

Development of a Compact, High Load PZT-Ceramic, Long-Travel, Linear Actuator with Picometer Resolution for Active Optical Alignment Applications

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Abstract:

This paper describes a high-force PZT-ceramic based linear actuator for long-travel, high resolution applications. Different modes of operation offer high bandwidth dither, step and constant velocity slew motion. The drive is self-locking and does not expend energy to hold a position. This development was originally undertaken for applications in the semiconductor industry and mature serial production actuators are now embedded in machinery to actively collimate heavy optic assemblies weighing 10's of kg in multiple axes with nanometer resolution.

Keywords: Piezo actuators, optical alignment, NEXLINE[®], nano-positioning

1. Introduction

Many large optical telescopes employ active position control for primary mirror surfaces using motorized mechanical actuators. The motion needed is generally quasistatic, to compensate gravitational and thermal effects. Another application for precision actuators within the telescope at a significantly faster motion response is the high speed tip/tilt control of a secondary or tertiary mirror.

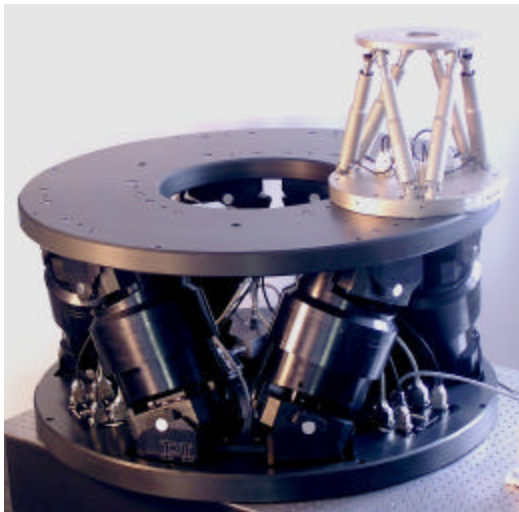


Fig.1.1 1000kg-class hexapod micropositioning 6DOF optics alignment system (1m diameter)

compared to 100kg-class hexapod (0.3m diameter)

Fig.1.1 shows a typical 6axis hexapod positioner designed for secondary mirrors. It performs micron level positioning using high precision motorized components, and some designs have integrated piezoelectric actuators for rapid tip-tilt movements of the secondary mirror.

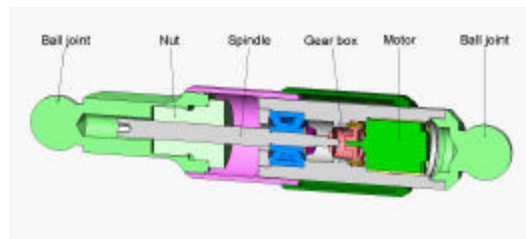


Fig.1.2 Design of a classical motorized actuator

The classical design for a motorized actuator consists of a DC motor with an encoder, gears and a leadscrew-nut assembly to convert the rotary motion to linear translation. The achievable performance depends, for the most part, on the choice of mechanical components and the control algorithms. The physical size and mass of the actuation system is load dependent and for primary mirror applications often include counterbalancing mechanisms for offloading the motion drives. With high precision gears and leadscrews (e.g. Harmonic Drive gearheads, zero backlash ball and roller screws) position resolutions of 0.1 to 0.5 μm can be

achieved. The resolution can be bettered by adding a piggy-back piezo actuator with a high-resolution linear encoder, or by using motion deamplification techniques at the expense of added complexity and part count. All applications mentioned above require minimal energy consumption during operation for thermal control. An essential requirement then is that the units be self-locking when not under power, something which has required the addition of a brake acting on the leadscrew or motor for classical mechanical actuators.

2. The Development of NEXLINE® Technology

Friction, play and the associated manufacturing tolerances of the mechanical components limit the achievable position resolution in motorized actuator technology. Piezoelectric actuators however, acting as analog positioning elements, are not subject to these limitations. The resolution of a piezo actuator is limited only by the noise on the control signal and is typically in the nanometer or picometer range. Unfortunately, the displacement available with the piezo effect is limited to about 0.15% of the length of the piezo ceramics block. The implementation of piezo actuation to longer travels (many millimeters) with high force has been very problematic over the years with vibrational/acoustic noise, low force and low reliability from high wear rates as major technological hurdles. The motivation behind the development of NEXLINE® drives therefore was to provide the advantages of piezo actuators over long travel ranges while overcoming the technological hurdles mentioned above in a compact modular actuator.

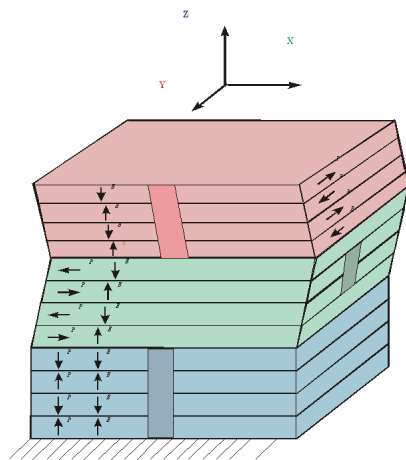


Fig.2.1 Combination of shear and linear piezo actuators

2.1 Dither Mode Operation

A NEXLINE® piezoelectric step drive consists of an arrangement of piezoelectric elements polarized in different directions. Shear piezos, highly preloaded against the runner, drive it perpendicular to the interface in a direction which depends on whether their control voltage is rising or falling. See Fig.2.2.

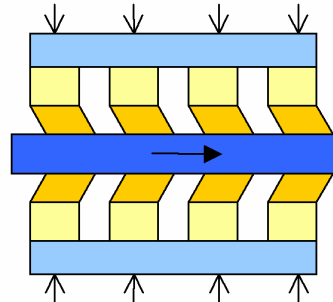


Fig.2.2 Dither mode of operation

In dither operating mode, all the drive piezos are operated in parallel and the stiffness and drive force can be scaled by increasing their number. Extremely high resolutions (picometer level) and high operating bandwidths can be achieved. However the travel range available in this mode is limited from 5 to 8 μm yet it is able to provide interferometric class position resolution for heavy optical surfaces or components

2.2 Slew Mode Operation

In order to overcome the travel-range limitation of dither mode, each shear piezo is bonded to a longitudinal piezo which provides a clamp/unclamp effect. When a clamping piezo retracts, its shear piezo lifts off the runner. The clamping piezos are driven in two groups 180° out of phase. This makes it possible to combine short steps of the shear piezos into a longer move of the runner in either direction. See Fig. 2.3.

Slew mode motion is divided into several different phases: Clamping piezos (group 2) unclamp, shear piezos (group 1) drive the runner forward while shear piezos (group 2) move backward, clamping piezos toggle, shear piezos (group 2) drive the runner forward while shear piezos group 1 move backward. The available travel range therefore can be scaled significantly with 10's of millimeters as a normal range.

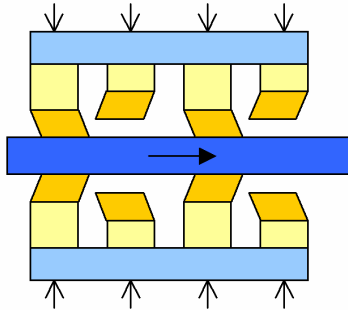


Fig.2.3 Slew mode operation

Slew mode motion begins and ends with zero control voltage on all piezo elements. This means that when powered down, the runner is held in place by the friction resulting from the high internal preload and can only be moved from its position by very high external forces.

In some applications, the discontinuities of the stepping motion described above can lead to undesirable oscillation of parts or assemblies. In such cases, it is possible for the slew mode controller to overlap the shear motion with the toggling of the clamping piezos, so that the piezos always clamp and unclamp the runner as it moves at a constant velocity. The operational compromise to obtain constant velocity slewing is lower force and step size compared to the full step slew mode.

2.2 Dynamic Park/Position Hold Mode

With the ability to slew and dither the Nexline actuator another mode of operation can be realized. Upon a power off condition the Nexline drive is programmed to remember it's position and by adjusting the voltage applied to the clamp and shear piezo actuators it will hold it's exact position at the moment of the power off condition even as the PZT actuators discharge from their operating voltage to a zero volt condition.

This mode can also be implemented when the Nexline is in operation by commanding it to hold position while auto zeroing it's bias voltage from programmed set points. Maintaining an average low bias voltage greatly extends the operational lifetimes of the Nexline actuator since PZT ceramic lifetime is proportional to the average operating bias voltage.

3. Application

This technology was originally developed for applications in the semi-conductor industry. There, heavy, extreme precision optics assemblies weighing 10's of kg must be positioned vertically and aligned in multiple axes with nanometer resolution. The coarse positioning requirements are for quasi-static motion over several millimeters to compensate for the relatively large mechanical tolerances in the manufacturing of machine components and structures. The fine positioning requirements, however, entail motion over a few microns with subnanometer resolution and sufficient bandwidth to also compensate for vibrational disturbances.

A significant requirement is that once on target, the position must be held with nanometer accuracy without having to apply voltage to the piezo elements. Fig.3.2 shows a linear actuator which meets the requirements listed above.



Fig.3.1 N-110 miniature NEXLINE® linear actuator. D-Sub-connector for size comparison, mass approx.0.3kg



Fig.3.2 N-215 high-force NEXLINE® linear actuator, CD for size comparison.

Operational Specifications:

Up to 20 mm stroke

50 picometer resolution

+/- 500 N (112 lb.) push/pull capability
 Actuator mass 0.9Kg
 Actuator volume – 240cc
 Stiffness – 45 N/micron
 Dynamic range over 2mm travel - >10,000,000

Also shown is a miniature version capable of 1.5 μm steps and forces to 50 N (see Fig. 3.1).

In contrast to classical linear actuators, a number of components such as leadscrew, gearbox and bearings can be dispensed with because the linear motion is generated directly. This makes it possible to realize very compact, low mass, high-load devices. Fig. 3.3 shows a hexapod made with fully nonmagnetic NEXLINE® actuators for a complex alignment application involving superconducting magnets.

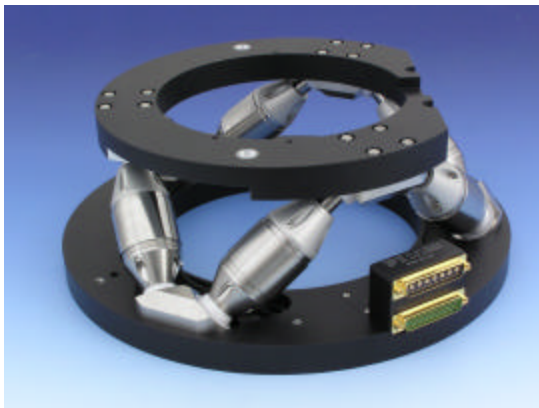


Fig.3.3 Six-axis parallel kinematics piezo Hexapod w/ NEXLINE® actuators for use in high magnetic fields, 300 mm outside diameter, Travel ranges: 20 mm / 6 degrees, load capacity of 50 kg.

NEXLINE® actuators can be designed for a wide temperature range and are intrinsically vacuum compatible. Because of the temperature dependence of the piezo effect, the displacement of the individual piezo elements is reduced to about 30% at cryogenic temperatures. The maximum operating temperature of the PZT ceramics is about 120°C due to effects of thermal depoling.

4. Test Results

The performance of the actuators is proportional to the amount of shear piezos and the driving voltage applied to it. In slew mode, the maximum step size of the N-215 Linear Actuator at full driving voltage is typically about 6.5 μm . (See Fig. 4.1). The maximum

speed is proportional to the step frequency, which is generally limited by the controller used and by the amount of power available. Normal speeds are between a few hundred microns and a few millimeters per second. Reducing the amplitude of the voltages on the shear piezos results in smaller step sizes. (The minimal reproducible step sizes are limited from 5nm to 10nm. This is determined by the surface microroughness of the contact areas and by parasitic piezo movement due to the intrinsic non linearities in the piezo material.

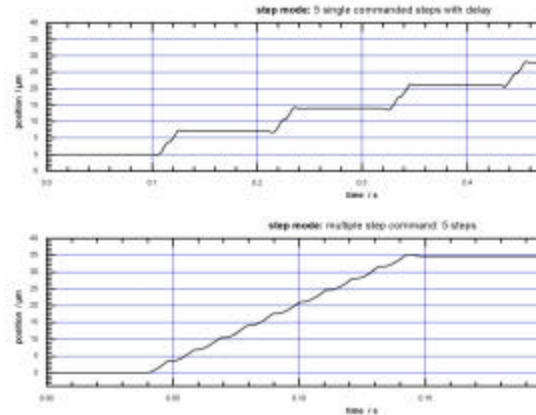


Fig.4.1 N-215 Linear Actuator, max. step size; top: 3 of 5 steps shown

Similarly, in dither mode, a reduction of the maximum control voltage swing will result in a decrease of the analog mode stroke. Fig. 4.2 shows measured values for the motion of the runner of about 1 nm in response to 3 V square-wave signal. The resolution limit could not be determined, because the resolution of the capacitive sensor which was used was only about 50 pm.

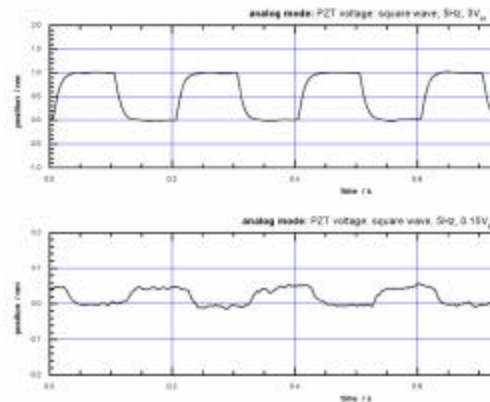


Fig.4.2 N215 Linear Actuator. Train of 1 nm steps (top) and 50 pm steps (bottom) in open-loop, analog mode.

As the force opposing the motion of the actuator is increased, the step size can be seen to decrease to zero. The reason is the elastic deformation of the piezo elements and the connecting structure, which leads to motion loss when the clamping piezos toggle. The maximum force which the actuator can withstand using maximum shear piezo control voltage amplitudes is called the *blocking force* and for the N-215 it is about 500 N.

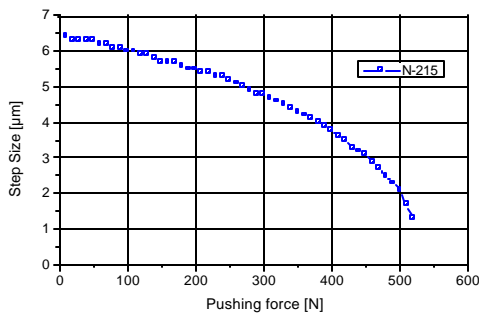


Fig.4.3 N-215 actuator characteristic step size versus pushing force

In the face of very high opposing forces—forces exceeding the normal preload times the friction coefficient—the runner would slide between the piezo actuators clamps (analogous to a slip clutch effect) and be driven to the mechanical hard stop. Those forces would need to be greater than 700 N.

5. Conclusion

The development of the piezoceramic linear motors described here demonstrates that it is possible to combine long travel ranges, ultra-high resolution and high force in a unified drive design. This drive additionally due to its high stiffness can move heavy loads dynamically. The drive is intrinsically self-locking and does not expend energy to hold a position. This development as noted earlier was undertaken for applications in the semiconductor industry and multiple units in our lifetime test facility have demonstrated lifetimes of $>10^8$ slew and $>10^9$ dither mode cycles to date in continuing durability tests. The lifetime design goal of these actuators is 10 years in a vacuum environment. More testing is necessary for cryogenic applications and for mountain top observatory environments. From our experiences in extreme industrial applications a simple and low cost dry air purge of a few cc's per hour will insure long

actuator lifetime for ground based observatory environments.

The applications for ground and spaced astronomical telescopes with their associated instrumentation packages range from primary mirror segment positioning, active truss structures, and embedded coarse/fine position control in space constrained instrument packages. From a cost standpoint; NEXLINE actuators are higher in cost than conventional micropositioning drives; yet when the requirement demands coarse/fine position control with nanometer level resolution; they are cost competitive, simpler to integrate; and occupy much less volume and mass than equivalent force hybrid mechanical actuation designs.

References:

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