational maneuvering for retargeting and translational motion for orbit adjustment and threat avoidance. The major challenge associated with such missions is the need for control over a wide range of amplitudes and frequencies, ranging from tens of degrees at less than 1 Hz to a few μradians at hundreds of Hz. TRW's internally funded Precision Control of Agile Spacecraft (PCAS) project is concerned with developing and validating in hardware the tools necessary to successfuly complete the combined agile maneuvering/precision pointing missions.

Development has been undertaken on a number of fronts for quietly slewing flexible structures. Various methods for designing slew torque profiles have been investigated. Prime candidates for rapid slew/settle scenarios include Inverse Dynamics and Parameterized Function Space. Joint work with Professor Bayo at the University of California, Santa Barbara and Professor Flashner at the University of Southern California have led to promising torque profile design methods. Active and passive vibration suppression techniques also play a key role for rapid slew/settle mission scenarios. Active members with local control loops and passive members with high loss factor viscoelastic material have been selected for hardware verification. Progress in each of these areas produces large gains in the quiet slewing of flexible spacecraft.

The main thrust of the effort to date has been the development of a modular testbed for hardware validation of the precision control concepts. The testbed is a slewing eighteen foot long flexible truss. Active and passive members can be interchanged with the baseline aluminum members to augment the inherent damping in the system. For precision control the active members utilize control laws running on a high speed digitial structural control processor. Tip and midpsan motions of the truss are determined using optical sensors while accelerometers can be used to monitor the motions of other points of interest.

Preliminary results indicate that a mix of technologies produces the greatest benefit. For example, shaping the torque profile produces large improvements in slew/settle performance, but without added damping settling times may still be excessive. With the introduction of moderate amounts of damping, slew/settle performance is vastly improved. On the other hand, introducing damping without shaping the torque profile may not yield the desired level of performance.

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Introduction

In the past, slew and/or reorientation maneuvers of flexible spacecraft have been performed over long periods of time so that no significant energy is imparted to the structure's flexible modes. Reorientation of the spacecraft was accomplished by pumping energy into the rigid body modes and rolling off the control system before the frequencies at which the flexible modes occurred. Separation of the control system bandwidth and the flexible mode frequencies allowed this technique to work.

Many of the future space missions will not have the advantage of a separation in control system bandwidth and flexible mode frequencies. The separation becomes blurry, and even overlapping, when the structure begins to get large in size or the control system bandwidth increases. The former significantly reduces the flexible frequencies of the system while the latter represents the case of a very rapid slew or reorientation maneuver. For such systems, attempts to quietly reorient the structure using these older methods for generating slew torque profiles are doomed to failure. New torque profile design techniques are required which take into account the overlapping control system bandwidth and flexible modes. In addition, designing in damping relaxes the requirements on the bandwidth of the slew controller and increases the robustness of the system to parameter uncertainty.

When new slew torque profile design methodologies and damping techniques are discovered, they have to be demonstrated in hardware. This allows the effects of hardware limitations on the performance of the slewing system to be documented. Furthermore the robustness of the slew and damping techniques in a scaleable/traceable testbed can be demonstrated.

Relation to Previous Work

Large angle quiet maneuvers have been an active area of research over the past 10-15 years. A survey of ground-based test facilities for such demonstrations is given by Das [1]. He focuses on space structures with both large angle reorientation maneuvers and vibration suppression for rapid slew/settle mission scenarios. The early work focused on accomplishing the slew/reorientation maneuver in minimum time using gas thrusters. As such, predominantly bang-bang controllers were used to accomplish the maneuver [2]. Improvements to the slew methodologies improved the performance that could be obtained using bang-bang actuators [3], but performance was not at a level that would be required for some proposed space missions.

Theoretically, a significant amount of work has posed the rapid slew/settle problem as a two point boundary value problem and solved for the torque profiles using standard optimal control solution procedures. Breakwell [4] posed such a solution using standard fixed-time linear quadratic Gaussian regulator control theory with a modal decomposition of the flexible body. A suggested improvement by Junkins [5] "smooths" Breakwell's torque profiles, thus somewhat reducing the bandwidth requirement on the reorientation actuators. The methods based on optimal control theory, though performing very well for the nominal system, are sensitive to uncertainties in the plant, the environment, or the specific hardware being used.

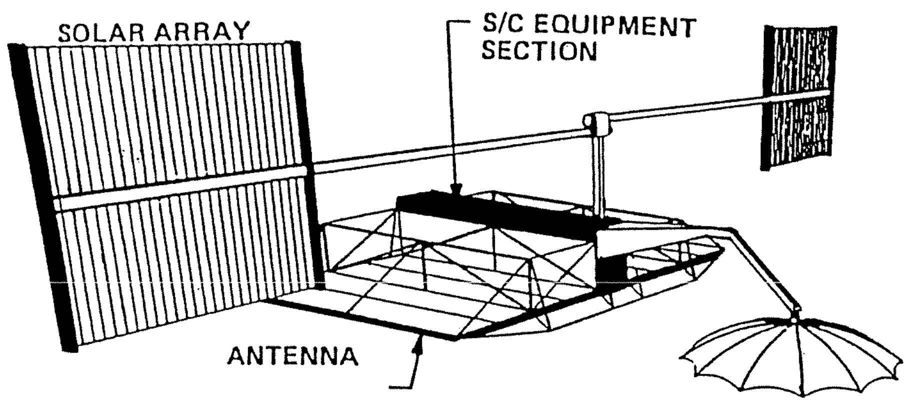
Robotics reorientation goals are similar to those of slewing/reorienting a flexible spacecraft. A fixed maneuver is to be accomplished with minimal residual vibrations at the conclusion of the maneuver. As such, some of the inverse dynamics design methods [6,7] for generating slew torque profiles have shown promise for quickly and quietly reorienting flexible manipulators. Furthermore, preliminary studies have shown that the inverse dynamics methods are less sensitive to parameter uncertainties than the optimal control methods.

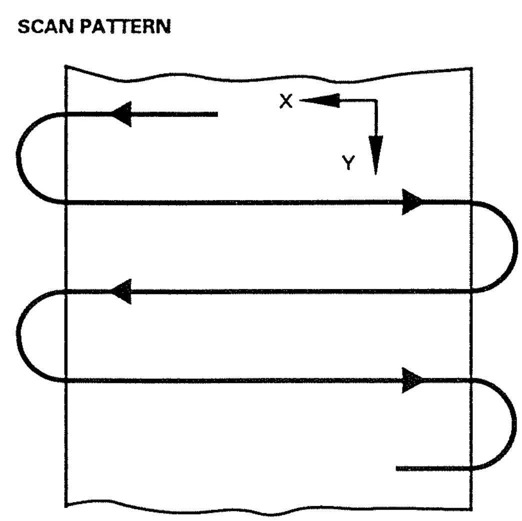
Regarding vibration suppression during and following the reorientation maneuver, internal sensing and actuating devices are required so that the flexible modes can be damped without effecting the rigid body modes. In this manner, a separation in topology between the slew controller and vibration controller can be drawn, though the bandwidths of the controllers may still overlap. Fanson et al [8] have shown the types of vibration suppression performance that can be obtained in fixed position static trusses. Their work utilized piezoceramic stack actuators and internal force measurements to achieve 25-35 dB attenuation of peak vibrations. Improvements in materials processing at TRW [9,10] have led to the piezoceramic sensors and actuators being embedded within the layup of graphite composite members.

Applicable Space Missions/Typical Mission Scenarios

A number of proposed space missions contain operational scenarios which require reorientation and target acquisition. Of these missions, some have extremely rapid reorientation rate goals, fast slew/settle times, and/or precision pointing/alignment needs.

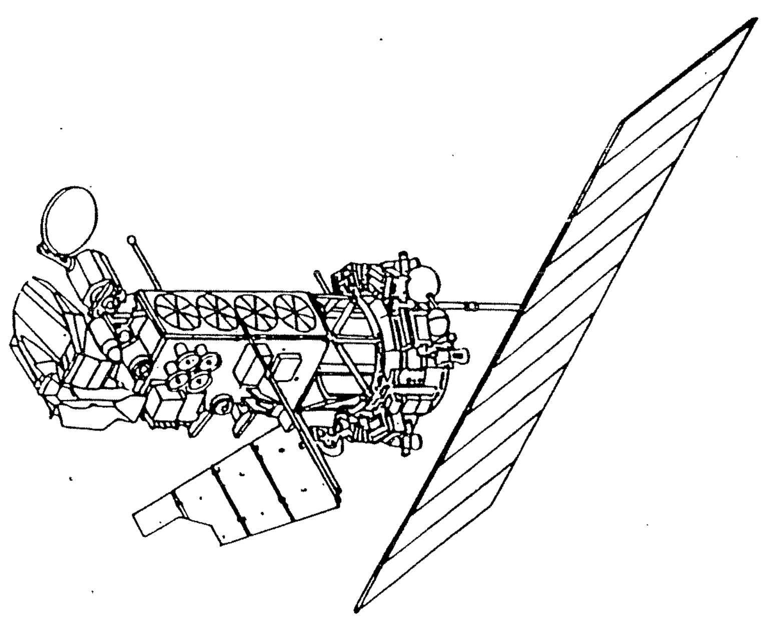
Typical of the large agile space missions are scanning surveillance spacecraft such as Space Based Radar/Space Based Wide Area Surveillance (SBR/SBWAS) missions. These spacecraft must be large to maintain suitable signal strengths and be agile during scan maneuvers. During a typical raster scan maneuver, minimizing the time spent in the turnaround and settle phase of the scan will increase the duty cycle of the mission. Due to their large size, structural modes will lie within the bandwidth of the attitude control system. Harmful controls/structure interactions will be present which jeopardize the settle/pointing performance of the spacecraft. SBR/SBWAS missions would significantly benefit from the technology presented in this paper. The combined quiet slew torque profile design methodology and active/passive damping would increase SBR/SBWAS turnaround and settle performance as well as increase critical component pointing accuracy.





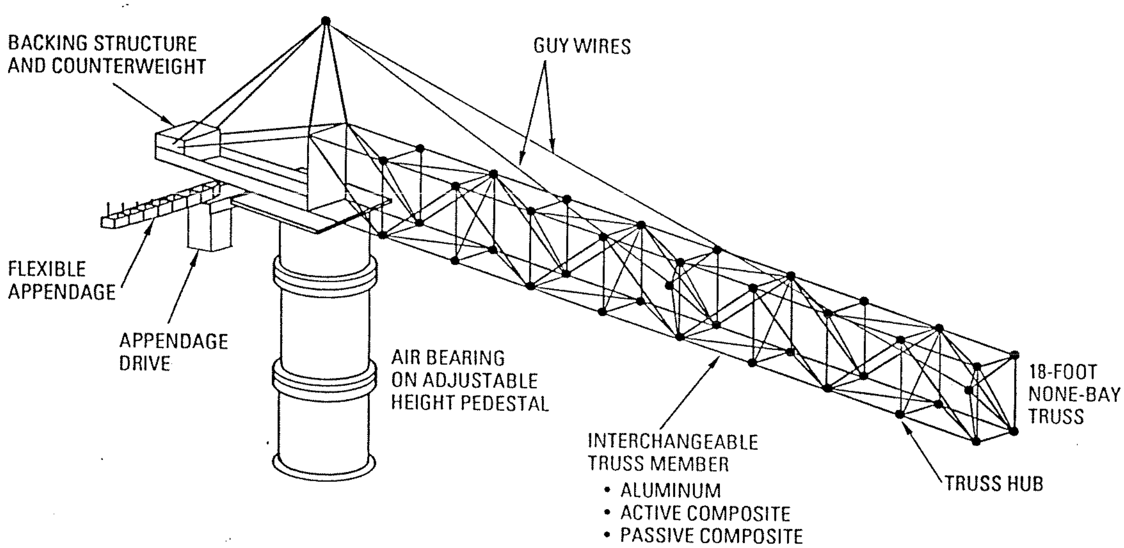
Applicable Space Missions/Typical Mission Scenarios (Cont.)

Spacecraft which must be quieted from the effects of internal and external disturbances would benefit from the active and passive damping presented herein. Such spacecraft are proposed large optical interferometers, Defense Support Program (DSP) satellites, Defense Meteorological Satellite Program (DMSP), and Lightsats. In each of these instances, onboard disturbances and thermal/environmental disturbances threaten the operational mission. Active and/or passive vibration suppression and isolation could eliminate the harmful effects of the disturbances and restore mission integrity.



Testbed Overview

A nine bay, eighteen foot long slewing truss has been developed at TRW for use as a quiet slewing testbed. The baseline truss consists of threaded hub joints and aluminum truss members. All of the hubs and members are threaded so that any members can be replaced with active and or passive composite members without disassembling the complete structure. A stiff aluminum backing structure serves to counterbalance the structure over the simulated control moment gyro (CMG) and to provide a dragless mounting platform for optical sensor cameras and cables. (All performance sensors and actuators are described on the following pages.) The total weight of the truss is approximately 90 pounds, with the hubs accounting for 60 pounds and the truss members accounting for the remaining 30 pounds. The simulated CMG is mounted on a pedestal which also serves to keep the truss near eye level and to mount cables and slew limit switches/stops.

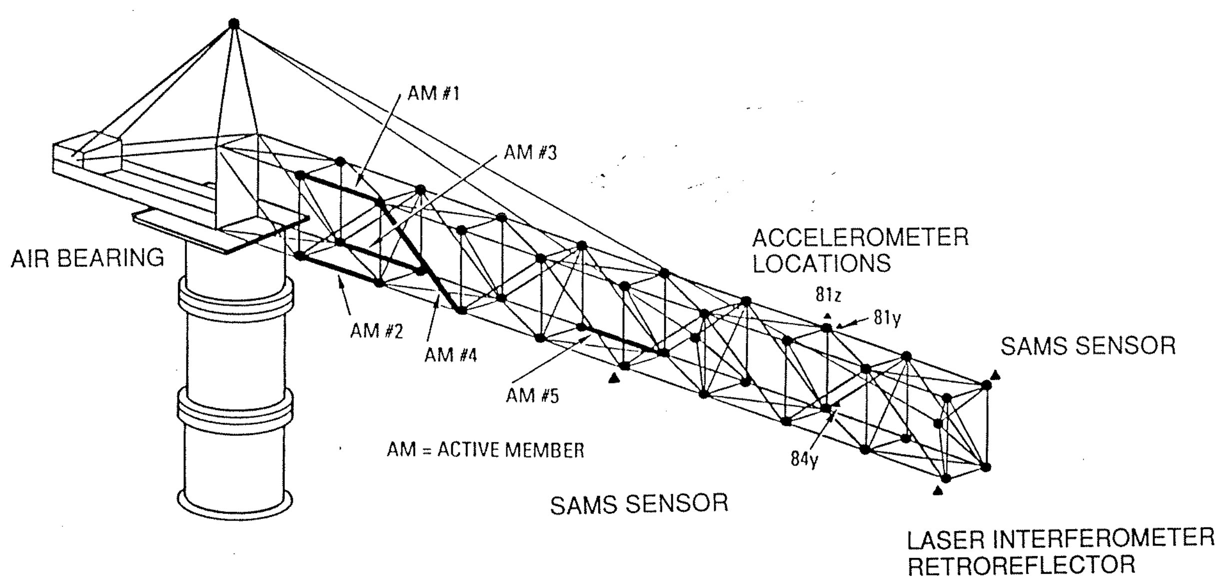


Sensor and Actuator Layouts

A combined air bearing/slew torque motor simulates typical CMGs for reorienting the structure. The air bearing has the capability to support 500 pounds (i.e., truss, backing structure, and equipment) and can withstand 100 inch pounds of overturning moment. The motor used to slew the truss/backing structure can supply up to 40 ft-lbs of torque. Maximum angular accelerations of greater than 4 deg/sec^2 can be produced with the testbed in its current configuration. An optical encoder is integral with the slew torque motor and provides angular position measurements for the base of the truss.

Optical sensors and accelerometers provide performance data during and after the slew. TRW's Surface Accuracy Measurement Sensors (SAMS) provide vertical and horizontal displacement measurements at the tip and midspan of the truss. The receivers of the SAMS sensors are mounted on the backing structure of the truss and rotate with the truss. Thus these sensors provide information concerning the flexible motion of the truss. A laser interferometer retroreflector is mounted at the tip of the truss and is used to provide absolute motion (i.e., rigid plus flexible mode motion) measurements. The interferometer itself has resolution down to 10 nanometers and is mounted on an optical bench.

Additional measurements on the performance of the truss are obtained using four accelerometers. Three of the accelerometers are mounted at the eighth bay of the truss and oriented such that vertical, horizontal, and torsional motions at that station can be obtained. A fourth accelerometer is mounted at the second bay of the truss and provides horizontal motion information during and after the slew maneuvers.



Typical Modal Content

A summary of the first few modes of the slewing testbed is given in the table below. Though the modes are not necessarily closely spaced, they are not widely separated either. The separation is approximately typical of those expected for primary structure modes for some future space missions. The mode at 1.8 Hz is a quasi-rigid body mode caused by the interaction of the truss/backing structure inertia and the electronic stiffness in the air bearing/motor drive electronics. The primary horizontal bending mode (i.e., slew plane bending mode) at 6.3 Hz has a moderate amount of damping due to the electromagnetic damping in the air bearing/motor assembly. All of the remaining modes have levels of damping expected from a threaded joint type structure.

Table 1: **Slewing Testbed Modal Content**

Mode	Description	Frequency (Hz)	Damping (ζ)
1	Rigid Body Slew Mode	0.0	
2	Motor Electronics Mode	1.8	
3	Vertical Bending Mode	4.7	0.7
4	Horizontal Bending Mode	6.3	2.0
5	Torsional Mode	12.9	0.2
6	2nd Horizontal Bending	26.3	0.8
7	2nd Vertical Bending	34.1	2.7
8	2nd Torsion	41.6	0.4

Test Facilities

The test facilities containing the slewing testbed were designed and built with precision, quiet measurements in mind. A seismically isolated pad supports the pedestal/testbed and the optical bench which contains the interferometer. In this manner, disturbances such as nearby foot traffic, automobile traffic, and ocean wave motion will not upset tests in progress. Both the ceilings and the walls of the facility are covered with sound and light absorbing material to minimize stray vibrations and light reflections. A special quiet air conditioning system was installed that can be turned off during precision tests and turned back on for user comfort.

Various secondary tests have been conducted in the test facility. A number of passive damping applications have been tested using a modal survey system. These applications include printed circuit boards, reaction wheel assembly isolators, and passive member component development tests. Other active member tests and demonstrations have also utilized the PCAS test facility. These range from optical level pointing and resolution tests to eyewitness damping demonstrations.

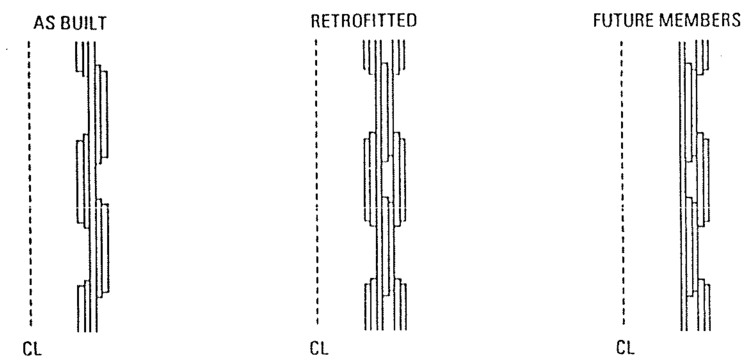
Passive Member Description and Component Testing

Passive composite members with cocured viscoelastic material (VEM) were designed, fabricated, and tested for use in the slewing testbed. The members were constructured in a manner similar to those presented in [11] and shown in the figure below.

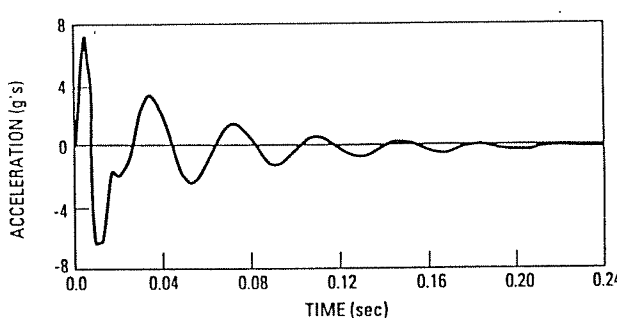
The idea is to weave the dynamic load from stiff graphite constraining layer through the VEM to the opposite stiff graphite constraining layer. In this manner, dynamic shear loads are routed through the high loss VEM. The fiberglass which runs continuously along the length of the tube provides a parallel elastic load path to prevent creep of the VEM under static loads.

Initial tests yielded a disappointing 2-6% damping with the additional drawback that the members were difficult and labor intensive to build. A retrofit VEM/graphite constraining layer bridge was added (see middle diagram of figure) which yielded damping levels up to 18%. A typical time history for the cantilever impact test is shown below. Due to time constraints, the passive members were not incorporated into the slewing testbed. System level slew and damping performance on the testbed will be reported when they become available.

Future members will utilize the VEM/graphite constraining layers and VEM/graphite constraining layer bridges only on the outside of the tube in order to simplify the fabrication procedure. (See right side diagram in the figure below.)

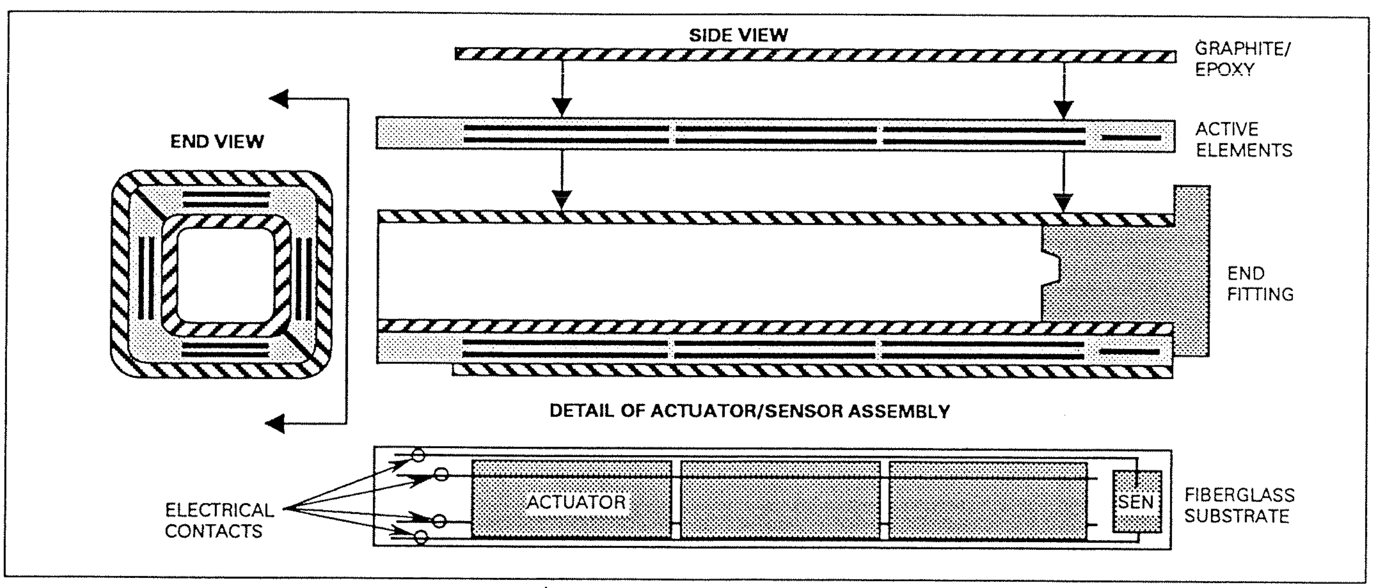


AS BUILT	RETROFITTED	FUTURE MEMBERS
2-6% DAMPING	2% DAMPING AT ROOMTEMP	HIGH DAMPING
DIFFICULT TO BUILD	18% DAMPING AT ELEVATED TEMP	CAN THERMALLY SWITCH DAMPING IN OR OUT
NOT WEAVING LOAD THRU VEM AS DESIRED	CAN THERMALLY SWITCH DAMPING IN OR OUT	EASIER TO BUILD
	DIFFICULT TO BUILD	



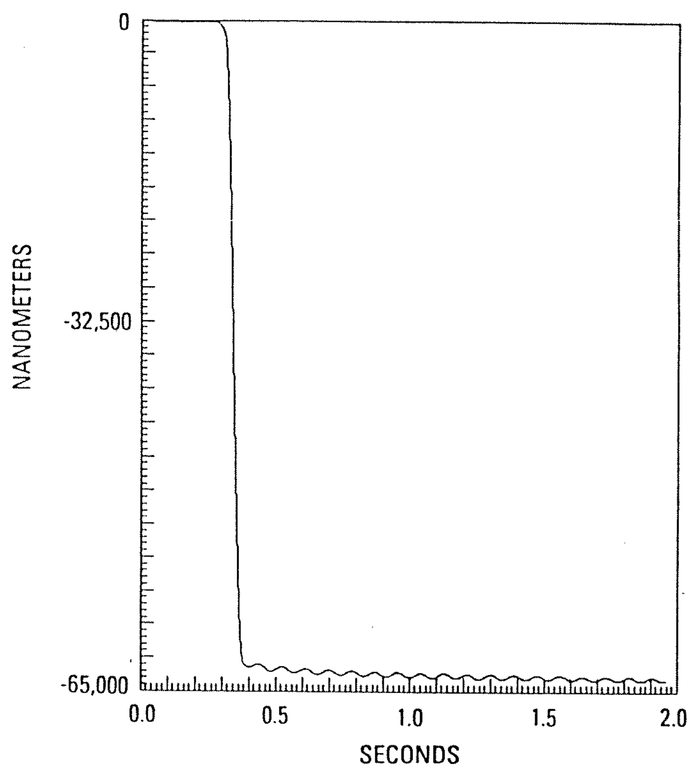
Active Member Description

Active composite members for vibration suppression during and following the slew were designed, fabricated, and integrated with the slewing testbed. The active members utilize separate piezoceramic wafers for the sensors and the actuators. Each side of the square truss members has one actuator string and two sensors. One of the sensors is colocated with the actuator string while the other is nearly colocated. By averaging these two sensor measurements, the transfer functions that the active members "see" can be tailored to be advantageous for the local control loop design task. The layup of the composite host material for the active members was arrived at by matching the stiffness of the members that are to be replaced and by maximizing the actuation capability of the resulting strut.



Active Member Characterization Testing

A number of component level tests were done on the active members to characterize their actuation characteristics. A creep test was performed by clamping one end of the strut, applying a step voltage, and measuring the resulting tip displacement. Three different levels of applied voltage were used in order to calculate the linearity of the actuation with applied voltage. The numerically filtered results of these tests are shown in the figure and table below. (The data was numerically filtered to eliminate the undamped oscillations and give a quasi-steady state result.) The free end of the active member achieves 98% of the steady state level in 0.2-0.3 seconds and total creep levels for all cases are less than 2.0%. Even when applying voltages greater than the recommended maximum field strengths (i.e., greater than 700 V/mm) the strut behaves very well and shows very little creep or nonlinear behavior. These results compare favorably with those reported in [12] where a piezoelectric stack was used for the actuator.



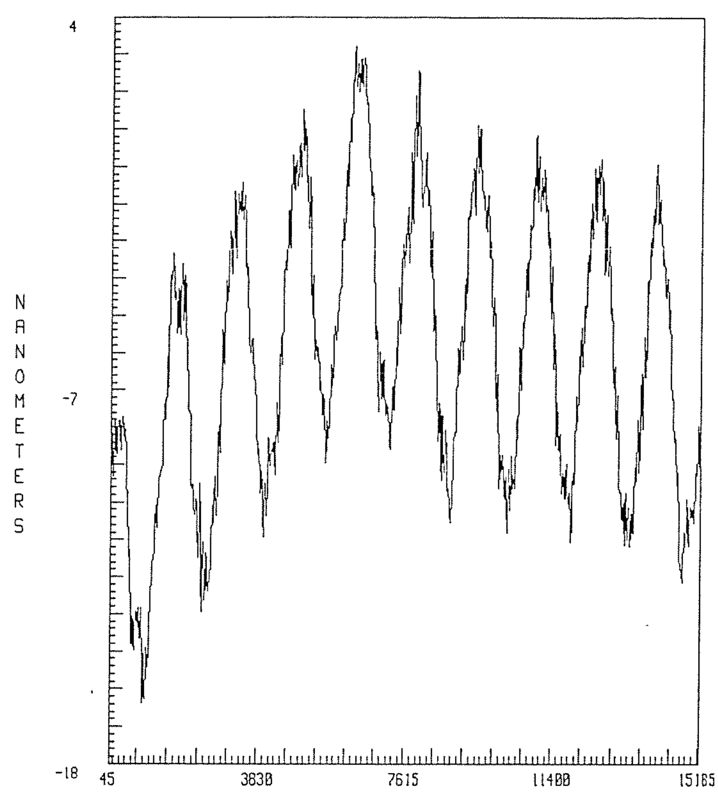
Active Member Characterization Testing (Cont.)

Parameter	TRW Active Member with Embedded Actuators			JPL PZT Actuator*
Field Strength Change	210 V/mm	528 V/mm	788 V/mm	700 V/mm
Bias Voltage	0 V	0 V	0 V	350 V
Time to 95% of Step	<0.1 sec	<0.1 sec	<0.1 sec	6 sec
Time to 98% of Step	0.2 sec	0.2 sec	0.3 sec	>50 sec
Total Creep	1.0%	1.5%	2.0%	8%

*Piezoceramic stack design

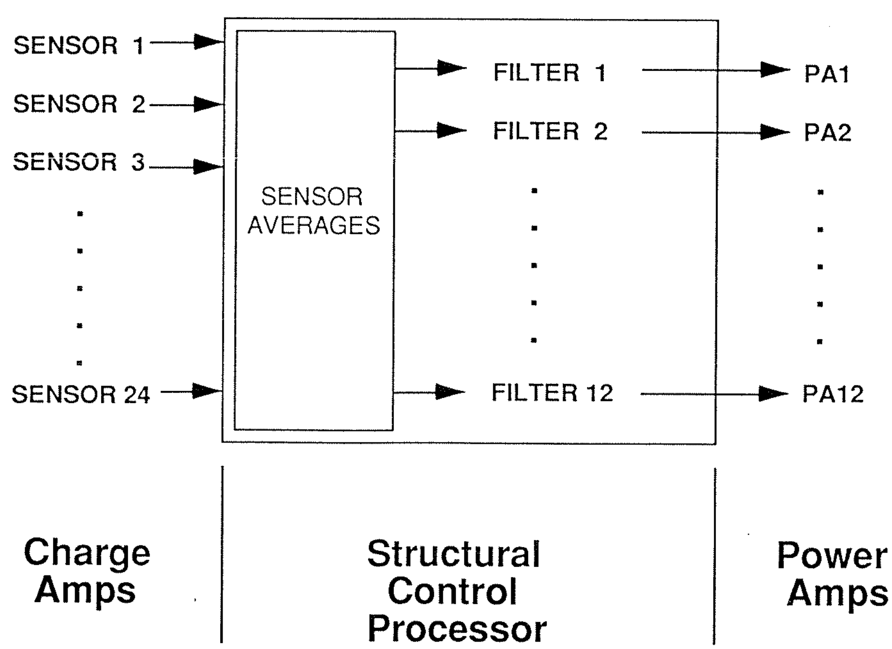
Active Member Characterization Testing (Cont.)

A second component level test was run in order to verify the active members' capability for performing microdynamic shape and vibration control. In this case, very low level sinusoidal voltages were applied to the actuators and the resulting free end tip displacement monitored with a laser interferometer. The results of this test are shown in the figure below. The sinusoidal pattern is still visible down to the 10 nanometer resolution of the laser interferometer. With the delivery of an enhanced laser interferometer (e.g., resolution down to 2.5 nanometers), the limit of the active members' microdynamic control capability will be explored.



Structural Control Processor

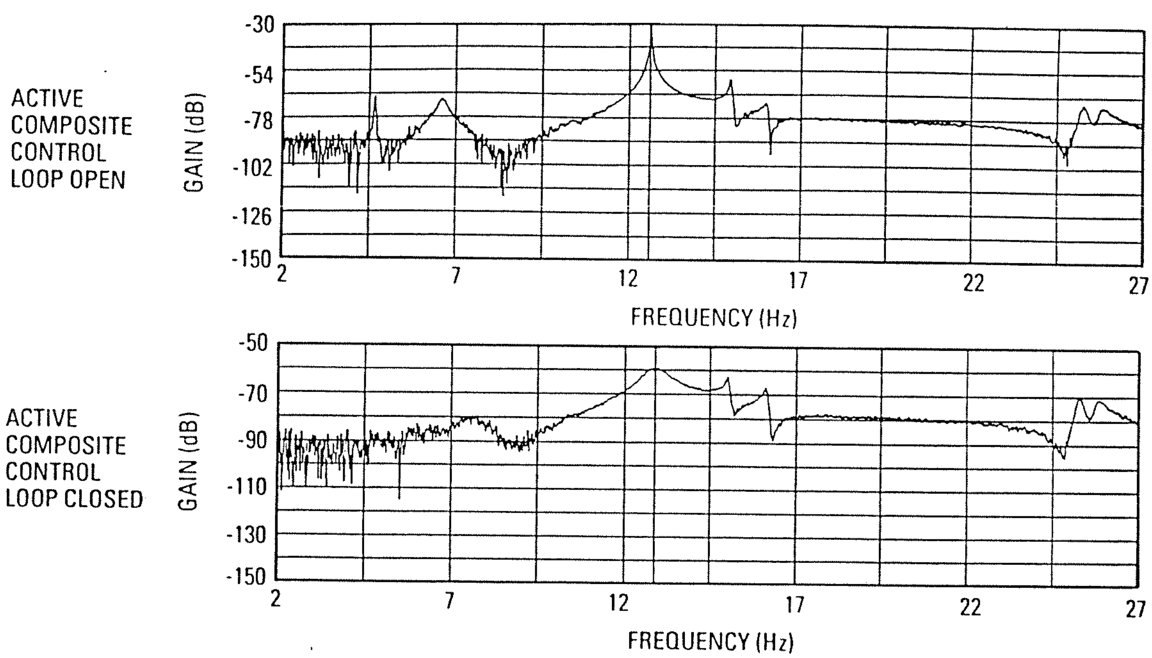
Control loops around the active members are implemented using a flight-qualifiable high speed digital processor. A schematic of the processor is shown in the figure below. Two boards allow the implementation of 12 digital filters with a maximum order of 9 zeros and 10 poles each. In its current configuration, each of these filters can take measurements from all of the 24 sensor measurements and drive a single active member. (Thus the Structural Control Processor can drive a total of 12 active members.) For the results of multimode damping on the slewing truss testbed to date, each digital filter runs at 2.8 kHz. On benchmark tests of the processor itself, a throughput rate of 10.0 kHz per 10th order digital filter is achievable. A recent upgrade allows the filter parameters and gains to be adjusted in real time, lending the Structural Control Processor to adaptive control algorithm development and verification.



Active Damping Performance

The open and closed loop active damping performance of the slewing testbed is shown in the following figures. Five active members were placed at strategic locations within the truss. Four of these members were used for control purposes while a fifth was used to provide a white noise disturbance source. Accelerometers monitored the open and closed loop performance of the truss. Second order Positive Position Feedback (PPF) loops were used local to each member in generating the closed loop results.

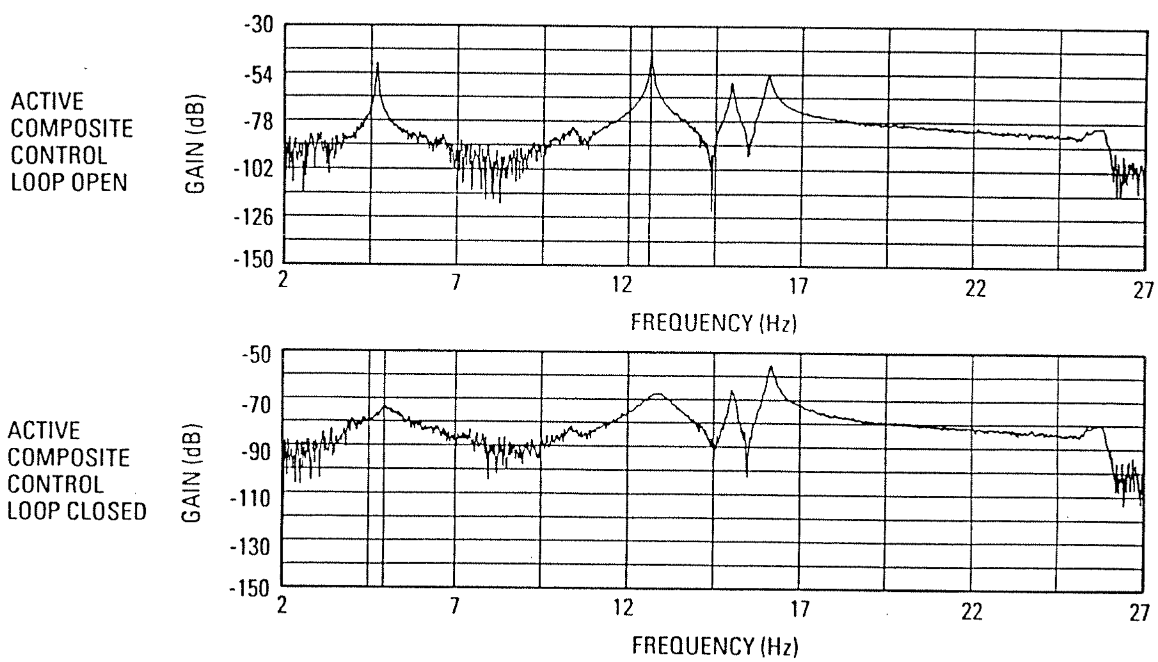
Undamped and damped horizontal plane motions (i.e., slew plane motions) are shown in the figure below. In the undamped case, maximum horizontal motions are obtained in the primary vertical, horizontal, and torsional modes. With the loops closed, the vertical mode at 4.7 Hz is attenuated down to the threshold of the accelerometers, the horizontal mode has been significantly reduced, and the torsional mode has been attenuated by 30 dB. None of the higher modes have been affected, indicating no harmful control spillover effects. The higher modes could be damped if they significantly affect the slew performance and if a higher order control law is used.



HORIZONTAL RESPONSE

Active Damping Performance (Cont.)

Undamped and damped vertical motions are shown in the following figure. Again the primary vertical, horizontal, and torsional modes have been attenuated to a significant degree. These results were generated using approximately 40 volts maximum drive to the active members and using less than 4 Watts of power consumption in both the active members and the electronics that drive them. These results demonstrate that significant amounts of system level damping can be achieved with the active members using very few struts, very little power, low voltage drive, and low order local compensators.



VERTICAL RESPONSE

Typical Slew Results

Open loop slew results for the testbed are shown in the figure below. The figure shows the tip displacement time history during and after the maneuver. In this case, a bang-bang slew torque profile was used to generate a 16° slew. Note that the first horizontal plane mode at 6.3 Hz is excited during the slew maneuver. At the conclusion of the slew, the 1.8 Hz motor electromagnetic mode dominates the response. This performance is typical of an initial spacecraft design where rigid body modes, flexible modes, and electronic modes are present in the system. Without careful and systematic identification of the system (including the electronics drivers), the performance of the system may be far below the requirements.

The second figure shows the same maneuver but with a bang-bang torque input tuned to cancel out the 1.8 Hz mode. The flexible modes of the structure are still excited during and after the slew, but the 1.8 Hz mode is almost completely eliminated from participating in the post slew response. Slight variations in the frequency at which the electromagnetic motor mode occur prevent a complete cancellation of the 1.8 Hz mode.

FIGURES

Conclusions

Both a systems and a component level approach to making flexible spacecraft more agile and precise has been presented. The systems level approach dealt with designing the slew torque profile, placing the active members in strategic locations on the truss, and with designing the overlapping bandwidth control systems. The approach at the component level dealt with active and passive members for precision damping and shape control.

The experimental results presented here have shown that significant amounts of system level damping can be achieved with the active members using very few struts, very little power, low voltage drive, and low order compensators. All of the technologies discussed in this paper, slew torque profile design, active/passive damping, and the high speed digital processor, are mission enabling technologies for many of the next generation of precision agile spacecraft.

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