159 Swanson Rd.
Boxborough, MA 01719
Phone +1.508.475.3400
dovermotion.com

Limitations of Piezos

By Kevin McCarthy, Chief Technology Officer

All translation stages require a set of ways, as well as a means of actuation to produce motion along the guideways. There are a number of actuation technologies available to choose from, and one of these makes use of the inverse piezoelectric effect. This is an effect in which the application of an electrical voltage to selected materials produces an extension or contraction in that material. Due to the very low magnitude of this expansion or contraction, all practical implementations of the piezo effect rely upon either reiteration or amplification to produce useful motion. Piezo actuators come in a variety of physical configurations, as listed below:

1. Piezo stacks
2. Piezo stacks with mechanical amplification
3. Bimorphs
4. Inchworms
5. Resonant piezo actuators
6. Piezo tubes

PIEZO STACKS

The inverse piezoelectric effect was first discovered by Pierre and Jacques Curie in 1881. Today, the most common materials used for piezo actuators are either barium titanate or PZT (lead zirconate titanate) ceramics. The ratio $\Delta L/L$ (change in length to length) for an applied voltage is quite small for a single piezoceramic element, and so most actuators are composed of a large number of thin plates, referred to as a piezo stack (Fig.1). The voltage applied to the stack is distributed to each of the plates within the stack, in a parallel configuration. Depending on the nature of the piezo material (soft vs. hard), the applied voltage range is typically either +/- 1000 volts (hard, or high voltage), or +/- 120 volts (soft, or low voltage stacks). Piezo stacks by themselves are fragile and unable to produce force in both directions; these limitations can be significantly reduced if the stack is mounted within a housing, and powerful springs are used to produce a high internal preload.

Housed piezo stacks with internal preload springs are useful positioning actuators, but suffer from several limitations. The most obvious limitation is that of limited travel; typical piezo stacks range in travel from 10 to 200 microns. This The number of plates grows with increased travel, increasing both stack length and cost as travel increases. A stack capable of 200 microns of motion (which appears to be the upper limit among commercially available devices) will typically be about 200 mm. long. Another limitation is a significant amount of hysteresis, or variation of travel vs. applied voltage between forward and reverse movement. This can be as much as 15% of full travel! In addition to hysteresis, there is a drift problem, in which motion continues to slowly creep after a position step. While the use of a linear position feedback transducer and a closed loop servo control can overcome hysteresis and drift, this comes at considerable added cost and complexity compared to the inherent simplicity of an open loop voltage commanded piezo stack. When operated in closed loop mode, an additional concern arises. The payload mass and the stiffness of the piezo stack produce a high Q resonance, whose natural frequency can be surprisingly low for realistic tooling and part masses. The high Q of this resonance can complicate efforts to notch it out, and the end result is often that a lower than desired servo bandwidth must be accepted. In general, piezo stacks with internal preload and closed loop position feedback can be useful positioners, but will provide limited travel, may be longer and more expensive than desired, and will be limited to moderate servo bandwidths unless the payload mass is quite small.

PIEZO STACKS WITH MECHANICAL AMPLIFICATIONS

The inevitable conflict between the available travel and practical requirements of most applications leads piezo designers to adopt a variety of travel enhancing techniques. One of these is to add a mechanical amplification of the piezo movement to increase travel. To avoid issues such as play and stiction, the mechanical amplification is typically achieved using a flexural hinge, with a lever amplification between the input (the end of the stack) and the output (stage moving carriage). The advantages of this scheme are that larger travels can be attained, and that a shorter and lower cost piezo stack can be used. The downsides are significant, however, and include a reduction of the allowable load by A, the lever amplification, with the stiffness falling by the amplification ratio squared. More critically, the natural frequency of the combination is reduced by the amplification ratio. This has serious implications for system bandwidth, and hence dynamic response.

BIMORPHS

Bimorphs are components that consist of a pair of thin piezo elements bonded together, with conductive electrodes on the outer surfaces, and, in some cases, at the interface between the plates. They function in an analogous manner to a bimetallic strip, with voltages of the proper polarity producing a contraction in one plate and an expansion in the other. As a result, the plate bends to one side, with amplitudes of a millimeter or more. While they can be used for the positioning of very small payloads, they suffer from very low stiffness and very low load bearing capacity, and are appropriate in a limited subset of positioning applications.

INCHWORMS

Inchworms incorporate two radial and one axial piezo elements that surround a cylindrical guide rod, and certainly deserve credit as an innovative attempt to increase travel. In this case, the system control orchestrates a sequence in which the first radial element is clamped, the axial element extends, and the second radial element clamps. The first radial element can then be released, the axial element retracts, and the process repeats, akin to the motion of the insect for which it is named. While remarkable as an idea, the resulting product is limited to speeds of a few millimeters per second, is fussy to align and quite fragile, has a limited service life, and exhibits "print-through" of the clamp events on the velocity profile. While the technique offers good stability and stiffness at rest, the disadvantages usually predominate.

RESONANT PIEZO ACTUATORS

This type of piezo device, several versions of which are commercially available, offers extended travel (from millimeters to meters) with moderate resolution, and is the most practical implementation of the piezo effect for travels beyond the range of stack actuators. In this design, one or more ceramic fingers are preloaded against a ceramic spar, and piezo elements are used to drive the fingers in an oscillatory motion against the spar. The combination of extension and bending create an elliptical motion of the tip, which can be used to impart motion to the stage. The piezo elements are parts of a high-Q, high frequency, resonant LC tank circuit. The ceramic spar sets the length of travel, and the system has the advantage that when no motion is commanded, the fingers act as a brake, preventing stage motion. When teamed with an appropriate position feedback device, servo loop controller, and linear (or rotary, for that matter) bearing guideway, the result is a compact, reasonably effective long-range piezo actuator. Despite this, the system has a number of disadvantages when compared to direct drive methods using permanent magnets and coils. The dominant issue is that there is significant friction to overcome. This is inevitable, since the fingers must be preloaded against the ceramic, and yet must move relative to it. The greatest problem posed by this friction is the very large deadband in the transfer function; these devices essentially convert a command voltage to a velocity. If these two quantities were strictly proportional (as are current and force in a magnetic drive), things would be better, but the transfer function turns out to have a friction generated deadband (the range of command voltage for which there is no resulting motion) of several hundred volts. This is a non-linearity you could drive a truck through; given that servo electronics is based upon linear control theory, this wrecks havoc with the desire to close a stable, well-behaved loop. Some efforts have been made to compensate for the deadband with a friction bias, but since the friction varies with preload along the travel, no one value will suffice. The friction also produces wear, which limits the lifetime of the device and produces particulates. This wear is more pronounced when a limited region of the travel is used repetitively (as is typical in photonic assembly). The efficiency of these devices is quite low, so that high device heating can occur if appreciable mechanical energy must be imparted to the stage; this is particularly an issue in vacuum systems. The available force falls off with speed, and for most systems a top speed of ~ 100 mm/sec. is required to allow sufficient additional force to overcome bearing stiction. While the fingers do offer a braking function at rest, they have a finite stiffness, and this can lead to unexpectedly low resonant frequencies for moderate sized payloads. All in all, resonant piezo actuators are the best attempt to date to produce extended travel via the piezo effect, but they can in nearly all cases be surpassed in performance by non-contact magnetic drive.

PIEZO TUBES

This last design variant has been mentioned both for the sake of completeness, and because they are cool. Piezo tubes consist of a thin-walled cylinder composed of a piezo ceramic, with an outer and inner metallized layer. The outer layer is sectioned into four 90 degree quadrants with wire leads, and a common lead is also attached to the metal layer on the ID. One end of the tube is fixed, and the other end carries a small (tens of grams) payload. The tube body serves as a flexural guideway for the resulting motion. Depending on the polarity and magnitude of the voltages applied to the electrodes, either X, Y, or Z axis translation can be produced, albeit with quite limited travel (a handful of microns, depending on tube dimensions; Z travel is less). Nevertheless, the ability to perform independent three axis motion with a single, very compact actuator / guideway is remarkable. The resolution is extremely fine, and piezo tubes of this type are used in atomic force microscopes with sub-Angstrom resolution.

ABOUT THE AUTHOR...
Kevin McCarthy is the chief technology officer of Dover Motion.