DESIGN OF A PIEZO ACTUATOR FOR CRYOGENIC ENVIRONMENTS

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INTRODUCTION

The Next Generation Space Telescope (NGST) planned to launch in 2008 will utilize a large mirror with a diameter of approximately eight meters. The Hubble Space Telescope (HST) will be taken out of commission in 2010 and NGST will be a replacement that will also look at the infrared spectrum of light [1]. Because the transportation vehicle (Space Shuttle Orbiter) has a capacity for an object only 4.57 m in width, the new mirror must be able to fold for transportation. When the mirror is unfolded, the focal point will be adjusted by an array of actuators pushing along the non-reflective side of the mirror. These actuators must have high-resolution static position capability to adjust the optical surface and power off set-and-hold to conserve the onboard power supply. Some of the key requirements include 10 to 20 nm resolution, 6 mm of stroke and a mass less then 40 grams.

Linear motors utilizing piezoelectric actuators seem obvious solutions with products such as Burleigh's Inchworm or the New Focus Picomotor. However, piezo ceramics show extremely diminished strain in cryogenic temperatures (approximately one-sixth of that at room temperature). Recently, TRS Ceramics from State College, Pennsylvania, has developed a single crystal piezoelectric material. This material is capable of producing strains in cryogenic environments similar to those of conventional piezo ceramics at room temperature. This new technology brings the Inchworm and Picomotor back into contention.

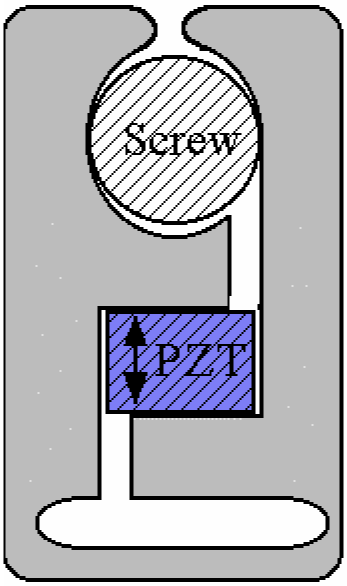
Other challenges still remain to be addressed on these designs including size, weight and power off set-and-hold. One way to address the power off set-and-hold is to build the device such that a fine pitch screw is rotated inside a fixed nut to produce axial displacement. Because of the small pitch angle of the threads, axial load is not enough to overcome rotational friction thereby producing no motion.

DESIGN FOR PIEZOELECTRIC MOTORS

Traditionally, there are two types of precision motors: The first is an Inertia Clamp design that relies on the mass, acceleration and applied forces (including variations between static and dynamic friction) of the system. The second is an Active Clamp design that relies more heavily on static friction and clearance between actuators and displacing components.

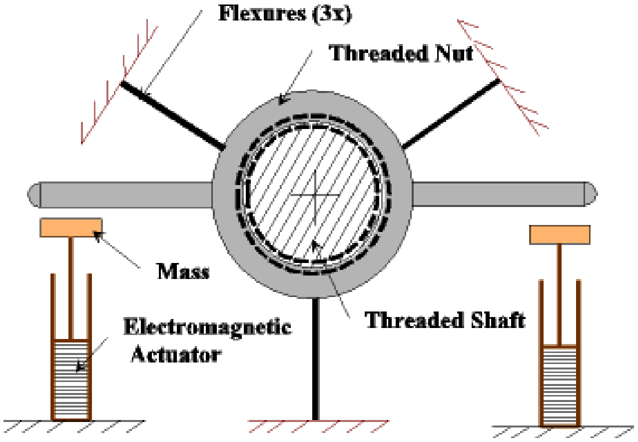
INERTIA CLAMP DESIGN

Conventional piezoelectric ceramics are often used for precision motion control such as in the New Focus Picomotor [3] seen in Figure 1. This device depends on the difference between the static and dynamic coefficient of friction at the screw/nut interface to convert the small displacement of the piezoelectric crystal to a useful rotation of the screw. A slightly elongated nut can be distorted with a piezoelectric actuator (PZT). The rapid expansion coupled with the inertia of the screw will force the threads on each side of the nut to slide in opposite directions. When the piezo is slowly retracted, the friction in the threads provides the torque to turn the screw in a stationary nut (not shown) and thus extend the end of the screw.



This is a relatively inexpensive device (~$400) but the current design is not acceptable for the cryogenic environment. First, the difference between the static and dynamic friction coefficients needed for the operation of the Picomotor may not be the same in space environment as at room temperature. Second, the strain available from the standard polycrystalline materials is severely reduced at low temperatures.

Another inertia clamping system was developed by Steward Observatory at the University of Arizona (see Figure 2). The design also utilizes a fine pitch screw but instead of piezoelectric actuation, it uses electromagnets to produce an impulse force. The impulse force accelerates the nut suspended by three flexures. The friction force between the nut and screw accelerates the screw but at the same time the nut is slowing down as it winds up the flexures. When the nut and screw reach the same velocity, the friction between the two is maximum and the flexures slow down and stop the nut and screw. The energy stored in the flexures then unwinds the nut and returns it to the nominal position returning the screw with it. Since the screw slipped relative to the nut in the first part of the stroke, but not during the return part, the screw undergoes net rotational displacement and thus an axial displacement as well.



To model this system, a finite difference program was created that estimated the forces, displacements and directions of each component during one cycle. Variables such as the geometry of the screw and nut (diameter, mass), velocity of the mass when it hits the nut and properties of the flexures (thickness, length and width) were varied and the final displacement of the screw was calculated. This model was used to study the sensitivity of the system to operating conditions (such as friction) and the dimensions of each component.

A major concern is magnitude and velocity dependence of the friction in a space environment and how much that will affect resolution and displacement. Smooth surfaces in a vacuum, such as space, tend to stick together and create very large friction coefficients. The friction will also produce a hysteresis effect when these motors switch directions. This hysteresis is due to the deforming nut (Picomotor) and flexures (Steward Observatory) not returning to the nominal position after every cycle.

Active Clamp Design

An active clamp design differs from an inertia clamp in that it relies on static friction to cause motion and clearance (or very little contact) for retraction. Burleigh's Inchworm [2] is a commercial example of such a design. These types of actuators rely on a clamping-displacing-unclamping-retracting cycle on a slideway or bar. The Precision Engineering Center has created an active clamping design based around a fine pitch screw similar to those mentioned above. The actuator, designated the "Cryoworm", uses one piezoelectric actuator for clamping a screw and a second actuator to cause rotation. The design of the clamping nut is shown in Figure 3. It was built around a slightly modified #8-80 screw where the threads were machined off on a portion. This portion allows the nut to clamp the screw on a smooth surface eliminating damage to threads and reducing wear of the alumina tip. Another threaded nut, which is attached to ground, converts the rotational motion into axial motion.

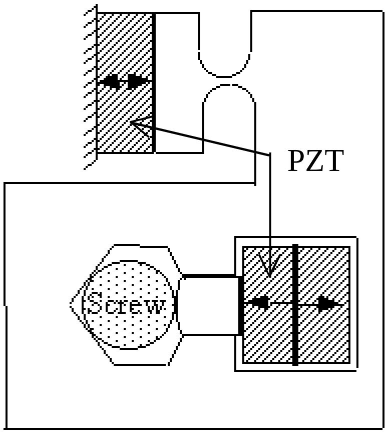
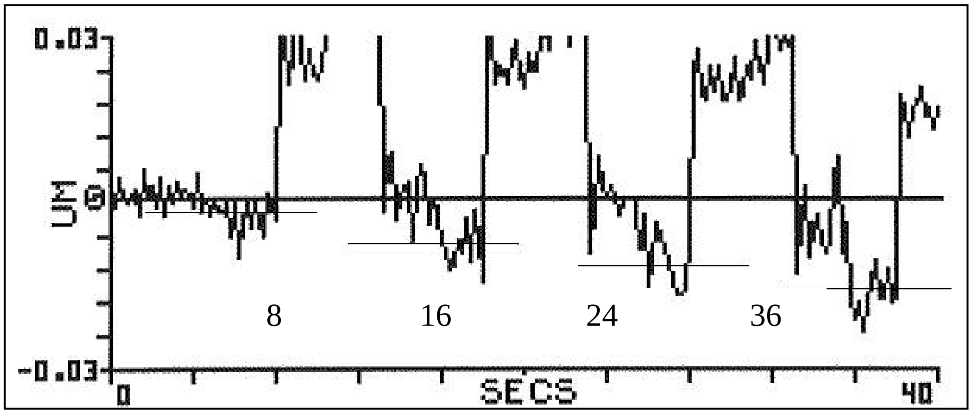


Figure 3: Clamping Nut of Cryoworm

Two square waves, 90˚ out of phase, are used to drive the clamp and rotation actuators. Figure 4 shows 3 cycles of the clamp/rotation process. The process starts with the rotational actuator, which is energized at about 8 seconds in Figure 4. A large step in the displacement of the end of the screw accompanies this actuation step because the screw is pushed radially in the stationary nut and the screw tends to move axially due to the shape of the threads. The clamp actuator is then actuated (at 10 sec) to attach the screw to the clamping nut. This action also moves the screw in the nut and produces a step. The next step is to de-energize the rotational actuator (at 14 sec) which results in a drop in the displacement by removing the side load on the screw. Finally, the clamp force is removed from the screw at 16 sec and the new position of the end of the screw is reached. For the three cycles shown in Figure 4, the average motion for each step is 3.6 nm.

There are a number of design issues that need to be addressed. A large preload on the end of the screw will reduce the step deflection discussed above by keeping the screw centered in the nut. The stiffness of the flexure both axially and rotationally plays an important role on the operation of the motor. If it is too stiff in bending, it will induce a lateral load on the screw but no rotation. If the axial stiffness is too low, it will waste the small stroke of the piezoelectric stack without causing rotation. A possible solution is to redesign the clamping nut with two symmetrical rotational PZT's on either side of the screw. With this configuration, the forces created by the two bending flexures are cancelled out thereby transferring only a moment.



CONCLUSION

Two types of actuators have been discussed, inertia and active clamping. There are advantages and disadvantages to both types of actuators.

- The computer model indicated that the inertia clamping design is very sensitive to the magnitude of the friction between the nut and the screw as well as the variation in that friction with relative velocity. The initial energy from the actuator is coupled to the nut by friction and it is possible to make the screw end up clockwise or counterclockwise from the initial position by changing the input energy or the initial speed of the nut. Consequently, changing the friction coefficient can have a similar effect. Thus uncertainty in the frictional properties is the biggest unknown in this type of design.
- The active clamping design depends upon coupling the nut and the screw through a change in normal force rather than friction coefficient. Since the piezoelectric material has a very small stroke, this implies careful control of the shape and dimensions of the components. For an active clamping motor to be assembled and tested at room temperature and transported to space for operation, appropriate materials and designs must be used to accommodate the thermal expansion coefficients.

REFERENCES

1. Brown, R.A. Hubble Space Telescope Web Site. "HST Second Decade," http://sso.stsci.edu/second_decade/
2. Fasick, J.C., "Development of a Nanometer Resolution Constant Velocity Piezotranslator", MS These, N.C. State University, 1998.
3. New Focus.com web site. "MRA and Rotating Shafts". http://www.newfocus.com/Online_Catalog/6/145/1106/body.html