Chapter 29: Principles of Active Vibration Control: Piezoelectric Materials

Applications

Piezoelectric crystals are now used in numerous ways:

1. High voltage and power sources

Direct piezoelectricity of some substances like quartz, as mentioned above, can generate potential differences of thousands of volts.

- The best-known application is the electric cigarette lighter: pressing the button causes a spring-loaded hammer to hit a piezoelectric crystal, producing a sufficiently high voltage electric current that flows across a small spark gap, thus heating and igniting the gas. The portable sparkers used to light gas grills or stoves work the same way, and many types of gas burners now have built-in piezo-based ignition systems.

- A similar idea is being researched by DARPA in the United States in a project called Energy Harvesting, which includes an attempt to power battlefield equipment by piezoelectric generators embedded in soldiers' boots. However, these energy harvesting sources by association have an impact on the body. DARPA's effort to harness 1-2 watts from continuous shoe impact while walking were abandoned due to the impracticality and the discomfort from the additional energy expended by a person wearing the shoes. Other energy harvesting ideas include harvesting the energy from human movements in train stations or other public places.

- A piezoelectric transformer is a type of AC voltage multiplier. Unlike a conventional transformer, which uses magnetic coupling between input and output, the piezoelectric transformer uses acoustic coupling. An input voltage is applied across a short length of a bar of piezoceramic material such as PZT, creating an alternating stress in the bar by the inverse piezoelectric effect and causing the whole bar to vibrate. The vibration frequency is chosen to be the resonant frequency of the block, typically in the 100 kilohertz to 1 megahertz
range. A higher output voltage is then generated across another section of the bar by the piezoelectric effect. Step-up ratios of more than 1000:1 have been demonstrated. An extra feature of this transformer is that, by operating it above its resonant frequency, it can be made to appear as an inductive load, which is useful in circuits that require a controlled soft start. These devices can be used in DC-AC inverters to drive cold cathode fluorescent lamps. Piezo transformers are some of the most compact high voltage sources.

2. Sensors

The principle of operation of a piezoelectric sensor is that a physical dimension, transformed into a force, acts on two opposing faces of the sensing element. Depending on the design of a sensor, different "modes" to load the piezoelectric element can be used: longitudinal, transversal and shear. Detection of pressure variations in the form of sound is the most common sensor application, e.g. piezoelectric microphones (sound waves bend the piezoelectric material, creating a changing voltage) and piezoelectric pickups for Acoustic-electric guitars. A piezo sensor attached to the body of an instrument is known as a contact microphone. Piezoelectric sensors especially are used with high frequency sound in ultrasonic transducers for medical imaging and also industrial nondestructive testing (NDT). For many sensing techniques, the sensor can act as both a sensor and an actuator – often the term transducer is preferred when the device acts in this dual capacity, but most piezo devices have this property of reversibility whether it is used or not. Ultrasonic transducers, for example, can inject ultrasound waves into the body, receive the returned wave, and convert it to an electrical signal (a voltage). Most medical ultrasound transducers are piezoelectric.

In addition to those mentioned above, various sensor applications include:

- Piezoelectric elements are also used in the detection and generation of sonar waves.
- Power monitoring in high power applications (e.g. medical treatment, sonochemistry and industrial processing).
- Piezoelectric microbalances are used as very sensitive chemical and biological sensors.
- Piezos are sometimes used in strain gauges.
- Piezoelectric transducers are used in electronic drum pads to detect the impact of the drummer's sticks.
- Automotive engine management systems use piezoelectric transducers to detect detonation by sampling the vibrations of the engine block and also to detect the precise moment of fuel injection (needle lift sensors).
- Ultrasonic piezo sensors are used in the detection of acoustic emissions in acoustic emission testing.
- Crystal earpieces are sometimes used in old or low power radios.

![Piezoelectric disk used as a guitar pickup](image)

**Fig. 8.8 Piezoelectric disk used as a guitar pickup**

### 3. Actuators

As very high electric fields correspond to only tiny changes in the width of the crystal, this width can be changed with better-than-micrometer precision, making Piezo crystals the most important tool for positioning objects with extreme accuracy — thus their use in actuators. Multilayer ceramics, using layers thinner than 100 microns, allow reaching high electric fields with voltage lower than 150 V. These ceramics are used within two kinds of actuators: direct Piezo actuators and Amplified Piezoelectric Actuators. While direct actuator's stroke is generally lower than 100 microns, amplified Piezo actuators can reach millimeter strokes.

- **Loudspeakers:** Voltage is converted to mechanical movement of a piezoelectric polymer film.
- **Piezoelectric motors**: piezoelectric elements apply a directional force to an axle, causing it to rotate. Due to the extremely small distances involved, the piezo motor is viewed as a high-precision replacement for the stepper motor.

- **Piezoelectric elements** can be used in laser mirror alignment, where their ability to move a large mass (the mirror mount) over microscopic distances is exploited to electronically align some laser mirrors. By precisely controlling the distance between mirrors, the laser electronics can accurately maintain optical conditions inside the laser cavity to optimize the beam output.

- **A related application is the acousto-optic modulator**, a device that scatters light off of sound waves in a crystal, generated by piezoelectric elements. This is useful for fine-tuning a laser's frequency.

- **Atomic force** microscopes and scanning tunneling microscopes employ converse piezoelectricity to keep the sensing needle close to the probe.

- **Inkjet printers**: On many inkjet printers, piezoelectric crystals are used to drive the ejection of ink from the inkjet print head towards the paper.

- **Diesel engines**: high-performance common rail diesel engines use piezoelectric fuel injectors, first developed by Robert Bosch GmbH, instead of the more common solenoid valve devices.

- Active control of vibration using amplified actuators.

- X-ray shutters.

- XY stages for micro scanning used in infrared cameras.

Fig. 8.9 Metal disk with piezoelectric disk attached, used in a buzzer.
4. Frequency standard

The Piezo-electrical properties of quartz are useful as standard of frequency.

- Quartz clocks employ a tuning fork made from quartz that uses a combination of both direct and converse piezoelectricity to generate a regularly timed series of electrical pulses that is used to mark time. The quartz crystal (like any elastic material) has a precisely defined natural frequency (caused by its shape and size) at which it prefers to oscillate, and this is used to stabilize the frequency of a periodic voltage applied to the crystal.
- The same principle is critical in all radio transmitters and receivers, and in computers where it creates a clock pulse. Both of these usually use a frequency multiplier to reach the megahertz and gigahertz ranges.

5. Piezoelectric motors

Types of piezoelectric motor include:

- The travelling-wave motor used for auto-focus in reflex cameras
- Inchworm motors for linear motion
- Rectangular four-quadrant motors with high power density (2.5 watt/cm$^3$) and speed ranging from 10 nm/s to 800 mm/s.
- Stepping piezo motor, using stick-slip effect.
All these motors, except the stepping stick-slip motor work on the same principle. Driven by dual orthogonal vibration modes with a phase difference of 90°, the contact point between two surfaces vibrates in an elliptical path, producing a frictional force between the surfaces. Usually, one surface is fixed causing the other to move. In most piezoelectric motors the piezoelectric crystal is excited by a sine wave signal at the resonant frequency of the motor. Using the resonance effect, a much lower voltage can be used to produce a high vibration amplitude.

Fig. 8.11 A slip-stick actuator

Fig. 8.12 SPA motor using CEDRAT APA
Stick-slip motor works using the inertia of a mass and the friction of a clamp. Such motors can be very small. Some are used for camera sensor displacement, allowing anti shake function.

**Reduction of vibrations and noise**

The previous studies shows the various ways to reduce vibrations and noise in materials by attaching piezo elements to the material. When the material is bent by a vibration in one direction, the vibration-reduction system responds to the bend and sends electric power to the piezo element to bend in the other direction. Future applications of this technology are expected in cars and houses to reduce noise. In a demonstration at the Material Vision Fair in Frankfurt in November 2005, a team from Germany showed several panels that were hit with a rubber mallet, and the panel with the piezo element immediately stopped swinging. Piezoelectric ceramic fiber technology is being used as an electronic damping system on some HEAD tennis rackets.

**Piezoelectric accelerometer**: A piezoelectric accelerometer (Fig) that utilizes the piezoelectric effect of certain materials to measure dynamic changes in mechanical variables. (e.g. acceleration, vibration, and mechanical shock). As with all transducers, piezoelectric accelerometers convert one form of energy into another and provide an electrical signal in response to a quantity, property, or condition that is being measured. Using the general sensing method upon which all accelerometers are based, acceleration acts upon a seismic mass that is restrained by a spring or suspended on a cantilever beam, and converts a physical force into an electrical signal. Before the acceleration can be converted into an electrical quantity it must first be converted into either a force or displacement. This conversion is done via the mass spring system shown in the figure to the right.
Piezoelectric accelerometers are widely accepted as the best choice for measuring absolute vibration. Compared to the other types of sensors, piezoelectric accelerometers have important advantages:

- Extremely wide dynamic range, low output noise - suitable for shock measurement as well as for almost imperceptible vibration
- Excellent linearity over their dynamic range
- Wide frequency range
- Compact yet highly sensitive
- No moving parts - no wear
- Self-generating - no external power required
- Great variety of models available for nearly any purpose
- Acceleration signal can be integrated to provide velocity and displacement

The high impedance sensor output needs to be converted into a low impedance signal first. For processing the sensor signal a variety of equipment can be used, such as:

- Time domain equipment, e.g. RMS and peak value meters
- Frequency analyzers
- Recorders
- PC instrumentation

However, the capability of such equipment would be wasted without an accurate sensor signal. In many cases the accelerometer is the most critical link in the measurement chain. To obtain precise vibration signals some basic knowledge about piezoelectric accelerometers is required.
Accelerometer design is based on:

- Shear system
- Compression system
- Bending or flexure system

The reason for using different piezoelectric systems is their individual suitability for various measurement tasks and their varying sensitivity to environmental influences. The following table shows advantages and drawbacks of the 3 designs:

<table>
<thead>
<tr>
<th></th>
<th>Shear</th>
<th>Compression</th>
<th>Bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>Low temperature transient sensitivity</td>
<td>High sensitivity-to-mass ratio</td>
<td>Best sensitivity-to-mass ratio</td>
</tr>
<tr>
<td></td>
<td>Low base strain sensitivity</td>
<td>Robustness</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Technological advantages</td>
<td></td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Lower sensitivity-to-mass ratio</td>
<td>High temperature transient sensitivity</td>
<td>Fragile</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Relatively high temperature transient sensitivity</td>
</tr>
</tbody>
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Shear design is applied in the major part of modern accelerometers due to its better performance. Compression and bending type sensors are still used in many applications, however.

![Fig. 8.14 (a) Shear System](image-url)
Shear mode designs bond, or "sandwich," the sensing crystals between a center post and seismic mass. A compression ring or stud applies a preload force required to create a rigid linear structure. Under acceleration, the mass causes a shear stress to be applied to the sensing crystals. By isolating the sensing crystals from the base and housing, shear accelerometers excel in rejecting thermal transient and base bending effects. Also, the shear geometry lends itself to small size, which minimizes mass loading effects on the test structure. With this combination of ideal characteristics, shear mode accelerometers offer optimum performance.

![Compression System Diagram](image)

Fig. 8.14 (b) Compression System:

Compression mode accelerometers offer simple structure, high rigidity, and historical availability. There are basically three types of compression designs: upright, inverted, and isolated. Upright compression designs sandwich the piezoelectric crystal between a seismic mass and rigid mounting base. An elastic stud or screw secures the sensing element to the mounting base. When the sensor is accelerated, the seismic mass increases or decreases the amount of force acting upon the crystal, and a proportional electrical output results. The larger the seismic mass is, the greater the stress and, hence, the output are.
Fig. 8.14 (c) Flexural (Bending) System:

Flexural mode designs utilize beam-shaped sensing crystals, which are supported to create strain on the crystal when accelerated. The crystal may be bonded to a carrier beam that increases the amount of strain when accelerated. This design offers a low profile, light weight, excellent thermal stability, and an economical price. Insensitivity to transverse motion is also an inherent feature of this design. Generally, flexural beam designs are well suited for low-frequency, low-g-level applications like those which may be encountered during structural testing.

**Accelerometer Selection:**

The accelerometers are selected on the basis of various factors as:

- Operating frequency range
- Operating magnitude of accelerations
- Temperature and strain range
- Choice of mountings and distance of measurements

Below table is shown the selection criterion of accelerometer.
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Accelerometer properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude and frequency range</td>
<td>Sensitivity, maximum acceleration and natural frequency</td>
</tr>
<tr>
<td>Weight of the object</td>
<td>Must be less than 1/20\textsuperscript{th} of total object weight</td>
</tr>
<tr>
<td>Measurement of vibration</td>
<td>Integration for all dynamic parameters should be proper with the time domain measurement</td>
</tr>
<tr>
<td>accelerations/velocity and displacement</td>
<td></td>
</tr>
<tr>
<td>Temperature transient, strain, magnetic</td>
<td>Operate in sensible range</td>
</tr>
<tr>
<td>field, acoustics noise and humidity</td>
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<tr>
<td>Mounting: spot mounting, temporary</td>
<td>For spot... use probe; for temporary .... use wax and for long term......... Use stud and screw</td>
</tr>
<tr>
<td>measurement and long term measurement</td>
<td></td>
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<tr>
<td>Distance between accelerometer and object</td>
<td>Accelerometer with ICP feature</td>
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