Quieting Technologies for Precision Slewing Spacecraft

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Abstract

Experimental results are presented for advanced vibration suppression technology for slewing or reorienting space structures. Combinations of slew torque profiles and active truss members are used for precise, quiet slews. At the heart of the vibration suppression hardware is the use of active truss members running on a digital control processor. The active members consist of graphite epoxy composite members with embedded piezoceramic actuators and sensors. Control laws for each active member were implemented on a digital processor running at a 2800 Hz throughput rate per channel. A number of uncoordinated and mildly coordinated control schemes are described and slew/settle results for each are presented. The vibration suppression concepts are demonstrated on a nine bay, eighteen foot long flexible truss. Tradeoffs have to be made in balancing the number of active members used in the truss and the complexity (i.e., order) of the compensator used for each member.

Introduction

This paper describes work on quiet agile spacecraft at TRW Space and Technology Group. A number of future space applications require rapid reorientations followed by precise pointing and alignment of optical and/or infrared sensors. In order to function properly, these spacecraft must accomplish a specified maneuver and then acquire data with sensors that have very tight pointing requirements. For optical sensors, the pointing requirements correspond to a few nanometers over distances of tens of meters of lightweight, flexible structure.

Moderate amounts of torque profile shaping and some of form of structural control will be necessary to achieve this level of system performance. For torque profile determination, a number of methods have been proposed. Breakwell [1] developed a method for optimally slewing flexible structures based on classical regulator theory. Junkins [2] proposed an improvement to that method which accomplishes the same maneuver with less excitation of structural modes. Because these methods were based on classical regulator theory, the performance obtained is sensitive to the knowledge of the plant. Bayo presented a direct method for the solution of the inverse dynamics of a single link [3] and multi-link [4] flexible manipulators. Joint torques necessary to produce a desired end motion were determined. Numerical studies have shown that the joint torques were less sensitive to plant perturbations than other methods. On the issue of structural control, active members have been shown to be effective at removing vibrations from key points on flexible structures [5]. Many of the more promising active members use piezoelectric actuators either in a stack [5] or embedded within the layup of a composite member [6]. Though the early work with piezoelectric actuators involved passive shunts to dissipate the vibrational energy, maximum performance and robustness requires active control compensators tailored to the specific structure and task at hand.

The approach described in this paper relies on combined slew torque profile design and active vibration suppression. Torque profiles which yield a suitable maneuver with very little residual vibration can be obtained using inverse dynamics. Any vibrations produced during or following the slew can be damped very rapidly using active members in conjunction with local loops. Hardware verification of these concepts for quiet maneuvering structures is demonstrated on a flexible slewing testbed.

Testbed Description

The testbed for demonstrating the precision slew/settle technologies is the nine bay, eighteen foot long truss shown schematically in Figure 1 [7]. Aluminum truss members are used as the baseline testbed configuration. Each joint consists of a 1.6 pound threaded hub which allows single members of the truss to be removed without disassembling the entire truss. As a result, composite active members can be placed at key locations in the testbed to suppress vibrations and control the shape of the truss. At the base of the truss is a simulated control moment gyro implemented using a combined air bearing/single axis motor drive. Torques up to 43 ft-lbs are available for slewing and/or reorienting the truss. The backing structure is used to counterbalance the weight of the truss

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(i.e., keep the tipping moments on the air bearing to a minimum) and to provide a frictionless/dragless routing for instrumentation cables.

Accelerometers are located on the testbed as shown in Figure 1. With these locations and orientations, vertical (Z) motions, horizontal (Y) motions, and torsional motions of specified points on the truss can be determined. In addition, optical sensors monitor deflections at the midspan and tip of the truss. The optical sensors are TRW's Surface Accuracy Measurement Sensors (SAMS). Disturbances can be injected into the structure using a composite active member located in the second bay of the truss (see Figure 1). Random noise fed to the active member during and after the slew would represent a dirty disturbance source.

Active Member Description

The active members consist of graphite epoxy composite host material with embedded piezoceramic (PZT) sensors and actuators. The PZT actuators were encapsulated in fiberglass prior to embedding in the graphite in a manner similar to that described in [6]. All four sides of the square active members contain actuators which are linked together to produce axial forces only. Likewise, sensors colocated with the actuator and sensors nearly colocated with the actuator are linked to produce only axial strain measurements.

Component level tests were performed on the active members to characterize their creep, actuation behavior, and any local/micro dynamic effects. Creep levels were determined by applying a 120 Volt step (630 V/mm) input to the actuator and monitoring the axial displacement of the free end of the member with a laser interferometer. Results of these tests are shown in Figure 2. The member reaches 98% of its final elongation in 3 seconds. These creep levels compare favorably with those reported in [8] where greater than 50 seconds were required to attain a 98% value. The difference in the results can be explained by noting that the PZT is an integral part of the composite active member in the present work, whereas in [8] the PZT is stacked and preloaded.

Tests were performed to characterize the actuation behavior of the active members. A sinusoidal voltage of various amplitudes was commanded to the active member and the quality of the resulting free end tip displacement monitored. Throughout the input voltage range, repeatable tip displacements of 42 nm/V were observed. The free end tip displacement for a low voltage case is shown in Figure 3 where the peak to peak tip displacements are approximately 10 nm. These component level test results give promise to achieving the goal of microdynamic control using active members.

The first mode of the active member/end fitting assembly, with one end clamped and the other free, was near 1500 Hz. Thus actuator dynamics can be ignored for the suppression of vibrations below 100 Hz in the present case.

Compensator Description and Implementation

Both Positive Position Feedback (PPF) and Strain Rate Feedback (SRF) compensators were used in this work for the local loops around the active members. Positive Position Feedback gives narrow band damping and a second order rolloff at the expense of low frequency flexibility. At the natural frequencies of the structure PPF is equivalent to an electrical analog of a tuned mass damper. Damping over a wider frequency band can be achieved with SRF compensators at the expense of using a higher order compensator and greater stability concerns. Strain Rate Feedback gives wide band damping and a first or third order rolloff with the drawback of being somewhat sensitive to zero locations in the transfer functions.

Uncoordinated control was initially implemented. In this case, an independent PPF or SRF compensator is tied around each active member's sensors and actuators. The control laws themselves were implemented digitally on a 12 channel Structural Control Processor (SCP). The SCP has the capability of running 12 tenth order digital filters at a rate of 30 kHz per channel.

Experimental Results

Initial results for the quiet slew/settle problem have been obtained. Typical open and closed loop frequency responses for the truss in the slewing configuration are shown in Figures 4 and 5. Table 1 summarizes the open and closed loop damping in each of the first 3 flexible modes. The first three modes which contribute significantly to the response of the truss have been heavily damped. In addition, some of the higher modes could be damped if necessary using a higher order compensator.

Relatively high open loop damping was observed in the horizontal bending mode due to the interaction of the truss modes with the internal control loops in the air bearing. Even still, enough strain energy exists in the active members to allow this mode to be damped approximately down to the resolution limits of the accelerometers. In addition, the vertical bending mode at 4.7 Hz was damped down to the resolution limits of the accelerometers. The torsional mode response at 12.6 Hz was reduced by 30 dB even though only one active member was placed in a manner to be able to sense it and actuate on it. These levels of damping were achieved using approximately 40 Volt maximum actuator signals and less than 4 Watts of power consumption.

Concluding Remarks

This work has demonstrated that quiet reorientations/slews of precision structures can be accomplished using various technologies. The main technologies demonstrated were shaping the slew torque profiles using inverse dynamics and adding damping to the structure through the use of active members. The active members were shown to be capable of microdynamic control due to the lack of creep and hysteresis at low levels of actuation. Vibration attenuation levels greater than 30dB were observed when closing the local loops around the active members. Both power consumption and maximum voltage levels required to achieve these 30 dB peak vibration reductions were within the current capability of spacecraft power systems.

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Table 1: Open and Closed Loop Damping

Mode	Description	Frequency (Hz)	Open Loop $\zeta(\%)$	Closed Loop $\zeta(\%)$
1	Vertical Bending	4.7	0.7	10.9
2	Slew Plane Bending	6.3	2.0	6.3
3	Torsional Mode	12.9	0.2	3.9

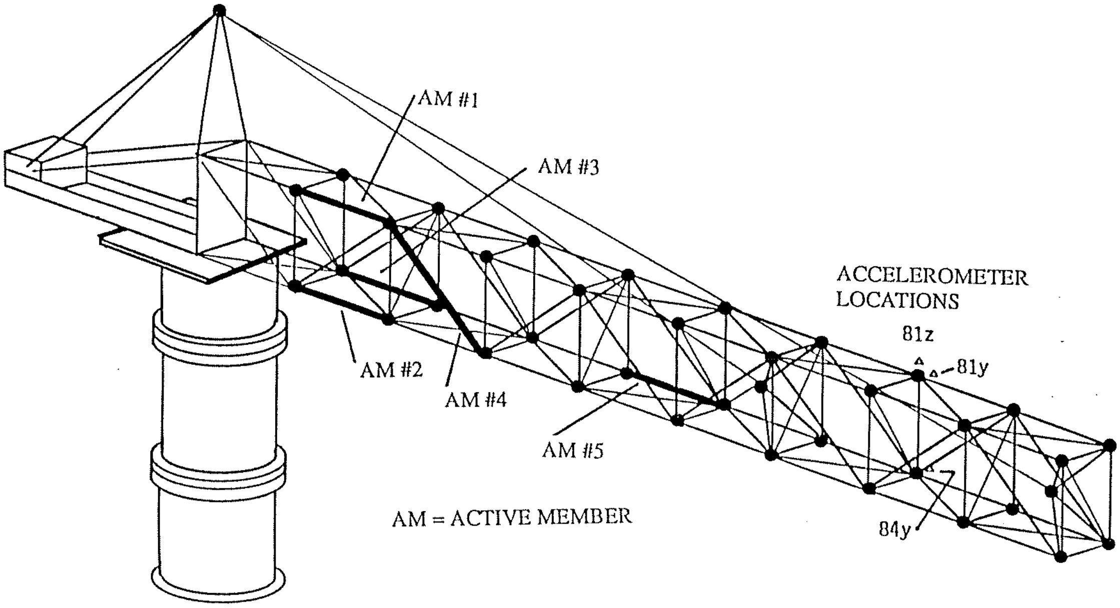

Figure 1: Multibay Truss Testbed

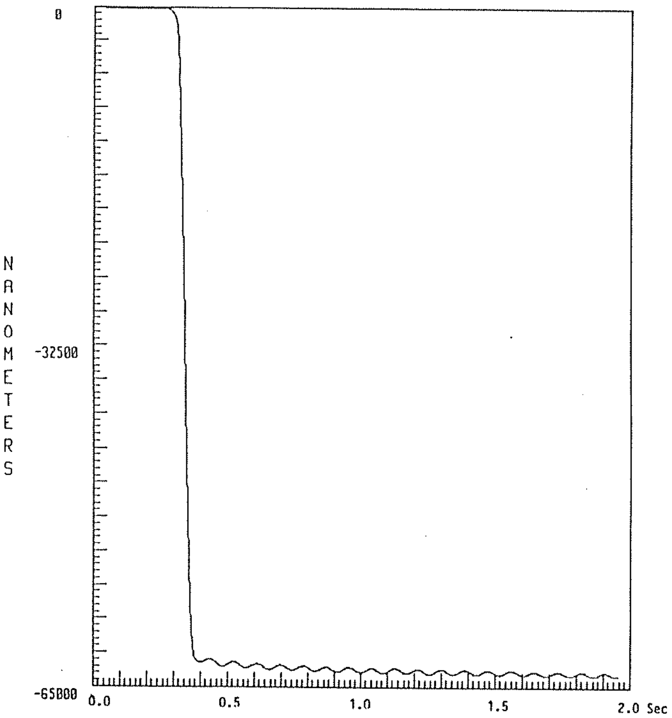

Figure 2: Active Member Creep Test Results

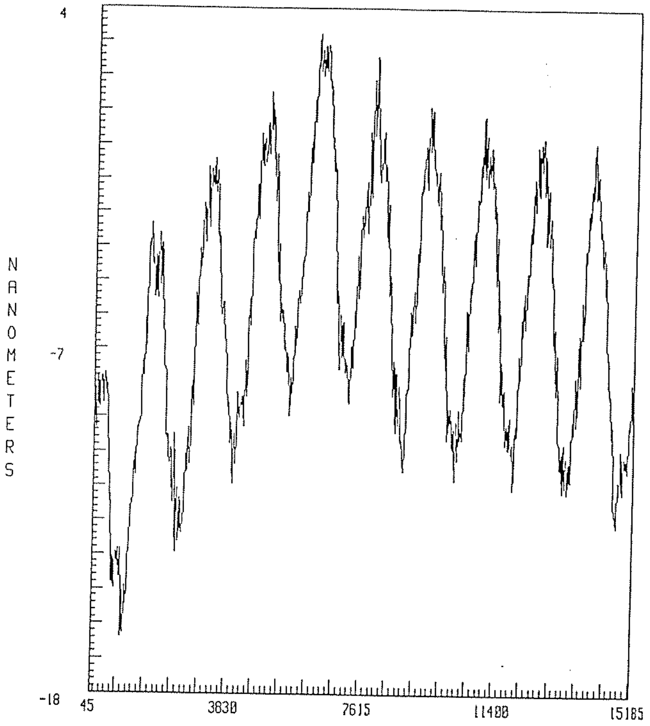

Figure 3: Low Level Active Member Actuation Characteristics

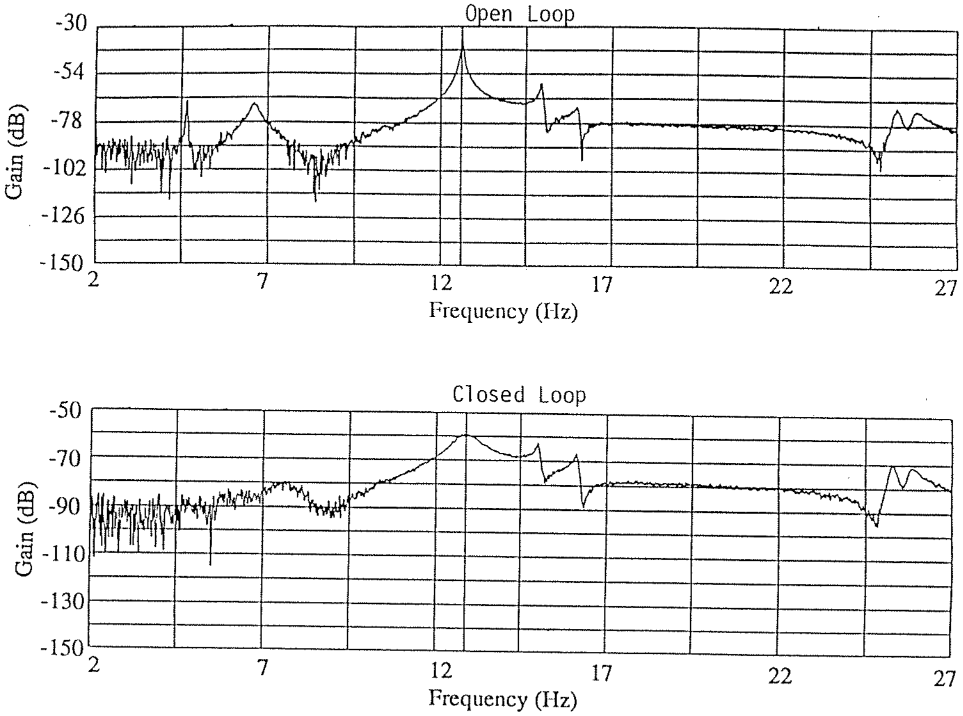

Figure 4: Open and Closed Loop 84Y Accelerometer Responses

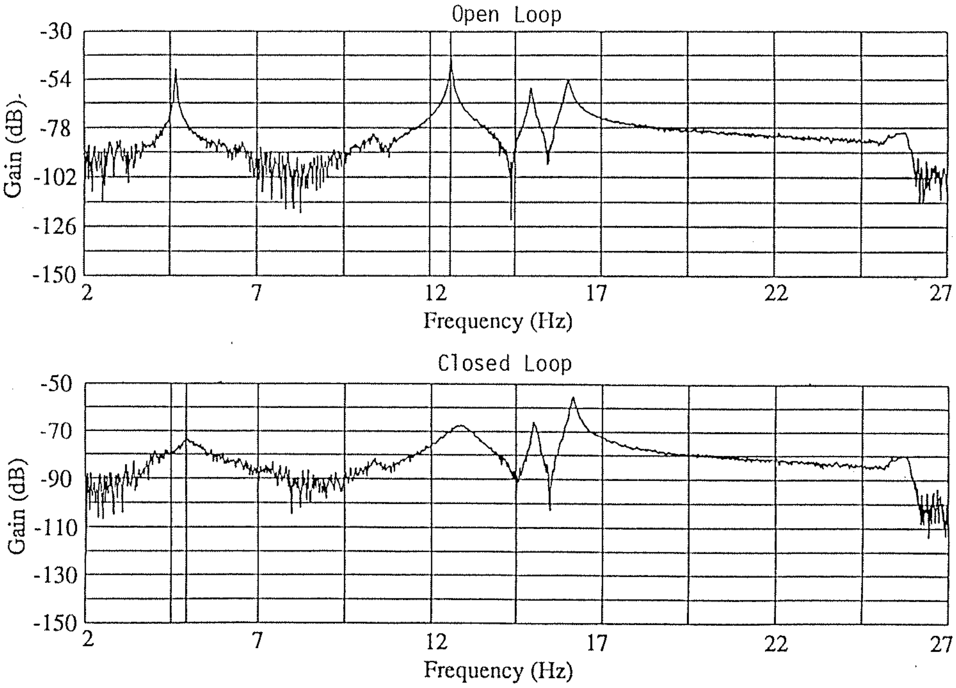

Figure 5: Open and Closed Loop 81Z Accelerometer Responses