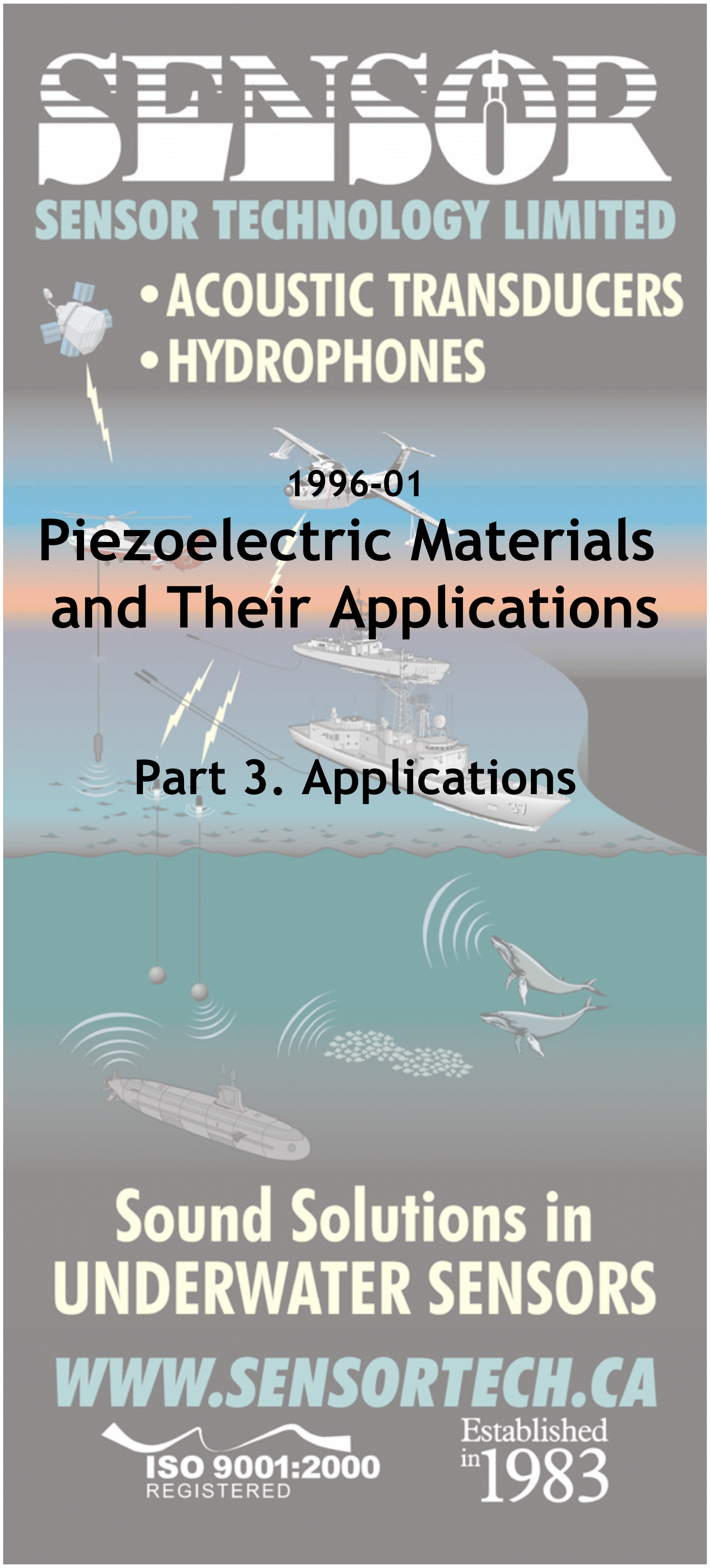
1996-01

Piezoelectric Materials and Their Applications

Part 3. Applications



Piezoelectric Materials and Their Applications

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Key words: piezoelectricity, piezoelectric ceramics, piezoelectric composites, piezoelectric polymers, electrostrictive ceramics, magnetostrictive rare earths

Abstract: Over 100 years ago, Jacques and Pierre Curie experimentally confirmed the presence of the piezoelectric effect in quartz, Rochelle salts and tourmaline single crystals. Within the last 50 years, a number of ceramic and polymer materials with non-symmetrical crystal structures have also been found to exhibit the piezoelectric effect. The discovery of strong piezoelecticity in these materials has led to their commercialization and has been a major factor in the development of a wide range of applications. This paper begins with a review of the fundamental properties of piezoelectric materials. A description of the important types of piezoelectric materials and their characteristics are presented next, followed by discussions of selected applications, with additional applications listed in tabular format.

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4. APPLICATIONS OF PIEZOELECTRIC MATERIALS

Piezoelectric materials have been used in hundreds of applications which span a wide range of products in the consumer, industrial, medical, aerospace and defence sectors. An exhaustive treatment of all of the applications is well beyond the scope of this work; however, a representative cross section of the more popular applications will be discussed in this section. The applications discussed in this chapter will be classified in terms of the direct and converse piezoelectric effects. For clarity, the fundamental aspects are discussed in detail with a representative example. Extensive application lists are presented in tabular form.

4.1 The Direct Piezoelectric Effect

As described in earlier sections, when a piezoelectric material is subjected to a mechanical stress a charge is generated across the material. The ability of a material to generate a charge or electric field when subjected to a stress is measured by the piezoelectric voltage coefficient (g). In accordance with the IEEE Standards on Piezoelectricity [5], the piezoelectric voltage coefficient relates the stress (T) to the generated electric field (E), under open-circuit conditions, as follows:

$$g=-\frac{\partial E}{\partial T}|^{D} \qquad (43)$$

From this equation, it can be seen that a large variation in electric field with a change in stress will result in a large value of g. Furthermore, since the electric field generated across the ceramic is dependent on the polarization of the material,

$$P=D-\epsilon_o E, \qquad (44)$$

a large g coefficient requires a large change in electric field or polarization. This implies that materials with large saturation polarizations will make better sensor materials.

In sensor materials it is desirable to have a response which varies linearly with changes in the measured quantity. As a result, the piezoelectric elements utilized in sensors generally operate in the linear region, such that the voltage generated across the element varies linearly with the magnitude of the mechanical stress. For a piezoelectric disc of a given thickness (t), the voltage (V) generated across the electrode disc when subjected to a stress (T) would be:

$$V=g\,t\,T. \qquad (45)$$

Hence, for a given piezoelectric material the amount of voltage produced by the ceramic subjected to a stress can be increased by increasing the thickness of the ceramic disc [105].

Table 8 summarizes a number of applications which utilize the direct piezoelectric effect. Some of the more popular applications of the direct piezoelectric effect will be discussed in the following paragraphs.

Table 8: Applications Utilizing the Direct Piezoelectric Effect

Process	**Application**	**Advantages**
Sensors - Structures and Materials		
Load Cells	**Industrial**: Force and pressure measurements.	High strength. Reliable and cost effective.
Velocity Sensor and Accelerometer	**Industrial, Automotive and Aerospace**: Velocity and Acceleration measurements. Vibration monitoring.	High accuracy in dynamic range. Non-magnetic. Electrically compatible.
Health Monitoring	**Structural**: Detection of acoustic emissions.	Durability Early warning of potential failure.
Sensors - Underwater Applications		
Hydrophones	**Marine Biology**: Monitoring marine life, fish, whales, etc. **Medical**: Monitoring of heart and circulatory systems.	Wide bandwidth. Ease of use, tunability and reliability. Diagnostic quantification. Reliability.
Other Applications		
Igniter	**Industrial and Commercial**: Gas ignition in welders, barbeques, lighters, etc.	Reliability and Safety. Compact design.
Remote Control	**Commercial**: Sensor in commercial remote controls	Ease of use and cost effectiveness. Compact design.
Microphones	**Commercial**: Detection of audible frequencies.	Cost effectiveness. Non-magnetic

4.1.1 Pressure and Force Sensors

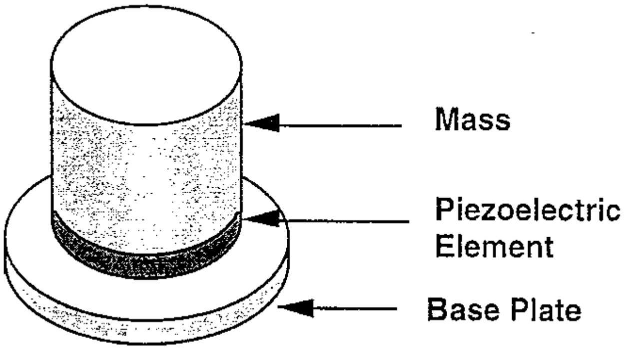
A number of sensor applications rely on the direct piezoelectric effect to measure pressure or force. Depending on the nature of the pressure or force being measured, the piezoelectric element may take on different shapes in order to take advantage of the different modes of operation available in the element. Generally, the thickness, radial and shear modes of a piezoelectric element are utilized in piezoelectric based devices.

For large dynamic pressure changes, the more durable ceramic disc or washer is favoured. These ceramics can sustain larger forces than most of the other ceramic shapes. These materials tend to be used in applications that are subject to harsh mechanical environments which involve large quasi-static loading or impact loading. Although these ceramics can be used to measure quasi-static loads, they are more accurate in the measurement of dynamic forces or loads since they are far less susceptible to dielectric losses in such cases. The ability of piezoelectric elements to measure changes in pressure or force has been utilized in a number of different sensor applications, including accelerometers, hydrophones and microphones.

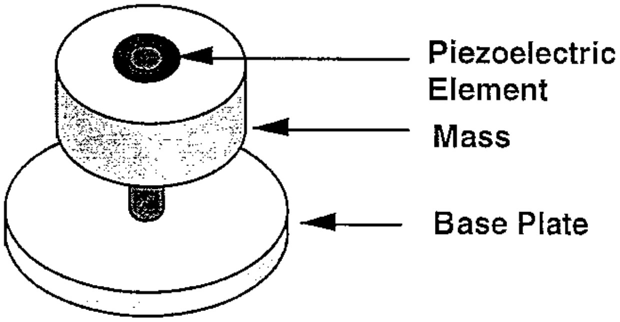
4.1.2 Accelerometers

Piezoelectric accelerometers rely on the piezoelectric effect to generate an electrical output which is proportional to an applied acceleration. The amount of charge generated across a piezoelectric material is proportional to the force produced by an inertial mass (F = ma). In other words, the total amount of accumulated charge is proportional to the applied force, which is proportional to the acceleration of the inertial mass.

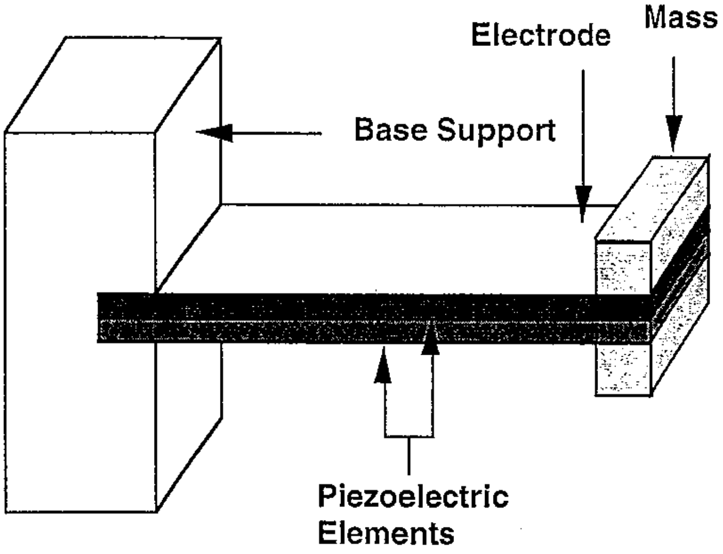
A variety of mechanical configurations are commercially available. Fig. 28 illustrates the shear, compression and flexural beam accelerometers, which are defined by the nature in which the inertial force of an accelerated mass acts upon the piezoelectric material [106]. Shear mode accelerometers bond or sandwich the sensing ceramic between a centre post and inertial mass. A compression ring or stud applies a preload force required to create a rigid linear structure. Under the acceleration, the mass causes a shear stress to be applied to the sensing ceramic. The shear geometry lends itself to miniaturization. Compression mode accelerometers are also a widely utilized design due to their simple structure, high rigidity and availability. In the compression accelerometer the piezoelectric element is placed between a inertial mass and rigid mounting base. When the sensor is accelerated, the inertial mass increases or decreases the amount of force acting upon the active element and results in a proportional electrical output. The larger the inertial mass, the greater the stress and, hence, the greater the output. Due to their inherently stiff structure, the compression designs offer high resonance frequencies and a broad, accurate frequency response range. This design is generally very rugged and can withstand high shock levels. Piezoelectric ceramics in flexural mode accelerometers are mounted such that when the sensor is accelerated, bending moments are generated in the ceramic element. These accelerometer designs offer a low profile, are light weight, and have excellent thermal stability. Insensivity to transverse motion is also an inherent feature of this design. Generally, flexural beam designs are well suited for low frequency, low acceleration level applications as may be encountered during structural testing.



a) Compression Accelerometer



b) Shear Accelerometer



c) Flexural Beam Accelerometer

Figure 28: Piezoelectric Accelerometers

4.1.3 Hydrophones

In underwater applications, the most efficient method of measuring acoustic pressure waves utilizes the piezoelectric hydrophone. Although the basic operating principle of the hydrophone is the direct piezoelectric effect, different piezoelectric element geometries are utilized in order to take advantage of different operational modes. For example, a simple directional hydrophone consists of a piezoelectric element disc encased in a polymer as illustrated in Fig. 29. Since the radial and thickness modes of a piezoelectric disc produce opposite charges when subjected to the same stress, it is often beneficial to clamp or isolate one of these modes in order to increase the sensitivity of the hydrophone.

Omnidirectional hydrophones operating at low frequencies utilize a piezoelectric tube element. The piezoelectric tube can operate in either the thickness or radial modes with the electrodes on the inner and outer surfaces of the tube. A typical hydrophone assembly is shown in Fig. 30. The hydrophone consists of four radially-poled cylindrical piezoelectric tube elements encased in a polymer [107,67]. The inside and outside electrodes, which are on the curved surfaces of the tubes, are connected in parallel. The tubes are separated physically and electrically by spacers and end caps are fitted to the ends of the assembly. The useful frequency bandwidth for end capped cylindrical elements usually depends on the largest dimensions of the cylinder and the properties of the end caps [108]. This type of hydrophone is often used in underwater communication, survey and surveillance applications.

4.1.4 Microphones

Microphones are similar to hydrophones in that both of these devices detect acoustic waves. However, a microphone differs from a hydrophone in that the acoustic waves travel in air as opposed to liquid. Typically, a microphone consists of a low mass diaphragm which is mechanically coupled to a piezoelectric element mounted in a cavity, as shown in Fig. 31. The vibrations of the diaphragm induce larger voltages in the piezoelectric element than would be possible in an uncoupled piezoelectric element [105,106].

4.1.5 Igniters

Igniters are often used to ignite combustible gases in lighters, stoves and barbeques. The piezoelectric based igniters utilize the direct piezoelectric effect to generate a voltage across two electrodes separated by a gap. It has already been established that if a piezoelectric material is subjected to an applied force, a charge is generated across the ceramic. When the electrodes of the ceramic are connected to a pair of secondary electrodes separated by a small gap and the voltage produced across the ceramic is large enough, it can produce arcing across the second electrode gap. Piezoelectric igniters are classified by the type of force used to generate the charge. An impact igniter uses a spring loaded hammer to dynamically induce the generation of charge across a piezoelectric cylinder, while the squeeze igniter applies a quasi-static load to the piezoelectric cylinder using a lever system [105]. Although the impact igniter, shown in Fig. 32, tends to be more compact than the squeeze igniters, the squeeze igniters have a large probability of ignition due to the multiple sparks which are generated during loading.

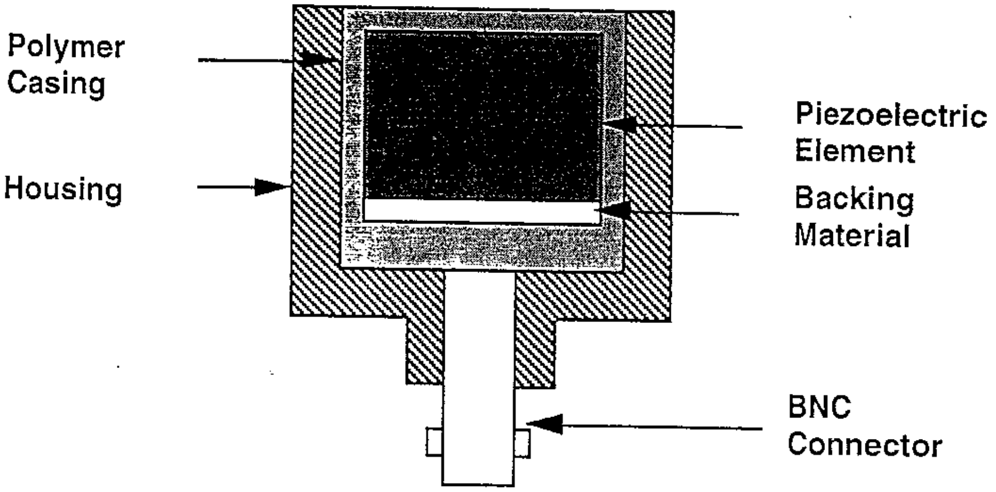
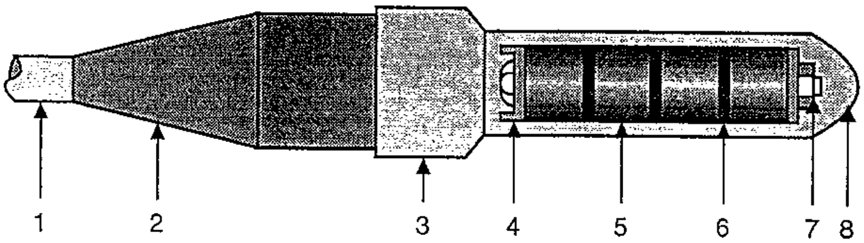


Figure 29: Polymer Encased Piezoelectric Hydrophone



1. coaxial cable	5. ceramic element
2. cable gland	6. ceramic washer
3. upper housing	7. tension bolt
4. top end cap	8. polyurethane boot

Figure 30: BM024 hydrophone assembly schematic.

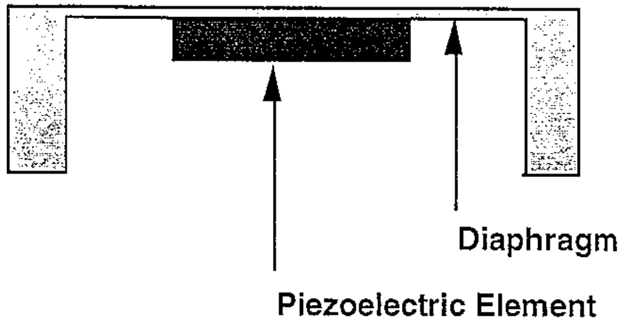


Figure 31: Piezoelectric-Based Microphone

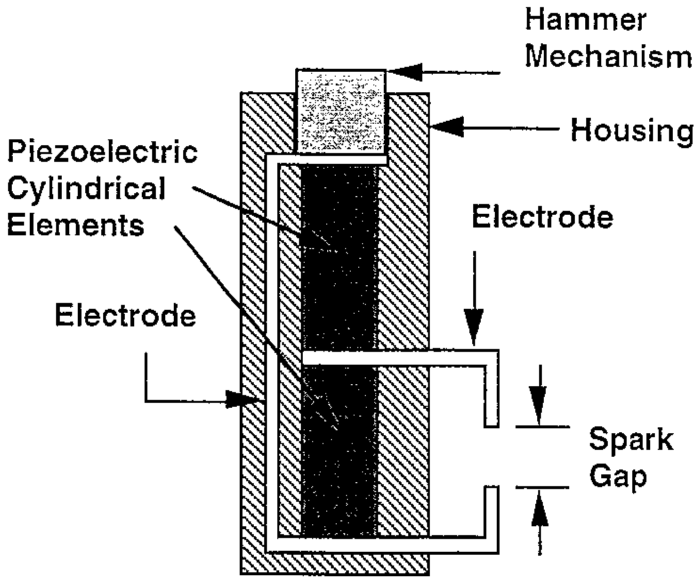


Figure 32: Piezoelectric Igniter Element

4.2 The Converse Piezoelectric Effect

The converse effect occurs when a piezoelectric material becomes strained when placed in an electric field. Under constant stress conditions, the general equation for the piezoelectric charge coefficient (d) can be expressed as the change in the strain (S) of the piezoelectric material as a function of the applied electric field (E):

$$d=\frac{\partial S}{\partial E}|^{T} \tag{46}$$

The piezoelectric charge coefficient (d) relates to the piezoelectric voltage coefficient (g) as follows:

$$d=\epsilon g \tag{47}$$

where ϵ is the permittivity [5]. Generally, a high g requires the material to have a high saturation polarization (P_s); while a high d has the additional requirement of having a high permittivity. As a result, a good actuator material does not always make a good sensor and vice versa.

For a piezoelectric disc with electrodes on the faces of the disc and with a polarization direction along the axis of the disc, the change in thickness (Δt) for an applied voltage (V) is expressed, as follows:

$$\Delta t=d_{33}V \tag{48}$$

while the change in diameter (ΔD) for a given applied voltage is expressed, as follows:

$$\Delta D=d_{31}V\frac{D}{t}. \tag{49}$$

These changes in dimension can be utilized in a number of actuator and transducer applications, some of which are summarized in Table 9. Only the more popular of these applications will be presented in the following paragraphs.

4.2.1 Actuators

The evolution of the piezoelectric actuators from the disc and tube elements to the more elaborate flextensional devices, which mechanically couple different modes of a piezoelectric element in order to enhance the displacement properties, arose out of the necessity to overcome the displacement limitations of the conventional piezoelectric element. However, the larger displacements achieved by flextensional devices come at the expense of lower operational frequencies and lower force generative capabilities as shown in Table 10.

Table 9: Applications Utilizing the Converse Piezoelectric Effect

Process	Application	Advantages
	Macrosonic Applications - Solids	
Welding	**Metals and Plastics**:	Fast
	Welding rigid thermo-plastics, seam welding film and fabric, metal-in-plastic insertion, etc.	Clean Economical
	Metal microbonding, lap welding of high electrical conductivity and dissimilar metals, seam welding sheet, etc.	Good weld integrity Possible to weld otherwise inaccessible areas.
Machining	**Dental**:	
	Prophylaxis teeth treatment.	Ease of use and less discomfort for the patient.
	Material Processing:	
	Vibration assisted rotary machining of hard, brittle materials.	Faster rates, longer tool life, better dimension control. Complex patterns.
	Impact grinding with abrasive slurries.	Faster rates, longer tool life, better finish.
	Vibration assisted drilling, tapping, and turning.	
Forming	**Metal Processing**:	
	Drawing thin wall metal tubing of large diameter-to-wall ratios.	Higher drawing rates. Allows drawing of different shapes.
	Drawing small diameter wire from difficult-to-form metals.	Faster drawing, less breakage, and better surface finish.
Cutting	**Material Processing**:	
	Vibration-assisted cutting of fibrous and spongy materials	Better cutting due to blade acceleration.
Cleavage	**Crystal and Ceramic Processing**:	
	Cleaving Crystals and laminated objects	High rate of impact and impact intensity.
Densification	**Metal and Ceramic Powder Processing**:	
	Powder compaction	Improves uniformity and density in complex molds.

(Table 9 Continued)

	Macrosonic Applications - Liquids	
Mixing	**Homogenization**: Pharmaceutical processing, waste treatment and chemical dispersion.	Assists in emulsification and dispersion processes. Reduces or eliminates surfactants. Fine uniform dispersion with no flocculation.
Cleaning	**Hospital and Industrial**: Cleaning, degreasing, and descaling parts and equipment.	Saves time and labour. Cleans normally unaccessible areas.
Atomization	**Medical, Commercial and Industrial**: Medical inhalation, nebulizating, fuel atomization, etc.	Smaller particle sizes. Control particle size.
Extraction	**Pharmaceutical Processing**: Extraction of fluids from flowers, fruits, plants, etc.	Reduced damage to contents. Speeds up extraction process. Increased yields.
Drying	**Commercial and Pharmaceutical**: Assists in the drying powders	High rate of drying for heat sensitive powders.
Degassing	**Chemical Processing**: Degassing of liquid chemicals, liquid metals and liquid glasses.	Better control. Safe for glass containers.
	Other Applications	
Shaker	**Industrial**: Vibrating sieves and hoppers	Higher material flow rates.
Micropositioners	**Commercial and Industrial**: Micropositioning of loads	High accuracy positioning.
Acoustic Generator	**Commercial**: Buzzers and alarms	Compact size and cost effective

Table 10: Actuator Properties and Related Applications

Displacement	Actuator Type	Blocked Force	Hysteresis	Response Time	Weight	Cost	Applications
Low Displacement Actuators							
< 1 μm	Piezoelectric Disc	400 kgf	3-15 %	fast	2 gm	low	High Resolution Positioners, High Power Transducers, Interferometers, Strain Inducers, etc.
< 10 μm	Piezoelectric Tube	250 kgf	3-15 %	fast	2 gm	medium	Ink Jet Printers, Microlithography, Scanning Tunnelling Microscopes (STM), Atomic Force Microscopes (AFM), etc.
10-100 μm	Piezoelectric Stack	100 kgf	< 3-15 %	good	200 gm	high	Deformable Mirrors, Active Suspensions, Stabilizers, Optical Fibre Switches, etc.
Medium Displacement Actuators							
< 200 μm	Monomorph	100 gf	3-15 %	low	< 5 gm	low	Transformer, Twister, etc.
< 200 μm	Moonie	200 gf	3-15 %	medium	10-20 gm	medium	Active hydrophone element, Micropositioner, etc.
< 100 μm	Rainbow	20 gf	5-15 %	medium	5-10 gm	medium	Variable Focus Mirrors, Valves, Relays, Micropumps, etc.
~ 1 mm	Bimorph	10 gf	5-15 %	medium	5-10 gm	medium-high	Benders, Buzzers, Printer Heads, Video Head Positioners, Microphones, etc.
High Displacement Actuators							
< 120 rpm	Standing Wave Motor	3.8 Kg cm (Torque)	low	low	200 gm	high	Variable Focus Camera Lens, Robotics, Non-magnetic Positioner, etc.
<20 cm	Inch-Worm Motors	1/5 kgf	low	low	200 -500 gm	high	Variable Antenna, Translators, Truss Control, Non-magnetic Positioner, etc.

Piezoelectric discs and washers are used in applications requiring small displacements and high generative force. However, some applications require actuators that are capable of generating large displacements while maintaining their abilities to generate large forces. For example, piezoelectric stack actuators are used in a number of flextensional underwater transducer designs. These transducers utilize the larger displacement capabilities of the stacks and the mechanical leverage between the active stacks and the passive components, to radiate large-amplitude sound waves in the presence of a significant water mass. Such stack-based transducers have been utilized as switches for optical fibre communication systems and as actuators in deformable mirrors.

In applications that require less force, but higher displacements, the piezoelectric tube can be utilized as a relatively inexpensive actuator. For example, Scanning Tunnelling (STM) and Atomic Force (AFM) Microscopes utilize piezoelectric tubes to achieve sufficiently large displacements while maintaining the necessary resolution to characterize the electronic surfaces of materials to atomic resolutions. The extensional displacement (ΔL) along the length (L) of a piezoelectric tube for a given applied voltage (V) is as follows [67]:

$$\Delta L = \frac{LVd_{31}}{w} \tag{50}$$

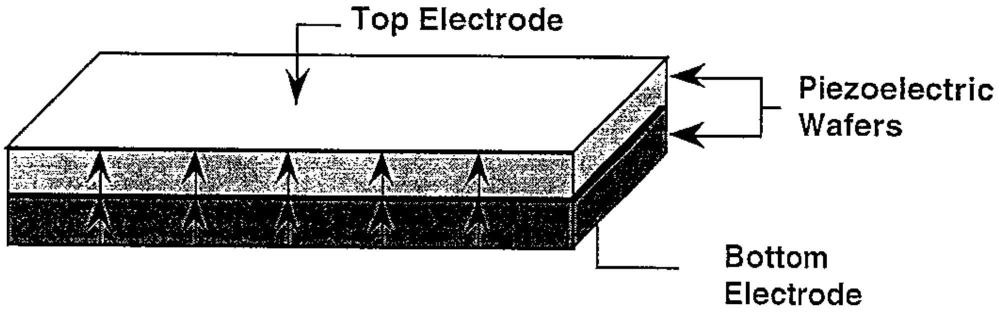
where w is the thickness of the wall of the tube. By segmenting the tube, one can also induce lateral motion in the tube. Similar technologies are being used in lithography, scribing and other applications [67].

Bimorph actuators are available in a number of different configurations, as shown in Fig. 33. Bimorph actuators consist of two thin piezoelectric plates bonded together [105, 106, 67]. When a voltage is applied across the bimorph, bending moments and forces are induced in the mechanically coupled system. When using a cantilever-type bimorph, the free end of the bimorph will become displaced with the application of a voltage. The displacement for a bimorph is given by:

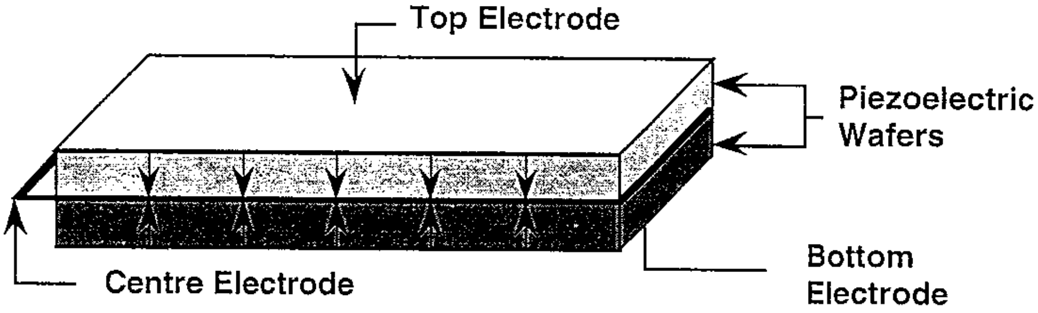
$$\delta = \frac{3d_{31}E_3L^2}{4h} \tag{51}$$

where L is the length of the bimorph and h is the thickness of one piezoelectric plate [109]. Bimorph actuators are generally used in applications requiring large displacements and relatively low forces, such as optical beam deflectors, printer hammers, loudspeakers, and video tape recording heads.

Recent literature describes a new type of actuator called the Reduced and Internally Biased Oxide Wafer (RAINBOW) [110]. Like the bimorph actuator, RAINBOW actuators utilize mechanical coupling in order to generate large displacements. As shown in Fig. 34, the RAINBOW actuator consists of a piezoelectric layer and a chemically reduced layer, which is created at high temperatures. The bilayered system becomes thermally stressed to create a dome shaped distortion in a disc shaped sample upon cooling from the reduction temperatures. Relatively large changes in the dome height of the RAINBOW can be induced with the application of a voltage which modifies the thermally stressed bilayer couple. The RAINBOW has been utilized in micropumps, variable focus mirrors, speakers and micro switches applications



a) Series Bimorph Configuration



b) Parallel Bimorph Configuration

Figure 33: Series and Parallel Bimorph Actuators

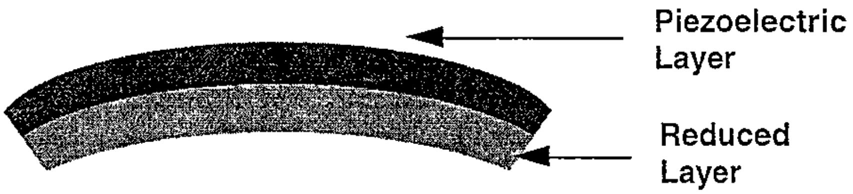


Figure 34: The Structure of a Reduced and Internally Biased Oxide Wafer (Rainbow)

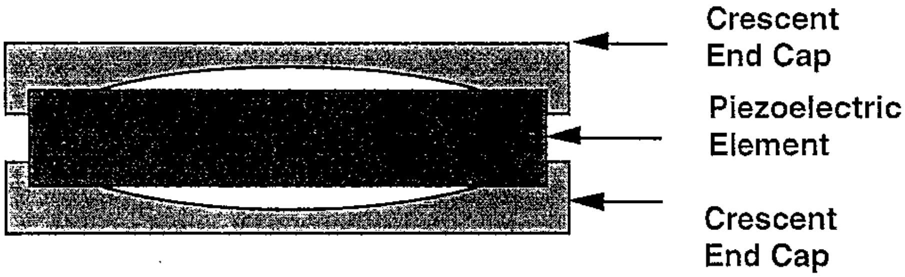


Figure 35: The Moonie Actuator

The moonie, shown in Fig. 35, is a miniature flextensional device that consists of a piezoelectric disc sandwiched between two small, crescent shaped metallic end caps [111]. These devices use the radial mode of the piezoelectric disc to produce strains in the crescent shaped metallic end caps which are perpendicular to the axis of the piezoelectric disc.

A number of piezoelectric motors with novel designs have also added to the dynamic range of piezoelectric actuators. The piezoelectric inchworm motor, for example, operates by using a number of piezoelectric elements to create a "grip and release" type action which generates motion [112]. Another type of piezoelectric motor consists of a thin washer piezoelectric element, an elastic body and a moving body, i.e. a standing wave motor. The most popular type of standing wave motor is the progressive wave or travelling wave motor. In this motor the elastic body is bonded to the piezoelectric washer which induces vertical and transverse waves in the elastic body, creating the travelling standing wave. This travelling wave moves the metallic rotor using the frictional force of the piezoelectric-elastic body (the stator) [113,114]. These piezoelectric motors have been utilized in robotic and precision machine tools, camera lens motors and windshield wiper motors.

4.2.2 Underwater Transducers

In underwater transducers, the piezoelectric elements are generally either encased in a housing with a polymer, similar to the hydrophone geometry presented in Fig. 29, or sandwiched between metallic end pieces [105,106]. In projectors (transmitters) consisting of a single piezoelectric element encapsulated in a polymer, it is important that the maximum amount of acoustic energy is transmitted from the transducer. For optimum transmission of the acoustic energy from the transducer, it is important that the thickness of the polymer layer between the piezoelectric element and the water be equal to a quarter wavelength. The quarter wavelength thickness is calculated for the polymer using the speed of sound (v_s) in the polymer and the resonance frequency (F_r) of the piezoelectric disc, as follows:

$$QuarterWavelengthThickness = \frac{\lambda}{4} = \frac{v_s}{F_r} \tag{52}$$

where the piezoelectric disc is manufactured to achieve the desired operating frequency for a specific resonance mode. In order to achieve a clean resonance, avoiding cross coupled modes and/or overtones, the ceramic disc element in the transducer should have an aspect ratio greater than 2.5 [106]. In the sandwich type transducer, the piezoelectric ceramic disc is clamped between two metallic end pieces. Since the ceramic is in a state of compression, the transducer element is less susceptible to damage due to tensile forces acting on the ceramic. In this configuration, the resonance frequency of the transducer is greatly effected by the property of the metallic end pieces, as opposed to being dominated by the piezoelectric ceramic. Fig. 36 illustrates the piston longitudinal vibrator, one of the most common commercial underwater transducers. Table 9 summarizes a number of popular underwater transducer applications.

4.2.3 Air Transducers

Air transducers convert electrical power to and from acoustic waves which travel in air. Unlike underwater transducers, in order to create audible sound waves of discernible amplitude, the air transducer must generate much larger displacements. Since air transducers do

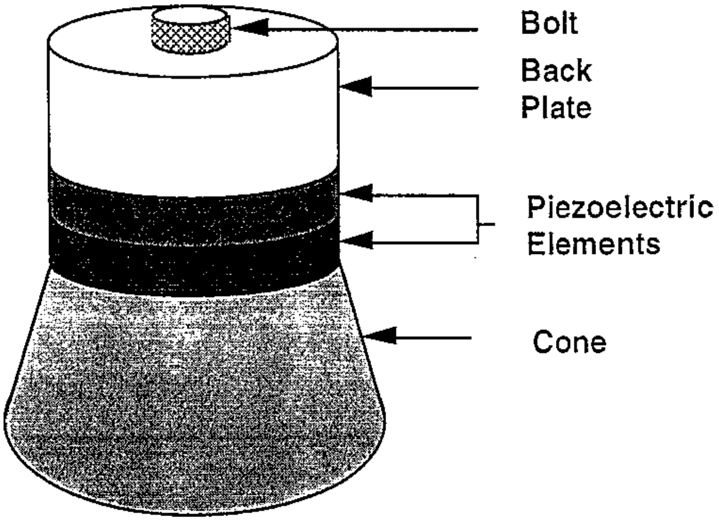


Figure 36: Piston Longitudinal Transducer (Tonpilz Transducer)

produce the forces required by underwater transducers, low force bender elements, such as the bimorph, can be utilized. These flextensional benders can be found in many transducer applications, such as beepers, audio speakers and tone transducers [105].

4.2.4 Electrical Wave Filters

As described earlier, the impedance properties of a piezoelectric ceramic vary as a function of frequency. Although a piezoelectric material is capacitive for most frequencies, these materials exhibited ohmic behaviour between the minimum impedance at the resonance frequency and maximum impedance at the antiresonance frequency. It is this property that is exploited in electrical filters. One of the important parameters of an electric filter is its bandwidth. This bandwidth spans the range of frequencies that pass through the filter with minimum attenuation.

Piezoelectric resonators made in the shape of thin discs or plates can be used in low and high frequency filter applications. In the low frequency regime, between 100 and 450 kHz, the planar mode of the ceramic disc or plate is utilized; while in high frequency applications that require frequencies between 5 and 15 MHZ, the thickness mode of the piezoelectric disc or plate can be utilized (Fig. 37). However, the thickness mode is more susceptible to overtones that manifests themselves as a series of sharp resonance frequency peaks near the thickness mode resonance peak. This series of resonance peaks makes it impractical for these ceramics to be used in high frequency filters. However, by decreasing the diameter of the electrodes and increasing the thickness of the electrodes, the frequency of the fundamental thickness mode of the piezoelectric element in the electrode region will be lower than in the outer region of the piezoelectric element. As a result, the outer region of the disc will damp, or 'trap' the overtone modes excited in the electrode region and a relatively clean resonance peak can be achieved [115].

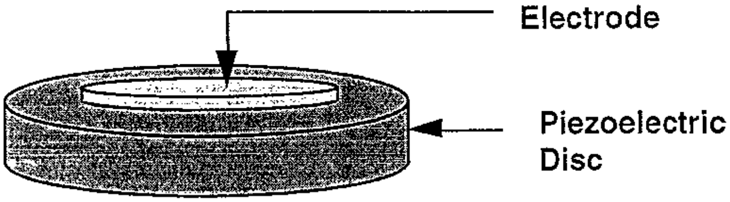
4.2.5 Ink Jet Printers

In some ink jet printers [116], the impulse ink jet (or Ink-on-Demand) is produced using a cylindrical transducer which is tightly bound to the outer surface of a cylindrical glass nozzle with an orifice of approximately 2-3 mils, as illustrated in Fig. 38. The piezoelectric tube transducer generates a pressure wave in the ink that accelerates the ink through the glass nozzle [117, 118]. If the impulse pressure wave is large enough to exceed the surface tension of the ink, an ink droplet will form at the orifice. As many as 32 of these systems would be incorporated into one single print mechanism to give resolutions of 240 dpi at a frequency of 4.8 kHz and a print speed of 200 cps in letter quality mode and 400 cps in near letter quality mode [119]. Ultimately, the operating frequencies of these systems are limited to approximately 10 kHz by the capillary action during refilling from a large ink cartridge [116].

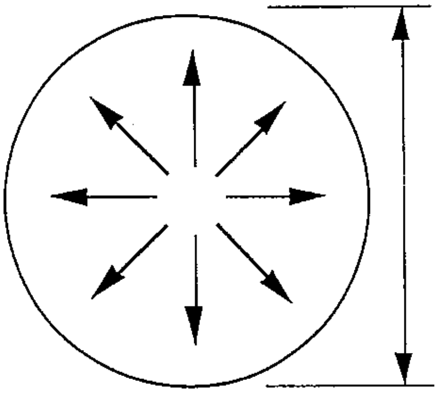
4.3 Applications That Utilize the Direct and Converse Piezoelectric Effects

4.3.1 Sonar

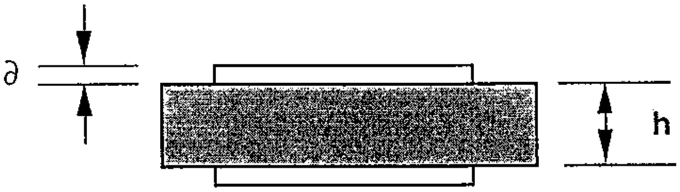
A number of applications utilize both the direct and converse piezoelectric effects to produce and detect acoustical signals. **Sonar**, an acronym for **so**und **na**vigation and **r**anging, is one of these applications. Essentially, an echo ranging sonar system transmits acoustic signals into the water and receives the reflected echoes from a target of interest (submarine, seamount, ocean floor, etc.) at a later time. The signals are generated by active transducers called projectors and



a) Electrical Filter Based on a Piezoelectric Disc



b) Low Frequency Electrical Filter (Radial Mode)



c) High Frequency Electrical Filter (Thickness Mode)

Figuer 37: Electrical Filter

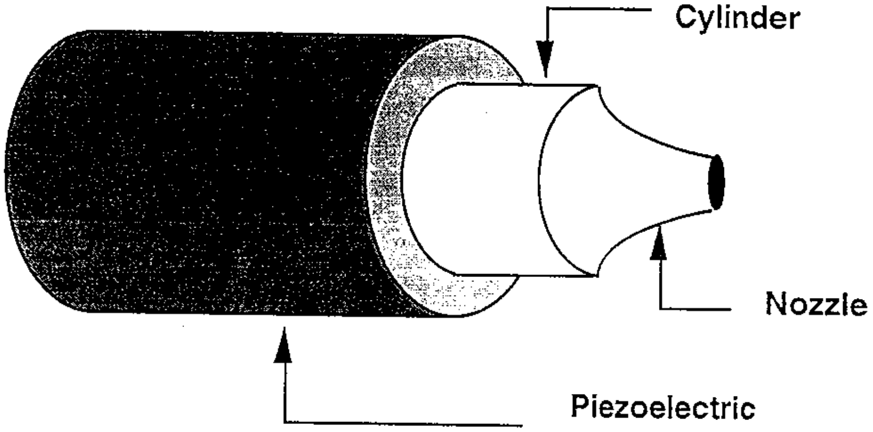


Figure 38: Piezoelectric Pump for Ink Jet Printer

the echoes are received by passive transducers called hydrophones. By measuring the elapsed time between signal emission and echo reception, the distance or range to the target can be determined. Directional receiver systems can also determine target bearing. The fundamental process for a typical echo ranging sonar system is illustrated in Fig. 39.

Since the echoes are embedded in noise upon reception, the hydrophone output is amplified and processed to enhance the echoes and reject the noise. Noise can be man-made or natural and is generated by such things as shipping, industrial activity, rain, waves, breaking ice, organisms, and seismic activity. Finally, the echoes are displayed to an operator in a variety of formats, depending on the purpose of the particular type of sonar system. Typical uses of sonar are listed in Table 11, along with applications like nondestructive testing and diagnostic imaging which uses similar technologies.

4.3.2 Delay Line Transducers

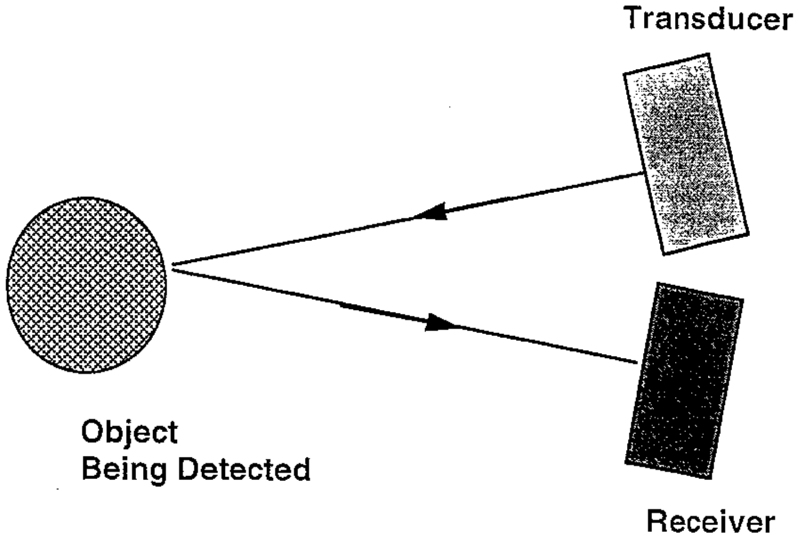
In electronic systems, it is often necessary to delay the progress of electrical signals for times on the order of several milliseconds. Electromechanical transducers can be used in devices that delay signals by transmitting into a suitably dimensioned delay medium as bulk acoustic waves. These waves propagate through the delay medium and are received by a second transducer that converts the acoustic waves back into electrical signals [105, 106]. Space requirements are reduced in some devices by reflecting the acoustic energy within the intermediate material to a second transducer, as illustrated in Fig. 40. Since it is important that the delayed signal closely resemble the original signal, the piezoelectric transducers should be linear over a sufficient bandwidth and the delay medium should be low loss and thermally stable. Some applications of acoustic delay lines are given in Table 11.

4.3.3 Surface Acoustic Wave Devices

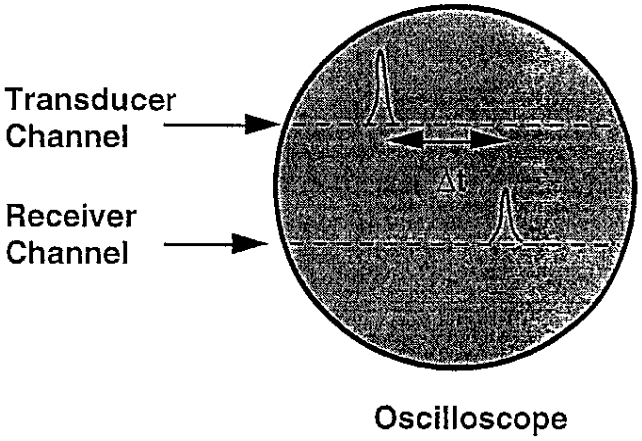
The surface acoustic wave (SAW) devices are based on the principle that an acoustic wave can be confined to a thin surface layer of a material. These surface waves, or Rayleigh waves, are a result of the combination of longitudinal and shear motion governed by the stress free condition of the surface. When such a wave is generated in a piezoelectric material, an electric field which varies with the amplitude of the surface wave is induced parallel to the surface of the piezoelectric material. By placing an interdigited electrode of width 'a' and electrode gaps of width 'b' on the surface of a piezoelectric material, as shown in Fig. 41, surface waves of wavelength ($\lambda_s = 2(a+b)$) can be detected, modified and/or transmitted along the surface. The lower operational frequencies are limited to about 30 MHz due to the size limitations on the SAW electrode; while upper frequencies are limited to several GHz by electrode fabrication techniques. The surface wave concept gives the user versatility in that the surface wave can be measured or modified as it propagates across the surface [120]. These devices have been used in delay lines, bandpass filters and matched filters for applications in the vhf and uhf regimes.

4.3.4 Smart Structure Applications

Smart structures are being utilized at an increasing rate in a number of different sectors of industry. The term smart structure (or intelligent) refers to a structure which has the intrinsic or extrinsic capabilities to repeatedly respond in a useful manner to an external stimulus. The external stimulus usually involves a change in the environmental conditions in the vicinity of the



a) Fundamental Architecture of Sonar



b) Signal Detection After Time (t)

Figure 39: Fundamental Sonar Architecture

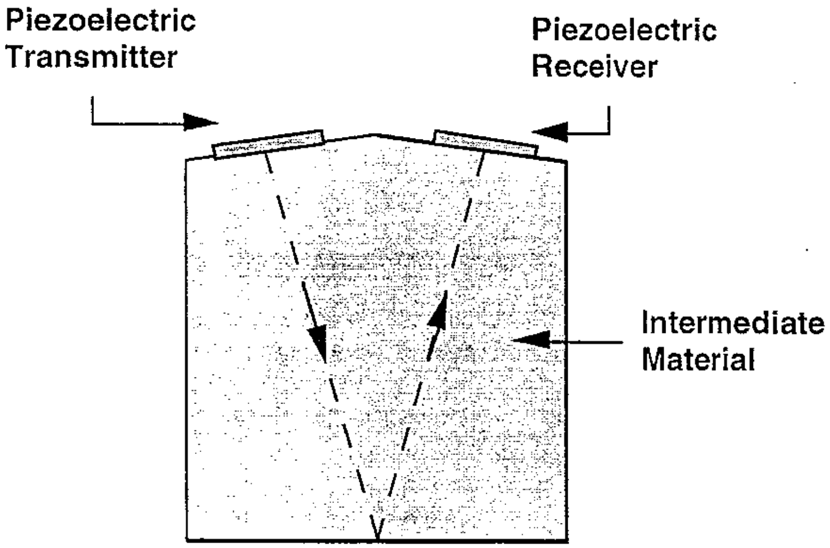


Figure 40: Piezoelectric-Based Delay Line

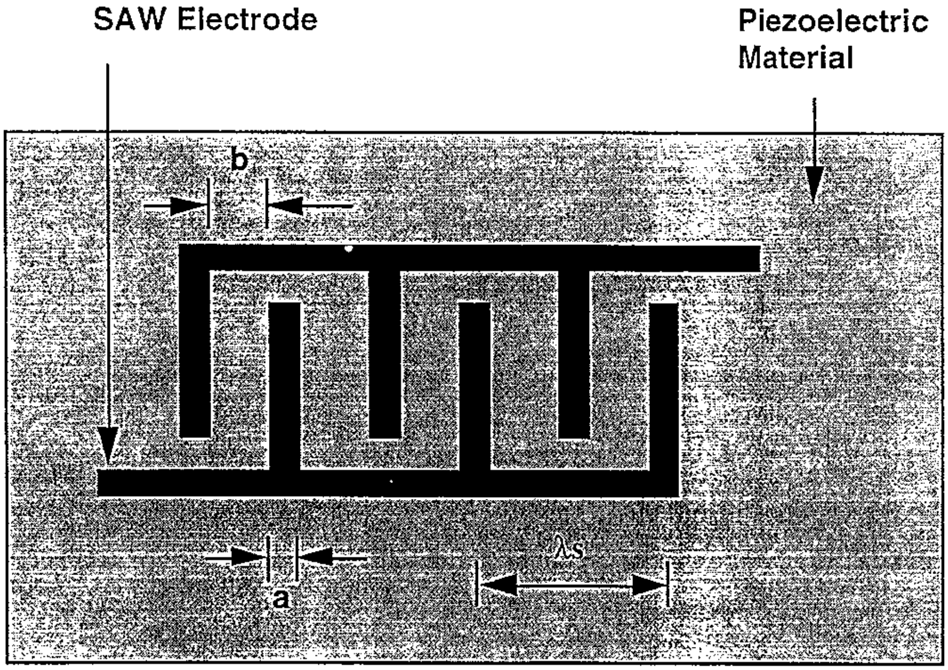


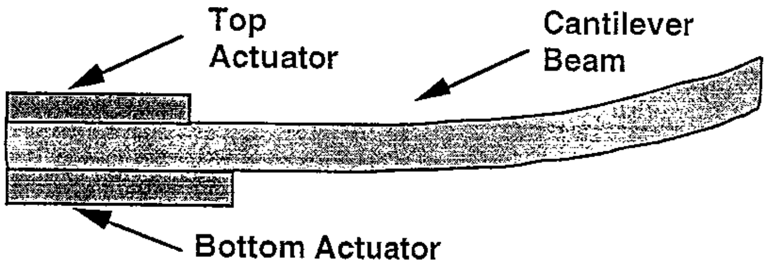
Figure 41: Surface Acoustic Wave Device

Table 11: Applications Utilizing both the Direct and Converse Piezoelectric Effects

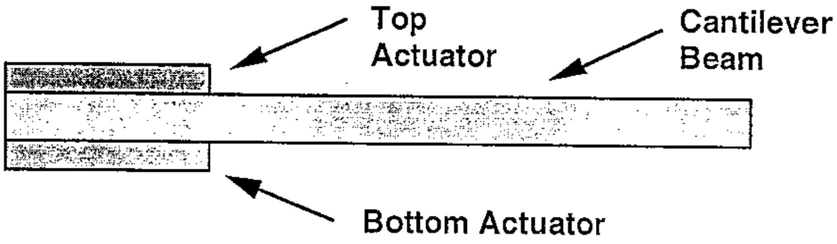
Process	Application	Advantages
Underwater or Liquid based Applications		
Liquid Level	**Industrial**: Liquid level monitoring of fuel in tanks.	Safe and reliable method of measuring liquid levels
Liquid Level	**Industrial**: Liquid level monitoring of fuel in tanks.	Safe and reliable method of measuring liquid levels
Underwater	**Military**: Military, active sonar systems, active homing torpedoes, mine-hunting sonar systems, etc. **Industrial and Commercial** : Depth sounders, subbottom profilers, side-scan sonar systems, fish finders, transponders, telemetry, communications, etc.	High electromechanical conversion efficiency. High intensity and power output capabilities. Tunability. Wide bandwidth. High sensitivity.
Flow Meters	**Industrial**: Measurement of the flow of fluids and solids. Environmental waste control and management.	High coupling coefficient. Reliable and low cost.
Material Characterization		
Non-Destructive Testing	**Metals and Composites**: Ultrasonic detection of cracks and voids.	Fast method of detecting hidden flaws.
Material Constant Measurements	**Industrial**: Density and porosity measurements.	Non-destructive.
Geological Measurements	**Geological and Industrial**: Thickness, density and porosity measurements.	High electromechanical conversion efficiency Low cost

(Table 11 Continued)

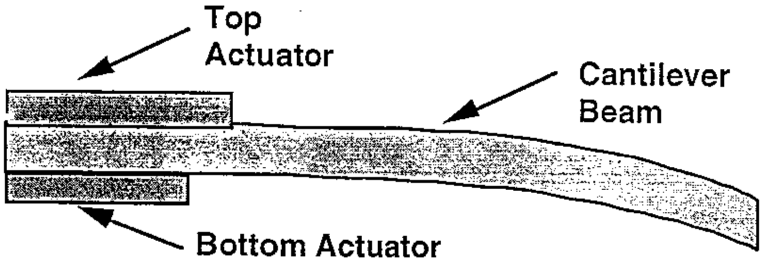
	Medical and Dental Applications	
Diagnostic	**Medical**: Differential diagnosis of malignant and benign tumors. Cardiovascular and blood flow imaging and measurements. Fetal monitoring in Obstetric and Gynaecology. Bone density measurements. **Dental**: Pulp cavity imaging.	Safe and reliable. Non intrusive.
	Smart Structure Applications	
Active Shape Control	**Industrial, Aerospace, Military and Commercial**: Strain or position measurement and control of different structural.	Piezoelectrics are suitable for embedding. High strain and force capabilities.
Active Vibration Control	**Industrial, Aerospace, Military and Commercial**: Vibration cancellation in structural beams, struts and/or panels.	High sensitivity to dynamic strains. Low power requirements. High strain and force capabilities.
Active Noise Control	**Industrial and Commercial**: Cancellation of audible frequencies in structural beams, struts and/or panels.	Piezoelectrics are suitable for embedding. High strain and force capabilities.



a) Top Actuator in Compression; Bottom Actuator in Tension



b) Both Top and Bottom Actuators are Inactive



c) Top Actuator in Tension; Bottom Actuator in Compression

Figure 42: Shape Control of a Cantilever Beam

smart structure, such as a change in light, temperature or pressure. The response of a smart structure may take the form of a change in colour, shape, conductivity or magnetization [121]. The following paragraphs discuss piezoelectric-based smart structures and their detection of and response to external mechanical stimuli.

4.3.4.1 Active Shape Control

Shape control of flexible structures have been used to improve the performance of aerodynamic and hydrodynamic lifting surfaces performance, to reduce drag on submersible components, and to correct for errors in mirrors, antenna and reflectors operating in the optical, radar, and IR spectra. Shape control of a relatively thin structure is achieved by sensing deformations using either surface mounted or embedded actuators attached to a thin beam or panel structure [122, 123]. As illustrated in Fig. 42, bending forces are produced by generating tension and compression on opposite sides of a thin cantilever beam. The degree to which a flexible structure will actually bend (or strain) is dependent on the dimensions and physical properties of the actuator and structural materials [122]. In this case the actuators do not directly bear the load that the structure must maintain. Another type of shape control involves placing the actuator in series with the loads or forces being controlled in order to generate a structural strain. Generally, these high strength single element or stack actuators operate linearly using just tensional and compressive forces to correct the structure deformations produced by exposure to large external forces.

4.3.4.2 Active Vibration Control

The same principle of inducing strains in shape control applications is used in active vibration damping applications. In fact, in some cases, vibration suppression is necessary in order to achieve the precision movements necessary for static shape control. In active vibration control piezoelectric elements are utilized to both detect vibrations that are disrupting the structure and to cancel out these vibrations by inducing counter vibrations into the structure. According to the principle of superposition, if the disruptive vibrations and the counter vibrations are of opposite phase and equal amplitude, then the two waves will cancel. This principle is utilized in a number of smart structure applications. For example, the Toyota piezo TEMS (Toyota Electronic Modulated Suspension), shown in Fig. 43, was developed to improve the handling and stability of the automobile for passenger comfort. The TEMS is based on a road stability sensor and a shock adjustor [124, 125]. The road surface sensor consists of a five-layers of piezoelectric ceramic mounted on the piston rod of the shock absorber. When a bump in the road is encountered, the sensor produces a voltage proportional to the resulting applied stress. This voltage is electronically monitored by the control system which then supplies a signal to a 88-layer piezoelectric stack actuator which counters the vibration produced by the bump. The actuator stack can produce displacements as large as 50 μm. These displacements are then hydraulically amplified displacements as large as 2 mm.

4.3.4.3 Active Noise Control

Active Noise Control (ANC) works on the basic principle of destructive interference, where the undesirable sound wave is countered with a sound wave of equal amplitude, but shifted by 180 degrees. The result is that the sound waves cancel each other out and the undesirable sound is eliminated. In order to produce a cancellation wave, an ANC system uses the following

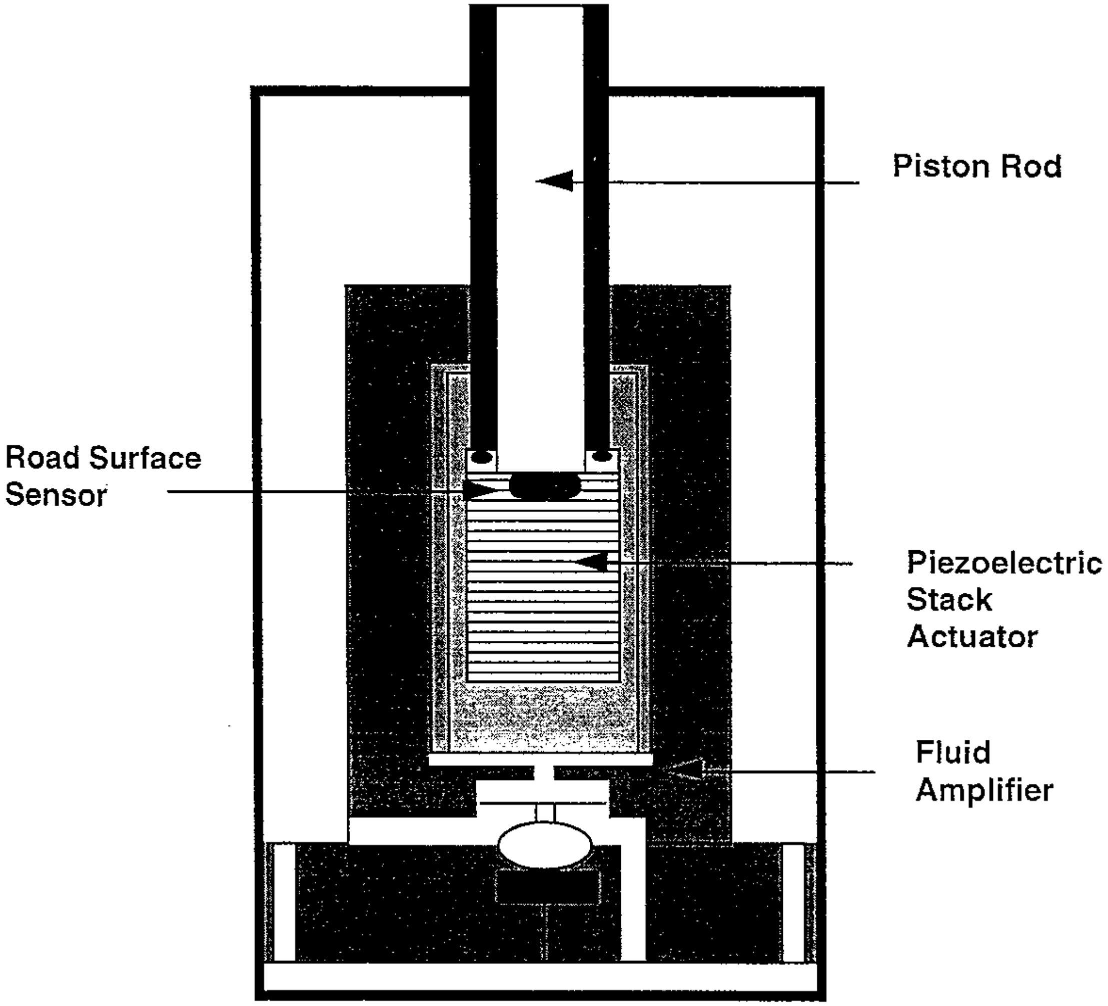


Figure 43: Active Suspension

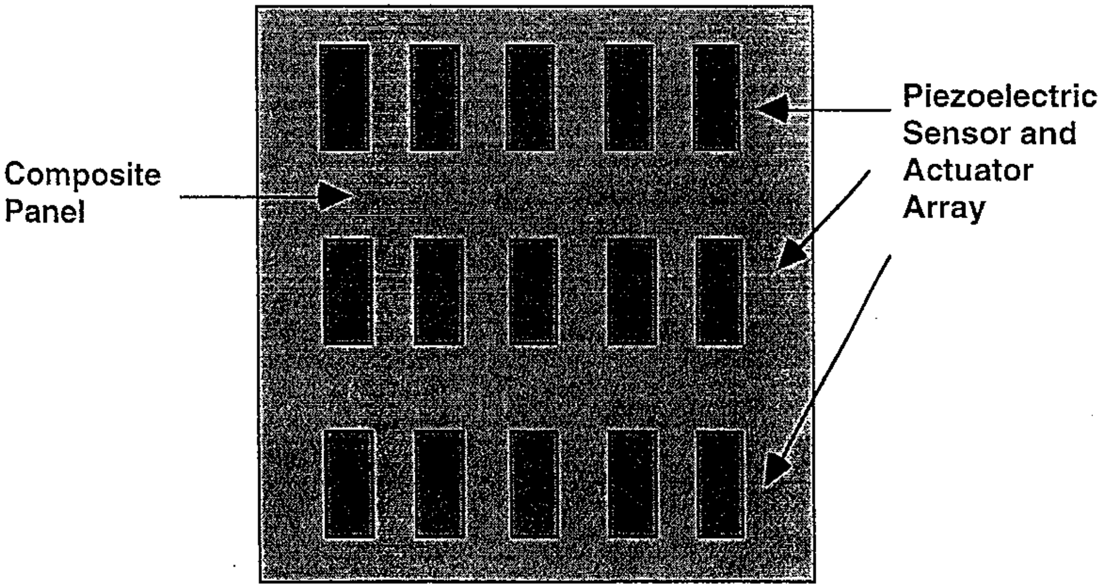


Figure 44: Active Composite Panel

basic components: a microphone, a loudspeaker and feedback electronics. These devices have already found applications in noise cancellation headsets, transformer quieting systems, and interior noise reduction in automobiles and aircraft [126]. One example of an ANC system utilizes a piezoelectric ceramic-based transducer array to reduce the omnidirectional low frequency hum produced by large power transformers. In this transformer quieting system, composite panels composed of surface mounted piezoelectric transducers and sensors were attached to the transformer tank, as shown in Fig. 44. Using active control, these smart panels were found to reduce the transformer noise by as much as 30 dB for the tonal noise levels and 10 - 20 dB for frequencies between 120 and 240 Hz [127, 128].

Acknowledgements

The authors would like to thank Sensor Technology Limited of Collingwood, Ontario for permission to reprint a number of figures and material from its product bulletins of 1991 and 1995. The authors appreciate the many valuable suggestions made by Drs. T.A. Wheat, A. Ahmad of Natural Resources Canada (Ottawa), Dr. B.K. Mukherjee of the Royal Military College of Canada (Kingston) and Dr. S. Varma of Sensor Technology Limited.

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