Piezoelectric motors go rotary

Mark Broderick, PhD
President and CEO
Discovery Technology International, LLLP
Sarasota, Fla.
dti-piezotech.com

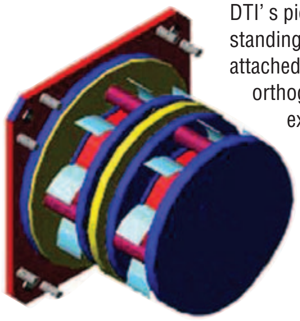
A novel, low-voltage, high-torque, rotary motor built around piezoelectric principles overcomes the limitations of conventional motors. The new piezomotors provide significant advantages in applications that need high resolution, short response time, smooth motion, and low drift. The motor also has accurate angular positioning essential for many high-tech and industrial applications. Until now, automated angular positioning devices have relied on rotary electromagnetic (EM) motors.

Drawbacks to EM

EM motors include steppers, vectors, and dc servomotors. Positioning controls compensate for some servo and flux-vector motor disadvantages. A few models have increased angular resolution, some to 4,000 steps/rev. An encoder measures position and angular speed in these designs so corrections can be made for system overshoot. This increases angular resolution without additional gearing. Still, the single most important cause of degradation in positioning accuracy in conventional EM motors with gears is the unavoidable mechanical tolerances of traditional transmissions.

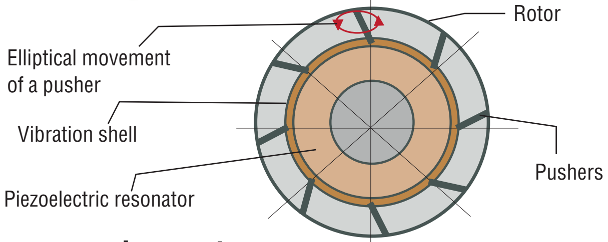
Another significant drawback of vector and servo motors is that they must continuously "hunt" to stay at a required position. This means they continuously sense small position errors to generate a correction necessary to hold the working

Model and schematic of new piezomotor – bi-directional configuration



DTI' s piezomotors work on a principal of exciting ultrasonic standing waves within a piezoelectric resonator. Pushers are attached to or form part of the piezoresonator. In general, two orthogonal standing waves with a controlled phase difference are excited in the resonator, each stimulating movement of the pushers in orthogonal directions. This results in elliptical movements of the pushers. These are held pressed against the rotor so their movement, by friction at the pusher contact area, generates rotor spin.

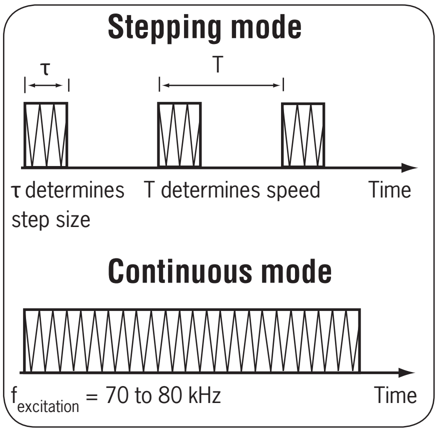
Inside a piezomotor



Comparing a stepper to a new piezomotor

Parameter	Equivalent EM Stepper Motor	Piezomotor (Model PM-22RS)
Positioner applications	Requires angular step reducer	Direct drive
Rotational range	360º	360º
Design resolution (no step reducer)	525 µrad (0.03º = 108 arc-sec)	<2.4 µrad (0.5 arc-sec)
Minimum controlled angular increment	525 µrad (0.03º = 108 arc-sec)	<4.8 µrad (1 arc-sec) Defined by the encoder
Backlash	0.1 to 1 of minimum increment	None
Hysteresis	Not available	<2.4 µrad (0.5 arc-sec)
Maximum speed	628 rad/s (6,000 rpm)	3.14 rad/s (30 rpm)
Maximum torque	0.1 Nm	0.5 Nm
Self-braking torque	Not available	0.51 Nm
Response time	10 ms	10 to 50 µs
Demand - to maximum speed	100 ms	0.3 ms
Velocity range (Stepped-continuous)	500 µrad/s to 20 rad/s with micro-stepping	5 µrad/s to 3.14 rad/s Defined by the controller
Reversal time at maximum velocity	100 ms	500 µs
Dynamic range bandwidth	100 Hz	2 kHz
Rotor moment of inertia	2.0x10^{-5} kg-m^2	0.7 to 2.0x10^{-5} kg-m^2
Load capacity	20 kg	20 kg
Supply voltage	12 Vdc	12 Vdc
Maximum power consumption	10 W	6 to 8 W
Nominal power consumption	6 W	5 W
Mass	0.6 kg	0.2 kg without encoder
Dimensions	50 x 55 mm	50 x 50 mm without encoder
Long term drift (@20 C)	Not available	< 2.4 µrad/hr (0.5 arc-sec/hr)
Controller	Analog or digital	Analog or digital

Comparison of key technical parameters of a typical piezomotor PM22RS with a comparably sized stepper motor.



Waveforms illustrate the basic principle of control in stepping and continuous modes of operation. Digital control allows accurate and repeatable sub-arc-second steps as well as continuous motion.

end on target. Dynamic response is invariably limited by sensor noise, motor inertia, and inductance.

Vector motors also track position with encoder feedback. One difference between vector and servomotor (other than the electrical difference) is the greater inertia of the vector motor's rotor. Vector motors use a variation on the squirrel-cage rotor – steel laminations and aluminum or copper bars – which add mass to the rotor. Generally, vector motors also have larger diameter rotors than do servos. Both factors increase a vector motor's moment of inertia, which in turn, limits acceleration.

The stick-slip effect, another factor limiting accuracy and resolution in EM motors, is the slight movement delay on the applied force. Stick-slip limits angular resolution, response speed, and tolerable overshoot. As a result, manufacturers of EM motors use gear boxes with high ratios. In theory, these should handle the degradation of angular resolution, but only at the expense of increasing hysteresis and backlash inherent in gear trains.

The new idea

The need for alternative rotary motors that overcome the limitations in EM motors has been met with the development by Discovery Technology International (DTI) of a range of low-voltage, high-torque motors based entirely on non-EM principles. The new motor uses ultrasonic piezoelectrics combined with a platform controlled by Digital Signal Processing (DSP) or analog methods. This provides a simplified design that eliminates the gear box altogether. Additional piezomotor benefits include a significantly short response time and zero-power consumption to hold or lock it at a fixed position making the motor an attractive alternative in applications such as motorized valves.

The piezomotors developed by DTI provide superior performance compared to conventional EM motors in certain applications. Benefits include micro-radian resolution and accuracy, extremely low hysteresis, and almost zero backlash. What's more, because the motor is non-EM it can also be manufactured with non-magnetic materials making it suitable for MRI and other related applications. The accompanying tables provide example specifications . The piezomotor's response is several orders of magnitude better than EM designs of comparable output. Furthermore, the piezomotor overcomes the disadvantages of conventional piezoelectric-based actuators, which require high-voltage (HV) power sources as well as HV linear-power amplifiers. The new motor operates on a compliance voltage of less than 12 Vdc.

Principles of operation

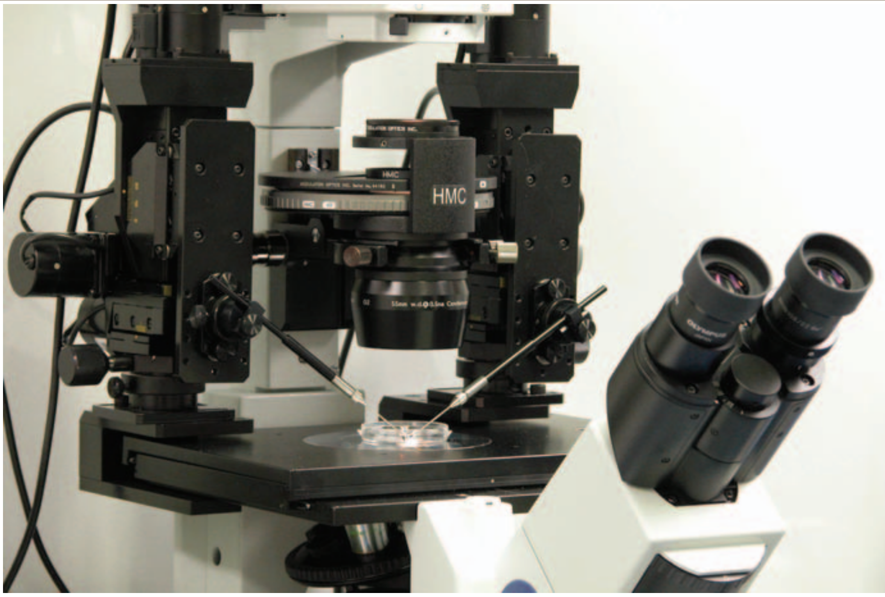
The piezomotor is controlled by a train of electrical pulses supplied by a digitally controlled ac voltage source to the piezoelement. The excitation voltage is applied to the piezoelement at its ultrasonic resonant frequency for the duration of each pulse. Motor speed is altered by varying either the repetition rate of the pulses or duration of each individual pulse. Modulation of the excitation voltage source, achieved using a digital controller, lets the piezomotor rotate either continuously or in a precise stepping mode. What's more, the inherent high torque and resolution of the piezomotor eliminates the need for a supplementary transmission or gear train and avoids the usual backlash effects that limit accurate tracking.

Older piezo actuators have shown faster response than steppers or servomotors, with a bandwidth typically above 1 kHz (as opposed to tens of Hz as in most advanced servomotors). But they have drawbacks not present in the new design.

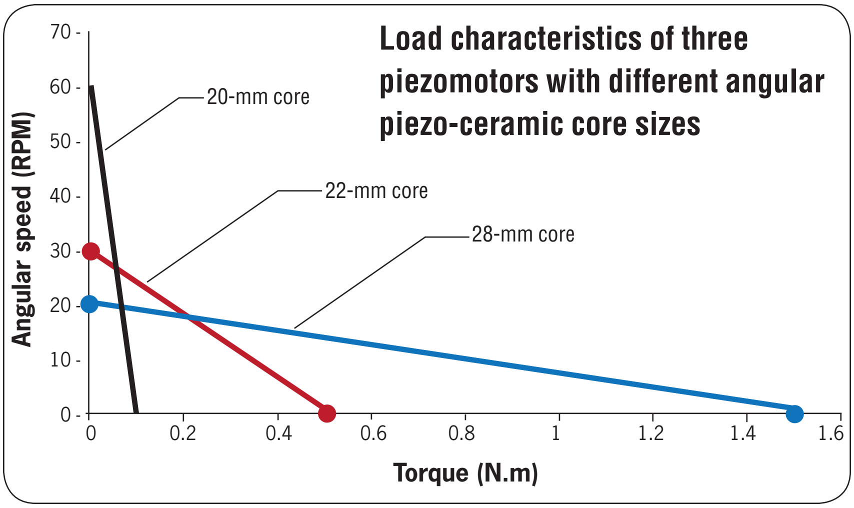
Comparing a stepper to a new piezomotor

Parameter/property	Stepper motor	Piezomotor
Type	Electromagnetic	Non-electromagnetic, PZT core
Angular resolution	Inadequate where high resolution required	Up to 3 orders of magnitude better than stepper motor
Backlash, hysteresis	Transmission or gear train makes these significant at high resolution	Negligible
How is torque applied?	Elastic, by electromagnetic force	Rigid, by friction force
Response time	Slow	2 to 3 orders of magnitude superior than stepper motors
Torque and dissipated energy when stopped	Applying braking torque consumes power and a static motor dissipates heat	Self-braking with max torque requires no power and static motor generates no heat
Jamming	Motor can overheat if jammed	Motor is not damaged if jammed
Power outage	Unpredictable with loss of track and position	Motor stops and holds position
Special applications	No MRI compatibility No EM pulse protection possible	Custom motor can be made: MRI-compatible; EM pulse prone

Key differences of piezomotor and comparable stepper motor



DTI's piezoelectric stem-cell nanomanipulator, model NM3D-25VP, shows two nanomanipulators attached to a microscope stage. Glass micropipettes (for intracellular micro-injection) are fixed on the nanomanipulators by tubular micropipette holders. The NM3D-25VP is a motorized (1 piezomotor per axis) XYZ positioning system capable of <4 nm steps. It can be controlled (via DSP) using joystick, or PC, or both. Competing designs require a separate device (called a cell penetrator) to penetrate the cell membrane. The NM3D-25VP, however, has a clever feature called PiezoThrust. During a PiezoThrust (initiated by a button on the joystick), the micropipette accelerates (> 5 m/sec^2) and smoothly penetrates the cell membrane without damaging the cell. The feature is only possible because of the piezomotor's unusual properties.



Piezo Rhino and Piezo Beetle

The company divides its ultrasonic piezomotors into two types depending on size and construction. Available as either unidirectional or bi-directional, commercially they are the Piezo Rhino and Piezo Beetle series. The Piezo Rhino is the larger motor (currently available up to 80-mm dia., but can be designed up to 1-meter dia.) and uses a combined rotary piezoresonator pusher to increase the coupling efficiency between stator and rotor. Being a resonance motor makes it more efficient, which also provides better resolution, efficiency and torque. The Piezo Beetles are miniature motors (less than 20-mm dia.) based on a single composite piezoelement-pusher component with bi-directional rotation in a compact design.

A range of products using the piezomotors are already in use in biomedical research, micro/electronics, optics and nanotechnology. They include computer-controlled nanopositioning stages with travel ranges from 10 to100 mm, *XYZ*-based nanomanipulators, rotary/angular stages, and miniature robotic systems.

How the new piezomotors stack up

Piezomotor Type	Piezo Rhino				Piezo Beetle
Motor Model *with encoder	PM-20RS*	PM-22RS*	PM-46	UPM-22	PM-8R/10R
Mode of operation	Cont/Step	Cont/Step	–	Cont/Step	Cont/Step
Uni or bidirectional	Bi	Bi	Uni	Uni	Bi
Max torque (Nm)	0.1	0.5	6	0.5	2 mN.m
Self-braking torque (Nm)	0.11	0.55	6	0.4	2 mN.m
Max speed (rpm)	60	30	140	30	100 (Cont) 1 (Step)
Min angular step (arcsec)	1	0.5	1	0.5	10
Dynamic range (kHz)	2	2	2	4	4
Supply voltage (V)	12	12	12	12	12 (or lower)
Operating current (mA)	<300	<400	15,000	<400	<100
Motor weight (g)	220	360	800	50	10
Dimensions (mm x mm)	Ø38x99	Ø50x100	Ø80x80	Ø50x30	Ø 8x13 Ø 10x15

Technical specification summary for Piezo Rhino and Beetle (Specifications depend on requirements)