

## CRYOCOOLER TIP MOTION SUPPRESSION USING ACTIVE CONTROL OF PIEZOELECTRIC ACTUATORS

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### ABSTRACT

Under Strategic Defense Initiative Office (SDIO) sponsorship the Jet Propulsion Laboratory is developing a flight experiment to demonstrate advanced control technologies for quieting cryocooler tip vibration in three axes. The experiment is scheduled to fly as a small 15-watt payload on the Space Technology Research Vehicle (STRV-1b), a small English satellite scheduled for launch on the Ariane-4 in late 1993. To meet stringent power, weight, and space constraints, the experiment makes use of a tiny 1/5-watt 80K Texas Instruments tactical Stirling cooler. Two different vibration-cancellation actuator techniques are being demonstrated: 1) an applique ceramic piezoelectric actuator set that is bonded to the coldfinger and stretches the coldfinger to cancel tip motion, and 2) a commercial low voltage piezoelectric translator set that similarly cancels tip motion by moving the entire cryocooler in three axes. Motion of the coldfinger tip is measured in all three axes to 10 nanometer accuracy using eddy-current transducers. Two types of control systems are also being demonstrated: 1) an adaptive feed-forward digital control system that continually updates the harmonic content of the steady-state command signal to each actuator to cancel the tip vibration, and 2) an analog control system that uses a bandpass filter to track the drive signal and suppress it. Either control system can be used with either actuator system.

### INTRODUCTION

If uncompensated, the moving parts and pressure pulses within the compressor and displacer of a Stirling-cycle cryocooler can create considerable mechanical vibration that can adversely affect the performance of a precision space-science instrument. This vibration can consist of either the transmission of vibration forces from the cryocooler into the instrument via the cooler supports, or vibratory motion of the tip of the cryocooler coldfinger relative to the instrument optical bench; this latter category--cold tip motion--is particularly important for applications where the detector is directly mounted to the cooler cold tip.

Considerable progress has been made in recent years using momentum compensated, back-to-back coolers together with active vibration control systems to minimize the level of transmitted vibration force [1,2,3]. However, much less emphasis has been placed on the challenge of cold tip vibratory motion suppression.

There are two fundamental manifestations of cold-tip vibratory motion: 1) motion of the coldfinger cold-tip relative to the base of the cold-finger, and 2) motion of the overall cryocooler including the coldfinger. The largest component of the cold-tip relative motion is caused by mechanical distortion of the cold finger caused by the large sinusoidal pressure variation (typically around 300 psi peak-to-peak) that is output from the cryocooler compressor. This cyclic pressure loading, which is fundamental to the Stirling-cooler operation, results in the cold finger undergoing cyclic elongation along its longitudinal axis, and can lead to lateral bending of the cold finger if the wall thickness of the cold-finger is not uniform around its circumference. The lateral motion is also amplified by the natural cantilever-bending-mode resonances of the coldfinger.

As shown in Fig. 1, the resulting motion of the coldfinger tip is often on the order of one to two microns in the longitudinal (Z) axis, and is somewhat less in the lateral (X,Y) directions [4]. Notice the high level of fifth harmonic in the lateral vibration in Fig. 1; this is caused by the first lateral bending frequency of the coldfinger being close to the fifth harmonic of the 60-Hz drive signal. Thus, the high frequency lateral response is considerably amplified by the lateral modal response of the coldfinger.

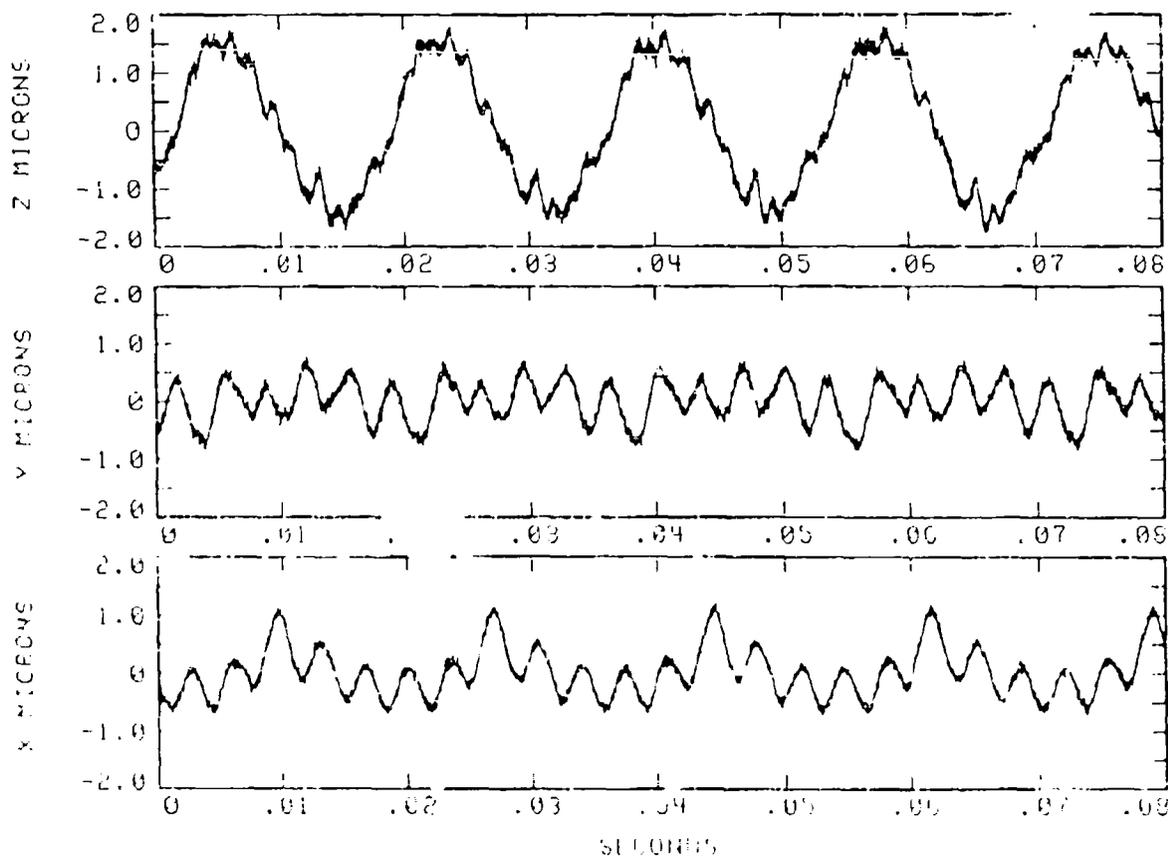


Fig. 1 Typical measured cold finger tip motion

### FLIGHT EXPERIMENT OBJECTIVES

The primary objective of the JPL STRV cryocooler vibration suppression experiment is to demonstrate the applicability of piezoelectric motion suppression technology to the problem of cryocooler cold-tip motion suppression. In addition to gathering engineering data on the performance of the unique control-system features, the experiment will also provide a flight-heritage ensuring that the technology has successfully dealt with the important spacecraft interface issues including launch survivability, tolerance to operating temperatures, EMI compatibility, and radiation hardness: in short, successfully building a flight experiment demonstrates that the technology is mature enough to fly. It is expected that the availability of successful flight data will speed the adoption of these technologies by future applications, as unexpected problems will already have been uncovered. Since a variety of techniques are being demonstrated, comparisons can be made between the techniques, and informed choices can be made for future projects.

In addition to the primary objectives for the experiment, there are also two secondary objectives: one is to measure the vibration of the satellite resulting from the operation of the cryocooler; the second is to provide a cryogenically cooled environment for a two-pixel IR-detector experiment mounted to the coldfinger tip. The IR experiment involves measuring the detector dark current as a function of the integrated radiation exposure as the satellite passes through the Van Allen belts. With the limited power of the STRV-1b satellite, the longest duration of continuous cooling is likely to be a period of a few days when the satellite is in continuous sunlight.

### SPACE TECHNOLOGY RESEARCH VEHICLE (STRV-1B)

The STRV-1b is a small 50-kg British Royal Aerospace Establishment (RAE) satellite [5] being designed to fly on a French Ariane-4, and will be placed into a geostationary transfer orbit that involves passing through the Van Allen belts twice per 10.5-hour orbit. As a result, the satellite will receive approximately 100 krad/yr radiation exposure at the outside of its structure, and will have a design life of one year.

The satellite is about the size of a PC computer (480×480×400 mm), is spin stabilized at 5 rpm, and uses a nutation damper and a magnetorquer to maintain spin stabilization. Power, which is extremely limited, is provided by solar cells on the surface of the satellite. Temperature control is entirely passive, with the internal payloads designed to operate between -50°C and 50°C.

Communications are provided by the RAE from Farnborough with a capability of 125 bits/sec uplink and 1000 bits/sec downlink. Data storage is limited to 50 kbytes of data and 30 kbytes of commands.

The mechanical part of the cooler experiment is allocated 1.75 kg of mass. In addition to the cooler, the total JPL STRV experiment includes an electronics box containing three radiation exposure experiments and the cooler electronics. This electronics box is allocated 4.75 kg of

mass and  $400 \times 150 \times 75$  mm of space. The radiation exposure experiments are a chip sized radiation monitor, an advanced IR detector, and a neural net chip. The STRV also contains a European radiation-environment monitor, a solar cell technology experiment, laser reflectors, and several technology items incorporated into the basic satellite design.

In one respect the STRV-1b satellite provides an ideal testbed for a hardware demonstration because the demanding constraints of its environment should encompass most future applications of vibration suppression technology. There is very little power, space, weight, or data storage. In addition, the thermal and radiation environments are very severe.

### CRYOCOOLER EXPERIMENT MECHANICAL DESIGN

Figure 2 illustrates the hardware elements of the experiment. These include:

- Texas Instruments 1/5-watt 80K tactical Stirling cooler
- Physik P-842.10 low voltage piezo translators
- $120^\circ$  tubular segments of Vernitron PZT5H applique ceramic bonded to the coldfinger
- Kaman SMU 9200-15N eddy current displacement transducers
- Lake Shore Cryotronics PT-111 platinum thermometers
- Kistler 8692B5M1 triaxial accelerometer
- Assorted structural elements including thermal mounting plate, motor-mount truss, titanium flexures, housing, housing bottom, and non-flight lid

The Texas Instruments 1/5-watt 80K tactical Stirling cooler is a back-to-back, dual-piston, linear-drive compressor with integral displacer mounted orthogonal to the compressor piston axis; this balanced, dual-piston cooler achieves a low vibration level below 5 N.

The cooler weighs 380 grams without electronics and is about 100 mm long by 40 mm in diameter. The coldfinger is about 70 mm long and 6.35 mm in diameter. In the experiment, the cooler will be operated with a cold-tip temperature of 95 K; this will require between 3.75 and 5.75 watts of input power, depending on the heatsink temperature between  $-32^\circ\text{C}$  and  $50^\circ\text{C}$ . The cooler is not designed to operate at heatsink temperatures below  $-32^\circ\text{C}$ .

### Piezoelectric Actuator Design

Two different vibration cancellation actuator techniques are being demonstrated in the experiment: 1) an applique ceramic piezoelectric actuator set that is bonded to the coldfinger and stretches the coldfinger to cancel tip motion, and 2) a commercial low voltage piezoelectric translator set that similarly cancels tip motion by moving the entire cryocooler in three axes.

In the first actuator technique a set of three ceramic appliques is used to stretch the coldfinger itself to cancel the cold tip lateral motions as well as the longitudinal motion. The process for

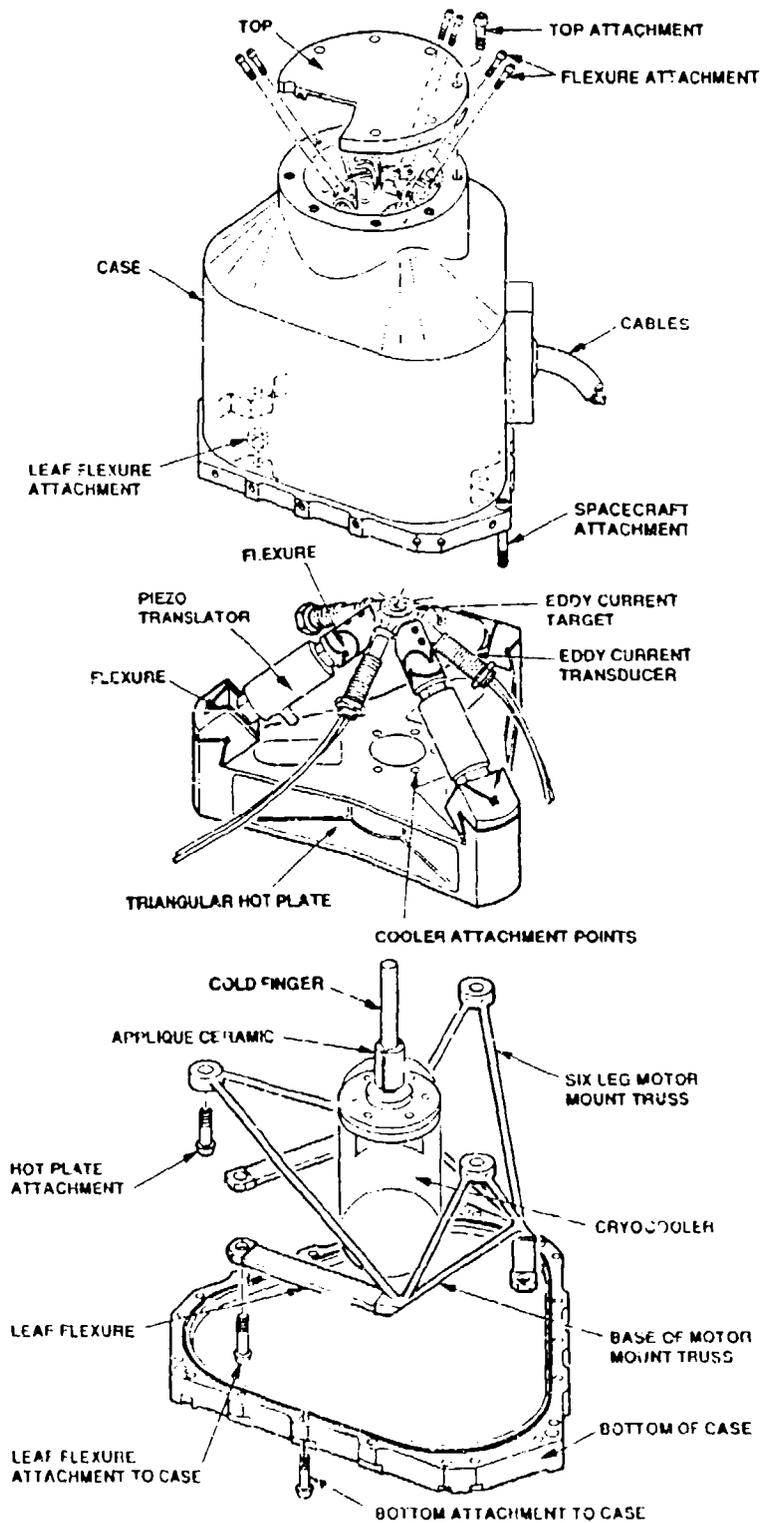


Fig. 2. Mechanical components of cryocooler vibration suppression experiment.

fabricating and using the applique ceramics was developed as part of the flight experiment.

The ceramic length (25.4 mm), thickness (1 mm), voltage (500 volts), and material (Vernitron's PZT5H) were selected to optimize the applique performance. The ceramic tube is cut into three parts using a diamond saw, and is bonded to the coldfinger using Hysol 9396. The bond line thickness is 0.0254 mm and is maintained with glass fiber threads uniformly wrapped around the coldfinger. During the bonding process, the specimen is clamped along its entire length between two precision-machined circular clamps. The clamp is designed to leave just enough room for the ceramic and bond-line without causing deformation. The coldfinger is also pressurized to 68 atm and raised to 93°C throughout the 1-hour bonding process. Conducting the bonding operation while pressurized and heated preloads the ceramic in compression upon cooling; this helps ensure that the ceramic will not be placed in tension during normal operation.

In the second piezoelectric actuation technique, three Physik P-842.10 low voltage piezo translators are used to move the entire cooler to cancel the tip motion. These piezos are designed to move 18  $\mu\text{m}$  at 120 volts, but are being operated at 32 volts to provide 4.8  $\mu\text{m}$  of motion. The actuators have been preloaded to 450 N to prevent the translators from experiencing tension during launch. The capacitance of these actuators is 1.8  $\mu\text{F}$ , and the power consumption is expected to be about 0.1 watts per actuator.

#### Eddy-Current Motion Sensing

To provide the necessary cold-tip motion feedback to the control system, motion of the coldfinger tip is measured in all three axes to 10 nanometer accuracy using eddy-current transducers. The Kaman SMU 9200-15N eddy-current transducers are a non-contacting method of precisely measuring the distance between an aluminum target attached to the coldfinger tip and the cryocooler experiment structural housing. The units have the additional advantage that their signal processing electronics are very small (about 5 cm by 5 cm of board space) and consume very little power (about 0.1 watts/channel). Although some penalty in sensitivity was accrued, the distance between the eddy-current transducer and the target was opened up to 0.5 mm to maintain sufficient clearance for launch. More clearance would be needed if the support structure was not as stiff as it is. The cooler supports (including the piezo translators) are designed to maintain the first-mode resonance above 400 Hz.

In another aspect of the transducer selection and operation, there was initially concern that the eddy-current electronics would suffer degradation due to the severe radiation environment. Subsequent testing revealed significant shifts in the DC measurement over the radiation range expected in flight. However, the AC gain of the device was not sensitive to radiation. As a result of these tests, and to increase tolerance to differential thermal expansion motion, the eddy-current transducers were AC coupled for this application.

#### Thermal and Vibration Instrumentation

To measure the temperature of the coldfinger and the heatsink, Lake Shore Cryotronics PT-111 platinum thermometers were selected based on their good radiation resistance [6]. Custom

electronics were developed to operate the thermometers in pulse mode so that current will only be applied to the thermometers when measurements are being made.

Finally, a Kistler 8692B5M1 triaxial accelerometer was selected to measure the very small acceleration levels associated with the cooler vibration. The expected vibration force--of the order of 5 N--will move the 50 kg spacecraft approximately 0.01 g at the cooler drive frequency of 60 Hz. The accelerometer was selected based on its good sensitivity and low power consumption. Again, custom electronics were developed to operate the accelerometers in the STRV environment.

### VIBRATION SUPPRESSION ELECTRONICS

Two types of control systems are being demonstrated in the STRV vibration suppression experiment: 1) an adaptive feed-forward digital control system that continually updates the harmonic content of the steady-state command signal to each actuator to cancel the tip vibration, and 2) an analog control system that uses a bandpass filter to track the motion signal and suppress it. Either control system can be used with either of the above two piezoelectric actuator systems. A block diagram of the overall experiment electronics is presented in Fig. 3.

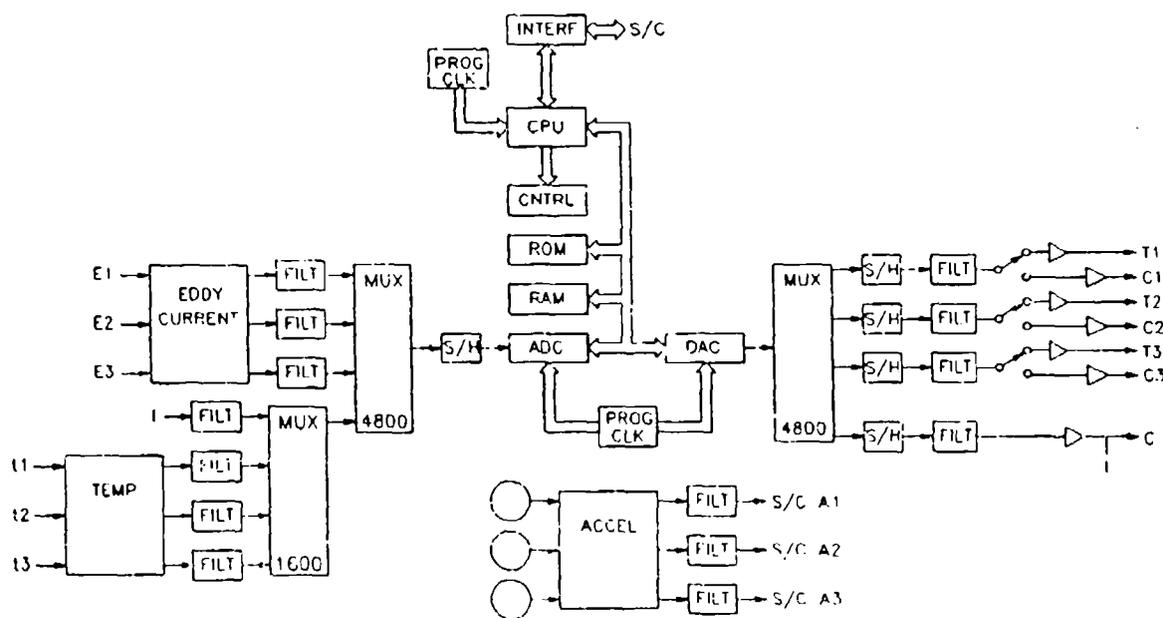


Fig 3. Block diagram of the vibration-suppression experiment electronics.

Digital Adaptive Feed-forward Control

The three-axis, digital adaptive feed-forward control system is based on the control of four signal generators: one 80-point digital waveform generator outputs a sinusoid to the cooler at the fundamental 60-Hz cooler drive frequency; the other three 80-point waveform generators output harmonic waveforms of the drive frequency to the piezo actuators and are adjusted to exactly cancel the cold-tip motion. The central processor unit (CPU) is used to setup the waveforms initially, and to update the waveforms to reflect gradual changes in the cooler transfer functions over time (approx. 1/3 second per update).

At the start of cryocooler operation, the waveform buffers are loaded with arbitrary sinusoidal command signals, and the change in the cold-tip displacement signals is measured. This provides the transfer function between the cooler drive electronics and the resulting cryocooler cold-tip motion. The resulting system of equations is then solved for the command signals that will cancel the vibration. From this point on, the system continuously updates the transfer functions and the command signals to cancel the tip motion. Corrections are always made one channel at a time. This allows the effect of the change on the three eddy-current transducers to be isolated.

Once underway, the CPU is not directly involved in operating the waveform generators. The waveform generator front-end continuously outputs the waveforms from the circular buffers. This is done using direct memory access (DMA) from the CPU to avoid bus contention between the four channel waveform generator and the CPU. Internally the memory is double buffered. One buffer is accessed by the DMA while the other buffer is accessed by the CPU. Switching between buffers is commanded by the CPU and occurs on the next frame boundary.

To drive the cooler and actuators, a programmable clock cycles through the data, converting the digital waveforms to volts with a 12-bit digital-to-analog convertor (DAC). The DAC output is demultiplexed and held with a sample-and-hold. The four sample-and-hold signals are filtered and amplified to drive the cooler and the vibration-suppression actuators. This electronics is illustrated on the right side of Figure 3.

To obtain the motion feedback signal, three eddy-current transducers are multiplexed and held for the ADC by a sample-and-hold. Again, access to the bus is managed using DMA to avoid bus contention. Also, the input data is double buffered in the same manner as the output data. Both the input and output buffers switch together, with one command, to keep the data synchronized.

The software extracts drive-harmonic amplitudes from the eddy-current signals using a curve-fitting procedure based on Equation 1. This deceptively normal-looking set of definitions hides the basic difference between a harmonic analysis and a general Fourier analysis. Normally there is no period,  $\lambda$ , for the signal to repeat, and the length of acquired data is arbitrary. In a harmonic analysis, the length of data acquired,  $n_s T$ , is one period,  $\lambda$ .  $T$  is the time between samples and  $n_s$  is the number of points in the buffer. In the STRV case,  $n_s = 80$  (10 points on 8 harmonics),  $\lambda \approx 1/60$  seconds,  $T \approx 1/4800$  seconds ( $60 \text{ Hz} \times 10 \text{ points} \times 8 \text{ harmonics}$ )<sup>1</sup>.

$$\text{signal}(t) = \sum_{m=1}^8 S_m \sin\left(\frac{2\pi m}{n_b T} t\right) + C_m \cos\left(\frac{2\pi m}{n_b T} t\right)$$

$$S_m = \frac{2}{n_b} \sum_{i=1}^{n_b} \sin\left(\frac{2\pi m}{n_b} i\right) \text{signal}(iT) \quad m = 1, 2, \dots, 8 \quad (1)$$

$$C_m = \frac{2}{n_b} \sum_{i=1}^{n_b} \cos\left(\frac{2\pi m}{n_b} i\right) \text{signal}(iT) \quad m = 1, 2, \dots, 8$$

Once the harmonic drive amplitudes have been determined using Equation 1, the change in the eddy-current signal ( $D_i$ ) from the previous time is calculated, and the ratio of the change in eddy-current signal to the change in command signal ( $C_i$ ) is calculated. This is done using Equation 2.

$$\frac{\partial D_k}{\partial C_j} = \frac{\Delta D_k}{\Delta C_j} = \frac{(C_n(k) + i S_n(k)) - (C_o(k) + i S_o(k))}{C_c(j) + i S_c(j)} = \quad (2)$$

$$\frac{[(C_n(k) - C_o(k)) C_c(j) + (S_n(k) - S_o(k)) S_c(j)] + i [(S_n(k) - S_o(k)) C_c(j) - (C_n(k) - C_o(k)) S_c(j)]}{C_c(j)^2 + S_c(j)^2}$$

In Equation 2, the subscript n means now, o means old, and c means command. The partial derivatives derived in the above process are next entered into Equation 3:

$$\begin{Bmatrix} \Delta D_1 \\ \Delta D_2 \\ \Delta D_3 \end{Bmatrix} = \begin{bmatrix} \frac{\partial D_1}{\partial C_1} & \frac{\partial D_1}{\partial C_2} & \frac{\partial D_1}{\partial C_3} \\ \frac{\partial D_2}{\partial C_1} & \frac{\partial D_2}{\partial C_2} & \frac{\partial D_2}{\partial C_3} \\ \frac{\partial D_3}{\partial C_1} & \frac{\partial D_3}{\partial C_2} & \frac{\partial D_3}{\partial C_3} \end{bmatrix} \begin{Bmatrix} \Delta C_1 \\ \Delta C_2 \\ \Delta C_3 \end{Bmatrix} \quad (3)$$

By inverting the matrix, Equation 3 is solved for the change in command signal needed to cancel the measured eddy-current displacements. Only one command is solved for at a time, using Cramer's rule. If more than one command is updated, it is not possible to identify which part of the change is caused by which command.

### Analog Control

To assess the relative advantages of digital and analog vibration control systems, the STRV experiment also includes an analog cold-tip motion control system based upon feeding back the eddy-current signals to adjust the command voltages to cancel the cold-tip displacements.

The feedback-system parameters are derived empirically, based upon measured properties of the complete cooler system. This is done by commanding a voltage on each command line, and measuring the resulting eddy-current displacements. This provides the parameters for a system of equations, similar to Equation 3 above, that can be inverted to provide the resulting coefficients for the analog circuit.

Unfortunately the equations for the ceramic appliques are not the same as for the piezo translators. For this reason, the control system must switch between the two systems of equations, depending on the actuators being used.

In order for the analog system to remain stable, the frequency content of the closed-loop circuit must be limited. The first structural flexibility of the system is expected to be the lateral bending of the coldfinger around 300 Hz. The next highest mode is a 420-Hz bounce mode where the cryocooler bounces on the translators. Around these frequencies the phase of the eddy current displacement will change significantly from the rigid-body response characteristic that predominates near the 60-Hz cooler drive frequency. As a result, the control system must be carefully designed to avoid instabilities at these frequencies.

Initial attempts to use a simple cutoff filter to achieve the necessary stability margin were unsuccessful. As a result, the final system design uses a system of tracking filters tuned to the drive frequency. These are implemented with switched-capacitor filters driven from the digital programmable clock.

### Cryocooler Drive Electronics

During operation, the electrical drive of the cryocooler compressor is also controlled by the digital controller electronics; this guarantees frequency and phase locking between the two systems. The cryocooler drive control includes closed-loop control of the cold-tip temperature, and closed-loop control of the cooler drive frequency to obtain maximum drive motor efficiency. This maximum motor efficiency is achieved if the cryocooler is operated at its mechanical resonant frequency, which also corresponds to the point where the cooler drive current and voltage are in phase (unity power factor).

Based upon cold-tip and heat-sink temperature measurements, the temperature controller works on a simple dead-band principle whereby two temperature limits (e.g., 94.75 K to 95.25 K) are established. When the coldfinger temperature is above the high limit, 95.25 K, the cooler drive voltage is increased slightly to drive the temperature down; when the coldfinger temperature is below the lower limit, 94.75 K, the cooler drive voltage is decreased slightly, allowing the temperature to increase. Precise control is not needed in this application.

In addition to the temperature measurements, the current going to the cryocooler is measured to establish the phase angle between the current and the voltage. Equation 1 is used to curve fit the current to calculate the phase angle. When the phase angles are the same, the drive frequency is on resonance. During operation, the current and voltage at digital frequencies on either side of the nominal 60-Hz frequency are used to update the drive frequency and bring the cooler back into resonance. The drive frequency is changed by the programmable clock in the flow diagram in Figure 3.

The frequency controller takes advantage of the rapid change in phase angle compared to the change in temperature. Frequency tables provide a starting point, and give changes to be applied for heatsink variations.

### SUMMARY

STRV-1b offers an interesting opportunity to test state-of-the-art piezoelectric adaptive control technologies in orbit. The many challenges associated with STRV, e.g., a maximum of 20 watts of power, poor thermal control, very little available weight, and a high radiation environment, have led to a number of innovative developments that should be useful for future applications.

Two types of control-system drive actuators have been developed and are being contrasted: an applique ceramic applied directly to the coldfinger, and piezo translators supporting the entire cooler. New, non-contacting, low-wattage, low-profile eddy-current transducers are being used to measure the cryocooler cold-tip displacement amplitudes.

Two types of control systems are also being contrasted: a fully adaptive digital control system that controls both the cryocooler and the vibration suppression, and an analog controller that uses a tracking filter to suppress the fundamental drive frequency. Either control system can operate either type of actuator. This redundancy provides some protection against total loss of the experiment due to single-point failures; however, several single-point failures do exist in the experiment (e.g., loss of the CPU).

The digital control concept developed here is applicable to a wide variety of vibration suppression hardware. Force cancellation, or dual drive coils, could easily be accommodated within the same control system.

### ACKNOWLEDGEMENT

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

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