DEVELOPMENT OF AN ACTIVE STRUCTURE FLIGHT EXPERIMENT

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Abstract

The design and development of the Air Force and TRW's Advanced Control Technology Experiment (ACTEX) flight experiment is described in this paper. The overall objective of ACTEX is to provide an active structure trailblazer which will demonstrate the compatibility of active structures with operational spacecraft performance and lifetime measures. At the heart of the experiment is an active tripod driven by a digitially-programmable analog control electronics subsystem. Piezoceramic sensors and actuators embedded in a graphite epoxy host material provide the sensing and actuation mechanism for the active tripod. Low noise ground-programmable electronics provide a virtually unlimited number of control schemes that can be implemented in the space environment. The flight experiment program provides the opportunity to gather performance, reliability, adaptability, and lifetime performance data on vibration suppression hardware for the next generation of DoD and NASA spacecraft.

Introduction

A number of upcoming SDI and DoD space systems will carry payloads and subsystems with stringent requirements for vibration and shape control, often in the presence of severe on-board environmental or mission induced disturbances. To mitigate the effects of these disturbances, it is necessary to exploit advanced controls/structure interaction (CSI) technologies. The Air Force and TRW's Advanced Control Technology Experiment (ACTEX) offers an opportunity to demonstrate this capability in space.

At the heart of many system identification and vibration control strategies is the use of active, or adaptive, structures. Typical active structures employ piezoelectric or piezoceramic sensors and actuators arranged in a stack configuration [1] or embedded within the layup of graphite epoxy members [2]. Fanson et al [2] have devloped piezoceramic stack active members and demonstrated 25-35 dB attenuation of peak vibrations in a truss structure. Their performance, however, was dependent on relatively high voltage levels (700 Volts) which are unavailable on current spacecraft and rely on piezoceramic stack actuators which exhibit significant amounts of creep [3]. Bronowicki et al [2] and Betros and Dvorsky [4] at TRW developed the processes necessary to embed piezoceramic wafers in graphite epoxy for use as structural control sensors and actuators. Their use was aimed towards general active structural components experiencing both axial and bending deformations. Good performance was obtained with voltage supplies near 100 Volts.

For these active structures to be incorporated into fully operational spacecraft, two points have to be demonstrated: 1) Typical on-orbit vibrations can be suppressed

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with currently available 28 Volt unregulated power systems; and, 2) Reliability, performance, and lifetime data have to be proven in the severity of the space environment. Along these lines, the Air Force and TRW have developed the ACTEX flight experiment.

The overall objective of ACTEX is to provide an active structure trailblazer which will demonstrate the compatibility of active structures with operational spacecraft performance and lifetime measures. Specific objectives of the ACTEX flight experiment are: 1) Demonstrate integrated active/passive damping using piezoceramic sensors and actuators embedded within the layup of graphite epoxy tubes; 2) Provide a capability to test vibration suppression algorithms in space using active structural components, sensors, and passive damping; 3) Validate preflight design and performance prediction tools by performing on-orbit system identification and health monitoring experiments; 4) Demonstrate the concept of adaptive structures using control laws which can be updated from the ground; and, 5) Collect data on the long term effects of the space environment on the active and passive control components.

Flight Experiment Description

The proposed flight configuration for the active structure is shown in Figure 1. The structure itself consists of a tripod with all three of its legs active. Hard constraints placed on the size of the experiment envelope by the Navy host spacecraft yielded a relatively tall narrow tripod. Cables (not shown in Figure 1) run from the sensors and actuators in the legs of the tripod as well as the accelerometers and thermistors through a feedthrough connector to the flight electronics mounted underneath. In this manner, the structure is exposed to the space environment to obtain maximum lifetime and reliability data while the electronics are mounted in the relatively benign environment inside the host spacecraft for maximum reliability and minimum radiation exposure.

The tripod is instrumented with 13 low noise accelerometers to monitor the input base motion and top plate motions. All three translational and all three rotational degrees of freedom of the top plate can be recovered from the accelerometer measurements.

Nine thermistors monitor the temperatures throughout the experiment structure. Of maximum interest are the active member temperatures so that actuation and sensing data can be obtained as a function of the real on-orbit thermal environment. Thus each leg of the tripod has two thermistors bonded to it. Active thermal control hardware is located on the top plate and the backing structure to maintain the survival temperature limits required by the accelerometers. Multi-layer insulation (MLI) is used on the top plate, the backing structure, and two of the active legs to maintain operational temperatures in a thermally-severe orbit. The third active leg of the tripod is not wrapped with MLI, but is instead painted with a leafing aluminum paint for thermal control. Data concerning the performance and reliability of the active members is thus obtained for two different types of thermal control.

Active Member Description

The active members utilize piezoceramic wafers embedded in a graphite epoxy layup for the sensors and the actuators. Square cross sections for the legs of the tripod were employed to ease the processing of the active members and to utilize the processes developed on a related contract [2,4]. The encapsulation and embedding process described in

[4] was used for easier handling of the PZT material and less susceptibility to cracking during the graphite epoxy cure process. Each side of the square tripod legs has a double-layered actuator string and two sensors. One of the sensors is colocated with the actuator string while the other is nearly colocated. Two sensors per leg give added redundancy to the experiment and allow averaging of the sensor measurements. 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.

Control and Data Acquisition Electronics

The experiment package consists of an active structure exposed to the space environment and an electronics package mounted inside the host spacecraft. The electronics package provides the following functions: 1) Circuitry which is used to actively damp the vibrations in the structure. A set of programmable filters take the sensor measurements and implement the desired compensator prior to amplifying the signal for application to the actuators; 2) Data collection and telemetry circuitry that collects wide band performance data from the actively damped structure and stores it in a solid state data recorder for subsequent downloading to the ground; and, 3) Circuitry to receive and process ground commands. These commands are used to configure the programmable compensators and to control the data collection and readout process.

The ACTEX electronics are packaged as nine subassemblies as shown in Figure 2. The slice module assemblies are held together by rods threaded at each end. Spacecraft connectors are located on the front side of the unit whereas interunit connectors are on the back. The slice dimensions are 8" (height) by 11.5" (width) excluding mounting features. Slice thicknesses vary depending on the components used on the enclosed printed wiring board, but are typically 1".

A block diagram for the ACTEX electronics is shown in Figure 3. The electronics consist of active strut electronics, command receiver and decoding logic, data acquisition electronics, a solid state data recorder, and power converter electronics. Each of these portions of the electronics is described in the following paragraphs.

The active strut electronics is the programmable circuitry used to damp tripod vibrations. Measurements from the PZT sensors are buffered and passed through a set of filters whose break points are programmable from the ground. The filtered and conditioned signals are amplified and used to drive the PZT actuators embedded in the tripod legs. By appropriately switching filters in or out of the path and by setting the filter break points, a number of different control laws can be used to achieve maximum damping performance from the tripod.

The command receiver and decoding logic electronics takes serial commands from the host spacecraft and decoded. The decoded commands are used to configure the active strut electronics and to control the data collection and readout operations.

The data acquisition electronics controls the sampling and digitizing of the high bandwidth experiment data. Twenty analog signals from the accelerometers, the active strut electronics, and the white noise are sampled, digitized, and shifted into the solid state data recorder. The process is controlled by a programmable controller via microcode residing in control PROMs.

The solid state data recorder has a data capacity of 64 Mbits and a serial data rate of up to 4 Mbits/second. Operation of the data recorder is controlled via the command receiver and decoding logic.

The power converter electronics converts the 28 Volt fused spacecraft bus power into secondary voltages required by the ACTEX electronics. The spacecraft power is switched through two relays to provide fail-safe operation.

In addition, a white noise generator is available for use with the ACTEX experiment. The white noise generator can be used to perform system identification by driving the active tripod actuators and recording transfer functions, and can be used to perform damped forced vibration experiments by driving a disturbance source mounted on the ACTEX structure.

Ground Testing and Validation

Ground testing of the ACTEX tripod and electronics consisted of static proof loads, thermal cycling tests, random vibration tests, and functional/performance testing of the integrated experiment.

Each active member was statically proof loaded for proof of workmanship and strength adequacy. The test loads were obtained by applying the design loads of ±10 g's quasi-statically to the finite element model of the tripod and retrieving the worst case member loads. A test fixture was fabricated for an Instron axial test machine to generate these loads in a single active member. Transfer functions of the struts were taken before and after each set of loading conditions to verify the integrity of the PZT actuators and sensors. In addition, strain gages were mounted on the active members to measure the true strain enforced on the members. The static proof tests were pass/fail tests where any decreased actuation/sensing resulted in the active strut failing the test. Strain levels up to 1200 μstrain were seen during the test with no degradation in actuation/sensing capability.

Thermal cycling tests were run on the active tripod and the electronics to verify their operational and survivable limits. The electronics operated and survived at their test limits of 0/40° C. Recall that the electronics are mounted within the spacecraft and thus have a relatively benign thermal environment. The tripod, on the other hand, is exposed to space and can expect to see temperature limits of -157/148° C during extreme orbits. The experiment will not be running at these limits, but must nonetheless survive this environment. Operational limits of -89/113° C were set for the tripod based on prior program test data. Six thermal cycles were run with built in holds at the operational limits to verify the functionality of the struts. Holds were also built in at room temperature on the way up in temperature to verify the survivability of the struts during the previous thermal cycle. Active thermal control hardware functionality was also verifed during the thermal cycling tests. Typical transfer functions for the active tripod before and after thermal cycling are shown in Figure 4. As can be seen from Figure 4, no serious degradation in functionality was experienced during the thermal cycling tests.

Both the electronics and the tripod were subjected to base shake random vibration environments compatible with a Titan IV launch vehicle. The input spectra varied in magnitude between 10.5 g_{rms} and 11.1 g_{rms}, depending on whether it was a lateral or axial direction relative to the launch vehicle. Both the electronics and the tripod survived the three independent axes of testing, even with response levels approaching 300 g's peak in certain instances.

The dynamics of the active tripod were characterized on the ground prior to and during integration with the host spacecraft. This characterization data was obtained in the form of transfer functions for the active tripod and closed loop damping levels. A typical transfer function is shown in Figure 5 where the first lateral bending mode is near 23 Hz and the first torsional mode near 80 Hz. Another primary lateral bending mode exists near 23 Hz (due to the symmetry of the structure) but is orthogonal to the connectivity of this set of actuators and sensors. Another set of actuators and sensors does sense this other mode as well as the torsional mode. Using a strain rate feedback control law, damping levels went from 0.8% open loop to 22% closed loop in the primary bending modes and from 0.5% open loop to 6% closed loop in the torsional mode. Typical open and closed loop forced responses (i.e., top plate accelerometer response to disturbance actuator input) are shown in Figure 6. Both the primary bending mode and the torsional mode are significantly reduced in magnitude.

Concluding Remarks

The development of the Air Force and TRW's Advanced Control Technology Experiment has been described. Under the contract, the active tripod and electronics were designed, fabricated, tested, and integrated with the host spacecraft in less than fourteen months. A complete flight qualification test program proved the flight worthiness of the system. System level characterization tests demonstrated excellent system identification data and a 27-fold increase in the level of damping in the primary bending modes using a strain rate feedback controller. The design and resulting damping performance of the active tripod are representative of larger flexible structure control problems in that compromises have to be made between weight, power, actuator/sensor placement and sizing, flexibility and strength. Flight data, including on-orbit system identification and damping levels, adaptability, and reliability, will be reported as the data becomes available in late 1993.

Acknowledgements

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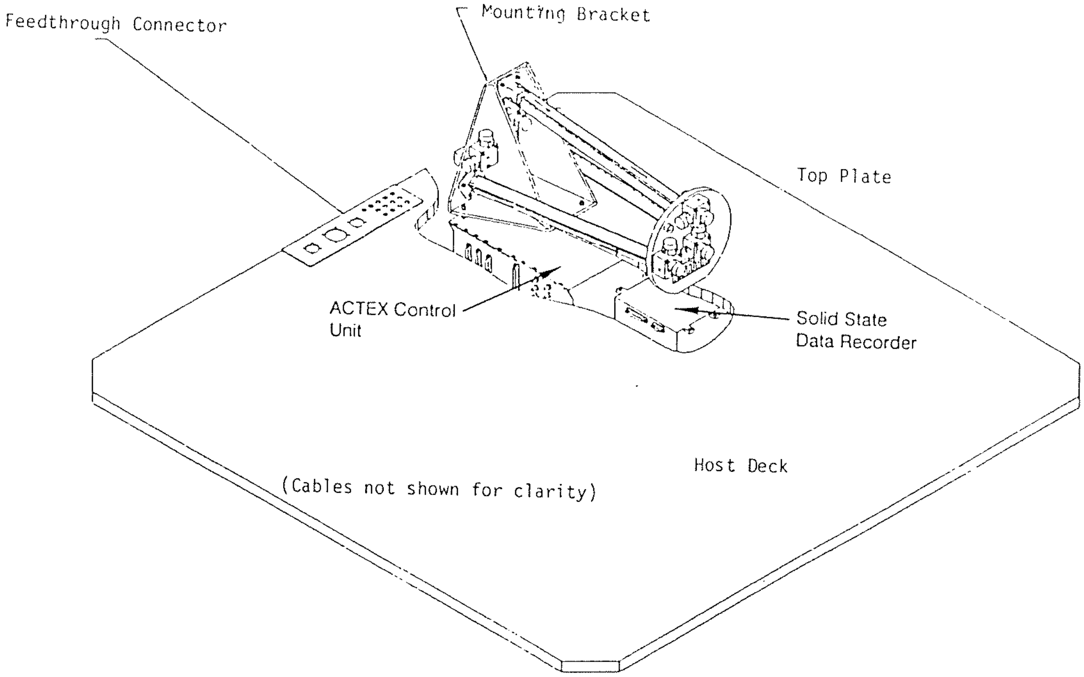
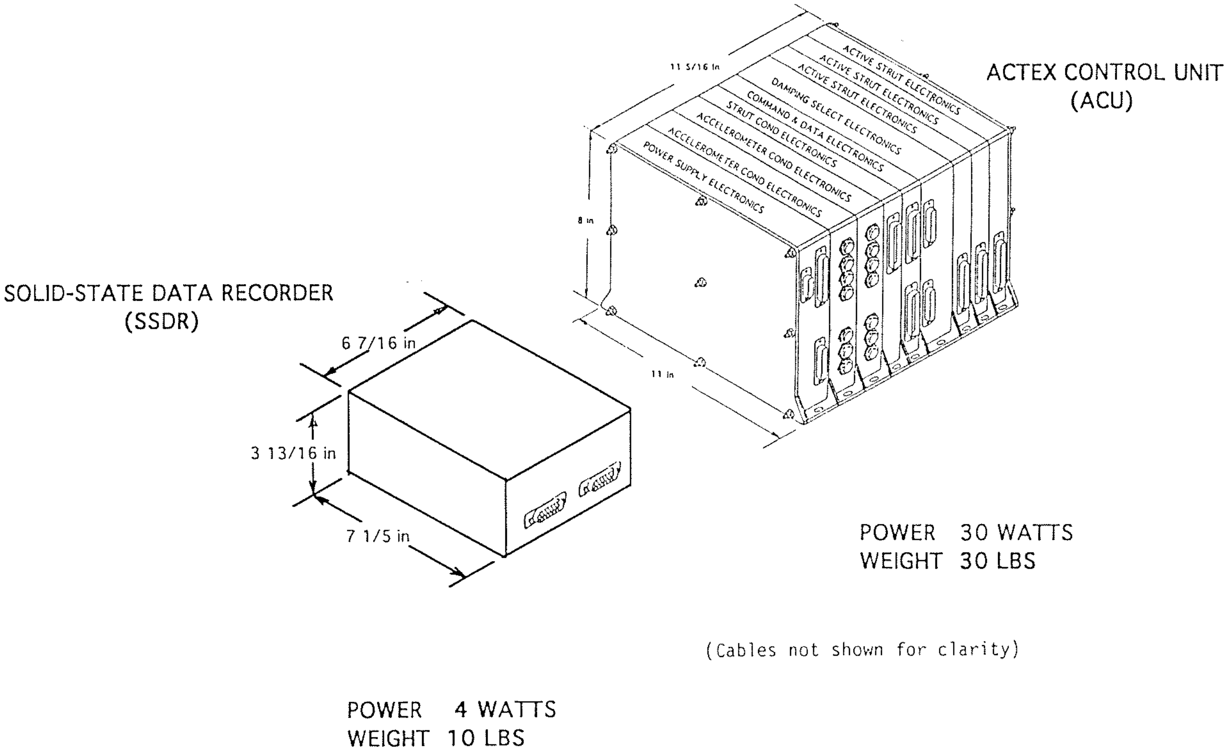


Figure 1: Active Structure Flight Experiment



(Cables not shown for clarity)

Figure 2: ACTEX Electronics Packaging

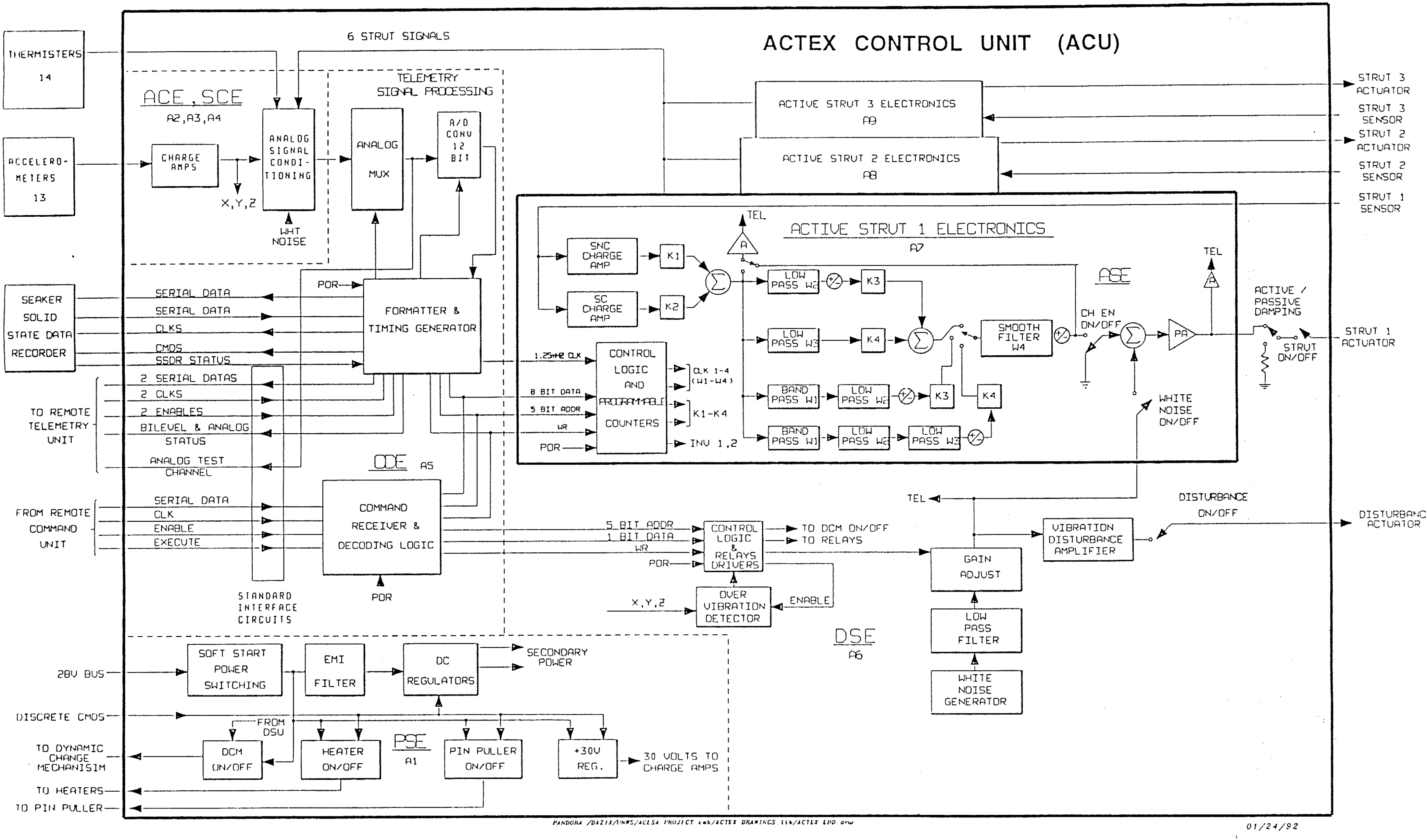
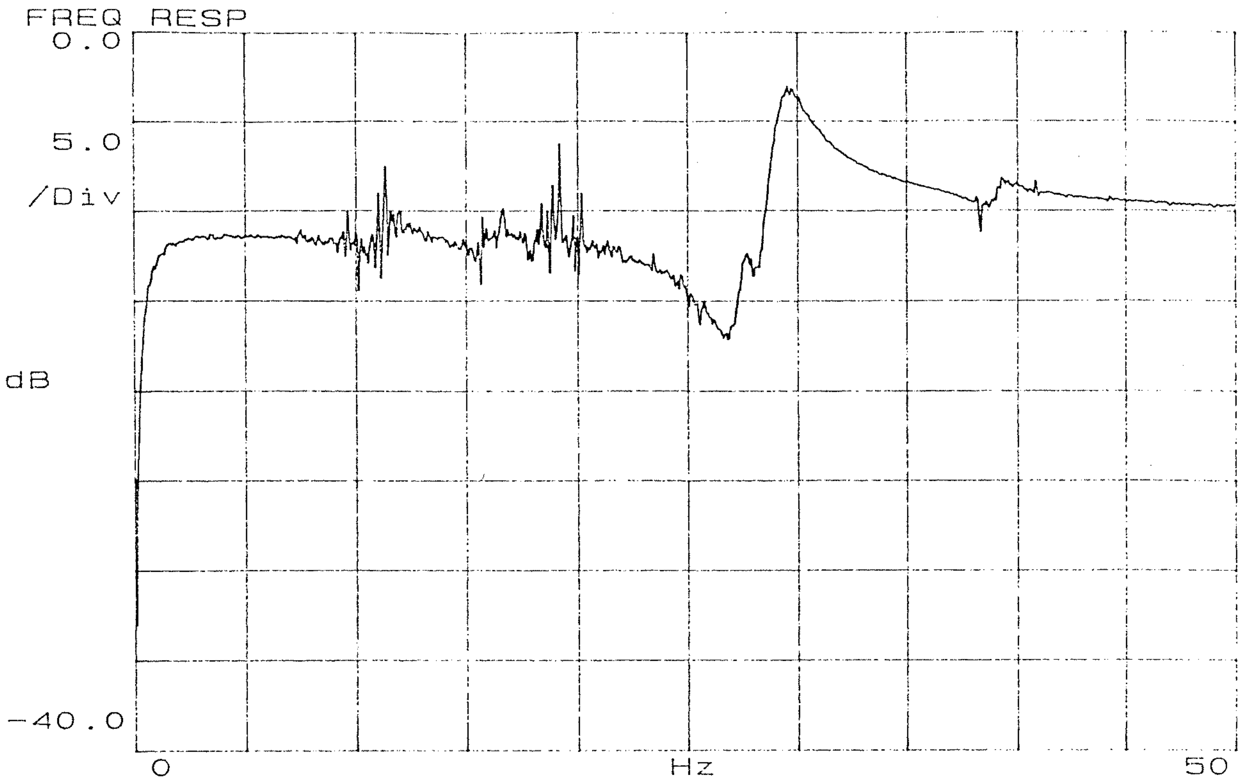
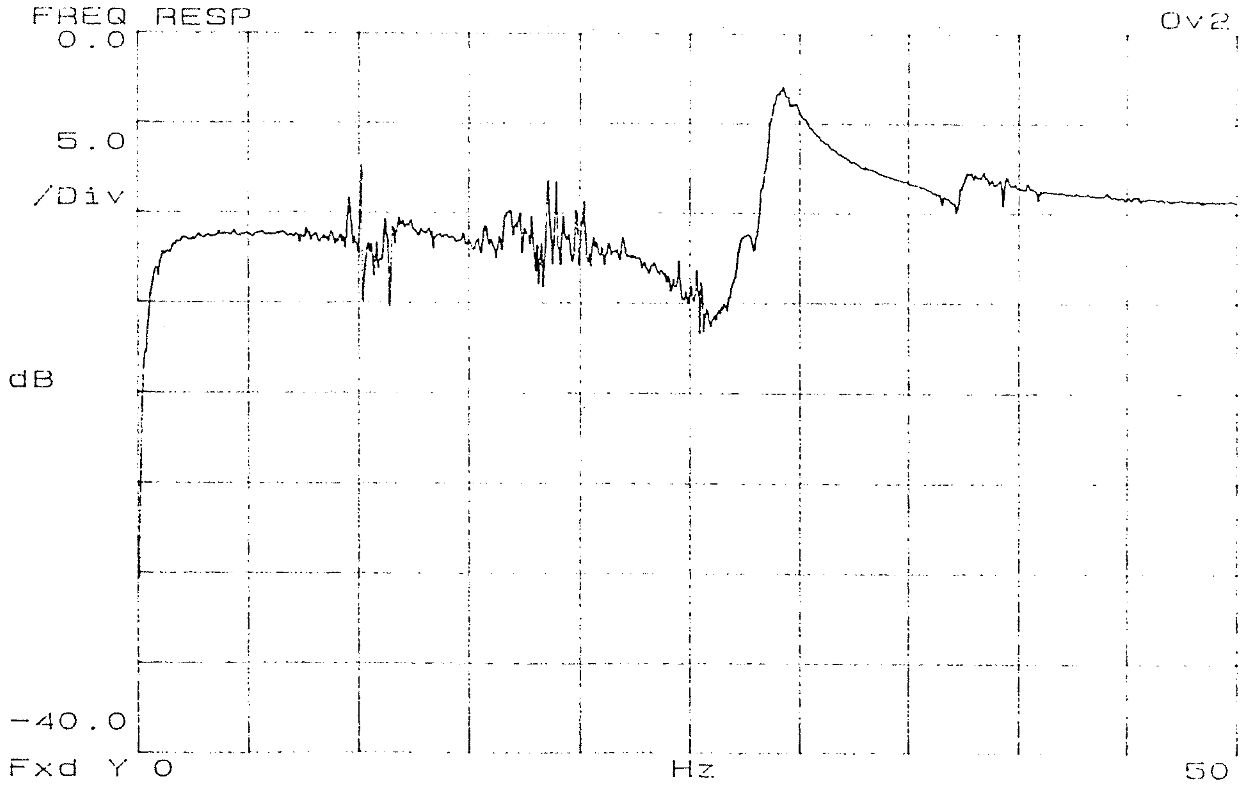


Figure 3: ACTEX Electronics Functional Block Diagram



Pre-Thermal Cycling Transfer Function, Ch. 2



Post-Thermal Cycling Transfer Function, Ch. 2

Figure 4: Before and After Thermal Cycling Transfer Functions

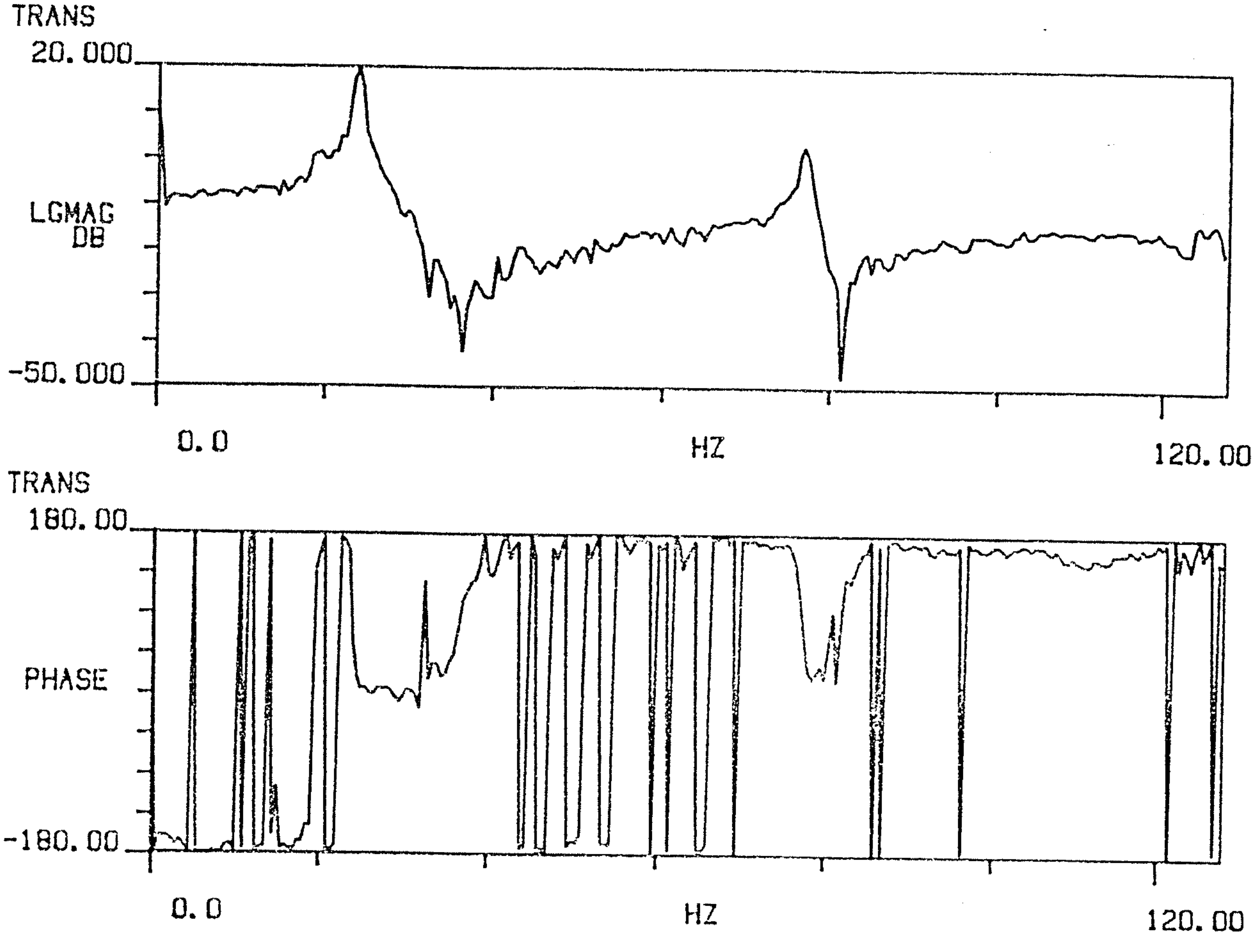


Figure 5: Typical Averaged Active Tripod Transfer Function

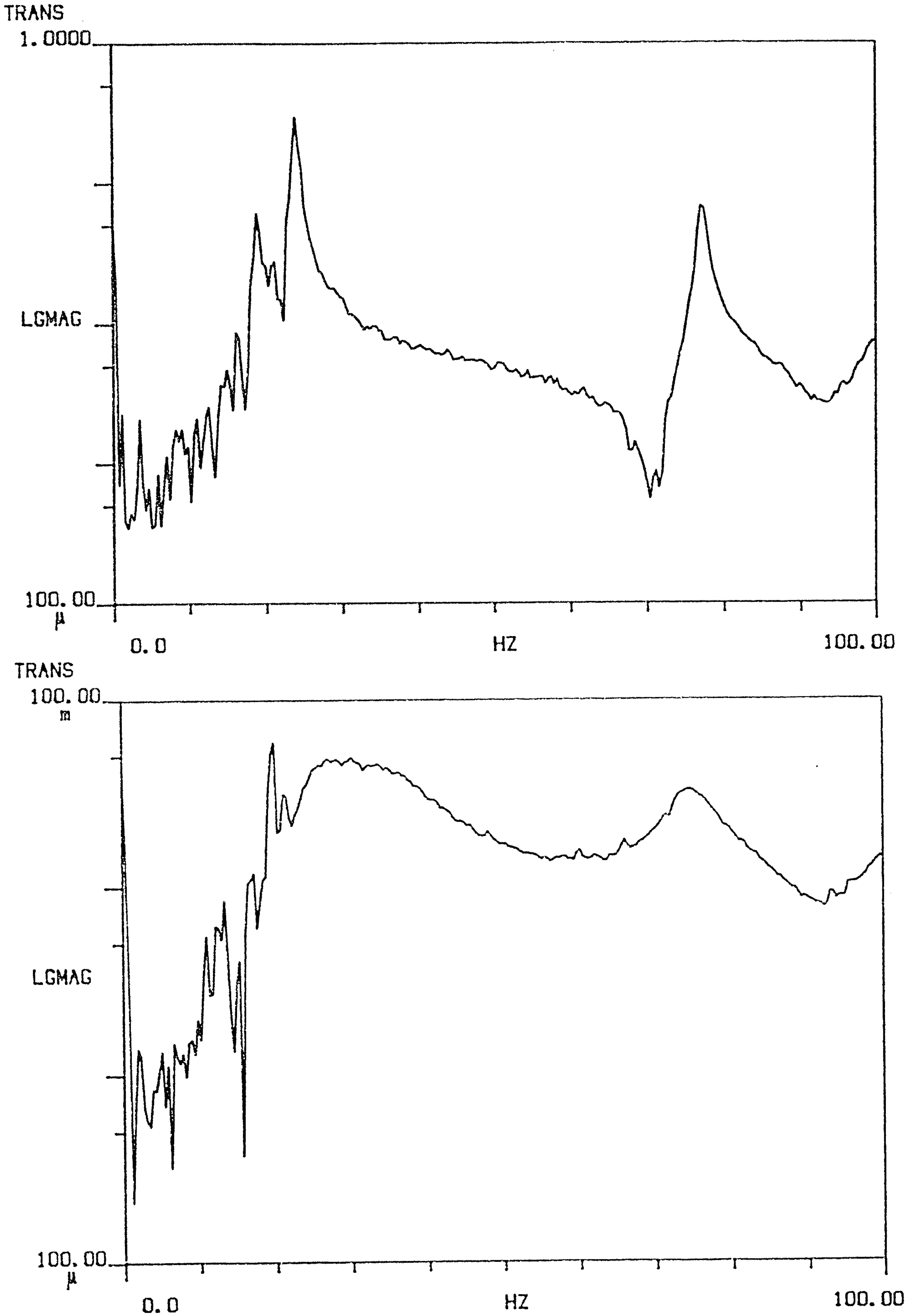


Figure 6: Open and Closed Loop Forced Response