SERVOMOTORS TAKE PIEZOCERAMIC TRANSDUCERS FOR A RIDE

Piezoceramic transducers cascaded with servomotors for motion control provide stable systems with unlimited travel and micron positioning.

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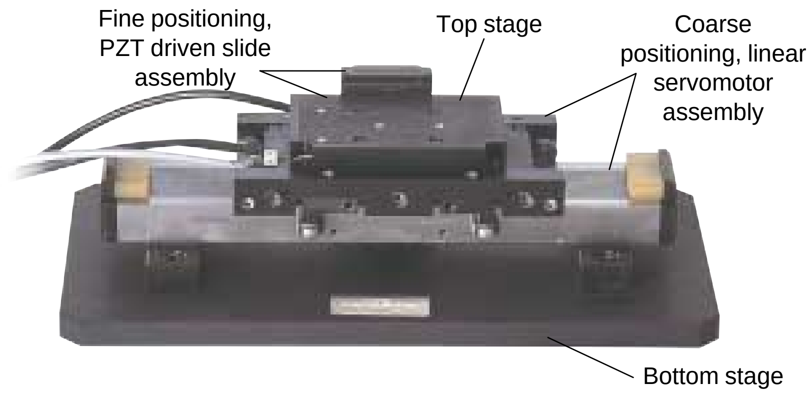


A typical compound motion control stage for one axis contains a linear servomotor for coarse positioning, and a PZT riding on its table for fine positioning. The servomotor drives to the approximate position and locks in place, while the PZT moves to the final commanded position, within a resolution as small as 5 nm.

Although electromagnetic servomotors are widely used in closed-loop motion-control systems, they have a few serious limitations when it comes to micropositioning. One is an instability called dither, motor-shaft oscillations that develop when the servoamplifier gain exceeds a certain threshold. Gain is usually set high to obtain the best possible system accuracy and repeatability, but beyond a certain point, the servomotor oscillates, washing out any further improvements.

Understanding the dynamic behavior of servomotors can help determine the type of compensation that might be needed to stabilize such a system, but even with the best methods at hand, it still might not reach the accuracy needed for some applications.

A viable alternative employs a piezoceramic transducer (PZT) in cascade with a traditional servomotor. The system gain can be set for coarse positioning with the servomotor and fine positioning for the piggy-back PZT. The combination has proven successful in critical positioning systems such as those for manufacturing semiconductor wafers.

A CLOSER LOOK

Before giving up on a servomotor, however, examine all possible options for tightening the system without generating dither, even though the factors that influence the servomotor's response are complex. For example, the most common math model used to express motor torque or force, a quantity proportional to the motor current, is approximate at best. Also, it's usually a mistake to assume the mass or inertia of the motor centers about one point, and the mechanical system is perfectly rigid. These assumptions could be valid, but usually only at low frequencies. When increasing system bandwidth, the smallest inaccuracies often combine at some point to drive the system unstable.

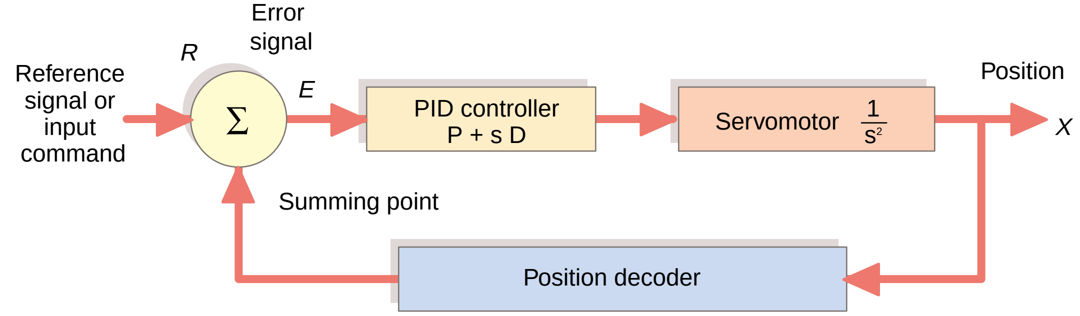
The ideal math model of a servomotor shows that the current produces a proportional acceleration. It also shows that motor position is the second integral of acceleration. But two integrators in a control loop make the system inherently unstable. Methods used for compensating and stabilizing such a system include modifying the dynamic response with digital filters. This reduces the loop delay.

Try compensating with high-pass filters first. Because of the two integrators, it's necessary to include both a proportional and derivative term in the filter to moderate the integrators. The derivative term increases gain in proportion to frequency.

But high-pass compensation filters also amplify disturbance inputs generated by noise or imperfect sensors. All such disturbances can induce dither around the commanded position. When the application calls for higher precision than is possible with high-pass filter compensation alone, then it's necessary to resort to an alternative actuator that does not suffer from these problems — such as the

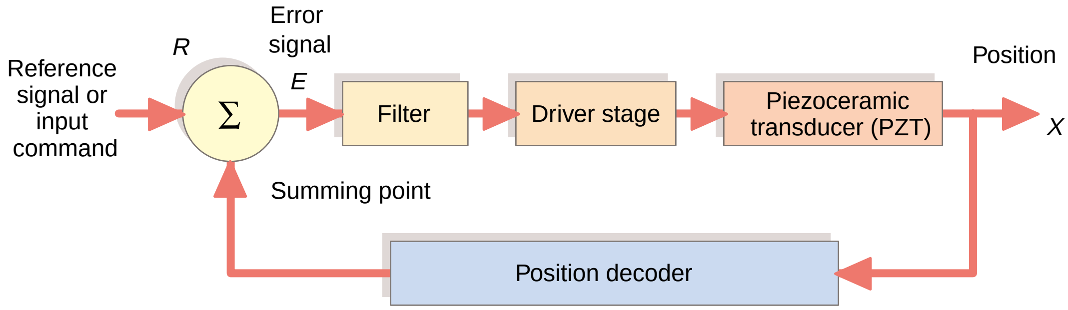
You can find related information at: www.penton.com / md / bde / motion_control / index.html (1.2 Positioning Components)

A simple servomotor feedback system



A typical servomotor control system contains two integrators in the servomotor. But the system can become unstable with two integrators, so digital filters may be included to reduce the loop delay.

A piezoceramic control system



An integrator usually serves as the compensation filter in a PZT control system. An integrator provides a stable and dither-free loop because it's a low-pass filter and cannot amplify noise and other disturbances.

piezoceramic transducer.

PIEZOCERAMIC TRANSDUCERS

Piezoceramic transducers eliminate some of the shortcomings common in electromagnetic servomotors because they are constructed much differently. (See MACHINE DESIGN, June 3, 1999, page 118, *Oscillating piezoceramics drive nanometer motors*.) PZTs convert voltage into motion by contraction and expansion. As the PZT expands, it can generate a substantial force of up to 100 N.

One major characteristic of the PZT is its inherent stability for positioning because no phase lag develops between the applied voltage and the motor response. The compensation filter can be set as a pure integrator to stabilize the loop. Moreover, the compensation filter does not need a derivative term. It is not a high-pass filter and doesn't amplify noise or other disturbances, which also makes PZT control systems stable and dither-free. But PZTs have one major disadvantage — travel is typically limited to 0.1% of stack length. This means that a PZT 1-cm long can move a distance of only 10 microns.

The length of PZT travel is proportional to its applied voltage. This provides the transfer function:

$$X/V = K$$

where X = position, microns; V = voltage, *volts*; and K = constant.

The equation is fairly accurate over a wide frequency range, typically up to 20 kHz, well above the bandwidth of motion-control systems. And because this model is so precise, it behaves consistently over the frequency range.

PZT control systems include a compensation filter often set as an integrator only, a driver, the PZT, and a position sensor. To analyze the dynamic response of such a system, shown in *Piezoceramic control system*, assume the combined gain of the PZT and the driver under an applied voltage of 0 to 10 V moves the PZT 10 microns. This sets the combined gain of the PZT and the driver to 1.0 micron/V. Now assume the position sensor has a resolution of 0.1 micron. This represents a gain of 10 counts/ micron. Finally, assume that the compensation filter has an integrator with the transfer function in the *s* domain:

$$G(s) = 100/s$$

The model of such a system is shown in *Math model of PZT system*. To analyze the system, use its open-loop transfer function:

$$L(s) = 1{,}000/s$$

The phase lag in the loop is limited to –90°, making it inherently stable. The system crossover frequency (ω_c) can be determined from:

$$|L(j\omega)| = 1$$

thus:

$$\omega_c = 1{,}000 \text{ rad/sec.}$$

To calculate the convergence time, assume the system is at a given position, and it has to move by one count of 0.1 micron. A position error of one count generates an output voltage that follows the equation:

$$V = 100\,t$$

Because 0.1 V moves the PZT by 0.1 micron, calculate the time to develop 0.1 V:

$$100T = 0.1$$

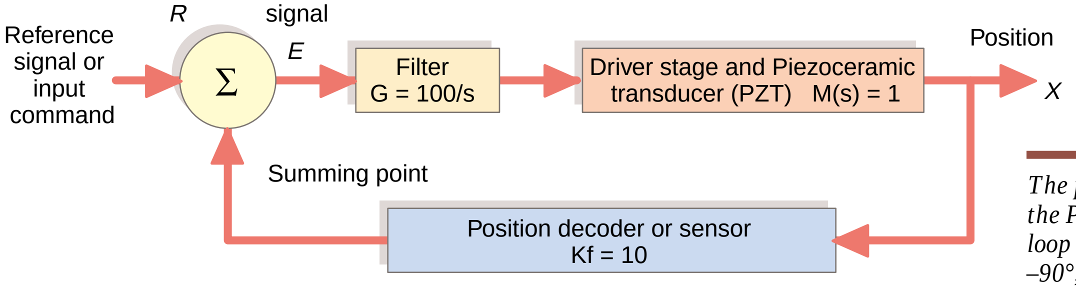
$$T = 1.0 \text{ msec.}$$

PZTs are often used in systems that need precise motion measured in microns. But by themselves, PZTs have limited use. To combine the benefits of

Alternative drive methods

DEVICE	TRANSFER FUNCTION	PID COMPENSATION	MOTION TIME: 3 MICRONS	MOTION TIME: 1 CM
Servomotor	K/s^2	PID	10 msec, may dither	100 msec
PZT	K	I	3 msec	N/A
Ultrasonic motor	K/s	PI	30 msec	100 msec
Compound motion system	N/A	N/A	3 msec	100 msec

Math model of PZT system



The phase lag in the PZT system loop is limited to –90°, making it inherently stable.

the PZT with a longer travel range, the transducer is used as the prime motive source in an ultrasonic motor.

ULTRASONIC MOTOR

Several methods convert PZT vibrations into unlimited linear moves. One uses the PZT as a plunger to push against a flat surface, moving it sideways. Another approach based on a mechanical arrangement locks both ends of the PZT. To advance the unit, the locking forces change sinusoidally on the right and the left in opposite phases. In addition, a sinusoidal voltage at the same frequency applied to the PZT produces sinusoidal expansion. The timing between the PZT expansion and locking forces produce sideways motion.

It appears at first glance the ultrasonic motor seems to have the advantages of the PZT along with the ability to move an unlimited distance. However, a careful examination reveals a few shortcomings. The first regards the dynamic response of the motor and its transfer function. While the PZT expands in direct proportion to the magnitude of the applied voltage, the ultrasonic motor on the other hand, accumulates those displacements over time. Therefore, the transfer function of this motor, relating the magnitude of the driving signal, V, to the displacement, X, is an integrator:

$$M(s) = K/s$$

This shows a delay in the response of the ultrasonic motor, but it's not nearly as large as that in an electromagnetic servomotor.

A second characteristic of an ultrasonic motor is that because it transmits motion through a friction force, it will have a deadband due to the friction. Often, an ultrasonic motor does not move until the input signal is greater than 10% of the maximum allowed voltage to overcome the friction. Such a deadband limits the ability of ultrasonic motors to move fast and accurately.

A third approach mounts the PZT on top of a servomotor to combine the best features of both, providing unlimited travel with positioning precision of up to 5 nm.

Methods for controlling such systems depend on the application. For example, when stepmotors are used for the coarse actuator, one approach drives the stepper to the proximity of the target and then activates the PZT for the final required precision.

A similar approach works when a servomotor is the coarse actuator. Once the servomotor nears the required endpoint, it is mechanically locked, often by removing air from an air bearing. This is followed by activating the PZT for the fine move. Experimental results indicate that such compound motion systems provide the best combination of high precision, rapid moves, and unlimited travel range. ■

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