Coldfinger Motion Suppression Using a Ceramic Applique

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Abstract

The development of a ceramic applique for the vibration suppression of a cryocooler coldfinger is a part of technology demonstration flight experiment. Three sectors of a piezoelectric PZT bonded to the coldfinger are used as actuators to control the motion of the tip. A technique for bonding the PZT material to the coldfinger was developed that minimizes tensile stresses in the ceramic during operation. Extensive development testing has been performed to verify the efficiency of the adhesive. and the coldfinger performance at cryogenic temperatures The problems encountered during the. fabrication and assembly of the cold finger are described. Results of tests are summarized.

Introduction

For space imaging missions or missile trajectory tracking, the optical instrument requires that its image detector, a charge coupled device (CCD) or infrared (1 R) detector should be kept at cryogenic temperatures. Further the CCD position should be stable to within tenths of a micron. A refrigerative system will meet the temperature requirements, however, vibrations induced by the variations of pressure inside the cooler will oscillate the CCD unless the motion can be suppressed by some means. A smart structural concept, adaptive motion suppression, sponsored by the Strategic Defense, Initiative Office (SDIO), was applied to a Stirling cryocooler to demonstrate this kind of motion suppression.

"l"he functions and applications of a stirling cryocooler in space science were discussed in References [1,2]. A Texas Instruments 1/5 Watt cryocooler was used to demonstrate. the concept. It was assumed that the mechanical design of the cooler was well balanced. The internal pressure variation of 60 PSI, inside the cold finger during a Stirling cycle at a mean pressure of 500 PSI caused the vibration. Displacements of the tip of the coldfinger resulting from the operation of a compressor at a frequency of 60 Hertz resulted in an amplitude of 3 micrometers peak-to-peak. To suppress this motion a simple concept of applying either a single tube piezoelectric ceramic applique or a piezoelectric wafer stack to the coldfinger was developed.

One way to suppress coldfinger motion is to stretch the coldfinger with a piezoelectric ceramic bonded to the coldfinger itself. Very little hardware is involved in this approach: just three pieces of ceramic applique and a little adhesive.. These three pieces are used to control lateral motion as well as vertical motion. From a control point of view this is a good actuator for motion suppression because the resonant frequencies of the system are relatively high. The ceramic actually stiffens the cold finger significantly, dropping the displacement of the tip from 3 microns peak-to-peak to 2 microns in the case. studied.

Since the effectiveness of a piezoelectric ceramic significantly decrease.. when the temperature drops, the applique should be located on the warm end of the coldfinger. The piezoelectric ceramic also acts as a thermal load path degrading the coldfinger performance slightly (the degradation in equivalent to a 0.1 Watt thermal load). The voltages required to operate the applique depend upon the size and type of piezoelectric and the desired movement. An optimal approach was used to determine the size, type and required voltage, based on the efficiency of the piezoelectric and thermal performance of the coldfinger. Generally, a high voltage is required for the piezo tube and a lower voltage for the piezo stack. Power conversion from 28 volts of spacecraft voltage to a desired voltage is required. The power requirement for the. system is very small, about 1 Watt.

The bonding process for attaching the ceramic to the coldfinger poses potential problems, Flight qualified adhesives must be used to avoid outgassing. Potential material property changes are. expected because of the large temperature extremes involved. The bond line must be thin to minimize losses from the ceramic. Uniformity of the bond line thickness is very important to achieve uniform response in the three directions. Significant bond line shear may develop which must be controlled to avoid debonding of the ceramic. A very large number of operating cycles are required which can fatigue the adhesive or the ceramic. A simple process that appears to have solved all of these problems has been successfully demonstrated.

'l'he object ive of the cooler vibrat ion experiment on the STRV- 1 b is to demonstrate, piezo elect ric act uator technology in space. The ceramic applique part of the experiment represents an effort to develop a simple vibration suppression technology applicable to cryo-coldfingers. This paper describes the development of applique ceramics for this application.

Adaptive Structural Concept

Theoretically, the tip movement of a coldfinger moves only in a vertical direction at the compressor operating frequency, but a lateral motion is observed experimentally. An actuator can be used with a feedback control loop to strain the coldfinger at 180° out of phase with the excitation so that the tip movement is suppressed. It is required that the adaptive concept be implemented with a minimum impact to the coldfinger design. Bonding an actuator to the. coldfinger with an adhesive will not change. the coldfinger design but will reduce the thermal performance of the cryocooler.

Various ferrous piezoelectric ceramics can function as the actuator. Electrostrictive ceramic material was initially considered. This material is attractive due to its low hysteretic property. It was dropped from consideration because of its temperature dependent characteristics. Instead piezoelectric (PZT) material was considered as an actuator. The soft PZT, 5H, was chosen because of its better performance. at the temperature of the root of the coldfinger. Two 5H piezoelectric devices were investigated for this application, First a 1 mm thick piezoelectric tube was tried with the poling direction along the radius of the tube. Second a piezoelectric stack with a wafer thickness of .005 " (M IL) and a hole in the center (OD of.5 inches and ID of .264 inches) was tried. The poling direction for the stack is perpendicular to the cross section of the stack.

The basic concept for these two applications to the coldfinger is completely different; the tube will shorten when the voltage is applied, which means that the tube is under tension and the coldfinger is under compression. On the other hand, the stack will elongate, with applied voltage, which means that the stack is under compression and the coldfinger is under tension.

It is preferred that the piezoelectric be under compression while it is actuated so cracking in the PZT can be prevented. For long life applications, the coldfinger was expanded by applying internal pressure while the piezoelectric was bonded to it. Creep of the adhesive and the piezo may reduce pre-compression. To be conservative, it was assumed that the piezo actuator material will operate under tension. To identify what the potential problems are, a teat of the piezo actuator under tension was performed in the laboratory.

A tube shaped actuator has a tendency to crack if the applied voltage is beyond its limit voltage. Recommended practice limits the applied voltage below 40% of the poling voltage. In order to limit the height of the piezo tube in this application, the voltage needed may exceed the limit. Also, the tube piezo can only be used to compensate a vertical movement. The horizontal motion cannot be controlled. Therefore, the tube piezo and stack piezo were cut into three equal sectors and were bonded to the cold finger 120° apart with a gap between them, Figure 1. A common ground is used among them. When equal voltages are applied to all three sectors they function as a single tube piezo actuator; only vertical movement is suppressed. When a different voltage is applied to each sector, the vertical movement is the average of the motion of the three sectors and the horizontal movement is the sum of the lateral motion of every sector. The three sector approach has the ability to suppress motions in both lateral and longitudinal directions and the cracking limitation in the tube was eliminated. The only drawback is the efficiency of the actuator drops slightly compared to the uncut tube. For this application, a tube piezo was emphasized.

Another small problem with the. segmented approach was providing electrical insulation among the sectors. If the segments were bonded together or otherwise were not free. to travel, the lateral motion was impaired, Also, there was considerable danger of shorting of the segments. The required electrical insulation was assured by inserting a kapton film in the gap and providing for freedom of travel between the segments.

An uncut tube piezo and a stack piezo, both bonded to an inconel coldfinger, Figure 2, were set up in the laboratory to verify the cracking phenomenon and the maximum limits of the operating voltage. Verification of cycling fatigue of the bonding adhesive and the piezo itself was another objective of the test. Results are summarized in the test section.

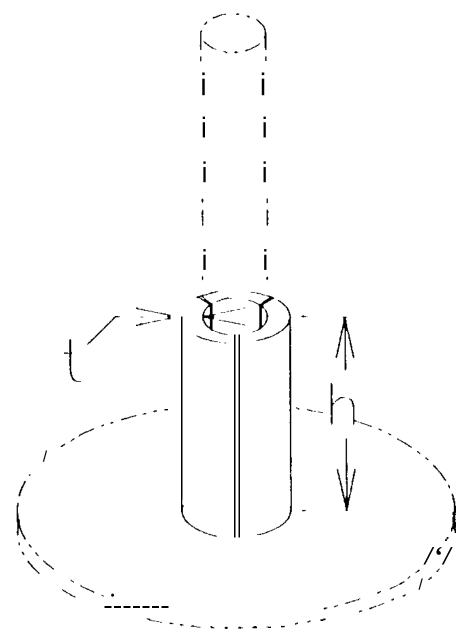

Figure 1. Ceramic Geometry

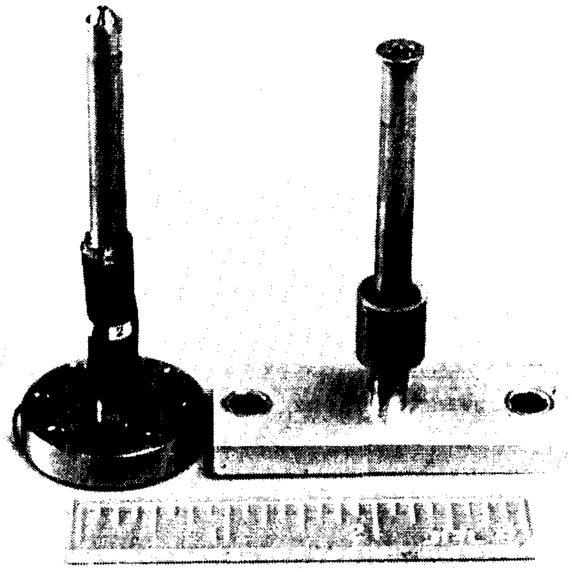

Figure 2. Coldfingers

Ceramic Applique Optimization

The ceramic applique is a piezo ceramic device applied to the root of the coldfinger. Conductive material is attached to the ceramic on either side creating a capacitor. When a voltage., V, is applied across the two conductive plates, the ceramic changes its height, h, proportionately. The change. in the dimension will be used to suppress motion at the tip of the coldfinger caused by pressure changes inside. Also, the applique will be split into three parts to allow control of lateral motions.

Several parameters must be established to design the ceramic applique. The height of the piezo, h, must be minimized since the piezo will act as a thermal load path on the coldfinger. The height should be as short as possible to minimize the cooling loss. The thickness of the ceramic, t, must be as thin as possible (a manufacturing limit) to get optimum performance. However, the voltage, V, used with a thin ceramic is limited to half the poling voltage. The maximum poling voltage is proportional to the ceramic thickness. The operating voltage, V, must be selected so that the power losses are not too severe. However, the performance is proportional to the voltage, so it is desirable to operate at a voltage as high as possible, These conflicting constraints create a design problem.

It is always possible to search the parameter space to find the optimum value. However, this become.. computationally intensive unless the answer is fairly well known from the start, The ceramic applique optimization is an example of the simplest analytical case, when the objective function is monotonic in its parameters. Under these circumstances, the optimum must fall along the boundaries described by the constraints with equality for the constraint value. If the constraints are also

MIN h

Subject to:

1) *Power(V,h,t)*: $\frac{C(h,t)\ V^2 f}{\eta(V)} \le P_{max}$

2) *Poling Voltage(V,t)*: $V \le rp\ t$

3) *Minimum Thickness(t)*: $t \ge t_{min}$

4) *Displacement(V,h ,t)*: d_{31} --- $g\ S(t) \ge x$

Where:

Capacitance(h,t): $C(h,t) = 2\,K\,\epsilon_0\,\pi \frac{\text{----------}}{\ln(OD/ID)} \approx 2\,K\,\epsilon_0\,\pi \frac{h}{t} R$

Efficiency(V): $\eta(V) \approx -.152.\ \ln\frac{V}{3162}$ $\eta(100) =$ *,75x,70 and* $\eta(1000) =$ *.25x.70*

Stiffness Ratio(t): $S(t) = \frac{A_c E_c}{A_C E_C + A_S \text{-}_s}$.-F-. ~ ~--~-~ $_c$ $_S w$

Design Parameters:
h = **height** of the ceramic
t = **thickness of** the ceramic
V = voltage applied across the ceramic

Design objectives:
P_{max} = power = 1,0 Watt
x = displacement = 2,953x 10’^{5} **inches**

Ceramic properties:
d_{31} = **piezo** electric **effect** = 1.079X 10”^{s} **inches/volt**
ϵ_0 = **dielectric constant** = **2,248X** 10^{-13} farads/inch
E_c = Young’s modulus = **6.96×10^6** psi
K = dielectric ratio = 3400 **(dimensionless)**
t_{min} = minimum **thickness** =- 1.969X 10^{-2} inches

Cooler/Coldfinger:
E_s = Young’s mod. =- 30X 10^6 psi
f = Drive frequency == 50 Hz
R = radius = 0.125 **inches**
w = wall thickness = 0.004 inches

Processes;
p =- poling voltage/inch = 40x 10^3 volts/inch
r = **usable/poling** voltage = 1/2
g = transmission of glue = 1/3

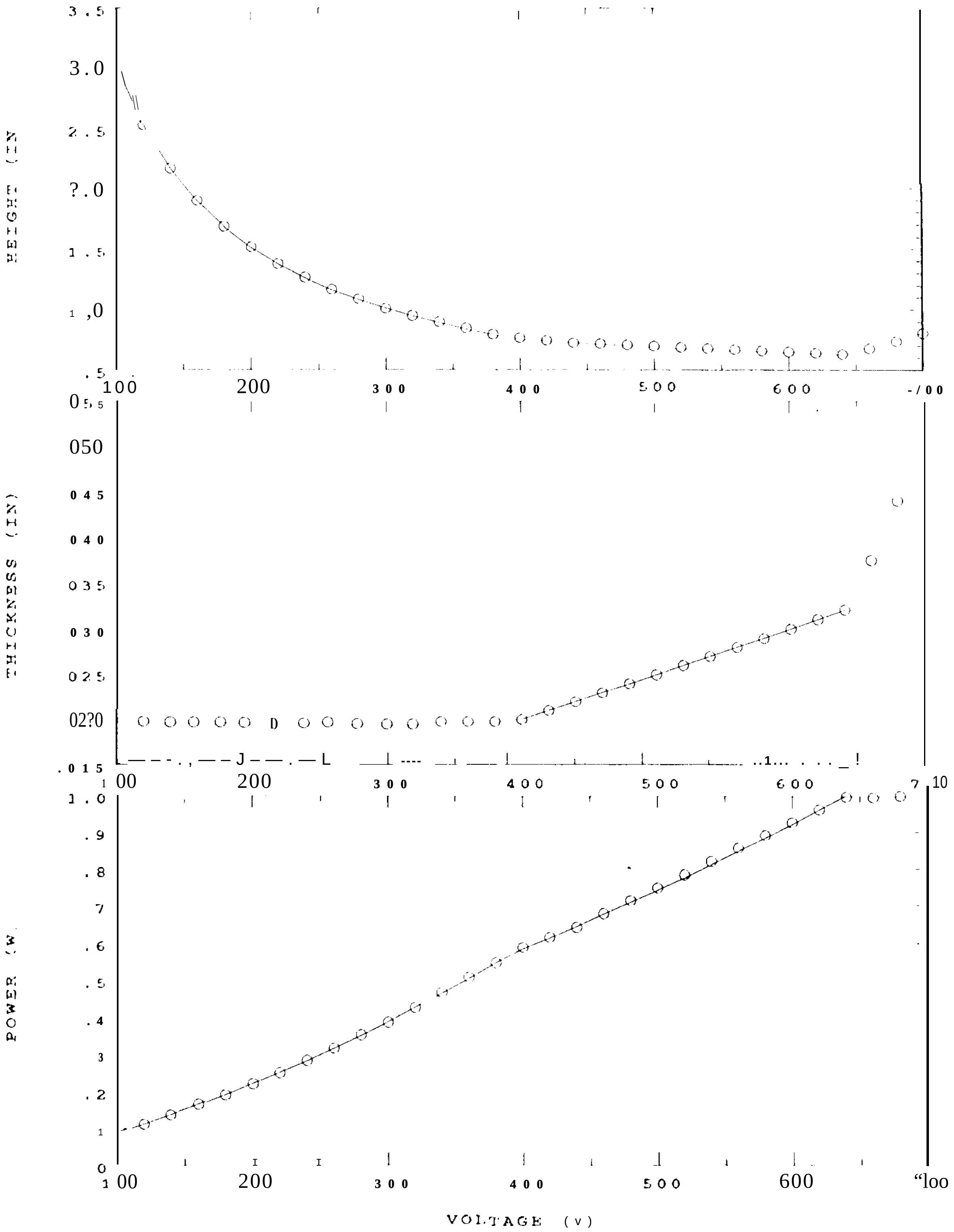

Figure 3. Optimum Parameter

monotonic in their parameters, then the optimum must occur at the intersection of two or more constraint equations. This is called the simplex method.

The power equation does not reflect the ceramic applique optimization for the application. It is possible, that the fundamental frequency, f, can be utilized to reduce the power requirement through a tuned power driver. The efficiency, λ, has not been estimated accurately as yet either. Instead two reasonable λ values were estimated and a smooth curve was passed through these estimates.

The poling voltage equation and the minimum thickness equations are well established and are developed by the manufacturer of the ceramic material. It is not clear if other manufacturers will agree with these equations. The equations used for this optimization are listed in the next page.

These equations have been programmed and the results have been found using the global search technique (circles) and the simplex method (line-s) in Figure. 3. The displacement and minimum thickness equations are effective. at low voltages, At around 390 volts the poling voltage and the displacement equations are effective. Finally, the. power limit is reached and all three equations are effective at the optimal thickness level.

The nominal case resulted in a minimum height, $h = 0.6$ in, with thickness $t = 0.032$ in, and voltage $v = 640$ Volts. These three curves are plotted versus voltage in Figure 3.

Adhesive Selection

An important element in integrating the actuator to the coldfinger is the bonding agent, the adhesive. The. requirements for a suitable adhesive are that it should have a high shear rigidity, high dielectricity, space qualified properties, and high workability. A wide range of adhesives are available in the industry. Adhesives ranging from a powder type to an epoxy base were investigated.

The test specimen for evacuating the adhesive consisted of two identical pieces of 5H piezoelectric strip, 3 inches by 1/2 inches and .039 inches in thickness bonded by an adhesive back to back on a 20 MIL thick aluminum strip, 5 inches by 1 /2 inches, Figure 4. Interferometric metrology was used to measure the response of the tip movement of the specimen when voltage was energized, Figure S. The thickness of the adhesive was controlled within 1.0 MIL to 1.5 MIL.

These test results were compared with the movement of a sample consisting of two free 5H piezoelectric strips, without aluminum strip between them. There was strong evidence that the powder type adhesive has lower strength and could easily be peeled off. It was not a good candidate. Ten epoxy type adhesives were initially chosen based upon their published data of rigidities and space applications. Figure 6 shows the. test results. A strong preference toward the HY-SOL 9396 adhesive is indicated. HY-SOL 9396 has akso been space qualified [3], The test specimen has a 7.7 microns tip movement at 400 volts. The efficiency is 80 percent. HY-SOL 9396 was chosen as the. adhesive to be used for this application.

Fabrication Process

During the fabrication of the adaptive coldfinger and the piezoelectric ceramic assembly, numerous problems were encountered. Two techniques are available for cutting the tube, a laser and a mechanical diamond saw. The heat generated by the laser made the electrode peel off and the material depoled along the cutting edges. It degraded the ceramic making it unacceptable for this application. Using the mechanical cutting device sometimes created trackings in the sectors even when a mandrel was inserted to hold the tube. Also, a slight variation in the size among three sectors after cutting was unavoidable.

The uniformity of the thickness of the adhesive between the ceramic and the coldfinger is a crucial factor determining the relative effectiveness of the three sectors of the ceramic piezo. A variable thickness induced not only uneven vertical deformation but also resulted in lateral motion. A small percentage of uniform glass breads was mixed into the adhesive to function as spacers in order to control the uniformity of the thickness. When an external pressure was applied, the excess adhesive was forced out and the thickness of the adhesive was controlled by the diameter of the glass bread. A uniform thread wrapped around the coldfinger also was used as a spacer. A clamp was used to hold the. sectors in place and to apply pressure to the sectors. This clamp was precisely machined to match the exact outside diameter of the ceramics.

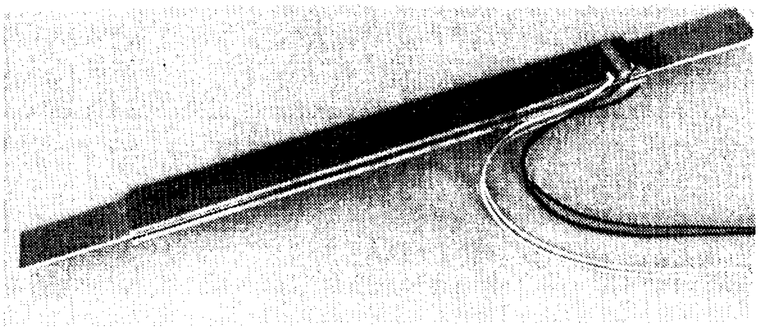

Figure 4. Adhesive Test Specimen

The adhesive used has a high dielectric property. It can be considered as a electric isolator between piezo sector and the inconel coldfinger. Air bubbles trapped inside the adhesive during mixing decrease the electric isolation. To control the air bubbles a vacuum procedure was used. A thin layer of primer was applied to the inconel coldfinger and fully cured before. the adhesive was applied. At the edges of the sector a small adhesive wedge was built to prevent peel off stress concentration at the interface.

It took seven days of room temperature cure for the HY-SOL 9396 to develop to a full strength. An accelerated high temperature cure at 250° F cut the curing period down to two hours. This procedure was used to assemble a specimen quickly. The piezo made of S11 PZT material did not depole at the accelerated temperature. During the curing, the excess adhesive in the gaps among those three sectors was cleaned and a thin kapton film was inserted in the gap to serve as additional insurance. for electric insulation between the individual sectors.

A pressure fixture was used to pressurize the coldfinger to 1000 PSI in order to elongate. the coldfinger during assembly. This insured that the piezoceramic material was under compression after assembly and cure.

To simplify the soldering of the lead to the inside electrode, the inside electrode was wrapped around to the outside of the tube. This wrapped end was inactive since there was no potential across it, thus it was located toward the cold end of the coldfinger. The leads were connected to the electrode either by a soldering gun or by a conductive silver filled adhesive. If a soldering gun is used, the heat impact to the piezo must be limited.

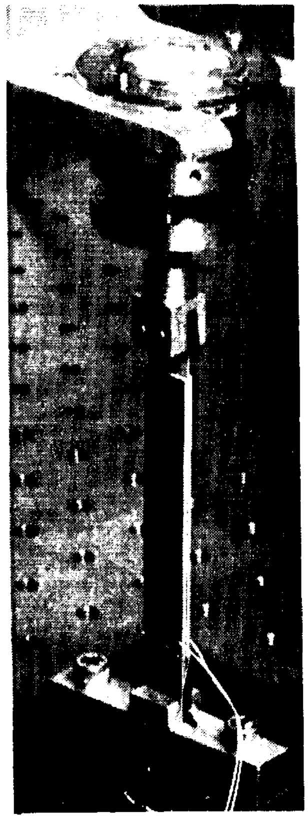

Figure S. Adhesive Test **Setup**

After implementing all of these careful procedures, an adaptive coldfinger was born. Regardless how carefully the work is done, there is always some slight variation in the response among three sectors. A test must be performed to determine the flexibility matrix of the coldfinger in three major axes corresponding to three sectors, Figure 7. Also, regardless of how carefully the work is done, there are always good specimens and bad specimens with no known fabrication difference between them.

Tests and Results

The tests performed can be divided into two categories; pre-qualification testing and actual coldfinger testing. The pre-qualification testing consisted of 1) adhesive testing as mentioned in the previous section, 2) piezoelectric tension tests in conjunction with adhesive tests, 3) fatigue testing of a single tube actuator, 4) cryogenic performance testing, and 5) precursor coldfinger testing. The actual flight coldfingers were performance tested in a flight configuration.

An interferometric laser system was used to measure displacement during the adhesive tests and a noncontact ing eddy current measurement system was used for all the other tests.

In the adhesive test, the 5H PZT piezoelectric elements acted to compress or stretch the central aluminum strip through the shear strain in the adhesive when a voltage was applied in the poling direction. The voltages used ranged from -400 volts to 400 volts. These represent 25 percent of the poling voltage. The test specimens were cycled to 10,000 cycles and the data was taken every 100 cycles for the first 1000 cycles and every 1000 cycles after that. No degradation in performances was observed. Test remits for the ten adhesives were reported in Figure. 6. The other significant conclusion obtained from this test was that, when a piezoelectric actuator was bonded to a metal surface, it withstood a tension stress inside the piezo itself without loss of efficiency. This lead to more extensive testing of tension capability of a piezoactuator.

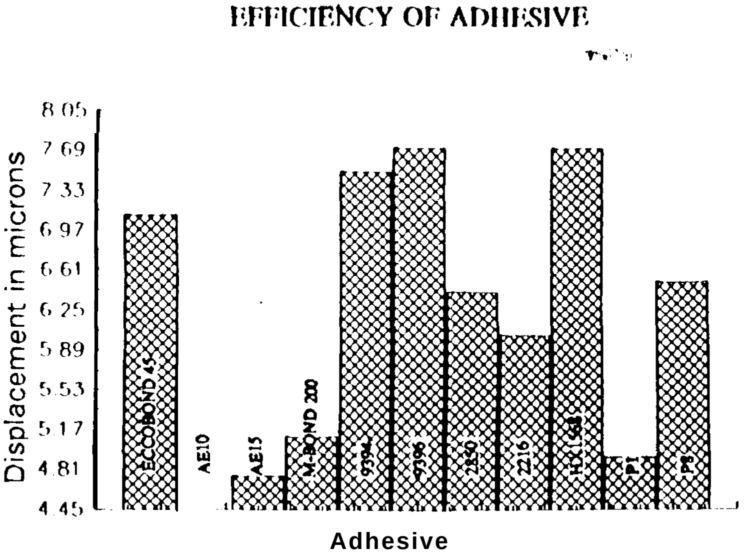

Figure 6. Adhesive Test Results

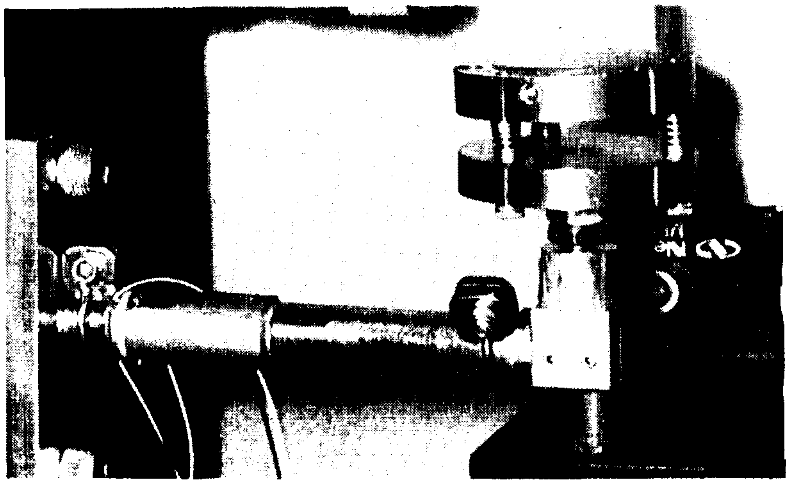

Figure 7. A Coldfinger Lateral Movement Test

The cold finger was internally pressurized to 1000 PSI before the actuator was attached. The actuator will be in compression at the operation pressure of 500 PSI. The creep behavior of both the adhesive and the piezoelectric material may eliminate the compressive strain state of the actuator. The worst condition was tested to identify the limit of the actuator under tension. Assuming there was no precompression, a single un-cut tube, was bonded to an inconel coldfinger with HY-SOL 9396 and tested without internal pressure. When a voltage was applied in the positive poling direction of the piezo, the actuator contracted and compressed the coldfinger forcing the actuator into tension and the coldfinger into compression. A 600 volt sinusoidal signal at 200 Hertz was applied to the specimen, a tube piezo specimen as shown in Figure 2, and data was logged every 1 million cycle at 60 Hertz, The results of the performance of the specimen are shown in Figure 8. The performance. of the specimen was not degraded even after 500 millions cycles. After the fatigue test the same specimen was tested in a cryogenic chamber to assess the effects of the temperature. The results showed that the only effect was the decreased performance of the piezoelectrics as predicted based on the material properties of the material.

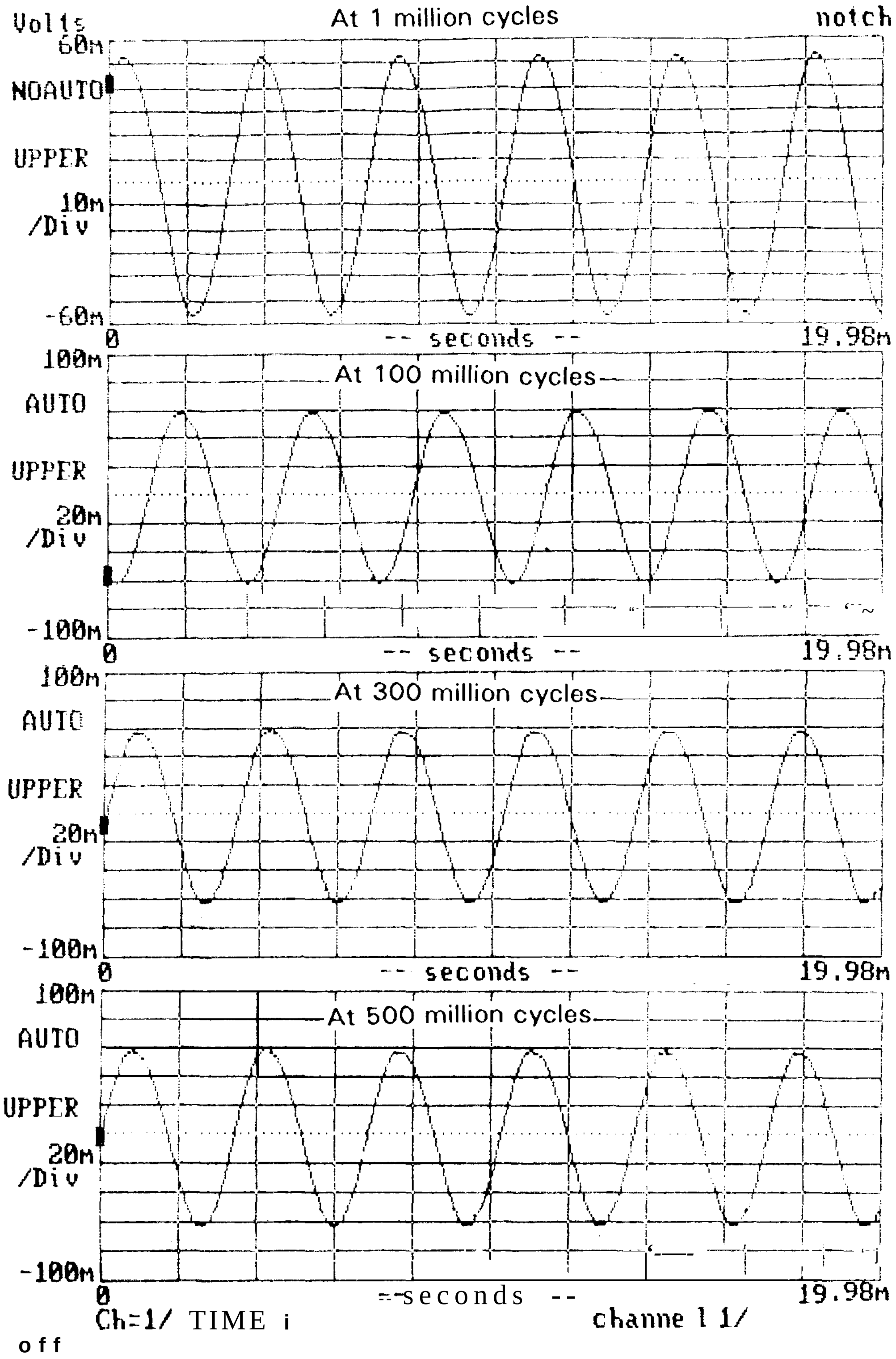

Figure 8. A Coldfinger Cycling Fatique Test Results

The flight coldfinger complete with three sectors of piezoelectrics was tested in a clean room environment to measure a 3 x 3 flexibility matrix required for control purposes. With 600 volts applied to the coldfinger either with an internal pressure of 1000 PSI and without, the vertical direction had a contraction of 4.32 microns with pressure and 3.81 microns without pressure. The relationship between the internal pressure and the performance is shown in Figure 9. The effect of the internal pressure on performance is insignificant, There was a lateral motion associated with non-symmetry of the three sectors. When a single sector of unpressurized cold finger, see Figure 7, was energized with 1000 volts, the ratio of movement in the vertical and lateral directions was 1 to 15. This ratio depends upon the workmanship of fabrication. Discrepancies in lateral motion can be canceled out by the control loop. The piezo stack study initially planned ran into trouble. The stacks as delivered from the manufacturer split along the electrode between layers. Splitting occurred either in shipping or in subsequent handling. It appears that some form of encapsulation or a preload device would be required to make the stacks work. Because of time constraints the stacks were not pursued further in spite of the fact that they appear superior from the point of view of performance and voltage.

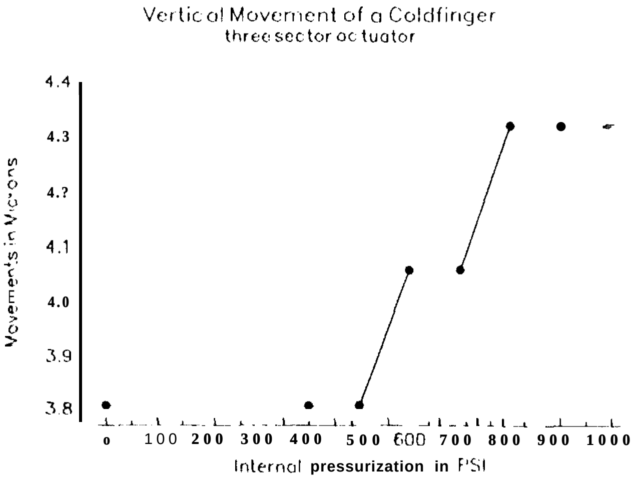

Figure 8. Pressure vs. Performance

Acknowledgement

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Conclusions

Motion of a coldfinger's tip in the range of 2 microns can be controlled by three sectors of piezoelectric PZT bonded to the coldfinger by an adhesive. A substantial tension force can be carried in the piezo if the piezo is reinforced by stronger elements bonded to the side of the piezo. While there may have been some micro cracking in the PZT, the electrode was still working. Therefore even a micro-cracked PZT works.

The fabrication process for a piezo applique of this type is a serious undertaking with many hazards. Even with a carefully controlled process, differences are observed between identical specimens. A certain amount of art remains in this kind of fabrication.

References

1. Glaser, R. J. Ross, R. G. and Johnson, D. L., "Cryocooler Tip Motion Suppression Using Active Control of Piezoelectric Actuators, " Proceedings of the 7th International Cryocooler Conference, Santa Fe, NM, November 17-19, 1992.

2. Glaser, R. J., Kuo, C. P., and Garba, J. A. "Application of Smart Structure Concept to Vibration Suppression of a Cryocooler Coldfinger," Proceeding of the 1993 North American Conference on Smart Structures and Materials, Jan. 31 through February 4, 1993, Albuquerque, New Mexico.

3. Carpenter, A. and O'Donnell, T. "Qualification of Room-Temperature-Curing Epoxy Adhesives for Spacecraft Structural Applications," Proceedings of SAMPE, May 8, 1989, Reno, Nevada.