STRV-1 B CRYOCOOLER VIBRATION SUPPRESSION

R. J. Glaser and J. A. Garba
Applied Mechanics Technologies Section
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

and

Lt. Col. Michael Obal
United States Air Force
Materials and Structure Program Manager
Ballistic Missile Defense Organization
Washington, DC 20301

Abstract

The STRV-1 b cryocooler vibration suppression experiment is a satellite flight demonstration of piezo vibration-suppression technology. A very small, tactical stirling-cooler was flown primarily as a vibration source. Two types of piezo actuators were demonstrated. Low-voltage piezo translators were used to move the entire cryocooler so that the tip of the coldfinger stood still. Also, high-voltage ceramic applique was bonded to the base of the coldfinger providing a second actuation method to compare with the translators. Three eddy current transducers were used to measure the coldfinger tip motion relative to the experiment case. The eddy current signal drove two types of control systems. A digital adaptive-feed-forward control system was used to cancel the tip motion of the cryocooler in three dimensions. An analog-comb filter controller was also developed to contrast the two techniques. Motion suppression does nothing to suppress the unbalanced forces in the cryocooler, so a triaxial accelerometer measured the vibration of the satellite in response to the cryocooler. Satellite/ground test results from each of the experiment systems are shown and the systems are compared.

Introduction

With NASA's thrust towards small spacecraft, the STRV-1 b Cryocooler (CRYO) vibration suppression experiment is an example of a small spacecraft experiment. STRV stands for Space Technology Research Vehicle.[1] The STRV -1 series are a pair of British satellites about the size of a large breadbox (48 x48 x40 cm and 55 kg, or 19× 19x 16 inches and 120 lb). Two STRV vehicles were launched piggyback below a communications satellite by an Ariane-4 on June 17, 1994. The orbit was a geostationary transfer orbit (GTO) - the orbit used to move satellites into geostationary orbit. It is a very long ellipse between 200 km and 36000 km that takes 10.5 hours to complete. This orbit was dictated by the communications satellite. It proved ideal for radiation effects experiments.

The satellites are spin stabilized with a magneto-torquer to control solar aspect angle using sun sensors. They are solar powered from panels attached to the sides of the spacecraft. The small size means that the experiments are even more power limited than usual. The total JPL power allotment for four experiments was 40 watt-hours every third orbit. As an additional hurdle, the thermal control promised for the spacecraft was -50°C to 50°C (-58°F to 122°F). Also, the orbit takes the satellite through the Van Allen belts twice per orbit, giving a radiation dose of about 100 Krad per year outside the satellite. Finally the satellite size limited the four JPL experiments to a coffee can sized space on one side and a shoe box sized space on the other side.

BMDO enlisted JPL to fly a cryocooler vibration suppression experiment on STRV - 1 b using piezo actuators. Cryocoolers are typically used to cool IR or CCD sensors to lower the thermal noise threshold.

Stirling coolers have a mechanical compressor so there is a significant vibration problem with optical instruments.

BMDO suggested a novel vibration-suppression technique: usc piezo materials to make the tip of the coldfinger stand still. By doing this the coldfinger does not transmit any vibration to the optical sensor. Shaking of the entire spacecraft is a secondary effect that this technique doesn 't address. BMDO proposed measuring the spacecraft acceleration to quantify this effect.

The experiment demonstrates the feasibilit y of using piezo materials for vibration suppression in space. It is a technology demonstration confirming that the technology is mature enough to fly. It demonstrates qualification of the piezos for launch and for space. Also, it demonstrates the design and qualification of low-power flight piezo drivers and control systems. Finally, a tactical stirling cooler is being operated in space in a very low powered environment. It is difficult 10 convince project managers that a ncw technology is ready to be used. The STRV- lb cryocooler experiment will speed up the application of these technologies by actually flying a cooler and piezo cooler vibration suppression, Any unexpected problems will already have been uncovered.

The STRV - 1 b cryocooler vibration control experiment is the first known adaptive vibration isolation experiment using PZT ceramics to fly in space. A similar JPL experiment using adaptive electrostrictive materials to provide for quasi static alignment of the Hubble optics[2] was flown in 1993 and successfully improved the Hubble optical performance. The STRV- 1 b experiment is one of four planned adaptive vibration control experiments funded by the Materials and Structures program in BMDO. The ACTEX 13, ACTEX 2[4] and the STRV-2 experiments will examine the performance of unimorph PZT sensors and actuators embedded in composite beams and ac[ivc/passive damping mechanisms for satellite vibration suppression and optical payload isolation and pointing. The ACTEX 1 and 2 experiments will be flown in 1995 and the STRV-2 experiment will be flown in 1997.

To increase redundancy and provide information about more than onc piezo actuator, two actuation methods were demonstrated: piezo translators and applique ceramics. Commercially available low voltage piezo translators displace the entire cryocooler to cancel the motion of the tip of the coldfinger. Motion is measured by three eddy current transducers. Also, high voltage (700 volts) applique ceramics arc bonded to the coldfinger and stretch it to cancel the tip motion. Two types of control systems were demonstrated for the same reason: a real-t imc analog control system and a digital feed-forward controller. Since a variety of techniques are being demonst rated, comparisons can be made between the techniques and informed choices can be made for other projects.

This is an ideal application for smart structures technology. The mot ions arc very small so commercial piezo actuators can be used. The motion along the coldfinger is primarily caused by the pressure driving the tip of the coldfinger. The two lateral directions exhibit a large amount of fifth harmonic of the drive signal. This is caused by the first lateral bending frequency of the coldfinger being close to the fifth harmonic of the drive signal. Both of these motions are steady state response so feed-ff~rward control can be used to eliminate the vibration. The waveform is repetitive so the control system can usc the waveform from an earlier period to cancel the mot ion. An adaptive control system must be used because the frequency and waveform changes as the heat sink temperature changes.

By del ivery day, winners and losers among the act uators and controllers were clear. The electronics for the high voltage ceramic applique were so difficult that time ran out try ing to implement them. Significant effort went into developing a reliable process to fabricate the applique.[5] The commercial translators were much simpler (o implement. The analog controller had to be designed to handle a single harmonic. in principal, a series of analog cent rollers could be designed that could handle more, however there wasn 't board space, t imc, or money. The design and circuitry effort for an analog controller were much simpler than the digital controller. However, the analog design had to be done after the mechanical plant was finished. In the end the flexibility of the digital design had clearly out performed the analog design.

Flight data has been very similar to ground test data for the fir st seven months. Over two hundred successful actuations of the digital control algorithm have been run. The digital controller reduces the vibration level down to the noise floor of the eddy current transducer. Similarly over 200 operations of the analog controller have been accomplished. The analog controller reduces vibration at the fundamental frequency by a factor of ten. Cooler operat ion has been verified down to 76 "K. Finally satellite acceleration levels with/without the cooler operating have been measured in space. These levels agree with ground measurements of the force levels put out by the cooler .('

A fcw difficulties existed at delivery and have continued into the flight. '1'here is a computer reset anomaly associated with a poorly shaped clock pulse. Delivery

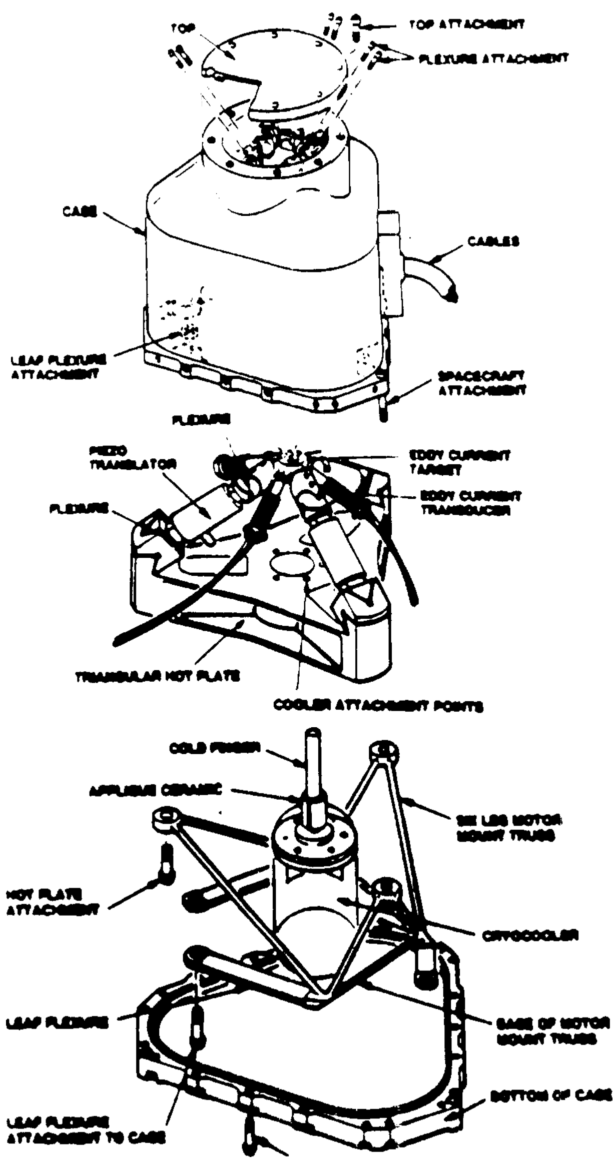


Figure 1. Mechanical Configuration

was late - the high voltage driver had to bc completed. The intermit tency was never adequately addressed. Another phenomenon was observed from space and tracked back to the ground test. The digital controller works well on the harmonic RMS in the control bandwidth but the wideband RMS docsn't go down as much as hoped. The bandwidth of the cent roller needs to bc wider to cover the frequencies of tbc cooler structural supports. On STRV - 1 b the support frequency was driven as high as possible so tbc analog controller would bc easy. It would bc easier and lighter to have the support frequencies lower. Unfortunately, it is too late to demonstrate this on STRV-1 b.

Mechanical Configuration

The mechanical configuration of the experiment is illustrated in Figure 1. The main active components arc the stilling cooler; three piezo translators, three segment applique ceramic actuators; and three eddy current transducers.

The 1/5 watt cooler is a commercially available unit that is part of a hand held, anti-tank system. The 6.35 mm (1/4 in) diameter cold finger was exchanged between the manufacturer and JPL before assembl y, Applique ceramic was bonded to the coldfinger and the coldfinger tip was modified to allow application of a gold plated eddy current target. The flight unit reached 95°K at 3.5 watts for a -20° C heatsink. For a 50°C heatsink it took 15 watts. Small size and low power consumption dictated the choice of coolers.

The high voltage (700 volts) applique ceramics were purchased commercially. Ceramic tubes were sawed into three segments using a diamond saw. Then the segments were bonded to the surface of the coldfinger using thread to insure the bondline thickness. During bonding the coldfinger was pressurized to the highest pressure the system would ever experience. Also, an oven cure was used above the maximum operating temperature. The pressurization and temperature insured a compressive preload on the ceramic sufficient to avoid tension (and cracking) in normal operat ion. Cooler assembly was made very difficult by the permanent deformation caused by the preload. As a result, the applique cracked down the length of the cylinder during the assembly process. After wiring around the cracks on the "wrap around" electrodes the ceramics performed as expected.

The low voltage (20 volts) piezo translators were relat ively easy to work with. They arc also a commercial product. Vacuum operation and temperature extreme options were used. One set of actuators was broken during a lab accident when high frequency wideband noise was sent into them at full amplitude. Also, grounding problems were encountered because the mechanical and electrical grounds were not sufficiently separated.

The eddy current transducers arc a commercial, non-cent acting system that measures to accuracies of about 10 nm over a small travel (±0. 127 mm and -10.005 in). The existence of a flight worthy miniaturized electronics board was a major consideration in the choice of systems. Hardware from the same purchase was subjected to electron beam radiation testing. There were DC shifts in the apparent position of the sensor duc to radiation. The gain was not significantly affected. Since the signal is AC coupled, the offset only limited the scaling used in STRV-1b.

in Figure 1 the main structural parts arc the case, the triangular hot plate, the motor mount truss, and the three mount ing ftcxurcs. Flexures arc used around the piezo transistors to avoid bending moments during launch. The piezo material is strong in compression but subject to cracking in bending or tension. The translators arc mounted in the shape of a 90° tetrahedron. This geometry insures that tile piezo stroke is effective in all three directions. Also, the translators and eddy current transducers arc mounted to a rigid ring in tbc case. This provides the mechanical ground plane. The hot plate is integrated with the cyrocooler and acts as it's thermal sink. in addition to the parts shown, 90 grams (0.2 lbs) of copper heat strap were added to move heat from the cooler to the case.

Electrical Configuration

The electrical configuration is shown in Figure 2. The processor is a UT69R000 rad-hard micro control] cr. Digital switches mapped into memory were used to switch between the analog/digital controllers and translator/applique act uators. Also, the programmable clock controlling the output frequency for the 12 bit ADC and DAC was memory mapped. The same clock drove the switched-capacitor filters for the analog controllers and ant i-al iasing fi lter for the accelerometer. Hardware double buffering was used for the DAC output buffer. The power amplifiers driving the low voltage translators (TI, T2, T3), high voltage ceramics (Cl, C2, C3) and cooler (C) caused the most problems.

Because of schedule and budget constraints, in the end, the hi.gh-voltage ceramics driver was flown without feedback on the high voltage stage. Also, the analog-control ceramic channel was never completed because it had a low probability of success without a high performance amplifier.

'f'he computer was selected for its radiation hardness. The architecture has a few idiosyncrasies. The boot address and hardware error entry arc both at address O. Any hardware error (or software jump to zero) causes the system to reboot. This can partially be overcome with a flag indicating the system has booted since the last hardware reset. Even with a flag, it would still be hard to separate software from hardware errors.

Unfortunately, the problem was just annoying on the ground. There arc adequate debug tools to find errors without core dumps. In space any hardware error throws all the diagnostic data away.

An additional idiosyncrasy is that the processor shift instruction doesn't handle shifts of zero length. A shift of "O" is left onc while a shift of "-l" is right 1. The lack of a zero shift (do nothing) makes sealing algorithms complicated. This can be overcome by writing a *shift* subroutine. Finally, the jump instruction automatically executes the next instruction. The assembler can be t old to add a NO}' (no operation, e.g., add zero to a register) after all jumps to handle this.

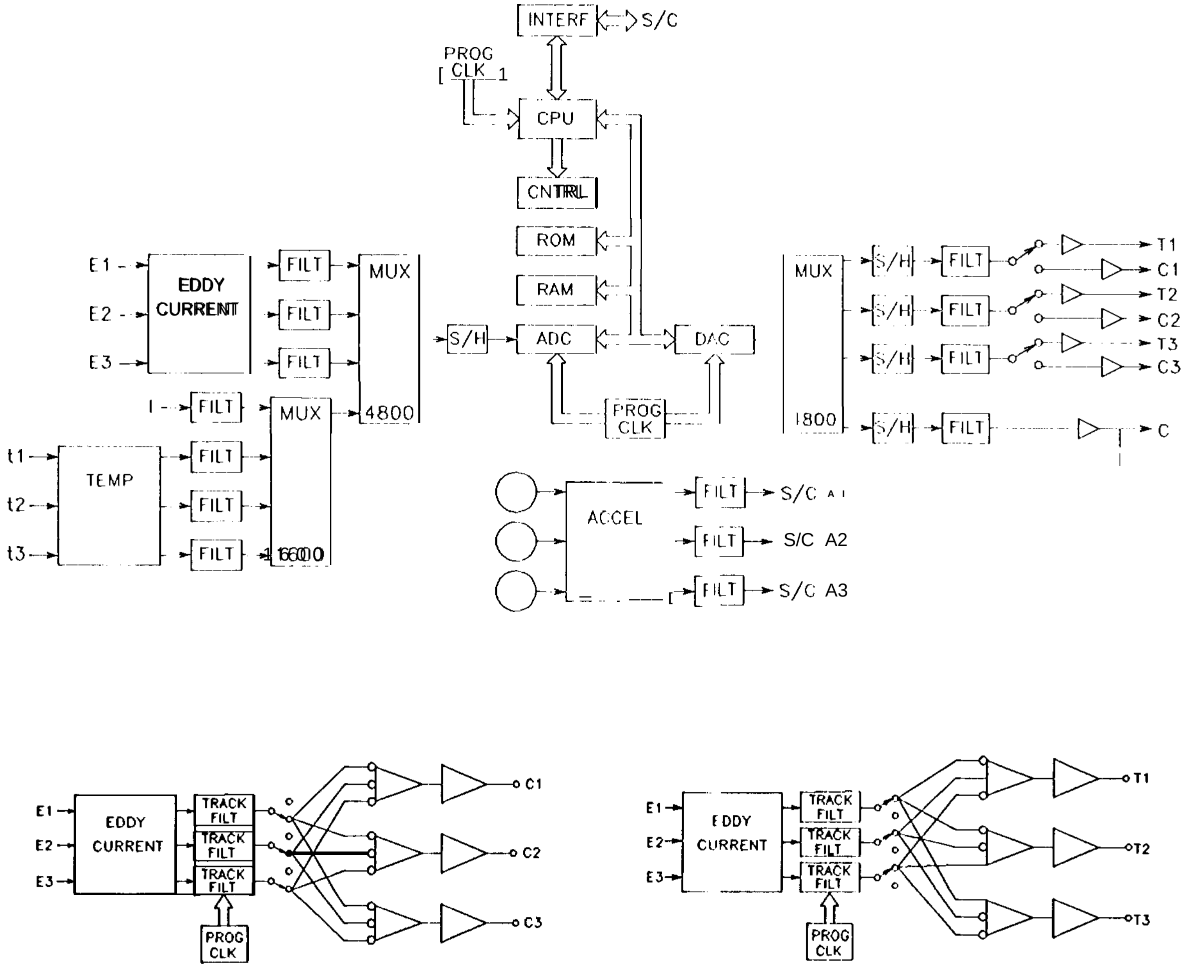


Figure 2. Electrical Configuration

Software

The computer had an assembler and linker but it lacks any compilers. The control algorithm had to be coded in assembly using *implied decimal point* integer arithmetic. This made the code compact (two versions fit in 8K of ROM). It also made coding very tedious. The algorithms were initially written in C. This code was spread out (still in C) so one assembly level instruction was on one line. Then the C was translated into assembly language by hand. There were still *numerous* debugging problems associated with the new assembly language and the new hardware.

The feed-forward algorithm used for the digital control takes advantage of the repetitive nature of the signal. The cooler operates at it's fundamental frequency around 62.5 Hz. The vibration is a steady state driven response so it occurs at the drive frequency. Thus the eddy current displacements are at the cooler frequency and all its harmonics (e.g., 62.5 Hz, 125 Hz, 187,5 Hz, . ..). The harmonics are present because there are non-sinusoidal forces inside the cooler. The harmonics are the only frequencies that need to be considered in suppressing the vibration. The drive signal required to cancel the vibration is a distorted sine wave with a period the same as the cooler drive signal.

initially, the experiment outputs pure tones at the harmonic frequencies to each actuator and measures the response at all three eddy current transducers. This measures the transfer functions between the actuators and sensors for the drive frequency based on the heatsink temperature. At each harmonic frequency this complex matrix is inverted (using Cramer's rule) producing a transfer function to calculate commands from eddy current readings.

The eddy current time histories arc converted to sine/cosine components in the frequency domain. Either the integral estimator or the least squares estimator lead to identical operations. The signal time history is multiplied by the sine/cosine at the frequency being estimated and summed over onc period. This sum is proportional to the sine/cosine harmonic component of the signal. Sine and cosine harmonic components arc interpreted as complex numbers using Euler's identity.

Sine/cosine values arc tabulated in a lookup table. Since tbc same buffers output the cooler drive and the vibration suppression, the sine table always requires the same time step and zero time.

The eddy current harmonics arc multiplied by the transfer functions calculated earlier, This produces command harmonics to update the time-domain command waveforms using the sine table lookup. Exponential smoothing and *long* time delays have to be added to slow the process down. Hardware t ransicnts from the change have to die down before more updates arc attempted.

These commands arc output continuously by the buffers until the next t imc the waveform is updated. The computer speed requirement is minimal, The algorithm has to be dramatically slowed down (e.g., 20 buffer cycles) to let the phase angles stabilize in the physical hard ware. The algorithm is not dependent on the hardware dynamic characteristics. The software can be prepared in parallel with the hardware,

Trade Study Results

The experiment was intended to compare digital/analog control and translators/applique actuators. Analog control is bet t cr for *mechanical engineering students* because of the cost is low and there is less to learn. Digital control is better for *flight projects* because the control design can be done in parallel with the mechanical design. Digital control is more adaptable than analog control. Besides, there has to be a digital system to talk to the system computer.

The applique ceramics arc light and cheap. However, installation has to he developed as a process. Many issues must be rcscarchcd: the choice of adhesive, the bond line thickness, bonding procedures, insulation between the segments, cleaning procedures, soldering procedures, and so on. The applique used on STRV- 1 b was high voltage. It is difficult to usc high voltage on spacecraft.

The ceramics arc more favorably located than the translators. The appl iquc t ransfer functions only involve coldfinger dynamics. The ceramics arc good insulators and don't hurl the cooler performance significantly. On the down side they do have significant heat capacity and this makes thermal steady state hard to reach. The flight cooler operated for 8 hours in the lab one time trying to reach steady state. Temperatures were still oscillating. Also, electrical ground is separated from mechanical ground by a thin glue line.

The translators arc more easily worked with. The cooler mount has to be *designed* to allow cooler motions. Also, the translators require flexures and a heavy case. The translator transfer functions involve the cooler mounting dynam its. 1 lowever, the translators arc low voltage. On spacecraft this is an overriding advantage from an electrical point of view.

It is possible to buy low voltage piezo stacks that resemble an applique, This device would be better for mass production where the added cost of development can be amortized over many units.

Based on STRV- 1 b there may be one synergistic effect. It should be possible to design a real-time wideband analog control system using the applique approach because the coldfinger resonant frequencies arc high and widely separated. The applique is most effective in the lateral directions. These arc the directions associated with jitter for an optical/IR sensor attached directly to the coldfinger. A controller like this could be designed as soon as the pressurized cold finger dynamics arc known. There arc major differences in coldfinger dynamics between the coldfinger tube and the final assembled coldfinger.

Digital/Translator Results

The most successful results from STRV-1b have used the digital control system with the low voltage translators. Typical performance is indicated in Figure 3 showing the reduction in harmonic RMS with time. The harmonic RMS is defined as the RMS sum of the eight control harmonics. The figure illustrates this result for each of the thı cc eddy current t ransduccrs, At time zero, the cooler has been slowly brought to full stroke and is starting cool down. The digital controller is turned on and the eddy current displacements are attenuated rapidly.

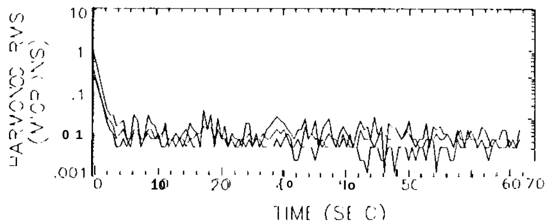


Figure 3. Component Harmonic RMS Using Digital Control/Translators

The displacement is controlled in 3D. The harmonic vector displacement can be calculated by taking the RMS of the three eddy current transducers at each time point. This amplitude starts around 1.5 microns.

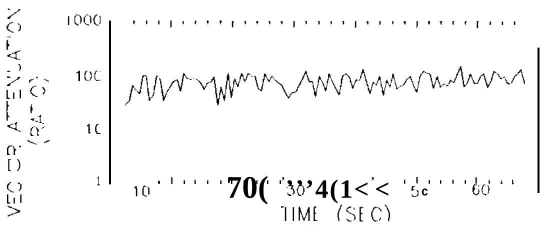


Figure 4. Vibration Attenuation Using Digital Control/Translators

Dividing by the amplitude at time zero, the amplitude attenuat ion can be plot [cd as shown in Figure 4. The average attenuation has been between 75 and 80.

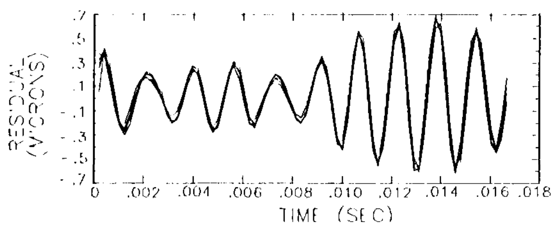


Figure 5. Residual Time History Over Onc l'cried

The wideband RMS t imc histories have been disappoint ing. They only go down by a factor four. Residual lime histories have been downloaded and examined to discover the nature of tbc vibration signal that remains. The residual time history is the signal coming from the eddy current transducers after the control has been t urned on. Figure 5 illustrates this result for the largest channel. The time axis is exactly onc period of the fundamental drive frequency for the cooler. Residual time histories from different times have been superimposed in Figure 5 to show that the system is near steady state. The residual is dominated by higher harmonics above the last control frequency at eight times the fundamental.

To discover the source of the residual (e.g., the controller or the cooler), the controller was commanded to only control six harmonics instead of eight. The residual was still dominated by harmonics above the eighth harmonic. This indicates that the cooler is driving the higher harmonics and the controller bandwidth needs to be extended still further to attenuate the wideband RMS successfully.

The controller bandwidth needs to extend past the cooler support frequencies. There is significant unbalance force at harmonics wc]] up into the frequency spectrum. The cooler support frequencies arc excited by these forces. On S1 RV- 1 b the support frequencies were made as stiff as practical. It was felt that higher support frequencies would help the cent rol system. It is clear from STRV-1b results that the support frequencies cannot be made high enough. The controller will have to handle considerably higher frequencies,

The STRV-1b electronics sampling rate is 4800 Hz. This frequency was picked to give ten points on the waveform for the output signal. The Nyquist folding frequency is 2400 Hz or the 40th harmonic. The hardware is capable of controlling higher frequencies. Unfortunately, due to schedule constraints at the end of tbc program and complete debugging of the software was not possible. At this point the maximum harmonic that can be controlled is eight duc to software limitations on array dimension sizes.

Analog/Ceramic Results

While the ceramic app] iqucs have not worked well on the satellite, they did on the ground using the breadboard analog, cent rol electronics, The high voltage amplifiers used for the breadboard were three large (25 lb each) colnnwrcial-amplifiers. They plugged into the wall and used vacuum t ubc technology,

The measured open loop transfer function for onc channel of the analog controller is shown in the top figure of Figure 6. The analog control circuit from Figure 2 was opened at the edd y current transducers outputs.

The pass band is the area of the "control channel" curve above unity gain. in this area there is significant feedback canceling any disturbance. At frequencies away from the pass band the gain is less than unity and the control system doesn 't change the plant. Each bandpass filter channel is designed to suppress the motion of onc of

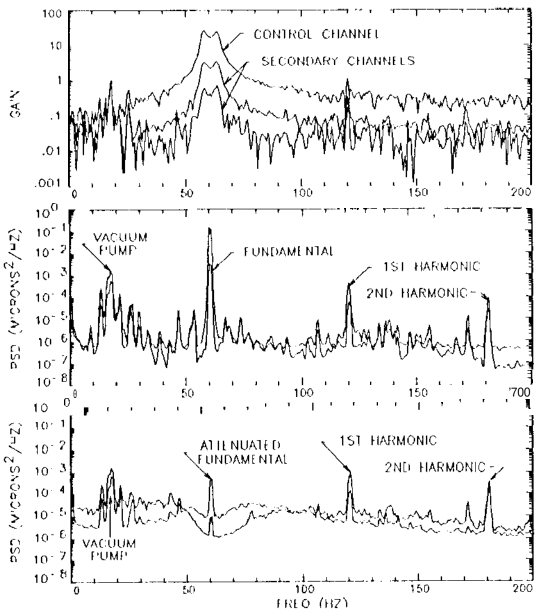
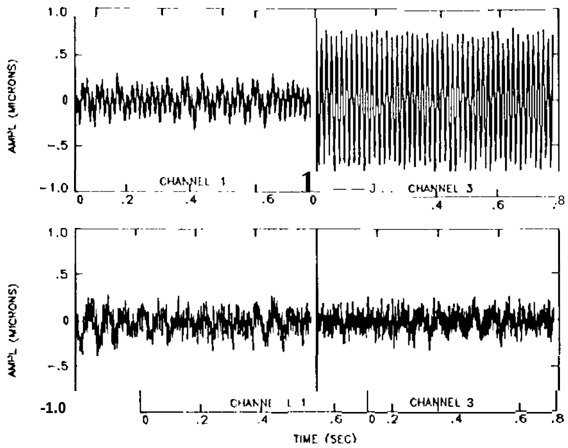


Figure 6. Analog Controller Frequency Domain Performance

the three eddy current signals. In the example, all three ceramic applique segments arc activated such that the coldfinger tip moves directly towards the number 1 eddy current transducer. The other two curves in the top figure from Figure **6** are the measured outputs from the other two eddy current channels. If the displacement to translation circuits were perfect, both channels would read at noise level, however, this accuracy is not really required.

The bottom two figures from Figure 6 show the closed , loop results. The middle figure is a power spectral density (PSD) for all three eddy current transducers with the cent roller off. Turning the cent roller on, the same PSD results arc shown in the lower figure. The controller reduces the fundamental by a factor of 400 in PSD or approximately a factor of 20 in response. The transfer functions for the other two filters arc similar to the onc illustrated.

This result is more dramatic in the time domain, as shown in Figure 7. The time histories for the largest two channels arc shown (channel 1 and channel 3). The top figures were taken with the control system off, Channel 3 is dominated by the fundamental frequency. The bottom figure illustrates the results with the control system turned on. The content of the fundamental frequency for both channels has been dramatically reduced. Of course, the other frequencies are still there since the controller docsn't address thcm.



I 'igure 7. Eddy Cur-rent Ilcforc/After Analog Control

Accelerometer Results

A triaxial accelerometer was flown attached to the cryocooler mechanical ground. This acceleromet er measures the gross motions of the satellite in response to the unbalance forces from the cooler. Dynamometer tests on the ground suggested that the unbal anccd force would have an amplitude of about 1 lb_f. The mass of the satellite is about 120 lb so the acceleration expected is 0.008 g at 60 Hz. This is a displacement of 0.5 microns at 60 Hz.

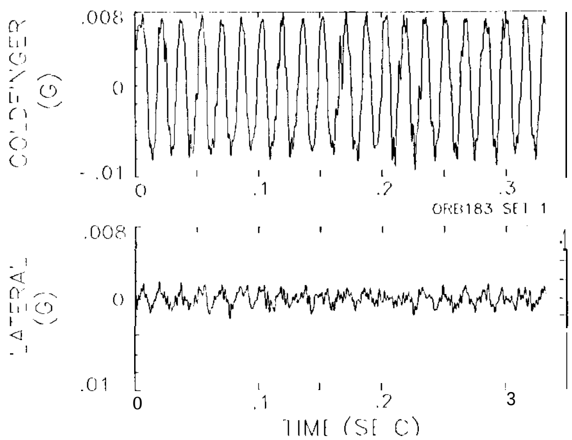


Figure 8. Satellite Accelerations Caused by the Cryocooler

The n ıeasured data from the satellite is shown in Figure 8. The satellite acceleration in the direction of the cooler coldfinger is shown labelled coldfinger. Onc of the two accelerations perpendicular to the cold finger is shown labelled lateral. Roth lateral accelerations arc very similar.

Cooler Results

To demonstrate that the cryocooler is operating correctly, cool clown curves have been generated on the satellite. Figure 9 illustrates these results for cooler strokes of one-half full amplitude and for full amplitude. The full amplitude cool down was done as a continuation of another cool down. This accounts for the major difference in slope between the two curves at the coldfinger temperature threshold,

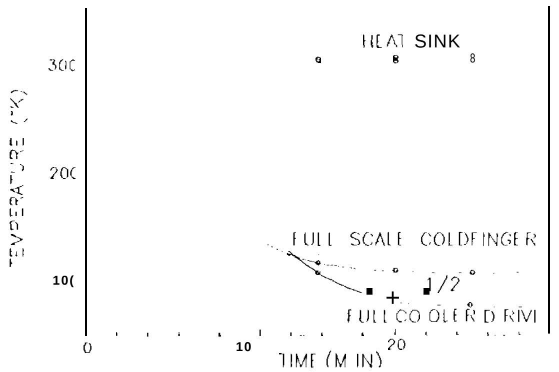


Figure 9. Cool Down Curves From the Satellite

Conclusions

STRV-1b has been a highly successful flight demonstration of piezo translator/applique ceramic actuators and also analog/digital control systems. STRV-1b has demonstrated the feasibility of using piezo materials for vibration suppression in space by making the tip of the coldfinger stand still.

In the process STRV-1b has flight qualified piezos for launch and for space. To the authors' knowledge, this is the first use of piezo electric materials for vibration suppression in space. There wasanearlier experiment cm the Hubble wide field planetary camera using piezo resistive technology in a jitter mirror.

The experiment designed and qualified low-power flight piezo drivers. The amplifiers have to drive large capacitive loads. Amplifier turned out to be a significant problem. More can be done to customize the electronics for piezo applications.

The adaptive feed-forward control algorithm and the control hardware used on STRV were designed for cryocoolers. By using the same buffers to control the cooler and the vibration suppression, phase synchronization between the cooler and vibration suppression is guaranteed. The hardware/software provides an easy answer if the frequency of tbc cooler has tobe adjusted while the controller is on. The algorithm used requires very little computation,

STRV-1b operated a tactical stirling cooler in a very power starved spacecraft. The cooler can only operate for about an hour with the existing spacecraft batteries. This may have future applications with the move towards miniaturized spacecraft.

Two unexpected problems were uncovered. Electronics for the high voltage ceramic applique were so difficult that time ran out trying to implement them. The use of high voltage needs to be minimized on spacecraft.

The second problem was that the vibration controller bandwidth must extend past the cooler support frequencies. A major effort was made to make the cooler supports very stiff. The first frequency of the experiment is about 420 Hz. The idea was to stiffen the supports enough that the analog control system would not have stability problems. Instead, the frequencies driven by the cooler moved out near the support frequency. Increasing the support frequency made the problems harder to deal with. The controller should extend past the support frequencies until the support isolates the cooler. For motion suppression, the harmonics have to extend out until the motion is stopped

Acknowledgment

The authors would like to acknowledge the large number of individuals who contributed significantly to the STRV cryocooler experiment. The British satellite builders and flight controllers were very competent and helpful. The French Ariane went off without a hitch. In the United States, the Deep Space Net (DSN) provided emergency backup support when required. The experiment team at JPL worked exceptionally long hours under tremendous schedule pressure to bring the experiment to a successful conclusion.

The work described in this paper wascarried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Ballistic Missile Defense Organization/Air Force Phillips Laboratory through an agreement with the National Aeronautics and Space Administration.

References

1. Ryden, K. A., "The Space Technology Research Vehicle (STRV - 1)," Proc. Roy. Acre. Sot. Conf. on Small Satellites, Culham Laboratory, UK, January 24, 1991,

2. Fanson, J. L., "On the Usc of Electrostrictive Actuators in Recovering the Optical Performance of the Hubble Space Telescope," *Materials for Smart Systems*, Materals Research Society, Boston, MA, 1994.

3. Manning, R. A., Wysc, R. E., and Schubert, S. R., "Development of an Active Structures Flight Experiment, " Proceedings of AIAA Design Conference, Irvine, CA, February 16-19, 1993.

4. Nyc, T., Castecl, S., Navarro, S., and Karaml, B., "Experiences wi(h Integral M icroelectronics on Smart Structures for Space, " Smart Material and Structures Conference, Paper No. 2448-21, San Diego, CA, February 1995.

5. Kuo, C. P., "Coldfinger Motion Suppression Using a Ceramic Applique," Proceeding of SPIE' Smart Structures and Materials Conference '93, Albuquerque, NM, January 31-February 4, 1993.

6. Glaser, R. J., Ross, R. G., and Johnson, D. L., "STRV Cryocooler Tip Motion Suppression, " Proceeding of 8th international Cryocooler Conference", Vail, CO, June 28-30, 1994.