



Standing Wave Piezoelectric Motors – How to Combine Speed, Accuracy and Unlimited Travel in Nanopositioning Applications



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Key Words

Nanopositioning, Piezoelectric, Motion Control, Piezoelectric Motor, Standing Wave, Ultrasonic, Positioning

Introduction

In photonics motion control applications, how do you combine speed with nanometric precision and unlimited travel? These seemingly conflicting requirements are uniquely addressed by ultrasonic, standing-wave, direct-drive piezoelectric motors. This technology provides unlimited linear or rotary motion of a ceramic tip that transfers drive to a target, operating in a manner similar to a DC servo motor but with much higher resolution, an order-of-magnitude higher speed and a wider dynamic range. This paper will review the technology of Nanomotion's patented standing-wave piezoelectric motors and explains how their combination of nanometric precision, near-silent motion and their ability to function in many challenging environments achieves the utmost in precision positioning in demanding semiconductor, medical and photonics applications.

The Piezoelectric Effect

Let's begin by looking at the piezoelectric effect. This was first demonstrated in 1880 by French physicists Pierre and Jacques Curie, Pierre being the husband of Polish-born, and double Nobel Prize-winning scientist Marie Skłodowska-Curie who conducted pioneering research into radioactivity. The Curie brothers found that certain materials, such as quartz or ceramic, were able to generate an electric potential when an external pressure was applied to the crystal. The word piezo derives from the Greek word πιέζειν (piezein), which means to squeeze or to press.

The Curie brothers later discovered the opposite of this effect in which an electric field applied across these crystals resulted in a small expansion of the material. This effect is known as the inverse piezoelectric effect and it is this phenomenon which is manipulated in modern piezoelectric motion control technology. Within piezoelectric materials, the charge centres of the positive and negative ions that make up the material are slightly separated within the material's crystalline lattice. In the presence of an external electric field, these small electric dipoles undergo a small displacement. This behaviour builds up stress within the piezoelectric material and causes the



material to expand or contract in approximate proportion to the applied voltage.

In piezoelectric materials these electric dipoles spontaneously line up into clusters called domains, similar to the domains in magnetic materials. In their natural state, the direction of the domains within the piezoelectric material are orientated randomly so the overall net effect and expansion is almost zero. The application of an external electric field can realign these domains within the piezoelectric material so that they are largely orientated in the same direction. After the removal of the electric field the domains hold their orientation. This reordering of the domains within the piezoelectric material produces a larger net effect and greater expansion of the piezo material in one direction.

Piezoelectric Materials

There are many materials, both natural and artificial, that exhibit a range of piezoelectric effects. Some inherently piezoelectric materials include Berlinite (structurally identical to quartz), cane sugar, quartz, Rochelle salt, topaz, tourmaline, and bone. Dry bone exhibits some piezoelectric properties due to the inclusion of apatite crystals, and the piezoelectric effect is understood to act as a natural biological force sensor. Examples of artificial piezoelectric materials include barium titanate (BaTiO_3) and lead zirconate titanate (PZT) upon which piezoelectric actuators are based that can be used in nanopositioning applications. These materials display large displacements in response to an applied electric field.

In recent years, growing environmental concern regarding toxicity in lead-containing devices and the EU's RoHS directive has spurred the development of lead-free piezoelectric materials. To date, this initiative has resulted in a variety of new piezoelectric materials which are more environmentally safe.

Applications for Piezoelectric Materials

The piezoelectric effect is very useful in many applications that involve the production and detection of sound, the generation of high voltages, electronic frequency generation, microbalances, and ultra-fine focusing of optical assemblies. It is also the basis of a number of scientific instrumental techniques with atomic resolution, such as scanning probe microscopes (STM, AFM, etc).

A relatively mundane application of a piezoelectric material is the electronic cigarette lighter (see Figure 1). Pressing a button causes a spring-loaded hammer to hit a piezoelectric crystal, thereby producing a sufficiently high voltage that electric current flows across a small spark gap, which heats and ignites the lighter fuel. Most types of gas burners and ovens have a built-in piezo based ignition system.

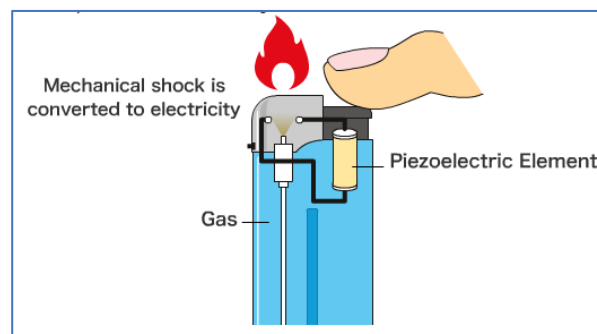


Figure 1: Compression of a Piezoelectric Crystal Generates a Spark that Ignites Lighter Fuel

In the field of piezoelectric sensors, the principle of operation is that a physical dimension, transformed into a force, acts on two opposing faces of the sensing element. The detection of pressure variations in the form of sound is the most common sensor application, which is seen in piezoelectric microphones and piezoelectric pickups for electrically amplified guitars. Piezoelectric sensors in particular are used with high frequency sound in ultrasonic transducers for



medical imaging and industrial non-destructive testing.

It is their use in precision motors that the piezoelectric effect is exploited in numerous photonics applications. Very high voltages applied to the piezoelectric crystal correspond to tiny changes in the width of the material, allowing the crystal width to be manipulated with nanometric precision. This allows piezoelectric crystals to position objects with extreme accuracy, making them perfect for use in motors, such as the various devices offered by Nanomotion.

Piezoelectric Motors

The basic principle of operation of a piezoelectric motor lies in the transfer of electrical energy into motion, by frictionally coupling a high frequency vibrating stator onto a motion axis, either linear or rotary. Among the various adaptations possible, that which Nanomotion employs is an ultrasonic motor based upon the combination of longitudinal (L1) and bending (B2) resonant modes (in other words, a standing wave or "AC" motor). This implementation has proven to be well suited to demanding optical applications, combining robustness, a high dynamic range of velocity, an unlimited travel and a high positioning accuracy. Other piezoelectric devices employ the so-called "DC" mode of operation, in which an applied voltage causes an extension or contraction of the crystal in one direction only.

The images below (Figures 2 to 5) illustrate the longitudinal compression and extension (L1) and the bending (B2) modes employed in a Nanomotion standing wave piezoelectric motor. Figure 6 demonstrates how the combination of the bending and stretching modes of the piezoelectric crystal translate into precise linear or rotary motion.

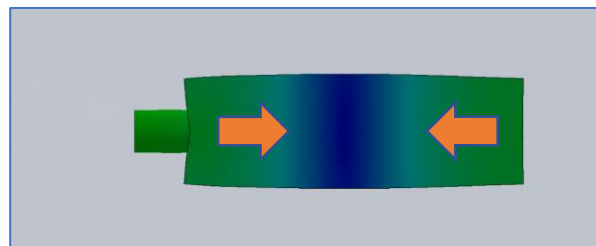


Figure 2: L1 Compression

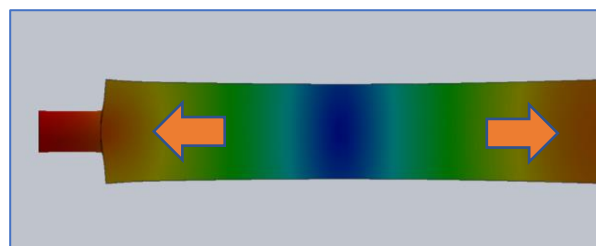


Figure 3: L2 Elongation

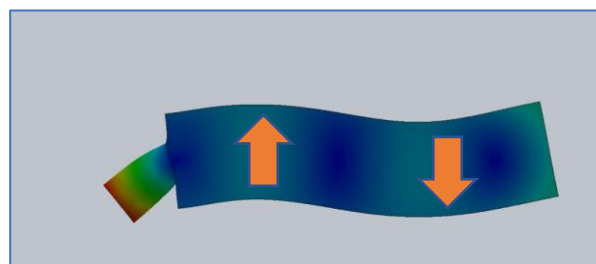


Figure 4: B2 Compression

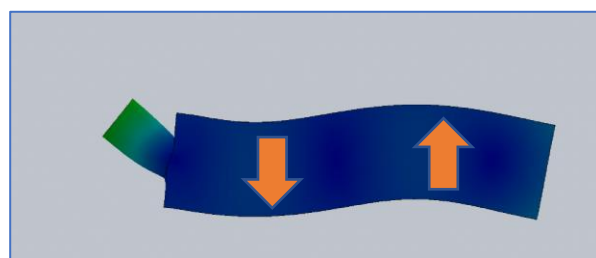


Figure 5: B2 Elongation



*Figure 6: Combining L1 & B2 Motion Provides
for Unlimited Linear or Rotary Travel*

In a piezoelectric motor, the piezoelectric element receives an electrical pulse, which in turn applies a directional force to an opposing ceramic plate, causing it to move in the desired direction. Motion is generated when the piezoelectric element moves against a static platform (such as a ceramic strip). This type of motion is known as “direct drive”, meaning no transfer gearing is required. A further benefit of Nanomotion’s implementation is that no backlash is exhibited and while the drive voltage is not applied, the ceramic plate remains stationary and generates a holding torque on the stage. Unlike other braking devices, the holding torque of the Nanomotion motor does not cause any positional shift.

The piezoelectric effect in a piezoelectric crystal converts an electrical field into a mechanical strain. In a Nanomotion motor, a defined electrical excitation applied to a specific ceramic geometry causes longitudinal extension and transverse bending oscillation modes in the crystal that are excited at a frequency close to the applied electrical signal. The simultaneous excitation of longitudinal extension and transverse bending creates a small elliptical trajectory of the ceramic edge, thus achieving the dual-mode standing wave motor patented by Nanomotion. This is illustrated

in the video below (Figure 7 – please click in the image to view the video).

By coupling the ceramic edge to a precision stage, a resultant driving force is transferred from the piezoelectric motor into the stage, causing the stage to move. The periodic nature of the driving force is at frequencies much higher than the mechanical resonant frequency of the stage, which allows for continuous smooth motion and unlimited travel. At the same time, the high resolution and accuracy which are typical characteristics of piezoelectric devices is maintained. Travel can be linear or rotary, depending on the coupling mechanism employed.

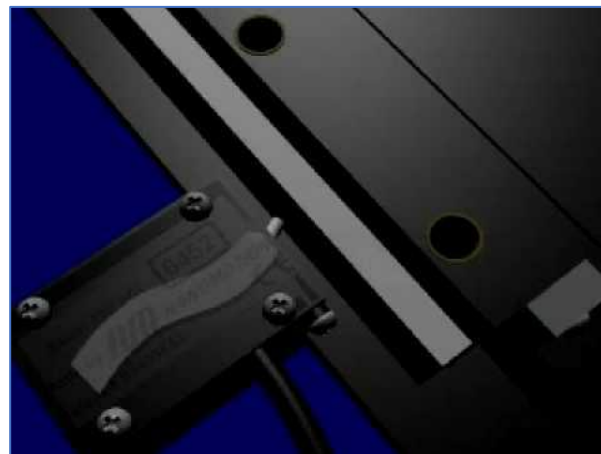


*Figure 7: Standing Wave (L1 + B2) Piezoelectric Motion
Transferred to Linear Motion of an Optical Stage
(please click in the image to watch the video)*

The characteristics of piezoelectric materials provides the perfect technology upon which Nanomotion developed its piezoelectric motors. Using patented piezoelectric technology, Nanomotion has designed a family of motors ranging in size from a single element that provides 4 Newtons of force, to an eight element motor that provides 32 Newtons. Nanomotion motors are capable of driving both linear and rotary stages, and offer a wide dynamic range of speed, from several microns per second to 300mm per second. The motors can be easily mounted onto traditional low friction stages or other positioning devices.



The operating characteristics of Nanomotion's motors provide inherent braking and the ability to eliminate servo dither when in a static position. Should the mass of the object that you wish to move exceed the load limit of one motor, multiple motors can be cascaded to increase the force of the motion system.

The typical performance provided by Nanomotion's standard FB-Series of linear stages (see Figure 8) and rotary stages is summarised in the table below. Note that not all specifications are achieved in one stage all at the same time.

Typical Performance of Nanomotion Stages

Parameter	Linear Stages	Rotary Stages
Range of Travel	20-60mm	360° (unlimited)
Moving Mass	2-35kg	0.2kg
Drift	<1nm/minute	<0.1μrad/minute
Linearity	±30nm	10%
Repeatability (unidirectional)	<3μm	<1μrad
Acceleration	<2m/sec ²	>300°/sec ²
Velocity	1μm/s to 300mm/s	>30°/sec
Cleanroom Compatibility	ISO Class 1 @ 25±1°C	ISO Class 1 @ 25±1°C

The benefits of Nanomotion's standing wave, ultrasonic, piezoelectric technology are manifold and include high power density and efficiency, high torque at low speeds and low power consumption, the use of entirely non-magnetic materials, no intrinsic magnetic field (no EMI), high vacuum compatibility, near silent operation, a direct drive with no gear mechanism and no backlash, fast response and short settling times, no hysteresis, compact form factor, and an inherent "hard brake" (providing a static hold without backlash or power consumption).

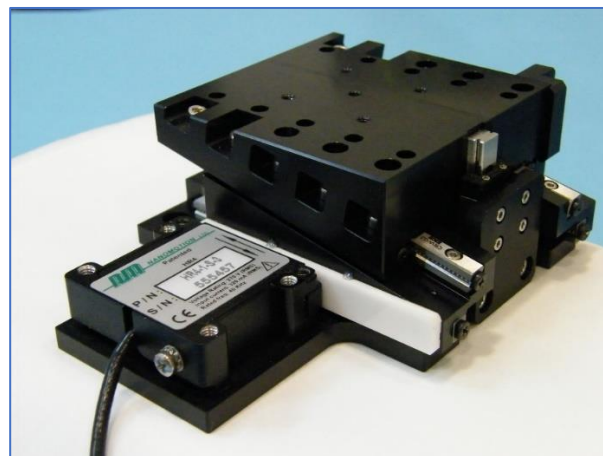


Figure 8: Nanomotion's FB Series of Precision Stages Provide Linear, Rotary, or Vertical Motion

Applications for Standing Wave Piezoelectric Motors

The unique attributes of Nanomotion's standing wave, ultrasonic, piezoelectric motor technology promotes its use in a vast range of demanding photonics, semiconductor and biomedical motion control applications. Example applications include:

- Linear (1, 2 & 3 axis), rotary & goniometer positioning stages.
- Autofocus modules for cameras, lasers & thermal imagers.
- Linear and rotary filter changers.
- Iris and shutter control.
- Automated XYZ fibre coupling alignment.
- Stabilised gimbals for small UAVs.
- Beam pointing correction and steering stabilisation.
- Combined autofocus and filter changers for hyperspectral imagers.
- Automated pan/tilt drives for theodolites & geospatial imagers.
- Sensor scanning platforms for low Earth orbiting satellites.
- XYZ stages for microscopy and cell imaging applications.
- Motion control inside an MRI scanner.



- 5-axis positioning for nanolithography.
- UHV XYZ & theta positioning for ion beam microscopy.

Further Information

For further information on the Nanomotion range of piezoelectric motors and nanopositioning equipment, please visit the [Pro-Lite web site](#).

About Nanomotion

Nanomotion designs and manufactures advanced motion systems, sub-system modules and piezo motor/drive components. Based on proprietary ultrasonic standing wave piezoelectric technology, Nanomotion's motors and motion solutions are suitable for a diversified range of applications from optronics to semiconductor, from medical to metrology and other industrial applications.

About Pro-Lite

Pro-Lite is the European channel partner for Nanomotion in Germany, Spain, Portugal, France, UK and Ireland. Pro-Lite is a supplier of specialist equipment and services with a technical focus in the following areas of photonics: instruments for measuring light and the optical properties of materials; photometry; lasers and laser safety equipment; opto-mechanics and nano-positioning equipment; optics and optical materials; and spectroscopy and spectral imaging. Pro-Lite Technology Ltd is part of the Pro-Lite Group of Companies, which includes Photometric & Optical Testing Services, SphereOptics Germany, Pro-Lite France and Pro-Lite Iberia.