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IDENTIFICATION OF EXPERIMENT DYNAMICS AND ENVIRONMENTAL EFFECTS ON THE ACTEX I FLIGHT EXPERIMENT

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Abstract

The Advanced Controls Technology Experiment I (ACTEX I) flight experiment has been on-orbit for more than two and one half years. During the orbital lifetime of the experiment, more than sixty experiments have been run. These sixty experiments include a number of system identification, closed loop control, and adaptive control experiments run under a wide range of environmental conditions. This paper discusses some of the expected and unexpected behavior that has been seen among those sixty experiments.

Along with verifying the expected behavior of the control hardware as described above, some unexpected behavior has been seen during the orbital lifetime of the ACTEX I flight experiment. One unexpected phenomenon that was seen was the instability of certain controllers due to extremely low frequency vibrations. The low frequency vibrations, assumed to be either attitude control system motions or solar array modes, were of the same magnitude of vibration as the flexible motion for a certain set of experiments. Another unexpected phenomenon that was seen was an extreme frequency dependence of host spacecraft modes with varying temperatures. Though the ACTEX I modes were stable with temperature (as witnessed by relatively invariant piezoceramic sensor/actuator transfer functions), modes assumed to be from the host spacecraft varied wildly. These modes were measured by the accelerometers on the flight unit and varied by 25% in frequency across the orbital temperature range.

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Introduction

There are a significant number of current and future space missions that have extremely stringent pointing and shape requirements. Unless these missions operate in a benign environment and have no sources of disturbance, then a purely structural design approach to meeting these stringent requirements is inefficient.

The field of adaptive or smart structures was born with the idea of making space-based observing systems quiet and stable [1-2]. In the face of uncertain or changing disturbances and environments, adaptive structures change in order to maintain performance requirements. A significant amount of work was performed on adaptive structures and has led to mature design and analysis tools [3-4] and ground-based test facilities [5]. There remained the task of demonstrating the space qualifiability, launch survival, space performance, and space reliability and health of adaptive structures.

The ACTEX I flight experiment was intended to demonstrate these key missing ingredients for full operational space mission use. As such, the flight experiment serves as a bridge between ground-based advanced controls technology demonstrations and mission-enabling use for current and future spacecraft.

The objectives of the ACTEX I flight experiment were to demonstrate active damping using embedded piezoceramic actuators and sensors, demonstrate on-orbit adaptive control, provide a capability to test different system identification and control algorithms, and to collect the long term effects of space exposure on the active control hardware.

The ACTEX I flight experiment hardware was designed, fabricated, tested, and integrated with the host spacecraft in the July 1991 through August 1992 timeframe. Anticipating a December 1992 launch, disappointment set in as a launch delay and a subsequent launch vehicle failure delayed the ACTEX I flight. Finally in July 1996, after 3.5 years in storage, we were given word that the unit was in space and ready for the first experiment. Over sixty experiments, as discussed in this paper, led to a plethora of data regarding the performance, adaptability, and reliability of smart structures in a harsh space environment.

Flight Experiment Hardware

Figure 1 shows an overview of the ACTEX I flight experiment hardware with flight cables and thermal blankets removed for clarity. Detailed descriptions of the hardware are available in References 6 and 7.

The flight structure consists of the active tripod structure shown in Figure 2. The tripod configuration was chosen to be traceable to typical precision sensor mounting schemes. In addition, the tripod yields structural dynamic characteristics that are simple enough to demonstrate the flight-readiness of smart structures for space use without being complex enough to have jeopardized the hardware delivery schedule.

Each leg of the active tripod consists of graphite epoxy host material with embedded piezoceramic sensors and actuators. The composite layup, which utilized T300 graphite for its high strength and low stiffness properties, has the piezoceramic sensors and actuators embedded in all four faces of each leg. On each face is a piezoceramic actuator of size 7.5" long by 0.48" wide by 0.010" thick, a piezoceramic sensor of size 0.5" long by 0.48" wide by 0.010" thick colocated with the actuator, and a piezoceramic sensor of size 1.0" long by 0.48" wide by 0.010" thick nearly-colocated with the actuator. Two sensors are provided along with each actuator so that the positive and negative feedforward of each sensor can be "averaged out" in the resulting controller transfer functions.

Seven accelerometers on the top plate of the tripod monitor the motions of the top plate. Six accelerometers on the bottom bracket of the tripod (i.e., the interface to the host spacecraft) monitor the input to the base of the tripod from the host spacecraft. Heaters and redundant thermostats on the top plate were used to maintain the temperature of the accelerometers within their calibration temperatures (i.e., above -55°C). The mass and inertia characteristics of the top plate were sized to yield natural frequencies in a range that is traceable to typical precision space sensor mounts.

A Dynamic Change Mechanism (DCM) was installed in the experiment in order to be able to command changes to the structural dynamics. The DCM involves 6 0.020" diameter strands of 175°C Nitinol wire that compresses a flexure at the top of one of the active members against the top plate, essentially locking out the flexure and stiffening the system. Because we did not ground test the ACTEX I flight unit in vacuum, it was difficult to tell the change in frequencies that could be expected during actuation of the DCM.

A Nitinol Release Device (NRD) held the top plate of the tripod down to the host spacecraft for launch. The launch restraint was needed with the soft structure to insure that the structural system would survive the launch environment. Because the NRD proved somewhat sensitive to misalignment during ground testing, there was concern whether the NRD would operate and release properly after 3.5 years in storage and a severe launch environment. Data from the first few system identification experiments confirmed that the NRD did unlatch.

Figure 3 shows the overall functional block diagram of the ACTEX I flight electronics. A detailed description of the electronics can be found in Reference 8.

The command and data handling electronics (CDE in Figure 3) is the primary interface between the host spacecraft (and ultimately the user on the ground) and the active structure. The CDE receives commands from the ground via the host spacecraft, decodes the commands, sequences experiments, controls the flow of data from the various sensors into the Solid State Data Recorder (SSDR), processes interrupts, and processes telemetry signals. Within the command and data handling electronics, the command receive and decode logic as well as the sequencer circuit are implemented in a Field Programmable Gate Array (FPGA).

The active controllers are implemented in the active strut electronics (ASE in Figure 3). The controllers were implemented in digitally programmable analog circuits. That is, analog filter types, gains, and corner frequencies are programmed by a digital interface from the command and data handling electronics. The programmable filters were based on switched capacitor filter technology, allowing filter parameters to be adjusted by changing the digital clock frequency supplied to the device. Various controller types, including strain rate feedback and Positive Position Feedback controller, and controller parameters, including controller orders, gains, and phasing, can be constructed via ground command. Analog power amplifiers are driven by the sensor signals that have been amplified, weighted, filtered, and inverted in the implementation of the desired controllers. Voltage levels were limited to the 28 Volt level corresponding to the host spacecraft supply voltage.

Other functions of the ACTEX I flight electronics include power conditioning and signal conditioning. The power conditioning electronics takes the 28 VDC spacecraft supply and filters and converts it to ± 5 VDC at 1 Amp, ± 15 VDC at 0.5 Amps, ± 15 VDC at 2 Amps, and ± 30 VDC at 0.5 Amps. Pulsed relay commands from the host can switch power to the heaters, the Nitinol latch, and the Nitinol-actuated DCM. The signal conditioning electronics contains the electronic components necessary to use the thermistor and accelerometer signals. An over-vibration circuit was included in the flight electronics to shut down the experiment if excessive vibrations are detected.

A block diagram of the ACTEX I flight system is shown in Figure 4. A PZT disturbance actuator, the ambient environment of the host spacecraft, and the three PZT control actuators provide inputs to the flight structure. Outputs available for recording and monitoring include the seven top plate accelerometers, the six bottom bracket accelerometers, three colocated PZT sensors, three nearly-colocated PZT sensors, the white noise signal, and nine thermistors. Only the three colocated and three nearly-colocated PZT sensor signals are available for vibration suppression purposes. Neither the bottom bracket accelerometer signals nor the top plate accelerometer signals are available for control purposes.

Typical Experiment Characteristics

The typical experiment run on the ACTEX I flight unit consisted of commanding the experiment to start an experiment in a pre-programmed sequence stored in PROM, overwriting certain parameters in the PROM with the desired parameters, and starting the experiment command sequence. The experiment procedure then executes, the system responds according to it's (and the host's) structural dynamics, and the measurements are stored in the onboard Solid State Data Recorder (SSDR). The host organization downlinks the data from the SSDR one page at a time until all 62 pages of the current experiment are available on the ground. This data was then ftp'ed from the host to TRW for processing in the ACTEX I Ground Data Handling System (GDHS). It should be noted that the data is still in the hexadecimal representation of the actual data.

Following conversion to decimal data, the time histories can be plotted and investigated for expected and anomalous behavior. Figure 5 shows the time history data for a top plate accelerometer and a PZT sensor from a typical system identification experiment. For this experiment, the three control actuators were sequentially used to excite the structure with white noise for ten second blocks of time followed by ten second blocks of quiescent (or ambient) response.

The time history data from the experiment can be processed with any number of convenient system identification algorithms to yield the desired frequency domain data. For the ACTEX I flight experiment, however, a hardware groundstation was built which allows rapid transformation of the time domain data to the frequency domain. Figure 6 shows the transfer functions for the top plate accelerometer and the PZT sensor time histories shown above. The transfer functions shown were computed for the 20-30 second block of time when control actuator 2 is driving the system.

Typical Orbital Operations

The first experiment was run on the ACTEX I flight unit in July 1996. The first few experiments were marred by host spacecraft telemetry and downlink errors. After fine tuning the downlink during the first three experiments, we did not experience further telemetry or downlink errors.

System identification experiments run during July and August of 1996 confirmed that the NRD had unlatched, the unit was receiving, decoding, and executing commands, and the unit was behaving as expected. A comparison of PZT sensor 1 transfer functions taken during ground testing of the ACTEX I unit in August 1992 and those taken on-orbit in July/August 1996 are shown in Figure 7. Note that with the exception of the ambient ground noise seen during ground testing, the transfer functions are virtually identical.

Following the system identification experiments and the sensor averaging experiment, the first closed loop control experiment was run in October 1996. Open and closed loop top plate accelerometer responses taken during this experiment are shown in Figure 8. Vibration attenuation of 16 and 15 dB was obtained in the first two modes of the system.

The E40R1 experiment demonstrated the performance of the DCM and the ability to command changes to the dynamics of the ACTEX I flight system. Run during an unfavorable (for the DCM) cold period of the orbit, activation of the DCM produced changes of 6.1% and 4.8% in the first two modes of the system. Figure 9 shows top plate accelerometer response data taken from the baseline closed loop experiment (solid line from the E30R1 experiment) and from the perturbed closed loop experiment (dashed line from the E40R1 experiment). The shifts to higher frequencies of the first two modes can be seen.

This pattern of running system identification and closed loop control experiments continued throughout the first three years of the ACTEX I orbital life. During this time period, we experienced a number of closed loop control experiments that went unstable. The instabilities that we saw were the result of two things, namely overly aggressive controllers or host spacecraft signals interfering with the controllers. The latter of these two will be discussed in the next section.

There were a number of experiments run in support of Guest Investigator requests. The majority of these experiments were "long duration shake" system identification experiments. The pre-programmed system identification that we had been using utilized a 10 second block of time where one control actuator was providing excitation. Run in this manner, transfer functions for all three control actuators could be obtained in a single 60 second experiment. The "long duration shake" system identification experiments entailed shaking the structure with a single control actuator for the entire 60 second experiment. A complete system identification would thus take 3 separate experiments to complete.

To the current date, the ACTEX I flight experiment remains healthy and continues to provide high quality system identification, environmental monitoring, and closed loop control data. A total of 62 experiments have been run on the ACTEX I flight unit over a wide range of environmental conditions. Temperatures of the active members ranged between -87°C and +129°C.

On-Orbit System Behavior

The ACTEX I flight unit saw a wide range of environmental temperatures during the current three years on-orbit. System identification and closed loop control experiments were run in these extreme conditions. With re-setting of control parameters, comparable levels of vibration reduction were obtained across the environment. Yet the effects of running experiments at different temperatures could be seen in the data.

Figure 10 and 11 show comparisons of the control transfer functions for experiments run in cold and hot conditions. The data was taken from the E1R16 and E1R17 experiments (solid line) run with active member temperatures as low as -82°C and from the E1R19 and E1R20 experiments (dashed line) run with active member temperatures as high as +129°C. Figure 10 shows the transfer functions between the three PZT control actuators and the three nearly-colocated PZT sensors. Figure 11 shows the transfer functions between the three PZT control actuators and the three colocated PZT sensors. In all cases, the transfer functions taken during the hot conditions show significantly higher feedforward levels than taken during the cold conditions. Generally speaking the feedforward went up about 4 dB with the 200°C increase in temperature. This increase in feedforward can be attributed to both the increase in piezoelectric constant with temperature for the Navy Type II piezoceramics on the ACTEX I flight unit and the decrease in stiffness of the composite materials as temperature increases.

We also saw a significant movement of modes with the extreme temperature environments. Figure 12 shows the open loop response of top plate accelerometer 4 for 5 experiments run at varying temperatures. The first two modes of the ACTEX I flight structure are fairly stable with temperature. However the mode just below 40 Hz, associated with the host spacecraft, varies a significant amount in frequency and magnitude of response. Figure 13 shows the effects of experiment temperature on frequency of the first three observed modes. The first two modes are bending modes of the ACTEX I flight structure and the third is assumed to be of the host spacecraft. Whereas the modes associated with the graphite epoxy/embedded piezoceramics are fairly stable, the modes associated with the aluminum host bus vary significantly.

With the E30R11 experiment run in August 1997, we noted the presence of a long period signal superimposed on the data. Figure 14 shows a comparison of unfiltered and filtered PZT sensor 2 time histories taken during the E30R11 experiment. The period of the signal, approximately 16 seconds, puts it in the frequency region of attitude control signals from the bus, solar array modes of the bus, or even a thermal snap phenomenon. The magnitude of the low frequency signal, in this case, is of the same level as that generated during the commanded disturbance. Without a filter in the controller to remove the low frequency signal from the PZT control sensors, performance and stability of the controllers can be expected to be compromised. In this case the low frequency signal did indeed drive the controller unstable.

Following the E30R11 experiment, we started watching explicitly for the low frequency signal. After running a number of system identification and closed loop control experiments at various temperatures, we could see a correlation between the presence of the low frequency signal and the environmental temperature. The higher the temperature that an experiment was run at, the more prominent the low frequency signal. Experiments run at colder or moderate temperatures showed no signs of the low frequency signal.

With the relatively long life of the ACTEX I flight experiment, we were given the opportunity to demonstrate the aging and reliability performance of the advanced control hardware. Figures 15 and 16 show transfer functions taken during system identification experiments run two years apart and at approximately the same temperature. In these cases, the experiments were run near -75°C. Figure 15 shows the transfer functions between the three PZT control actuators and the nearly-colocated PZT sensors. Over the course of two years on-orbit, the PZT actuators and the nearly-colocated PZT sensors have changed very little. The changes appear to be within the processing tolerance of the system identification algorithm. Figure 16 shows the transfer functions between the PZT control actuators and the nearly-colocated PZT sensors for the two experiments. Here it appears that a fairly substantial change has taken place in the colocated PZT 3 sensor. We are continuing to monitor this change with subsequent experiments.

Conclusions

The Advanced Controls Technology Experiment I (ACTEX I) flight experiment has been on-orbit for more than two and one half years. During the orbital lifetime of the experiment, more than sixty system identification, closed loop control, environmental monitoring, and adaptivity experiments have been run. These experiments were run under a wide range of environmental and orbital conditions to demonstrate the flight-readiness of the active control hardware. The conclusion of the current effort after three years on-orbit finds the control hardware performance not significantly different than when it was built and launched.

During the orbital operations of the ACTEX I flight experiment, both expected and unexpected behavior was observed. The system identification and vibration suppression capabilities of the embedded piezoceramic actuators and sensors were as expected. Both high quality system identification data and high levels of vibration attenuation were achieved. The unexpected behavior was closely related to the environmental and host spacecraft conditions. We measured extreme temperatures, low frequency signals from the bus, and bus modes shifting around or even disappearing with temperature. Related to the temperature swings of approximately 200°C, we witnessed a moderate change in actuation and sensing capability. In the spirit and goal of adaptive structures, the controller parameters could easily be adjusted to account for these changes and regain structural control performance.

The wide range of environmental conditions and experiments run on the ACTEX I flight experiment have served to demonstrate the flexibility, adaptivity, and flight-readiness of smart structures for operational space missions.

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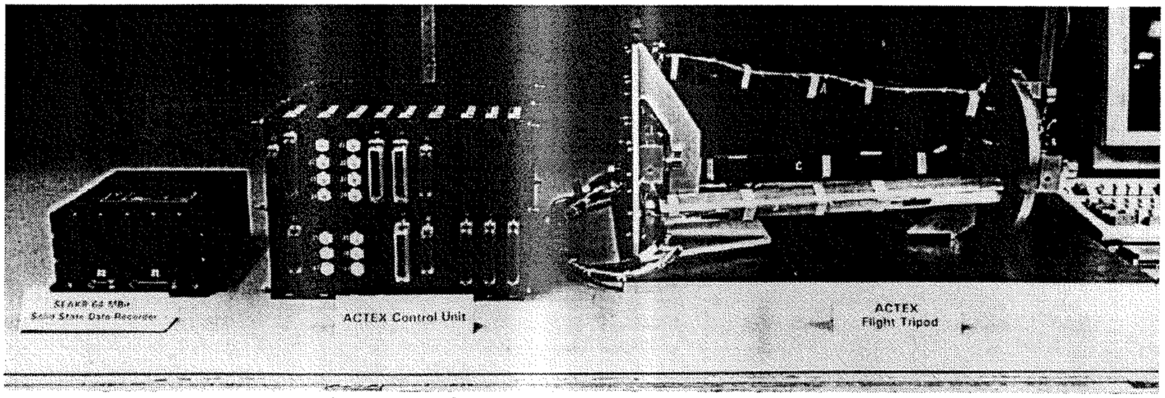

Figure 1. ACTEX I Flight Hardware Overview

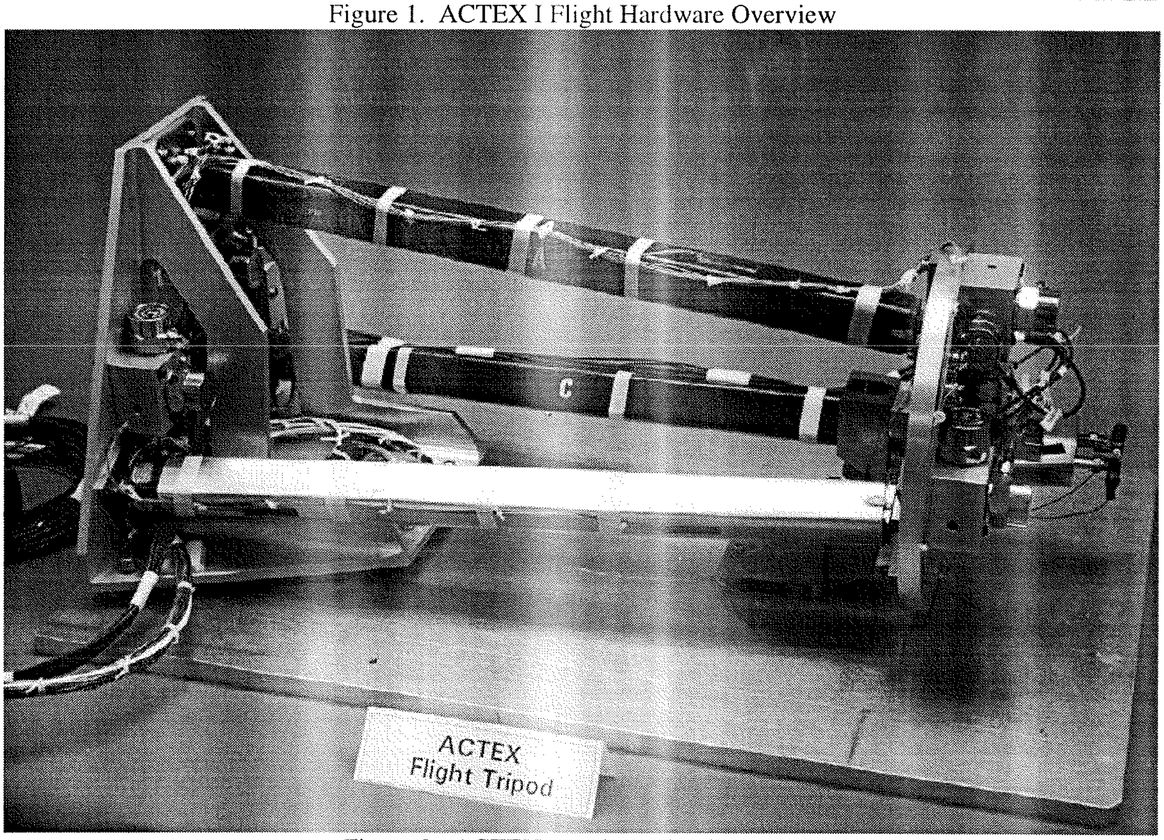

Figure 2. ACTEX I Active Tripod Structure

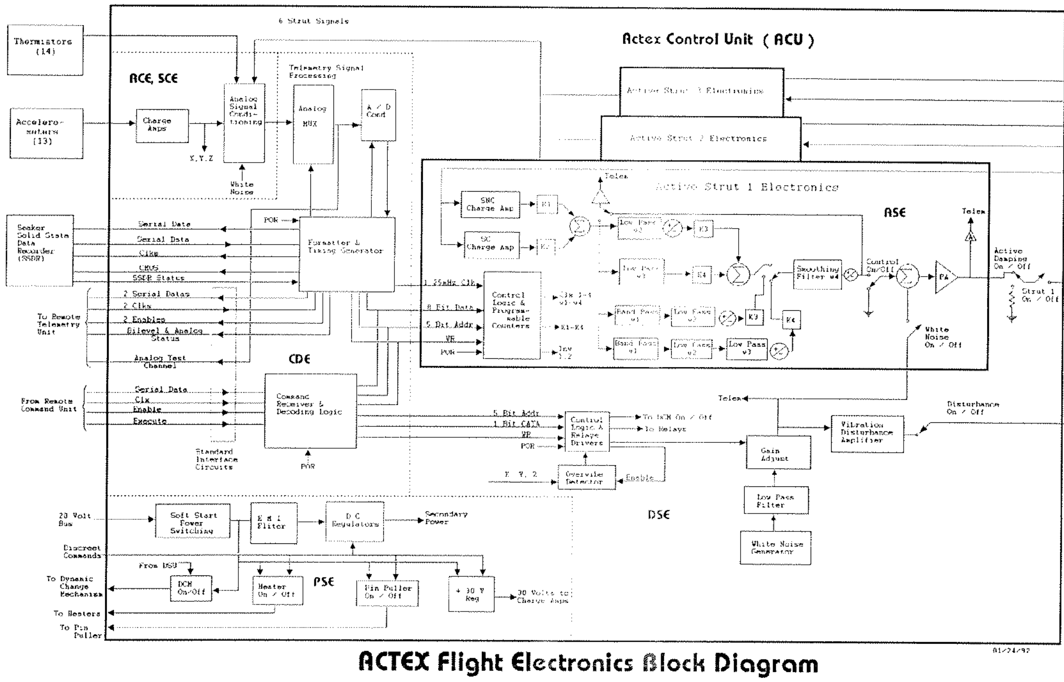

Figure 3. Flight Electronics Functional Block Diagram

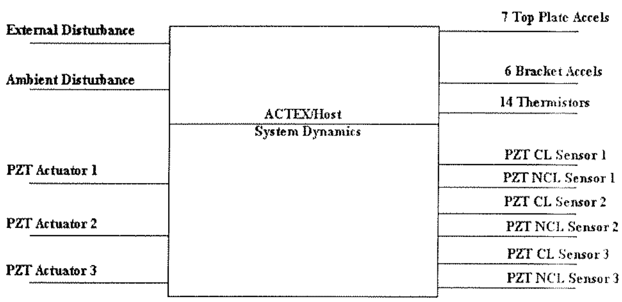

Figure 4. ACTEX I System Block Diagram

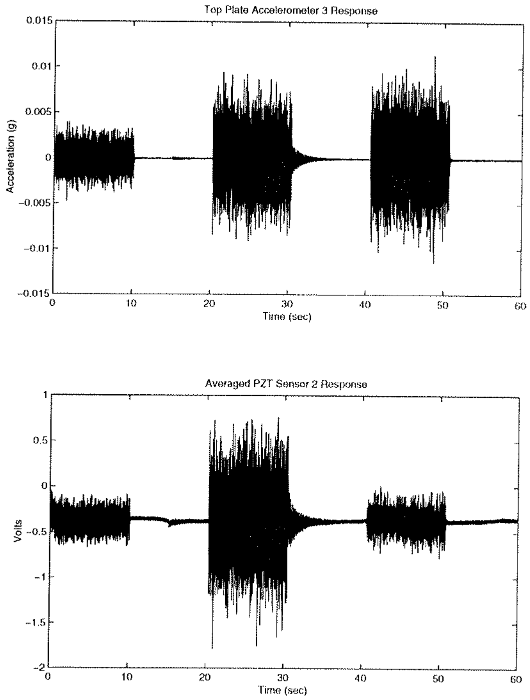

Figure 5. Typical System Identification Experiment Time Histories

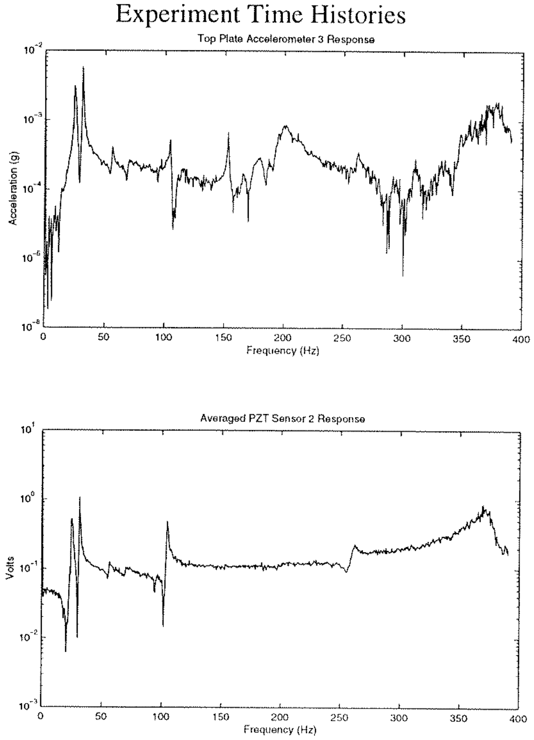

Figure 6. Typical System Identification Experiment Transfer Functions

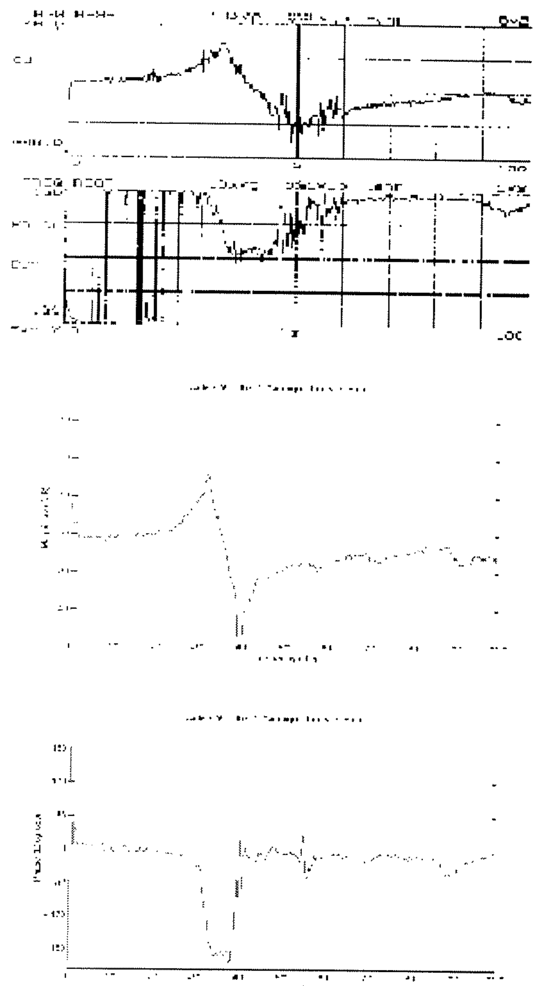

Figure 7. Ground and Space-Based Response Comparison

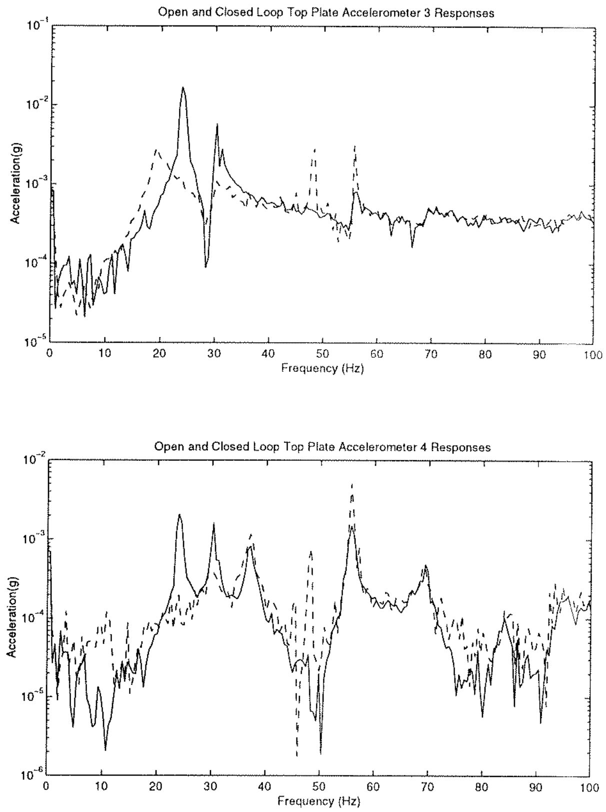

Figure 8. Open and Closed Loop Responses

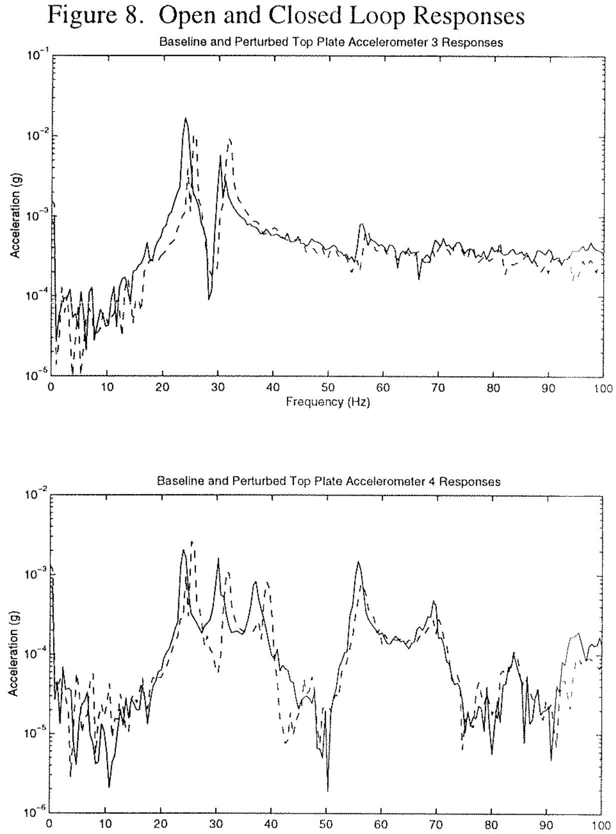

Figure 9. Baseline and Perturbed System Response

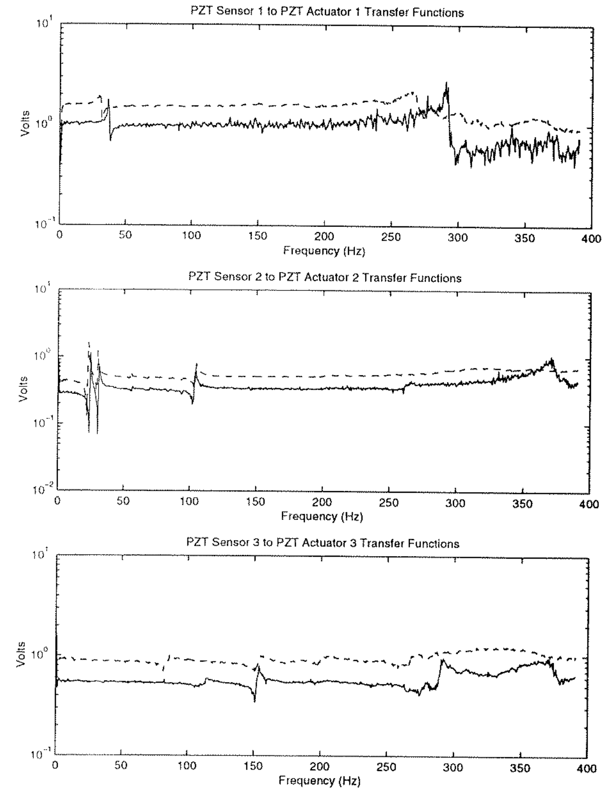

Figure 10. Environmental Effects, Cold and Hot Experiment Responses

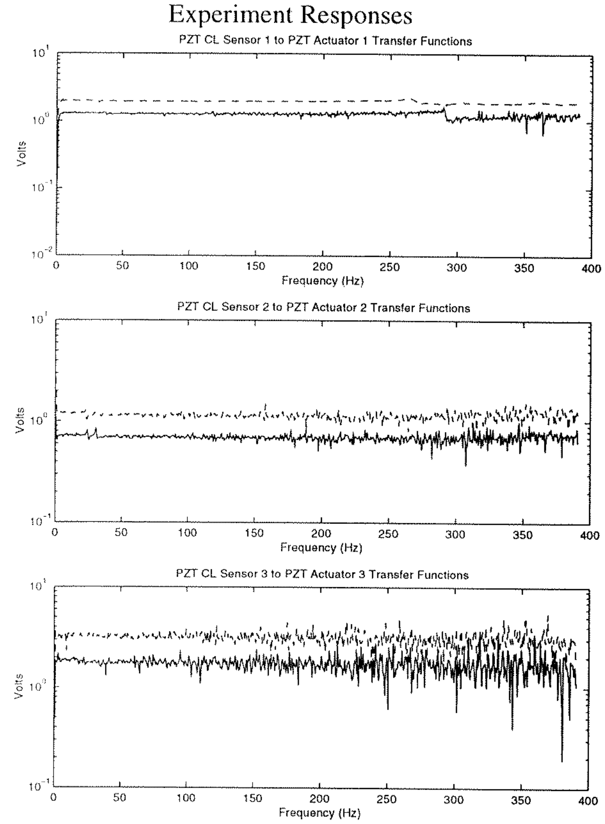

Figure 11. Environmental Effects, Cold and Hot Experiment Responses

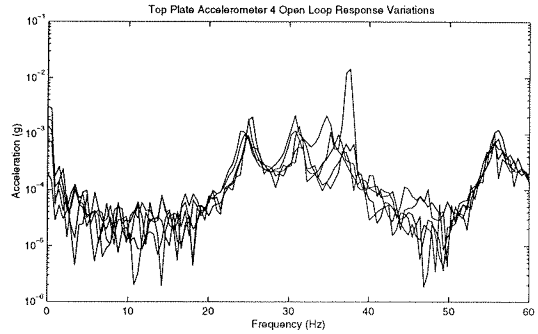

Figure 12. Top Plate Responses from Five Experiments

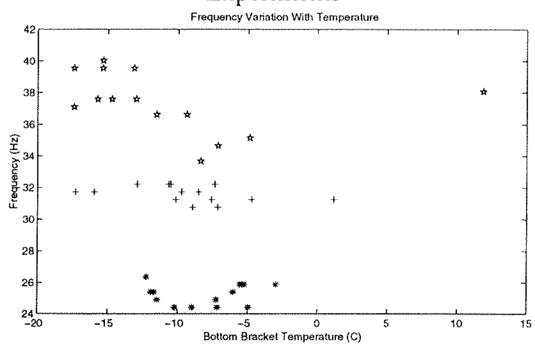

Figure 13. Effect of Experiment Temperature on Natural Frequencies

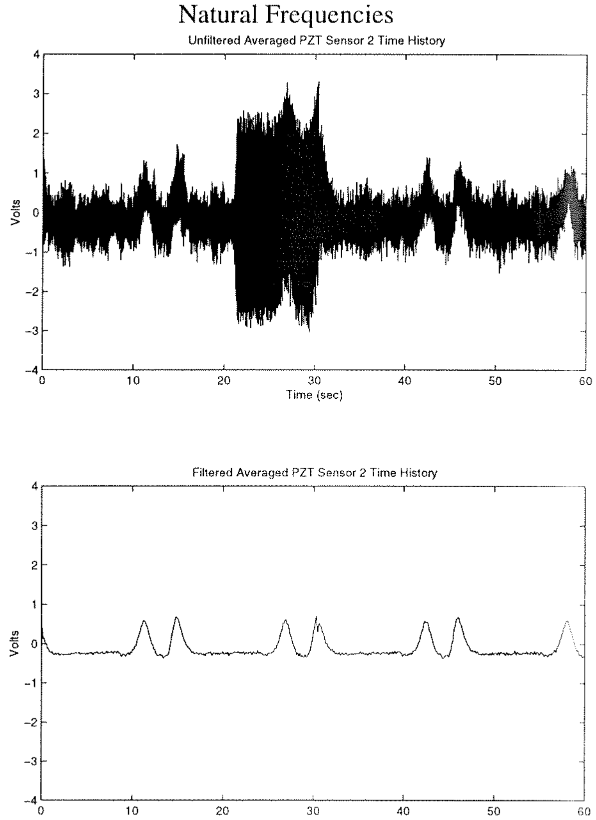

Figure 14. Unfiltered and Filtered PZT Sensor 2 Time Histories, E30R11

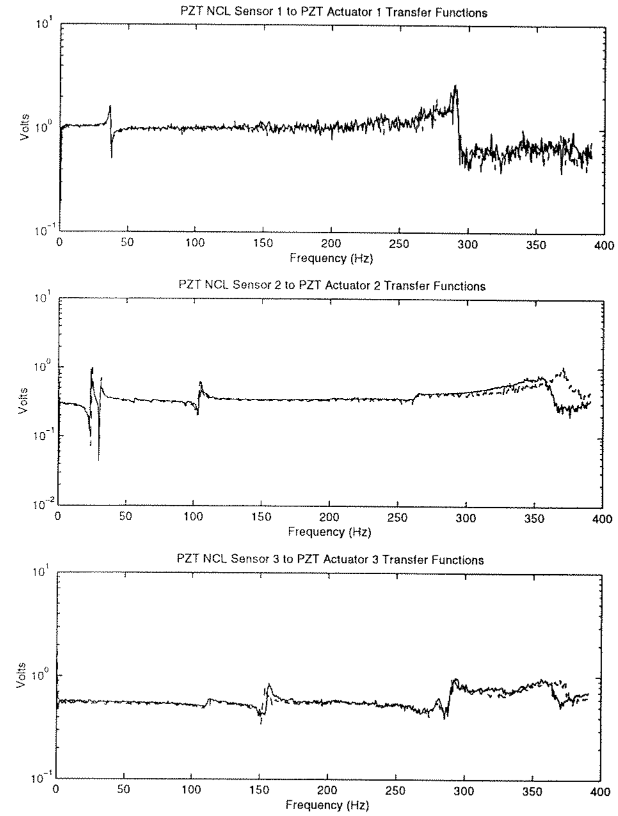

Figure 15. Aging Effects, Two Years On-Orbit

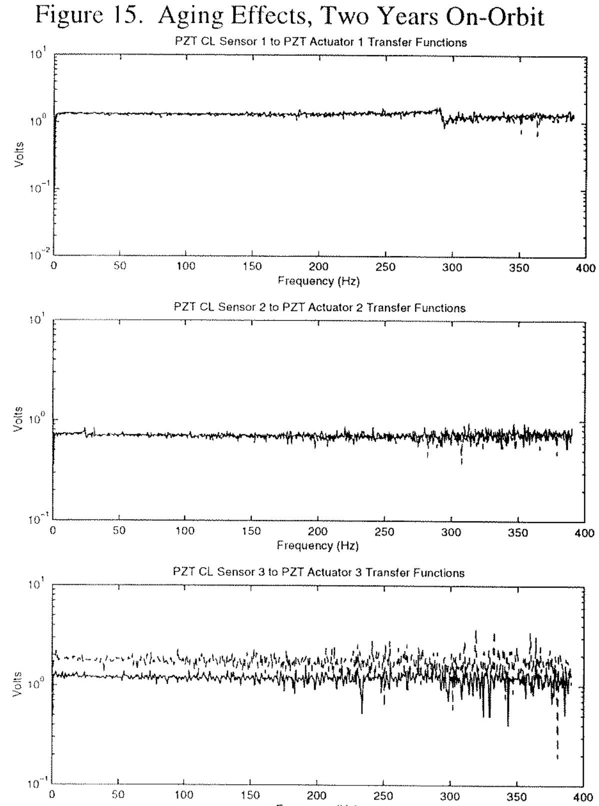

Figure 16. Aging Effects, Two Years On-Orbit