Piezoelectric polymer actuators for vibration suppression

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ABSTRACT

We have designed and built piezoelectric polymer actuators in a "bellows" configuration and have used them in a near-zero-g environment vibrations suppression apparatus. The actuator is based on poly(vinylidene fluoride) (PVDF) sheets produced by AMP and electroded to our specifications. The actuator consists of two bimorphs, each with a double-bend precurvature, glued together at their ends so that the actuator has its thickest air gap at the middle. Each bimorph consists of two sheets glued together. Each sheet is electroded completely on the outside (ground) side, and has three electrode areas on the other side. If the electrode on the middle half is positive, and on the outer two quarters are negative, the bimorph curvature and the actuator length increase; with opposite polarities they decrease. In the vibration isolation application, the box to be isolated has actuators mounted between it and its surrounding enclosure on the vibrating vehicle. Feedback control is provided to change actuator length to compensate for vehicle motions and vibrations. This feedback is provided by accelerometers and by laser diode position sensors. The inherent softness of the actuator provides good passive damping of higher frequencies. So far, a one-dimensional test of the system has been made using a mass on a "folded pendulum" as a "weightless" (no restoring force for small displacements) load. Also, a two-dimensional version was flown on NASA's KC-135, which provided 25-second near-zero-g intervals during parabolic flight segments. Our goal is three-dimensional isolation for space vehicle applications.

Keywords: Piezoelectric, Polymer, Actuator, Vibration isolation, Space vehicle

1. INTRODUCTION

1.1 Actuator Requirements for Active Vibration Suppression

Actuators for active vibration suppression have an additional set of requirements beyond those for general-purpose actuators. First, they must offer sufficient displacements up to the top frequencies to be isolated. Second, as a related requirement, if they are soft enough to damp higher frequencies passively, the top frequency to be damped actively can be lower than it would be for a stiff actuator. Third, size, mass, and power consumption should be as low as possible, preferably ten times lower than that of the device to be isolated. Fourth, for terrestrial applications the actuator(s) must be strong enough to support the weight to be isolated. This requirement is in conflict with the softness requirement. For space applications, this weight-supporting requirement is absent, and much softer actuators can be used to isolate a given load mass.

1.2 Materials for Vibration Suppression Actuators

A wide variety of materials are used for actuators. Shape memory alloys respond too slowly for most vibration isolation applications. Magnetic solenoids are heavy and have high power requirements, so are more applicable to isolation of heavy loads. Hydraulic and pneumatic actuators have plumbing connections and require compressors, so they introduce unwanted complexity for isolation of small devices. Piezoelectric and electrostrictive devices seem to be preferable for isolating small loads. They require little power and very small current, but they do need high voltage that requires care in design.

Piezoelectric materials have the advantage that the displacement is proportional to the applied voltage over a wide voltage range. Piezoelectric materials can be divided into three types - ceramics, crystals, and polymers. Piezoelectric ceramics consist of tiny piezoelectric crystals bonded together. They have the advantages that they can be formed easily into any

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desired shape, and that they are relatively inexpensive. Their particular disadvantages are inflexibility and brittleness, and low electrical breakdown field that limits their maximum field and correspondingly limits their maximum strain to 1 or 2%.

Piezoelectric crystals have recently been discovered that have piezoelectric strain as large as 1.7% in PZN-PT (lead zinc niobate-lead titanate solid solution). Such crystals are still expensive, and their durability is not yet well established.

Piezoelectric polymers are different from ceramics and crystals in that, besides being polymeric, they are only semicrystalline. Small "nanocrystalline" regions are surrounded by an amorphous matrix. The piezoelectric coefficients are small compared to those of ceramics or crystals. However, the polymers can be formed into thin, flexible sheets which are not brittle. The best all-round piezoelectric polymer is still PVDF (or PVF_2), which are abbreviations for poly(vinylidene fluoride). Its nanocrystalline regions are composed of parallel chains of $(CH_2CF_2)_n$ in which the positive protons lie on one side of each chain, and the negative fluorine ions on the other side, thus making the nanocrystal ferroelectric and hence piezoelectric.

While only crystals that lack a center of symmetry can be piezoelectric, all materials are electrostrictive. In an electrostrictive material, the strain is proportional to the square of the applied electric field, to lowest order. An electrostrictive material can act as a piezoelectric over a certain voltage range if a steady dc bias field is applied, in addition to the varying voltage that gives a correspondingly varying strain. Recently, foamlike or rubberlike electrostrictive materials have been developed which can provide very large strains, but with correspondingly low forces.

2. ACTUATOR DESIGN AND PERFORMANCE

2.1 Basic Actuator Design

The basic actuator is constructed with two double-S curve bimorphs. Its construction has been described previously,[1,2] and is shown in Fig. 1.

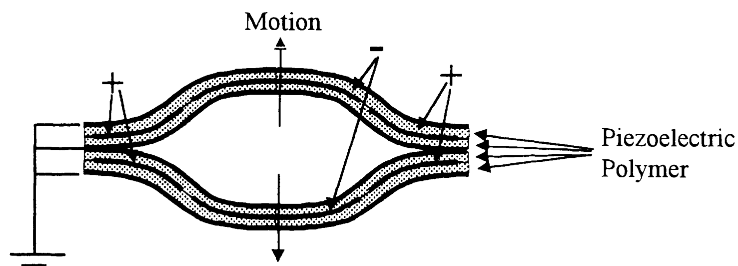

Figure 1. (from Ref. 2) Schematic end view of the actuator. The outer electrodes are grounded, whereas the polarities are reversed on the inner electrodes at the inflection points ¼ and ¾ of the way along the actuator, to enhance or diminish the precurvature with which the PVDF sheets in each bimorph are bonded together. Mechanical attachment points are at the top and bottom center of the actuator.

The PVDF sheets were obtained from Measurement Specialties, Inc. (formerly AMP) with special electroding to provide the electrode gaps at the ¼ and ¾ points as shown in Fig. 1, and to provide tabs and electrode strips along edges to facilitate making necessary connections. We cut four two-inch-square pieces from the flat as-purchased sheets to make each actuator. The next step is making two bimorphs by bonding two sheets together and pressing the pair between two curved forms while the adhesive sets, to provide the precurvature shown in Fig. 1. The third step is bonding the left and right ends of the bimorphs together, to produce the bellows-shaped actuator.

2.2 Actuator performance

The actuator performance was measured previously as functions of applied voltage and load.[3] Some results from this extensive set of measurements are shown in Fig. 2.

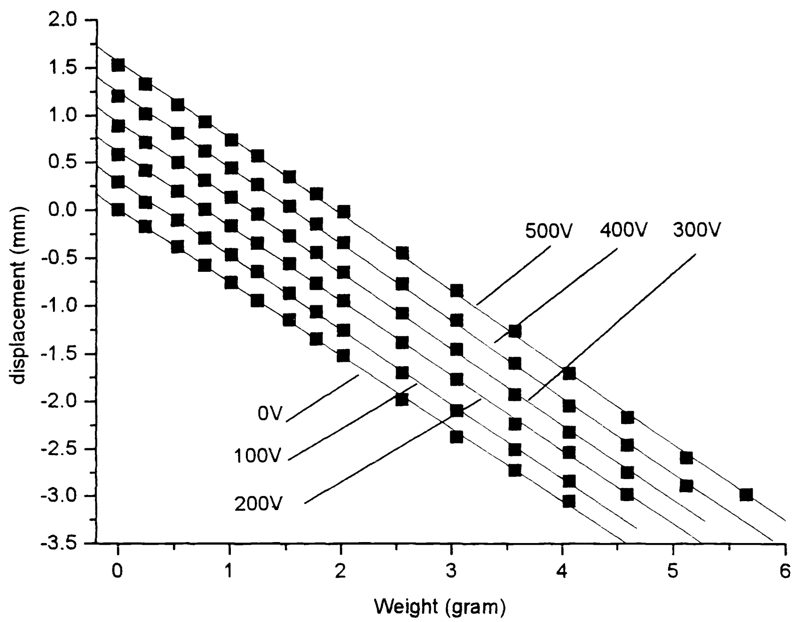

Figure 2. (from Ref. 3) Displacement *vs.* force for different applied dc voltages and supported weights.

From Fig. 2 it is seen that the displacement is near 1.4 mm for 500 volts dc applied voltage, and that 5 grams weight compresses the actuator by about 4 mm. The 500 volts is near the maximum practical voltage which can be applied without serious risk of electrical breakdown on the individual 28 micron thick PVDF sheet. This corresponds to a field of almost 18 MV/m.

2.3 Actuator mount

The actuator mount is a simple yet complicated device. Made from extruded polymer tubing, super-strong tippet material, and balsa wood, this simple device serves a very important function. The PVF_2 actuator cannot withstand much shear force. In response to this problem, a mounting device was designed to minimize the shear forces. The tippet material is a 0.5 mm diameter, 60-pound line which is used to attach the actuator to the wall of the shuttle and the experiment box. Hence, the shear forces are absorbed in this line instead of in the actuators. To avoid column buckling in the tippet line, the line is stiffened with the extruded polymer tubing. Four small tubes are bound together with one large tube. The electrical connections are threaded through these small tubes and the tippet line is threaded between the tubes and glued in place for stability with approximately 3 mm of line remaining between the wall and the tubing, as shown in Fig. 3. The tippet line is attached to the wall using a clamp fabricated out of 6061-T651 aluminum, and the polymer tubing is attached to the actuator with balsa wood.

One could ask why not eliminate the polymer tubing altogether and just use the 3 mm of line between the actuator and the wall? One could argue that it would be less weight, less mass, and easier to make. However, without the polymer tubing, the distance between the wall and the box would be small, hence the offset angle and the shear coupling would be large. The purpose of having a distance of 7 cm from wall to box is to allow the same motion to produce a smaller angle offset, thus minimizing the shear force and maximizing the force available for the *desired* displacement. The target offset angle is less than six degrees which will give an off-axis coupling of less than 10%.

The electrical connections are also included in this apparatus. The wires are housed in the polymer tubing that serves as insulation. They are then embedded into the balsa wood and routed to the proper connections on the actuator. The entire apparatus – actuators, mounting rods, aluminum clamp, electrical connection – is then attached to the shuttle wall and experiment box simultaneously. Each aluminum clamp is easily placed in aluminum pockets that are attached to the wall and box, and the electrical connection is plugged into the main power supply.

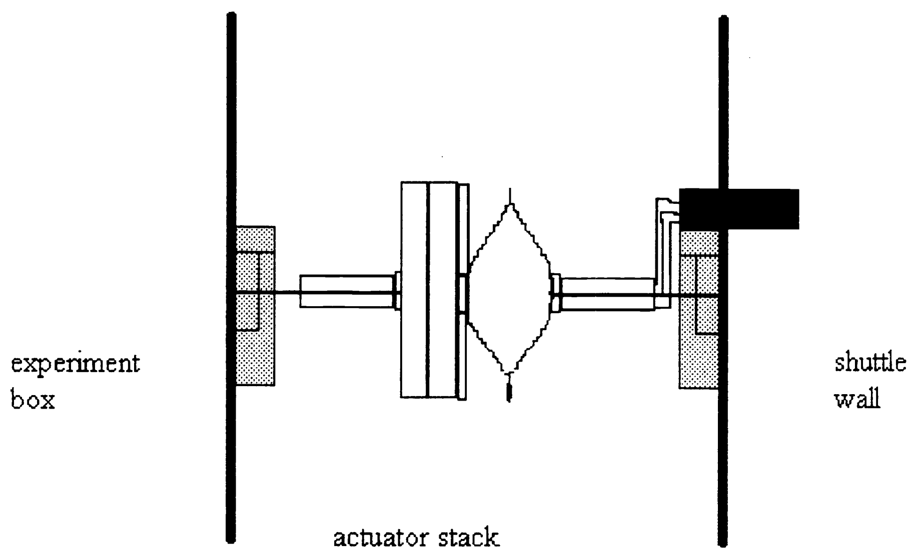

Fig. 3. Mounting arrangement to connect piezoelectric actuators between the box to be vibration isolated and the surrounding frame.

2.4 Finite Element Modeling of Piezoelectric Actuators

Predictive capabilities for the bellows actuator are being developed through the use of the ANSYS® finite element program. These capabilities are intended to help understand complex behavior of the actuator (for example, when out-of-plane behavior is encountered), examine troublesome areas of the actuator in detail (such as delamination at a glue joint), and to enable the design of an actuator that meets specific performance requirements.

ANSYS® provides plane and three-dimensional piezoelectric elements that model direct and converse piezoelectric behavior with both steady and transient loading. The program models piezoelectric behavior with the following linear constitutive equations:

$$\{T\} = [c]\{S\} - [e]\{E\}$$

$$\{D\} = [e]^T\{S\} + [\varepsilon]\{E\}$$

where {T}, {S}, {E}, {D} are, respectively, the stress, strain, electric flux density, and electric displacement matrices, and [c], [e], [ε] are the elastic stiffness, piezoelectric, and permittivity matrices, respectively. However, it is customary in the piezoelectrics community to write the constitutive equations as

$$\{S\} = [s]\{T\} - [d]\{E\}$$

$$\{D\} = [d]^T\{T\} + [\varepsilon_o]\{E\}$$

where [s] is the elastic compliance matrix, [d] is an alternative form of the piezoelectric matrix and $[\varepsilon_o]$ is an alternative form of the permittivity matrix. It is the values for the elements of these matrices that are reported in literature concerning material properties for PVDF. Thus the elements of [c], [e], and [ε] must be obtained from those of [s], [d], and $[\varepsilon_o]$. The necessary matrix manipulations are carried out with the use of Mathcad.

The piezoelectric capabilities of ANSYS® were tested for the plane element with converse piezoelectric behavior (applied electric field) and an applied steady voltage through the thickness of a piezoelectric bimorph cantilevered at one end. Voltage differentials applied across the thickness of the bimorph were chosen to produce, in one case, pure extension of the bimorph, and in another case, pure lateral bending. ANSYS® results were compared with hand calculations based on mechanics of materials assumptions. In both cases the ANSYS® results for mechanical displacement and stress were within one percent of the results obtained from the hand calculations. Electric displacement results were within 2 %. These results were obtained with the use of published properties for PVDF.[4]

Current modeling work is focused on establishing baseline performance of the bellows actuator in the absence of a glue layer, and examining the effects of the glue layer on actuator performance.

3. SYSTEM DESIGN AND PERFORMANCE

3.1 Overall System Design

3.1.1 Mechanical design

The experimental setup for payload isolation is a lighweight cube suspended inside a reference cube that is coupled to the vehicle experiencing a micro-G net acceleration. Sensors are mounted on both cubes to determine differential position and acceleration for control system feedback and data analysis. In the case of the KC-135 tests, a method for supporting the inner box within the limits of the actuators had to be developed. To this end, 8 specially designed funnels are mounted on the box to accept solenoid driven rods that will immobilize the cube when a steady net acceleration of more than 0.1 g is detected.

The inner and outer cubes are attached by 12 actuators working in complementary push-pull pairs mirrored on opposing faces so as to double the force in the direction of any single actuator's displacement. One actuator in this instance is two stacked bellows actuators as described above and in Fig. 1. The actuators are mounted two per cube face and arranged so the cube surface has 2-fold axial and 3-fold body diagonal symmetry.

3.1.2 Layout of control system elements

To gain a real-time measurement of inner cube displacement, position sensitive devices (PSD) are mounted center face on each of the X, Y, and Z axes. A laser diode is mounted on the outer cube opposite each PSD to provide the reference position from which the displacement of the PSD is measured. Accelerometers are also mounted center face on the cube's 3 axes but opposite the PSD's. The accelerometers are used to measure the differential accelerations felt by the inner and outer cubes which indicate the effectiveness of the active damping.

One important guideline in the layout of the components on the inner cube is to maintain inertial symmetry about the three axes. This diagonalizes the control system matrix, minimizing the nonzero terms, and as a result, minimizing the complexity of the control system that must be implemented.

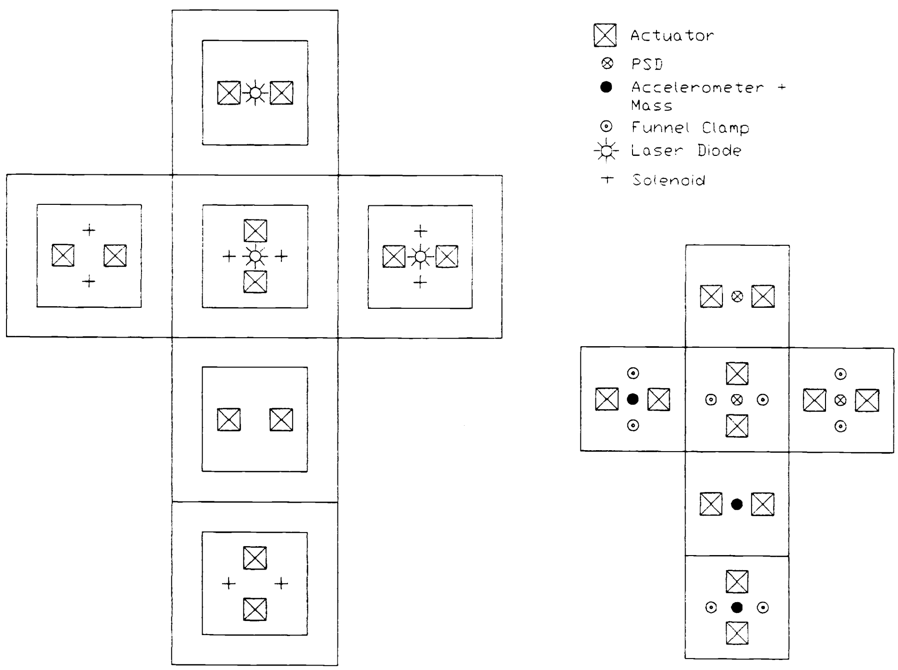

Fig. 4. Layout of components on frame (at left) and on suspended inner box (at right). Both boxes are shown in an unfolded view.

3.1.3 Electrical System

The currently used and proven vibration space vehicle isolation mount is current driven and of the magnetic type. The operation of the magnetic type requires large amounts of system power for proper actuation. For good science to be conducted, long periods of isolation are usually necessary, which would require long periods of this high power usage. Our system is designed to remedy this situation by using the voltage-controlled bimorph. The bimorph can be electrically modeled at low frequencies, as a simple capacitor in the 20 nF range. To operate the actuator, one must simply place a voltage on this capacitor. The actuator is basically linear (Fig. 2), so for every discrete amount of voltage added there is a proportional displacement. The bimorph also has limits to its displacement, placed on it by the breakdown voltage of its rather thin PVDF films. The breakdown voltage of the actuator is near 700 volts but is sensitive to the actuator construction (imperfections on an actuator decrease its breakdown voltage). The actuators require two high voltage signals, of equal magnitude but opposite polarity, applied to different parts of the bimorph central layer. The outer layers can thus be grounded to protect the actuator, apparatus, and operators from an accidental discharge from the surface of the bimorph.

There are three separate units to the electrical system.

1. To determine where the box is and how it is oriented, we have added 3 position-sensing devices to the box (PSDs). The sensors are mounted parallel to the sides of the inner box. Each provides two pieces of position information, namely its position along two axes in the plane of that side. This information must be decoupled to obtain the coordinates of the 6 degrees of freedom associated with the three-dimensional box system, namely the three positional (x, y, z) and three angular ($Ø_x$, $Ø_y$, $Ø_z$) coordinates. This is accomplished with a matrix of summation circuits and is then transferred to the control system.
2. The control system consists of a proportional-plus-integral-plus-derivative controller (PID). Information involving the actuator authority and frequency response for the control system was attained in the operation of an inverted pendulum, as described below. This pendulum was previously designed to support a frame of reference for low frequency seismic activity monitoring in the mHz range. Our test apparatus was designed for the purpose of isolating the actuator in one dimension and plotting its response to various input frequencies. The set of six total correction signals emerging from the PID controller is then passed on to the amplifiers.
3. The actuators require high voltages, but the output from the control system is in the one volt per millimeter range that is far from the necessary one hundred volts per millimeter required of the actuator. The design and creation of the high voltage network has been difficult because the system requires twelve amplifiers (six signals times two phases). The amplifiers are only low frequency (<50 Hz) because the natural damping by the "soft" actuators eliminates higher frequencies. The amplifiers are also low power because very little current is needed. Due to the number of amplifiers and their inaccessibility (necessary for high voltage) they must be highly reliable and must not fail if an actuator shorts. This is accomplished with a MOSFET transistor array linearized with an operational amplifier. The resulting signal is then passed on to the actuators to complete the control loop.

3.2 System Test Results

3.2.1 Bench tests

We tested the system with a one-dimensional "folded pendulum," as shown in Fig. 5 below. The vibrating space vehicle frame is simulated by a shaker which is driven at various frequencies. The load to be isolated from vibration is simulated by the horizontal arm of a folded pendulum.[5] This arm is supported on the left by an ordinary pendulum, and on the right by an inverted pendulum. With proper adjustment, the restoring force for small horizontal displacements is very small, as if it were suspended from a very long vertical line. This horizontal arm is attached to the midpoint between two piezoelectric polymer actuators. The other side of each actuator is attached to the shaker.

The accelerometer and PSD (Position Sensitive Detector) provide feedback signals to the control circuitry which controls the power supplied to the actuators. The very low restoring force for horizontal motion allows the system to act as if the large mass of the horizontal arm were weightless, so only its inertia comes into play, as in space. The system response for various frequencies and feedback parameters was examined, and agreed fairly well with the calculated response.[3]

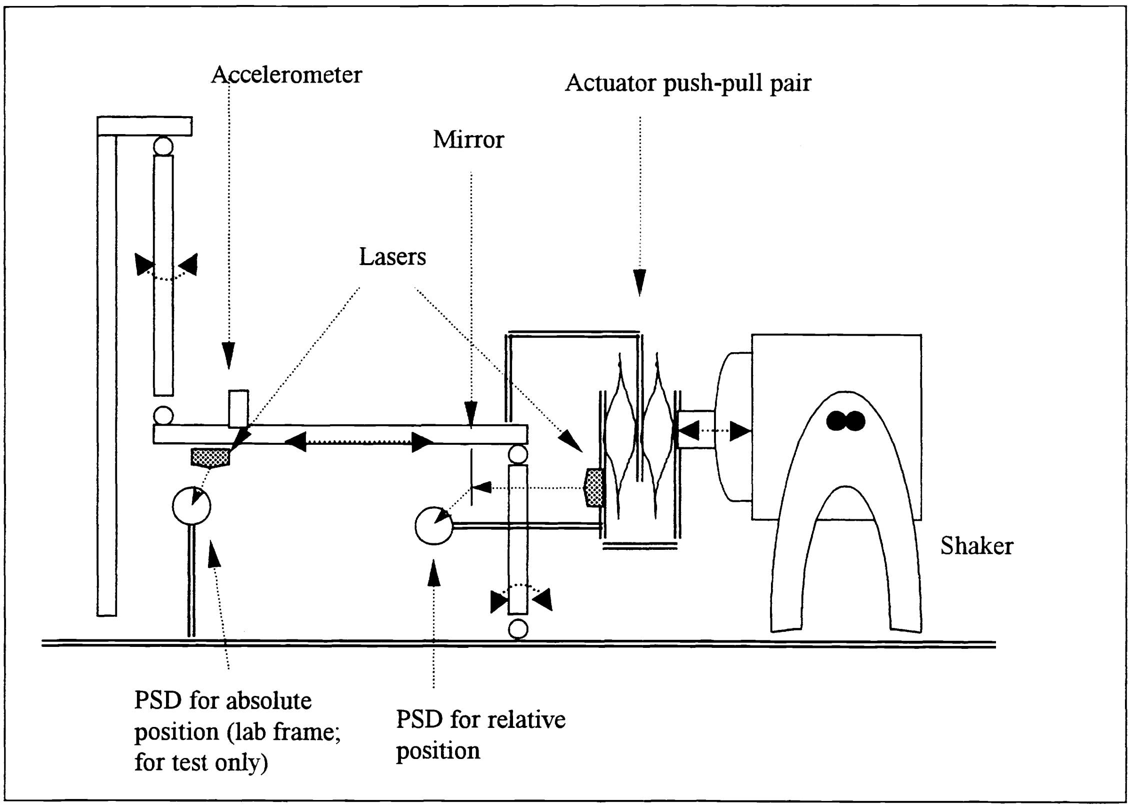

Figure 5. (from Ref. 3) Folded pendulum apparatus for testing one-dimensional feedback control system.

3.2.2 Tests on KC-135

We tested the system in March, 1998 at Ellington Field near Houston, on NASA's KC-135 that flies in zero-g parabolic arcs for 25 seconds. There were eight actuators arranged to damp motions in the horizontal plane. The system was quite effective in passively damping out higher frequencies. Two problems prevented testing with power applied to the actuators. First, the adhesive then used in constructing the actuators could not withstand the high temperature and high humidity environment in Houston, and delamination occurred. This delamination was extensive enough to break the connections needed to power the actuators, but not so extensive as to interfere substantially with their passive mechanical characteristics. We are now employing a different adhesive. We have tested actuators built with this adhesive in a homemade environmental chamber that simulates Houston conditions. Actuators subject to high static load survive under these conditions.

The second problem was the direct attachment of the actuators between the outer frame and the box to be isolated. This method of attachment, without the mounting arms shown in Fig. 3, caused excessive shear forces on the actuators caused by the residual vertical accelerations during nominal zero-g conditions. We have made two design changes that should solve this problem. First, we now have mounting arms to minimize shear forces. Second, we are constructing a box with twelve actuators which is to be isolated in all three dimensions, not just in a plane, so that vertical displacements will also be controlled. We are scheduled to test the new system at Ellington Field in late March, 1999.

4. CONCLUSIONS

Our system shows promise for isolation of small payloads from residual vibrations in space vehicles, and also for terrestrial systems for which the gravitational force can be mostly eliminated by negative spring constant suspensions. The upcoming tests at Ellington Field will show to some extent whether that promise can be fulfilled. Control system design parameters, however, must be considerably different for space vehicle applications than for the KC-135 for which residual vibrations are one to two orders of magnitude greater.

ACKNOWLEDGEMENTS

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