Principles of Active Vibration Control: Piezoelectric materials

Introduction:

Piezoelectric materials are materials that produce a voltage when stress is applied. Since, this effect also applies in the reverse manner; a voltage across the sample will produce stress within the sample. The word “piezo” is a Greek word which means “to press”. Therefore, piezoelectricity means electricity generated from pressure - a very logical name. Suitably designed structures made from these materials can therefore be made that bend, expand or contract when a voltage is applied. The piezoelectric effect was first discovered in 1880 by Pierre and Jacques Curie who demonstrated that when a stress field was applied to certain crystalline materials, an electrical charge was produced on the material surface. It was subsequently demonstrated that the converse effect is also true; when an electric field is applied to a piezoelectric material it changes its shape and size. This effect was found to be due to the electrical dipoles of the material spontaneously aligning in the electrical field. Due to the internal stiffness of the material, piezoelectric elements were also found to generate relatively large forces when their natural expansion was constrained. This observation ultimately has led to their use as actuators in many applications. Likewise if electrodes were attached to the material then the charge generated by straining the material could be collected and measured. Thus piezoelectric materials can also be used as sensors to measure structural motion by directly attaching them to the structure. Most contemporary applications of piezoelectricity use polycrystalline ceramics instead of naturally occurring piezoelectric crystals. The ceramic materials afford a number of advantages; they are hard, dense and can be manufactured to almost any shape or size.

Piezoelectric transducers have become increasingly popular in vibration control applications. They are used as sensors and as actuators in structural vibration control systems. They provide excellent actuation and sensing capabilities. The ability of piezoelectric materials to transform mechanical energy into electrical energy and vice versa was discovered over a century ago by Pierre and Jacque Curie. These French scientists discovered a class of materials that when pressured, generate electrical charge, and when placed inside an electric field, strain mechanically. Piezoelectricity, which literally means “electricity generated from pressure” is found naturally in many monocrystalline materials, such as quartz, tourmaline, topaz and Rochelle salt. However, these materials are generally not suitable as actuators for vibration control applications. Instead, man-made polycrystalline ceramic materials, such as lead zirconate titanate (PZT), can be processed to exhibit significant piezoelectric properties. PZT ceramics are relatively easy to produce, and exhibit strong coupling between mechanical and electrical domains. This enables them to produce comparatively large forces or displacements from relatively small applied voltages, or vice versa. Consequently, they are the most widely utilized material in manufacturing of piezoelectric transducers. The high modulus of elasticity of many piezoelectric materials is comparable to that of many metals and goes up to 105 N/mm^2. Even though piezoelectric sensors are electromechanical systems that react on compression, the sensing elements show almost zero deflection. This is the reason why piezoelectric sensors are so rugged, have an extremely high natural frequency and an excellent linearity over a wide amplitude range. Additionally, piezoelectric technology is insensitive to electromagnetic fields and radiation, enabling measurements under harsh conditions. Some materials used (especially gallium-phosphate or tourmaline) have an extreme stability over temperature enabling sensors to have a working range of 1000°C. The single disadvantage of piezoelectric sensors is that they cannot be used for true static measurements. A static force will result in a fixed amount of charges on the piezoelectric material. Table -1 shows the basic characteristics of sensing materials.

Principle	Strain Sensitivity	Threshold	Span to threshold ratio
Piezoelectric	Excellent	Very low	Very high
Piezo-resistive	Very low	Low	high
Inductive	low	Low	normal
Capacitive	low	Low	low

The single disadvantage of piezoelectric sensors is that they cannot be used for true static measurements. A static force will result in a fixed amount of charges on the piezoelectric material. Working with conventional electronics, not perfect insulating materials, and reduction in internal sensor resistance will result in a constant loss of electrons, yielding an inaccurate signal. Elevated temperatures cause an additional drop in internal resistance; therefore, at higher temperatures, only piezoelectric materials can be used that maintain a high internal resistance.

Piezoelectric vibration control has shown promise in a variety of applications ranging from consumer and sporting products to satellite and fighter aircraft vibration control systems. Piezoelectric transducers have been extensively used in structural vibration control applications. Their wide utilization in this specific application can be attributed to their excellent actuation and sensing abilities which stems from their high electro-mechanical coupling coefficient, as well as their non-intrusive nature. For vibration control purposes, piezoelectric transducers are bonded to or embedded in a composite structure. The types of structures which lend themselves to piezoelectric transducers are generally flexible in nature. The transfer functions of these systems are of high order, and their poles are very lightly damped. Control problems associated with these systems are by no means trivial. Piezoelectric shunt damping is a popular method for vibration suppression in flexible structures. The technique is characterized by the connection of electrical impedance to a structurally bonded piezoelectric transducer. Such methods do not require an external sensor, and if designed properly, may guarantee stability of the shunted system. Single-mode damping can be applied to reduce vibration of several structural modes with the use of as many piezoelectric transducers and damping circuits. However, in many cases, this may not be a practical solution since a large number of transducers will be needed if a large number of modes are to be shunt damped. This has encouraged researchers to develop multiple mode shunt damping circuits which use only one piezoelectric transducer. Piezoelectric transducers are used as sensors and actuators in vibration control systems. For this purpose, transducers are bonded to a flexible structure and utilized as either a sensors to monitor structural vibrations, or as actuators to add damping to the structure.

Piezoelectric principle:

Piezoelectric sensors rely on the piezoelectric effect, which was discovered by the Curie brothers in the late 19th century. While investigating a number of naturally occurring materials such as tourmaline and quartz, Pierre and Jacques Curie realized that these materials had the ability to transform energy of a mechanical input into an electrical output. More specifically, when a pressure [piezo is the Greek word for pressure] is applied to a piezoelectric material, it causes a mechanical deformation and a displacement of charges. Those charges are highly proportional to the applied pressure [Piezoelectricity]. A quartz ($SiO2$) tetrahedron is shown in Fig. 8.3. When a force is applied to the tetrahedron (or a macroscopic crystal element) a displacement of the cation charge towards the center of the anion charges occurs. Hence, the outer faces of such a piezoelectric element get charged under this pressure.

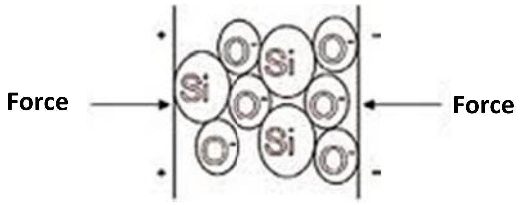
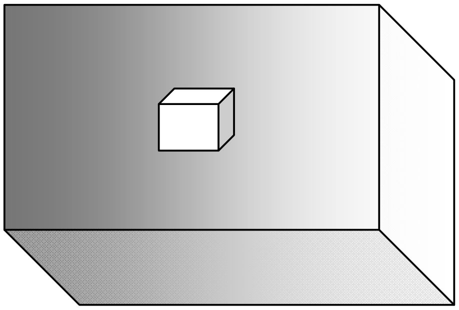
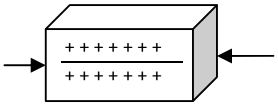


Fig. 8.3 Piezoelectricity of quartz

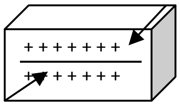
Depending on the way a piezoelectric material is cut, three main types of operations can be distinguished as 1. transversal 2. longitudinal and 3. shear.

A gallium phosphate crystal is shown with typical sensor elements manufactured out of it. Depending on the design of a sensor different “modes” to load the crystal can be used: transversal, longitudinal and shear (arrows indicate the direction where the load is applied). Charges are generated on both x-sides of the element. The positive charges on the front side are accompanied by negative charges on the back.

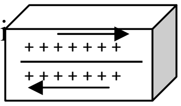




(a) Transverse direction



(b) Longitudinal di



(c) Shear direction

Fig. 8.4 A gallium phosphate crystal [Piezocryst]

Transverse effect: A force is applied along a neutral axis and the charges are generated along the d11 direction. The amount of charge depends on the geometrical dimensions of the respective piezoelectric element. When dimensions a, b, c apply to the main geometry:

$$C_y = -d11 \ x \ F_y \ x \ b/a \qquad (8.1)$$

where a is the dimension in line with the neutral axis and b is in line with the charge generating axis.

Longitudinal effect: The amount of charges produced is strictly proportional to the applied force and is independent of size and shape of the piezoelectric element. Using several elements that are mechanically in series and electrically in parallel is the only way to increase the charge output. The resulting charge is:

$$C_x = d11 \ x \ F_x \ x \ n \qquad (8.2)$$

where

$d11$ = piezoelectric coefficient [pC/N]
F_x = applied Force in x-direction [N]
n = number of elements

Shear effect: The charges produced are strictly proportional to the applied forces and are independent of the element's size and shape. For n elements mechanically in series and electrically in parallel the charge is:

$$C_x = 2 \times d11 \times F_x \times n \qquad (8.3)$$

In contrast to the longitudinal and shear effect, the transverse effect opens the possibility to fine tune sensitivity depending on the force applied and the element dimension. Therefore, Piezocryst's sensors almost exclusively use the transverse effect since it is possible to reproducibly obtain high charge outputs in combination with excellent temperature behaviour.

Piezoelectric materials can also be used as sensors to measure structural motion by directly attaching them to the structure. Most contemporary applications of piezoelectricity use polycrystalline ceramics instead of naturally occurring piezoelectric crystals. The ceramic materials afford a number of advantages; they are hard, dense and can be manufactured to almost any shape or size. Most importantly the electrical properties of the ceramics can be precisely oriented relative to their geometry by poling the material. The relationship between the applied forces and resultant responses of piezoelectric material depend upon a number of parameters such as the piezoelectric properties of the material, its size and shape and the direction in which forces or electrical fields are applied relative to the material axis. Three axes are used to identify directions in the piezoelectric element in the x, y and z axes of rectangular coordinates as shown in Fig. 3. These axes are set during the poling process, which induces the piezoelectric properties of the material by applying a large d.c. voltage to the element for an extended period.

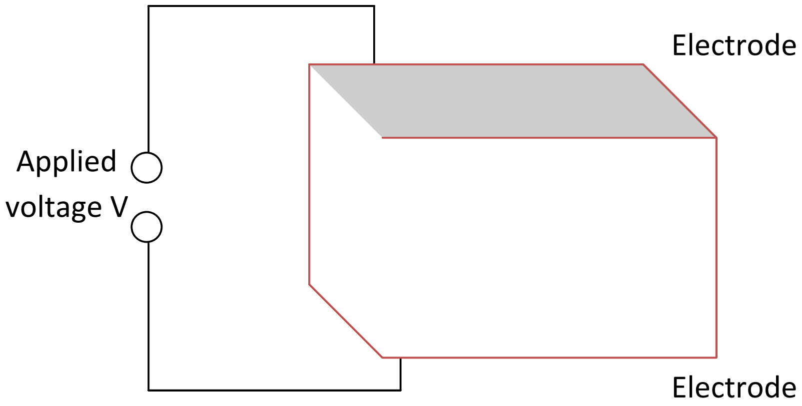


Fig. 8.5 Piezoelectric element and notation

The constitutive equations for a linear piezoelectric material when the applied electric field and the generated stress are not large can be written as (Uchino, 1994)

$$\varepsilon^i = S_{ij}^E \sigma_j + d_{mi} E_m,$$
$$D_m = d_{mi} \sigma_i + \xi_{ik} E_k, \quad (8.4)$$

where the indices i, j = 1,2,..., 6 and m, k = 1, 2, 3 refer to different directions within the material coordinate system. In these equations; ε, σ, D and E are respectively the strain, stress, electrical displacement (charge per unit area) and the electrical field (volts per unit length). In addition S^E, d and ξ are the elastic compliance (the inverse of elastic modulus), the piezoelectric strain constant and the permittivity of the material respectively.

Piezoelectric stack actuators: The actuation of elastic structures is based upon the static approach. The static response of an interaction between a piezoelectric element and a structure is first determined by coupling the constitutive relations of the piezoelectric element and structure with their equilibrium and compatability equations. Once the equivalent static force or moment due to the actuator is obtained it is then used as frequency-independent amplitude for a harmonically varying input to the system. This approximate approach has been found to provide reasonable results for relatively lightweight piezoelectric elements driven well below their internal resonance frequency. Most importantly, the static approach includes the distributed forcing function effects of the piezoelectric elements which will be shown to be a very important attribute for selective control of the states of the structural system. The first configuration of piezoelectric material we consider is the stack arrangement shown in Fig. 4 which is working against an applied external force F and an external stiffness represented by a spring. Two configurations of the actuator are shown. In Fig. 4 (a) the actuator is working against an external spring stiffness arranged in parallel with the actuator while in Fig. 4 (b) the stiffness is positioned in series. In both cases for zero voltage the external spring is in equilibrium and applies no stiffness force.

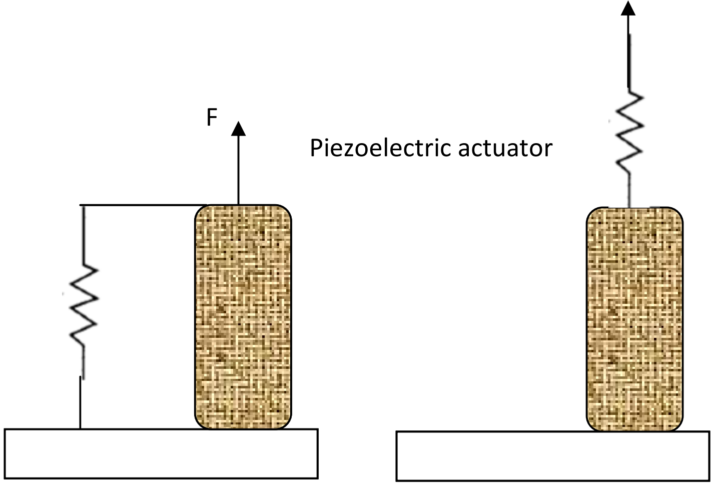


Fig. 8.6 Piezoelectric stack actuator working against an external stiffness load in (a) parallel (b) series with the load.

Materials both natural and man-made, exhibit piezoelectricity are as:

Naturally-occurring crystals

- Berlinite ($AlPO_4$), a rare phosphate mineral that is structurally identical to quartz
- Cane sugar
- Quartz
- Rochelle salt
- Topaz
- Tourmaline-group minerals

Other natural materials

- Bone: Dry bone exhibits some piezoelectric properties. Studies of Fukada et al. showed that these are not due to the apatite crystals, which are centrosymmetric, thus non-piezoelectric, but due to collagen. Collagen exhibits the polar uniaxial orientation of molecular dipoles in its structure and can be considered as bio-electret, a sort of dielectric material exhibiting quasi permanent space charge and dipolar charge. Potentials are thought to occur when a number of collagen molecules are stressed in the same way displacing significant numbers of the charge carriers from the inside to the surface of the specimen. Piezoelectricity of single individual collagen fibrils was measured using piezoresponse force microscopy, and it was shown that collagen fibrils behave predominantly as shear piezoelectric materials.

The piezoelectric effect is generally thought to act as a biological force sensor. This effect was exploited by research conducted at the University of Pennsylvania in the late 1970s and early 1980s, which established that sustained application of electrical potential could stimulate both resorption and growth (depending on the polarity) of bone in-vivo. Further studies in the 1990s provided the mathematical equation to confirm long bone wave propagation as to that of hexagonal (Class 6) crystals.

- Tendon
- Silk
- Wood due to piezoelectric texture
- Enamel
- Dentin

Man-made crystals

- Gallium orthophosphate ($GaPO_4$), a quartz analogic crystal
- Langasite ($La_3Ga_5SiO_{14}$), a quartz analogic crystal

Man-made ceramics

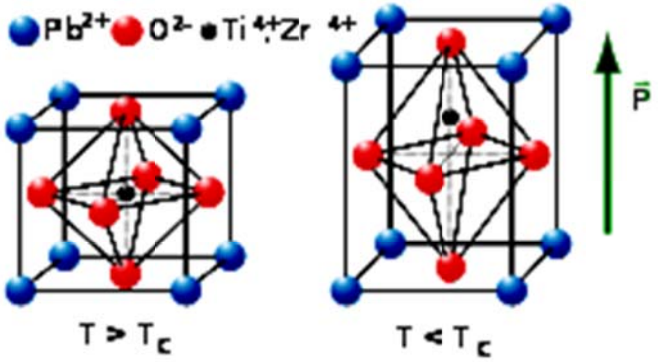


Fig. 8.7 Tetragonal unit cell of lead titanate

The family of ceramics with perovskite or tungsten-bronze structures exhibits piezoelectricity:

- Barium titanate ($BaTiO_3$)—Barium titanate was the first piezoelectric ceramic discovered.
- Lead titanate ($PbTiO_3$)
- Lead zirconate titanate ($Pb[Zr_xTi_{1-x}]O_3$ $0<x<1$)—more commonly known as PZT, lead zirconate titanate is the most common piezoelectric ceramic in use today.
- Potassium niobate ($KNbO_3$)
- Lithium niobate ($LiNbO_3$)
- Lithium tantalate ($LiTaO_3$)
- Sodium tungstate (Na_2WO_3)
- $Ba_2NaNb_5O_5$
- $Pb_2KNb_5O_{15}$

Lead-free Piezo-ceramics

More recently, there is growing concern regarding the toxicity in lead-containing devices driven by the result of restriction of hazardous substances directive regulations. To address this concern, there has been a resurgence in the compositional development of lead-free piezoelectric materials.

- Sodium potassium niobate (NaKNb). In 2004, a group of Japanese researchers led by Yasuyoshi Saito discovered a sodium potassium niobate composition with properties close to those of PZT, including a high T_C.[14]
- Bismuth ferrite ($BiFeO_3$) is also a promising candidate for the replacement of lead-based ceramics.
- Sodium niobate $NaNbO_3$

So far, neither the environmental impact nor the stability of supplying these substances have been confirmed.

Polymers

- Polyvinylidene fluoride (PVDF): PVDF exhibits piezoelectricity several times greater than quartz. Unlike ceramics, where the crystal structure of the material creates the piezoelectric effect, in polymers the intertwined long-chain molecules attract and repel each other when an electric field is applied.

Source:
http://nptel.ac.in/courses/112107088/28