SRI VENKATESWARA INTERNSHIP PROGRAM FOR RESEARCH IN ACADEMICS (SRI-VIPRA)

SRI-VIPRA

Project

Report of 2023: SVP-2301

"Applications of Piezoelectric Materials"

IQAC

Sri Venkateswara College
University of Delhi
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SRI VIPRA PROJECT 2023

Title : Application of Piezoelectric Material

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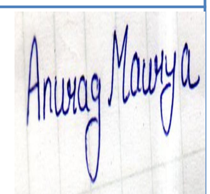
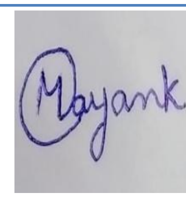
3		Anurag Maurya	1721145	B.Sc. Mathematics Honours	
4		Mayank Bharti	1721122	B.Sc. Mathematics Honours	
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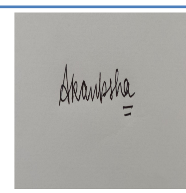
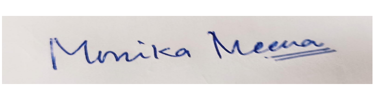
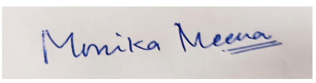
6		Akanksha Yadav	1821002	B.Sc. Physics Honours	



Signature of Mentor

Certificate

This is to certify that the aforementioned students from Sri Venkateswara College have participated in the summer project SVP-2301 titled "**Application of Piezoelectric Material"**. The participants have carried out the research project work under my guidance and supervision from 15 June, 2023 to 15th September 2023. The work carried out is a systematic review of the literature available on the above mentioned subject and is done in a hybrid mode.



Signature of Mentor

Acknowledgements

The students under this project would like to thank those who contributed for the completion of this research. First and foremost, we would like to thank the **administration of Sri Venkateswara College, University of Delhi** for giving us this learning opportunity that helped us develop valuable life lessons of perseverance, teamwork, resilience, cooperation , and most of all, the endless pursuit of knowledge. Second, we would like to convey our deep and sincere gratitude towards **Ms. Monika Meena** for providing invaluable guidance, support, advice, and provisions that help in the completion and success of this study. It was a great privilege and honor to work and study under her guidance. We would also like to express greatest gratitude to our **parents** for their endless love, prayer and support. This would not have been possible without their support given to us at all times. A big thanks to **Almighty God** for giving us the strength, knowledge, ability and opportunity to undertake this research study.
Lastly, our thanks go to all the people who have supported us to complete the research work directly or indirectly.

TABLE OF CONTENTS

INTRODUCTION

The time today is basically an advanced period of the metallurgical era. With advancement, the thirst to look for even advanced technology increases which simplifies human life in all aspects. Necessity catalyzes innovation, creativity, and change. The next generation of materials innovations is reckoned to be fueled with intelligent and low-carbon materials. Smart materials are one such product of this new emerging science and technology.

WHAT ARE SMART MATERIALS?

- Intelligence is the ability to learn from experience, comprehend complex situations, make choices, adapt, and act purposefully.
- An ideal smart material may be defined as a material that comprehends experiences, is self-aware, and responds purposefully.
- It is better to call the response smart, rather than defining the material itself. Therefore, **SMART MATERIALS** can be seen as those which provide a means of achieving an active smart response in a product that would otherwise be lacking and have potential to yield a multitude of enhanced capabilities and functionalities.
- They change their behavior in a systematic manner as a response to specific stimuli which can be altered.
- The various stimuli being pressure, temperature, electric and magnetic field, chemical or nuclear radiation, pH etc. The changeable properties can be shape, stiffness, viscosity, damping etc.
- The various names associated with smart materials are intelligent, advanced, organic, or responsive.
- The smartness is generally programmed by material composition, special processing, introduction of defects or by modifying the microstructure.
- The idea of "smart" structures has been adopted from nature, where all the living organisms possess stimulus-response capabilities.
- The smart materials are incorporated to build smart structures.

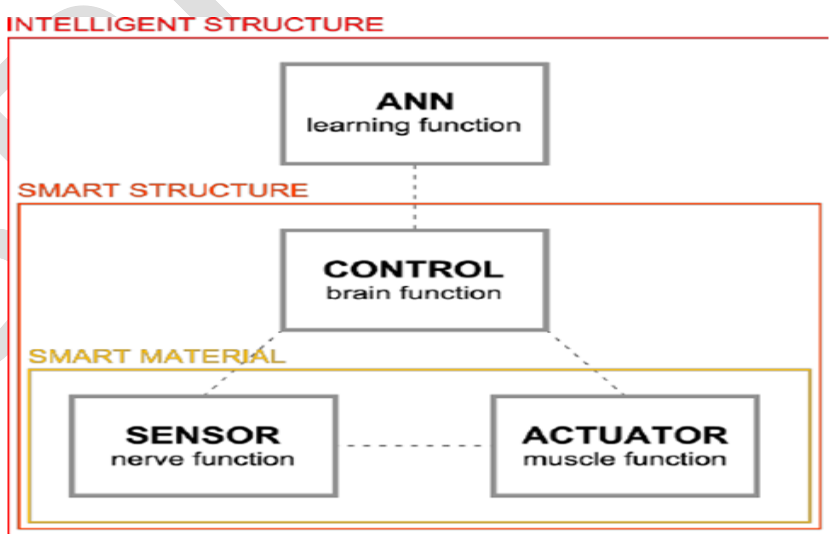


Fig. 01 Smart structures and smart materials

(Source: https://images.app.goo.gl/SPYc7psEox8Wpeer5)

CLASSIFICATION OF SMART MATERIALS:

ACTIVE:

- Active Smart Materials possess the capability of modifying their geometric and material properties under the application of electric, thermal, or magnetic fields, thereby acquiring an inherent capacity to transduce energy.
- Piezoelectric materials, SMAs, ER fluids and magneto-strictive materials are active smart materials.
- They can be used as force transducers and actuators.

PASSIVE:

- The materials, which are not active, are called passive smart materials.
- Although smart, they lack the inherent capability to transduce energy.
- Fiber optic material is a good example of a passive smart material.
- Passive materials can act as sensors but not as actuators or transducers.

DIFFERENT TYPES OF SMART MATERIALS:

1.SHAPE MEMORY ALLOYS:

- Shape memory alloys are materials that can be transformed into any shape but on heating or cooling it will remember its original shape and get transformed into the original shape.
- They are also referred to as “Intelligent Materials”.
- There are two types of SMAs:
    a. One-way SMA
    b. Two-way SMA
- These shape changes occur between two phase martensite to austenite. Martensite phase is stable at lower temperature and austenite phase is stable at higher temperature.

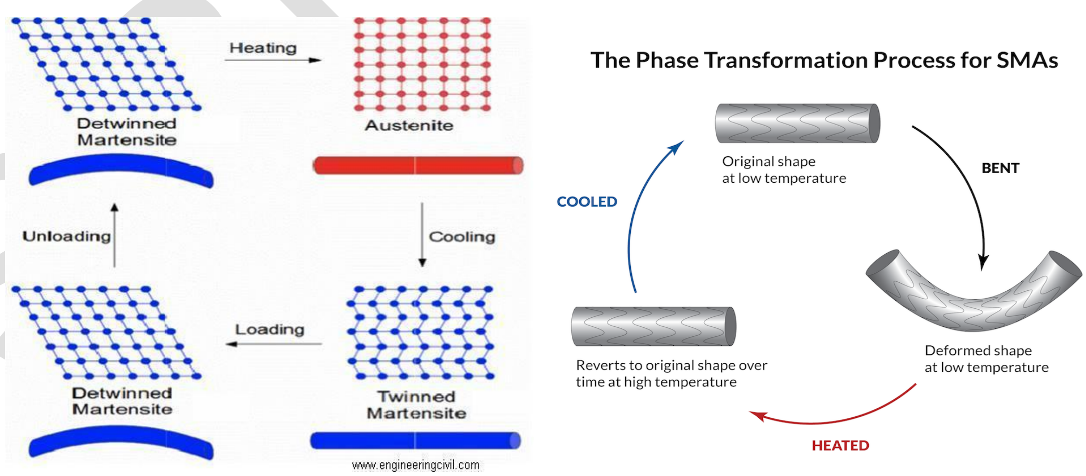


Fig. 02 Phase transformation process for SMAs

(Source: https://images.app.goo.gl/QJqfj6zbd2sZUyWN6)

- Shape memory alloys show two unique effects:
  a. Shape memory effect
  b. Pseudo elasticity
- Some examples of SMAs are NITINOL, Cu-Zn-Al alloy, Cu-Al-Ni alloy etc.
- They find applications in the field of aerospace, biomedical and robotics.

2. PIEZOELECTRIC MATERIALS:

- The term piezoelectricity is a blend of two terms: “piezo” which is a Greek term meaning pressure and “electricity” referring to electric charges.
- Piezoelectric are materials that exhibit an electrical polarization with an applied mechanical stress (direct effect), or a dimensional change with an applied electric field (converse effect).

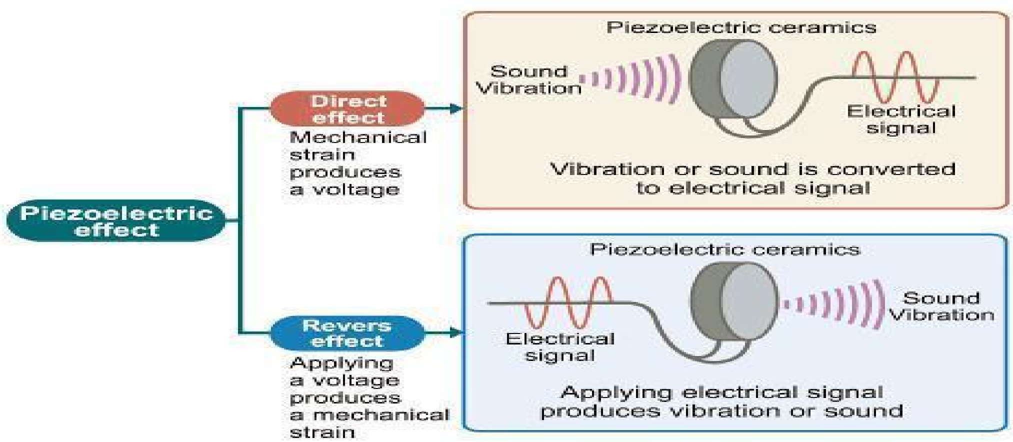


Fig. 03: Direct and converse piezoelectric effect

(Source: https://images.app.goo.gl/NrFXHSK4hUiPotkc7)

- They are used for both sensing and actuating devices.
- Examples: Quartz, lead zirconate titanate, barium titanate etc.
- They are used in lighters, acoustic instruments, piezo motor, portable speakers, adaptive optics, hydrophones and sonobuoys, fuse devices, depth sounders, thickness gauging, flaw detection, level indicators.

3. MAGNETO AND ELECTRO RHEOLOGICAL FLUIDS:

- Magneto- and Electro-Rheological Fluids change their rheological properties like stress and viscosity on the application of the magnetic and electric field respectively.
- MRFs are used in damper, clutch and buffer etc. MREs are widely used in adaptively tuned vibration absorbers. MRFs have the properties such as viscoelastic in nature, magnetic property, light in weight, controllable modulus and excellent sound absorbing.

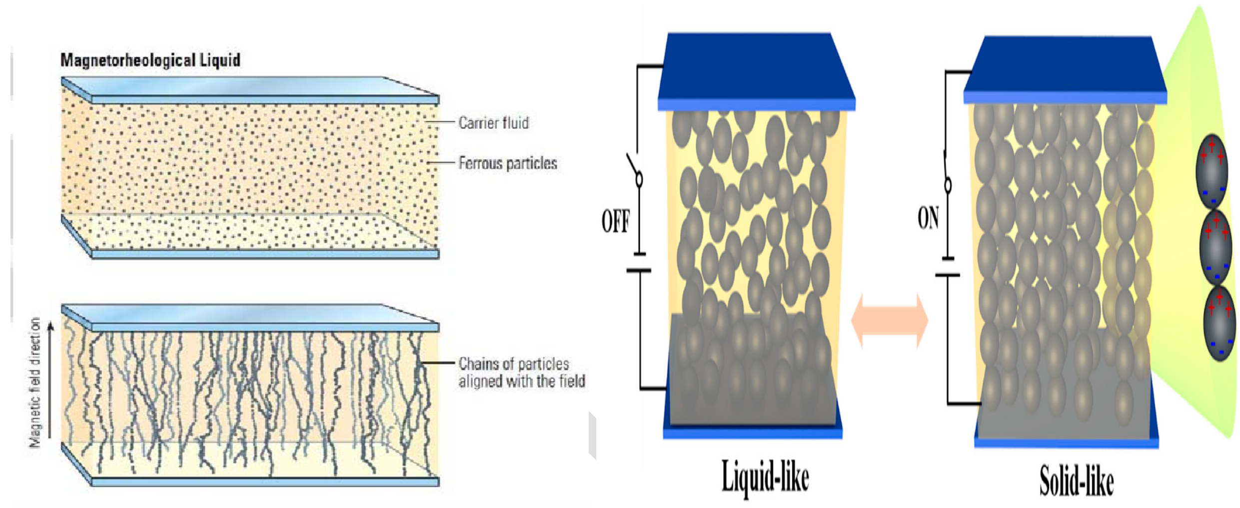


Fig:04 Magnetorheological and Electrorheological Fluids

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- The Electro-Rheological Fluids (ERFs) is the suspension of very small particles in electrical insulating fluid when the electric field is applied, they will rapidly form a solid-like structure in the direction of the field.
- ERFs have the properties such as stiff, damping coefficient is changed in the electric field, high dielectric constant, interfacial bond strength, constable rheology and dielectric in nature. They have wide application in Hydraulic Industry, Automobile Industry, Fluid Sealing Industry, Robot Industry.

4. MAGNETOSTRICTIVE MATERIALS:

- Magneto restrictive materials are materials that have the material response of mechanical deformation when Stimulated by a magnetic field.
- Shape changes are the largest in Ferro-magnetic and ferromagnetic materials.
- These materials are almost like the piezoelectric materials.
- Mechanical properties of magneto-strictive materials are: workability, moderate saturation magnetization, high coercivity, high chemical stability, high Curie temperature and high cubic magneto crystalline anisotropy

- Examples: Cobalt, Terfenol-D etc.
- These materials find applications in transducers, high frequency oscillators etc.

5. OPTICAL FIBER:

- A flexible and transparent fiber which is made by drawing glass/plastic to a diameter slightly thicker than the diameter of the human hair is called the optical fiber.
- They are associated with technology of data transmission using light pulses. They are used to transmit high-definition signals which have greater bandwidth and speed.
- Some uses of fiber optic cables include: advanced intrusion detection security systems, Optical chemical sensors, and optical biosensors, used to transmit power using a photovoltaic cell, as light guides in medical and other applications, Structural health monitoring, Spectroscopy.

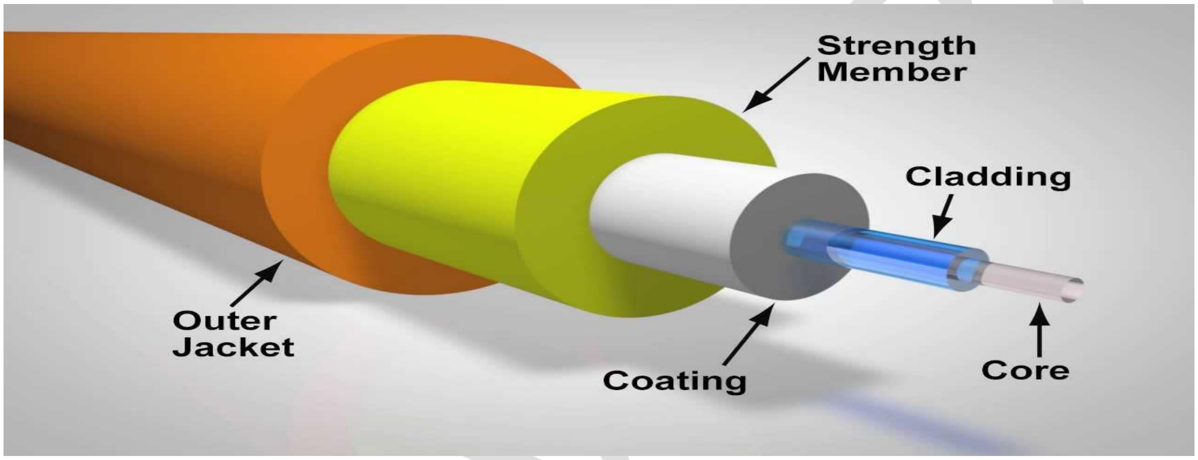


Fig. 05: An optical fiber

(Source: https://images.app.goo.gl/nyyXrVBtdPsxUntE8)

PIEZOELECTRIC MATERIALS

DEFINITION:

- Piezoelectric materials are materials that can generate internal electrical charge from applied mechanical stress. They also conversely have a geometric strain proportional to an applied electric field. They exhibit a linear coupling between mechanical stress and electrical potential.
- Piezoelectric effect is of two types:

a. Charge on applying stress– Direct Piezoelectric Effect
b. Strain on applying electric field – Inverse Piezoelectric Effect

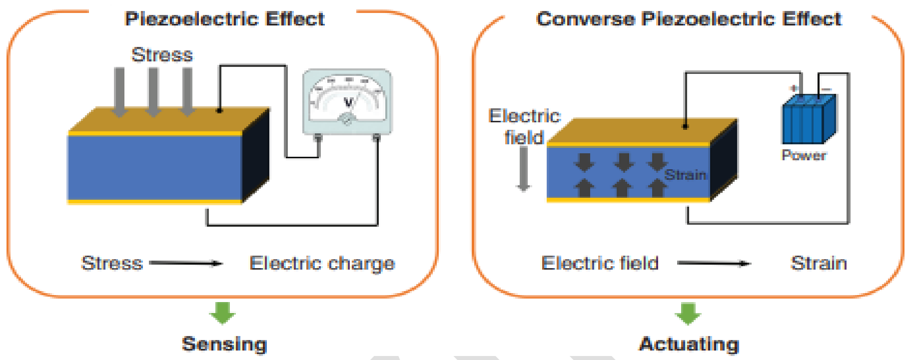


Fig. 06: Direct and converse piezoelectric effect

(Source: https://images.app.goo.gl/CWYnu2TiykcwhGvV8)

CLASS:

- Dielectric materials are basically electrical insulators, which become polarized by the peripheral application of the electrical field when placed across the plates of a capacitor.
- Piezoelectric materials belong to the dielectric group.
- Ferroelectrics are an experimental subset of pyroelectric materials.
- All ferroelectric materials are pyroelectrics, and all pyroelectrics are piezoelectric.

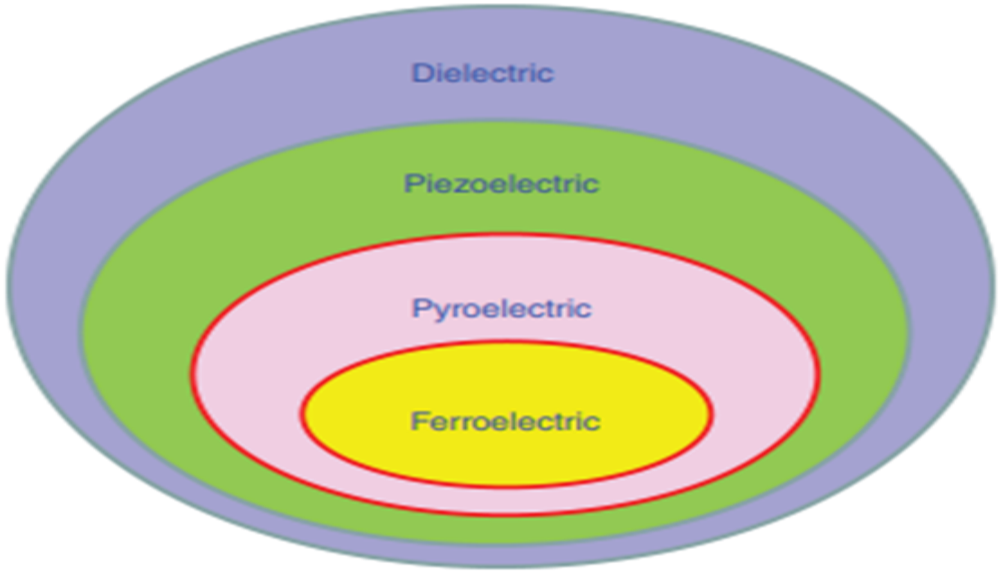


Fig. 07: Class of Piezoelectric materials

(Source: https://images.app.goo.gl/PKPFqyR576fpUN1r7)

DEVELOPMENT AND HISTORY:

- Coulomb is said to have conjectured that electricity might be produced by pressure; this led to experiments by Hauy and A C Becquerel with inconclusive results; he conjectured that experiments with crystalline minerals might show effects due to their anisotropy.
- **1880** - The first experimental demonstration of a connection between macroscopic piezoelectric phenomena and crystallographic structure was published in 1880 by Pierre and Jacques Curie. The name was coined by Hankel in 1881. Armed with that knowledge, they built the first piezoelectric quartz electrometer. However, the Curie brothers did not predict the inverse piezoelectric effect.
- **1881**-The inverse piezoelectric effect was deduced mathematically by Gabriel Lippmann in 1881. The Curies then confirmed the effect and provided quantitative proof of the reversibility of electric, elastic, and mechanical deformations in piezoelectric crystals.
- **1910** - The German physicist Woldemar Voigt published an enormous volume of material, "LehrBuch der Kristallphysik," detailing the known 20 piezoelectric materials and their properties. He also worked out and defined the mathematical coefficients that quantified the amount of electrical change produced with an application of physical pressure. This book's publication paved the way for practical applications of the piezoelectric effect.
- **1914** - During WW-I, the French scientist Paul Langevin turned his attention to how applied physics might aid in the war effort. He used quartz's piezoelectric properties to develop technological advancements for submarines, famously inventing the first device that could use echolocation to locate submarines in the ocean. This device, the quartz sandwich transducer, represented the first sonar technology.

- **1935** – Rochelle salt was used until barium titanate and PZT were discovered. George Busch discovered potassium dihydrogen phosphate, KDP.
- **1942-44** - During World War II, scientific groups in the United States, the Soviet Union and Japan discovered that some ceramic materials exhibited the same piezoelectric properties already known in crystals — but with dielectric constants up to 100 times greater. These ceramics, known as ferroelectrics and created by sintering powdered metallic oxides, turned out to be relatively easy to manufacture. In developing piezoceramics and their applications, the compound barium titanate ($BaTiO_3$) proved useful as a base for creating the necessary ceramic material. Using the resulting piezoceramics, research groups successfully developed new technologies like more sophisticated sonar systems, ignition devices, microphones, and audio transducers.
- **1950s** -Discovery of the barium titanate family of piezoceramics motivated development of the lead zirconate titanate family, an understanding of the correspondence of the perovskite crystal structure to electro-mechanical activity and a rationale for doping both families with metallic impurities in order to achieve desired properties.
- **1965-1970s** -Several Japanese companies and universities formed a "competitively cooperative" association and began to reap the benefits of steady applications and materials development work. From an international business perspective, they were "carrying the ball". Persistent efforts in materials research had created new piezoceramic families such as PZT, doped PZT, ceramic filters, ternary solid solution based on PZT, Lithium Niobate, Tantalate, Polyvinylidene difluoride etc.
- **1999**- Limitations on use of Pb lead to use of bismuth to create lead free ceramics.
- **20th century** -In the later decades of the 20th century, the commercial market for piezoelectric materials expanded significantly. As manufacturers developed newer devices, they relied more and more on advanced piezo products. Soon enough, piezoelectric materials made their way into many consumer devices. Today, piezoelectric materials find use in a wide array of commercial and industrial product

PROPERTIES:

Piezoelectric crystals/materials have several properties that make them unique and useful in a variety of applications. These properties include:

- **Voltage Sensitivity**: When a piezoelectric crystal is subject to mechanical stress, it generates a voltage. Conversely, when a voltage is applied to the crystal, it deforms. This property is known as piezoelectricity.
- **Inversion symmetry**: Piezoelectric crystals have a lack of inversion symmetry, which means that the crystal structure is not symmetric when flipped over. This is necessary for the crystal to exhibit piezoelectric properties.
- **Atomic Structure**: The secret of piezoelectric materials lies in their unique atomic structure. Piezoelectric materials are ionically bonded and contain positive and negative ions in the form of pairs called unit cells.
- **Anisotropic**: These materials are available in nature as an anisotropic dielectric with non-centrosymmetric crystal lattice i.e., they do not have any free electrical charges and the ions lack a center of symmetry.
- **Class**: Piezoelectric materials belong to the dielectric group.

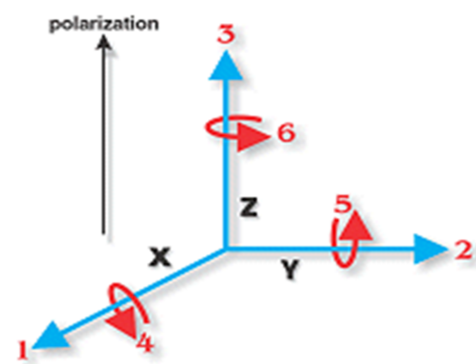
- **Temperature stability**: Piezoelectric crystals are relatively stable over a wide range of temperatures, making them useful in high-temperature applications.
- **Durability**: Piezoelectric crystals are robust and can withstand high mechanical loads and impacts. They are inherently brittle materials that show electromechanical coupling
- **Frequency response**: Piezoelectric crystals have a high resonant frequency, which makes them useful in high-frequency applications.
- **Frictionless movement**: Piezoelectric crystals can be used to create frictionless movement, which makes them useful in precision positioning applications.
- **Stress sensitivity**: Piezoelectric crystals have a high sensitivity to mechanical stress, which makes them useful for sensing applications.

PIEZOELECTRIC CONSTANTS AND FIGURES OF MERITS:

- The extent of piezoelectric properties in materials can be measured using piezoelectric coefficients, such as:
  Piezoelectric Charge Constant(d), Piezoelectric Voltage Coefficient(g), Dielectric Constant, Piezoelectric Stress Coefficient (e), Piezoelectric Stiffness Coefficient (h), Piezoelectric Coupling Coefficient (K), Mechanical Quality Factor (Q), Acoustic impedance (Z).
- These are also known as figures of merit.
- Because of the anisotropic nature of piezoelectric materials, the effect is direction dependent. Here,

a. axes 1,2,3 - X, Y, Z axis set
b. axes 4,5,6- shear/rotation

Figure 1.6 Directions of forces affecting a piezoelectric element



- The piezoelectric coefficients are defined with double subscripts, with the first subscript indicating the direction of the electrical field associated with the applied voltage/produced charge and the second subscript indicating the direction of the mechanical stress/strain.
- These piezoelectric constants are defined as partial derivatives evaluated at constant stress (subscript T), constant electrical field (subscript E), constant electrical displacement (subscript D), or constant strain (subscript S). These conditions can be regarded as “mechanically free,” “short circuit,” “open circuit,” and “mechanically clamped,” respectively.
- Apart from these coefficients, piezoelectricity is also affected by electric, elastic, and thermal properties.

Symbol	Name	Definition
d	Piezoelectric charge coefficient or piezoelectric strain coefficient	$d_{ij} = \left(\frac{\partial D_i}{\partial T_j}\right)_E = \left(\frac{\partial S_j}{\partial E_i}\right)_T$
g	Piezoelectric voltage coefficient (voltage output constant)	$g_{ij} = -\left(\frac{\partial E_i}{\partial T_j}\right)_D = \left(\frac{\partial S_j}{\partial D_i}\right)_T$
e	Piezoelectric stress coefficient	$e_{ij} = -\left(\frac{\partial T_j}{\partial E_i}\right)_S = \left(\frac{\partial D_i}{\partial S_j}\right)_E$
h	Piezoelectric stiffness coefficient	$h_{ij} = -\left(\frac{\partial E_i}{\partial S_j}\right)_D - \left(\frac{\partial T_j}{\partial D_i}\right)_S$

Fig. 08: Different piezoelectric coefficients

1. PIEZOELECTRIC CHARGE (STRAIN) CONSTANT, d:

- The piezoelectric charge coefficient relates the electric charge generated per unit area with an applied mechanical force
- The piezoelectric charge coefficient has unit Coulomb/ Newton (C/N).

$$d = \frac{\text{Strain developed}}{\text{Applied field}} = \frac{\text{Charge density (open circuit)}}{\text{Applied stress}}$$

- Large d constants relate to large mechanical displacements, which are usually sought in motional transducer devices. Important For Actuator Applications

2. PIEZOELECTRIC VOLTAGE COEFFICIENT, g:

- Piezoelectric Voltage Coefficient is defined as the ratio of the electric field produced to the mechanical stress applied. (Important figure of merit for sensor applications)

$$g = \frac{\text{Strain developed}}{\text{Applied charge density}} = \frac{\text{Field developed}}{\text{Applied mechanical stress}}$$

- The g-constants are calculated from the piezoelectric charge (strain) constant (d) and relative permittivity (ε) from the equation:

  $g = d/\varepsilon$ ------------(V m/N)

3. PIEZOELECTRIC COUPLING COEFFICIENT, K:

- The piezoelectric coupling coefficient (or the electromechanical coupling coefficient) is defined as the ratio of the mechanical energy accumulated in response to an electrical input or vice versa.

$$x = \sqrt{\frac{\text{Mechanical energy stored}}{\text{Electrical energy applied}}} = \sqrt{\frac{\text{Electrical energy stored}}{\text{Mechanical energy applied}}}$$

- In general, a useful parameter keff is frequently used to express the effective coupling coefficient of a resonator with an arbitrary shape, either at its fundamental resonance or at any overtone modes, and is expressed as follows: k2 eff = 1 − (fr fa)2 where f r and f a stand for resonating frequency and anti-resonating frequency, resp.

4. MECHANICAL QUALITY FACTOR, QM

- The mechanical Q_m (also referred to as Q) is the ratio of the reactance to the resistance in the series equivalent circuit representing the piezoelectric resonator, which is related to the sharpness of the resonance frequency.

$$Q_m = \frac{f_r}{f_2 - f_1}$$

5. ACOUSTIC IMPEDANCE Z:

- The acoustic impedance Z is a parameter used for evaluating the acoustic energy transfer between two materials. It is defined, in general, by:

APPLICATIONS OF PIEZOELECTRICITY IN MEDICAL SECTOR AND HEALTHCARE SECTOR:

Piezoelectric materials can be employed in monitoring many bodily signals because they convert mechanical energy into an electrical signal. They are especially applicable to monitoring dynamic pressure changes; many human vital signs consist of rhythmic activities like the heartbeat or breathing. In addition to creating implants, it can be used in a variety of medical treatments, most of which depend on the vibrational properties of the piezoelectric device. Major medical applications use the transducer application.

PIEZOELECTRIC TRANSDUCER:

- A piezoelectric transducer is a device that uses the piezoelectric effect to measure changes in acceleration, pressure, strain, temperature, or force by converting this energy into an electrical charge OR vice-versa.
- A transducer can be anything that converts one form of energy to another. The piezoelectric material is one kind of transducers. When we squeeze this piezoelectric material or apply any force or pressure, the transducer converts this energy into voltage. This voltage is a function of the force or pressure applied to it.
- Transducer can act as either actuator or a sensor.

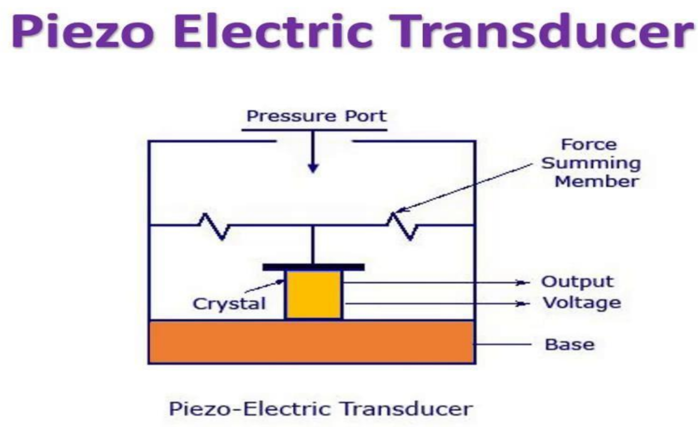


Fig. 09: A piezoelectric transducer

- Figure shows a conventional piezoelectric transducer with a piezoelectric crystal inserted between a solid base and the force summing member. If a force is applied on the pressure port, the same force will fall on the force summing member. Thus, a potential difference will be generated on the crystal due to its property. The voltage produced will be proportional to the magnitude of the applied force.

01. ULTRASOUND IMAGING:

- An ultrasound transducer converts electrical energy into mechanical (sound) energy and back again, based on the piezoelectric effect. It is the hand-held part of the ultrasound machine that is responsible for the production and detection of ultrasound waves.
- Piezoelectric materials can be made to vibrate via the converse piezoelectric effect to the point where they start emitting ultrasonic waves. At the same time, they can register mechanical energy such as sound and convert it into electrical energy by means of the direct piezoelectric effect.
- It consists of five main components:

a. Crystal/ceramic element with piezoelectric properties
b. Positive and ground electrodes on the faces of the element

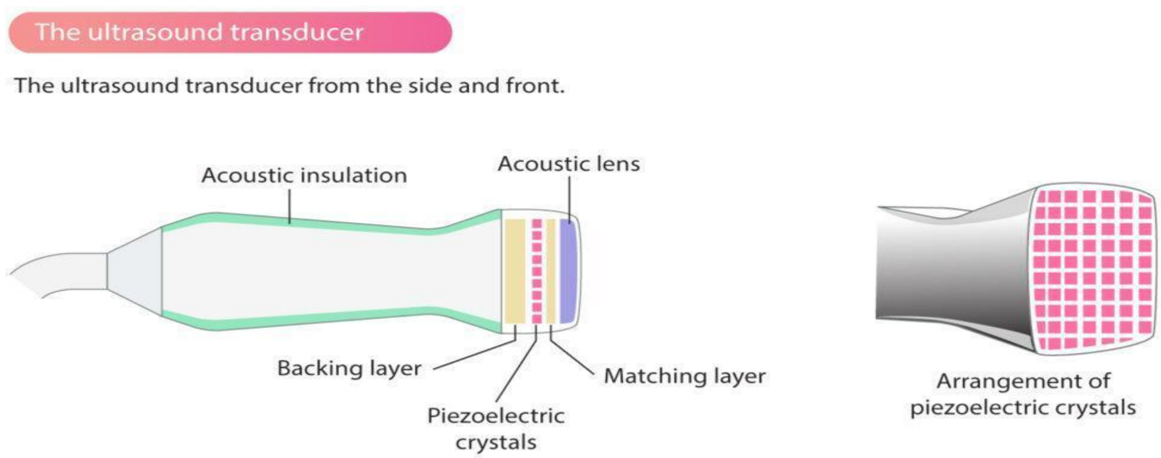


Fig.10: The ultrasound transducer
(Source: https://images.app.goo.gl/BKKgvG6GRQ1D6geg9)

c. Damping (backing) block
d. Matching layer
e. Housing

- Before scanning commences, a lubricant is typically applied to the patient's abdomen in order to improve between the scanner head and the skin tissue. Once applied, the transducer can start generating ultrasonic waves, emitting them into the body tissue. As the waves encounter tissue, bone etc., some of them are reflected.

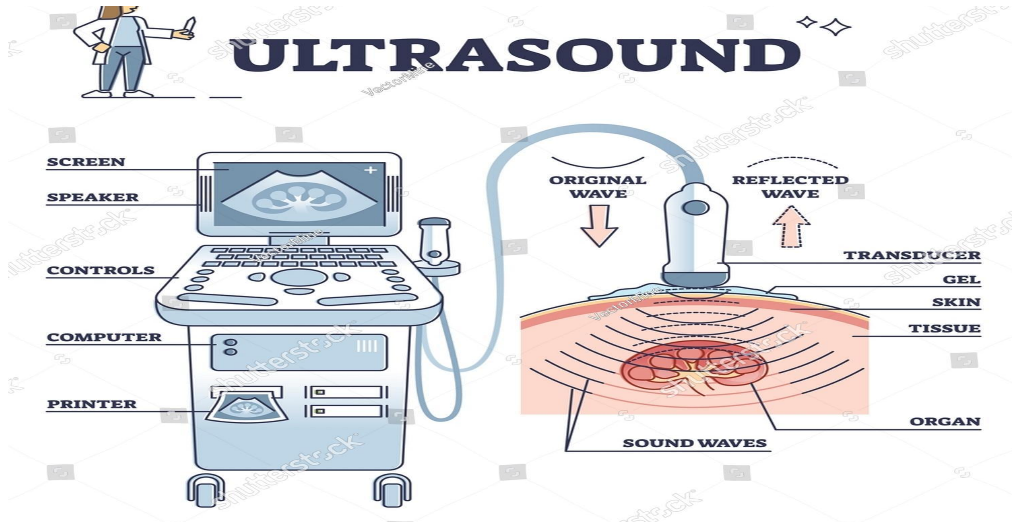


Fig.11: The ultrasound machine

(Source: https://images.app.goo.gl/UNbvzJqkq2t3pyPJ8)

- The intensity of the reflections is contingent. The reflected waves are then registered by the transducer and converted into an electrical signal which can be used to generate an image of the womb and fetus.
- Matter with a high degree of acoustic impedance will appear brighter on the image as it reflects a larger portion of ultrasonic waves.

02. MICRODOSING

- Micro dosing is another application of piezoelectricity and has become popular because it conserves the amount of medication dispensed and can reduce discomfort by avoiding injections.
- In some cases, an injected drug can be aerosolized in order to avoid injection. In this case, piezoelectric vibrations can break the drug into fine particles which can be carried in an air stream and inhaled by the patient. In the case of solids, a stacked actuator design is applicable by providing a single oscillation, rather than the consistent vibration.
- In a Micro dosing device, a glass tube is attached to the actuator and an electric signal stimulates the actuator providing a force to the tube and displacing a certain amount of the solid. Stacked actuators in fluid pumps can administer small single doses or a continuous flow. Fluid administration, like those for eye drops, often require small single doses.

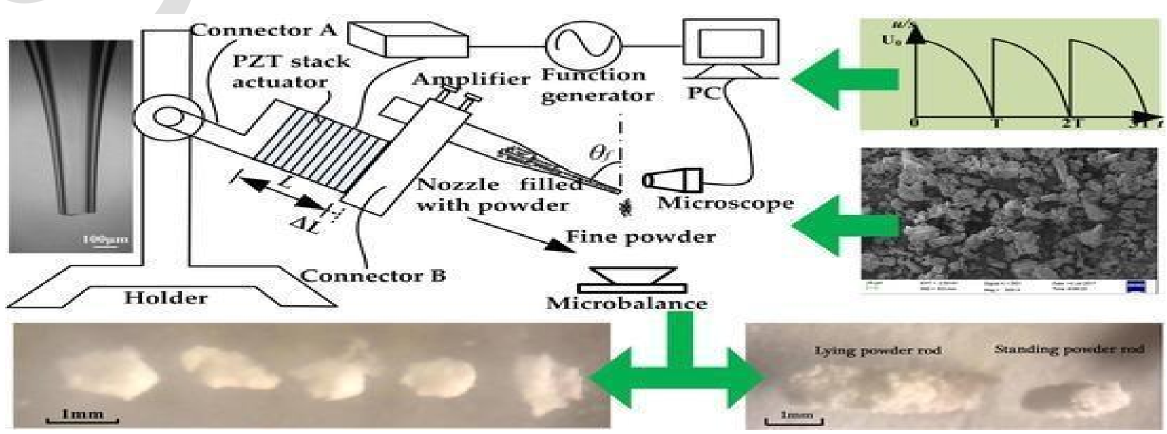
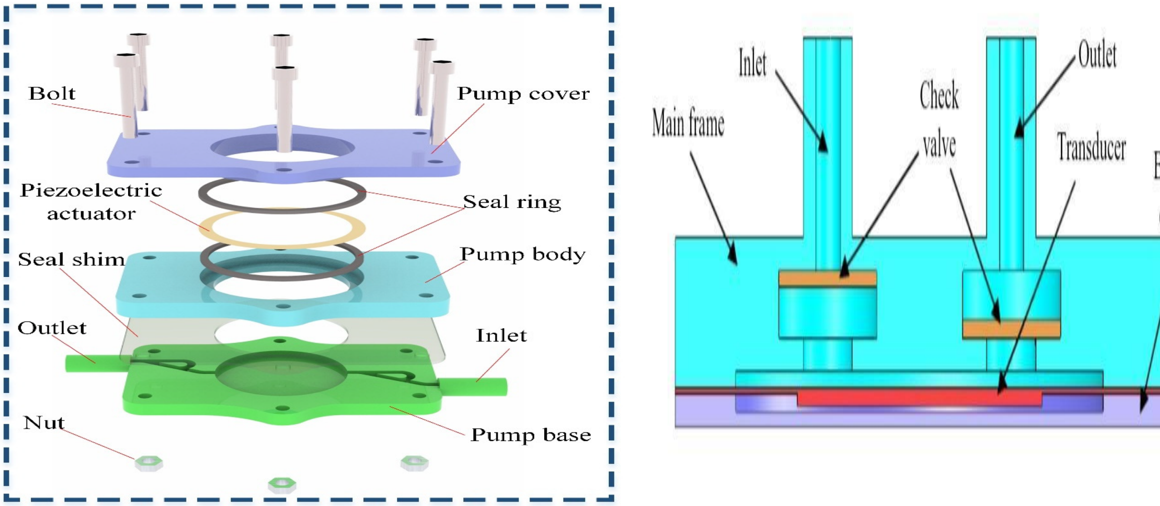


Fig.12: Micro dosing device

(Source: https://images.app.goo.gl/mVy6miqntXShHCUo8)

- A more complex form of controlled micro dosing can be accomplished through DIAPHRAGM PUMP.



(Fig.13: (L) Four chambered diaphragm pump, (R) Parallel cylinders pump

Source: https://images.app.goo.gl/wbD5upC7ExokeS9i7)

- Diaphragm pump has two types:

a. One pump design places four chambers in series where the voltage controls the degree of membrane fluctuation and the phase of the material controls its direction.

b. Other designs have parallel cylinders which are filled and emptied according to a certain sequence. The number of steps in the sequence determines the flow rate.

- Diaphragm pump enables continuous microfluidic delivery. They rely on movement of the actuator to compress gas in a pressure thereby changing pressure. When the actuator vibrates, chamber volume and inside pressure varies. As a result, liquid flows in and out during the vibration cycle. This is more suited for some dosing systems such as insulin dispensing.
- Though PZT is a popular material for biomedical pumps, polymer actuators such as PVDF-TrFE have been used as well.

03. SLEEP STUDIES:

- Physiological information such as respiratory rate and heart rate in the sleep state can be used to evaluate the health condition of the sleeper.
- Traditional sleep monitoring systems such as polysomnography need body contact and are intrusive, which limits their applicability. Thus, a comfortable sleep bio-signals detection system with both high accuracy and low cost is important for health care.

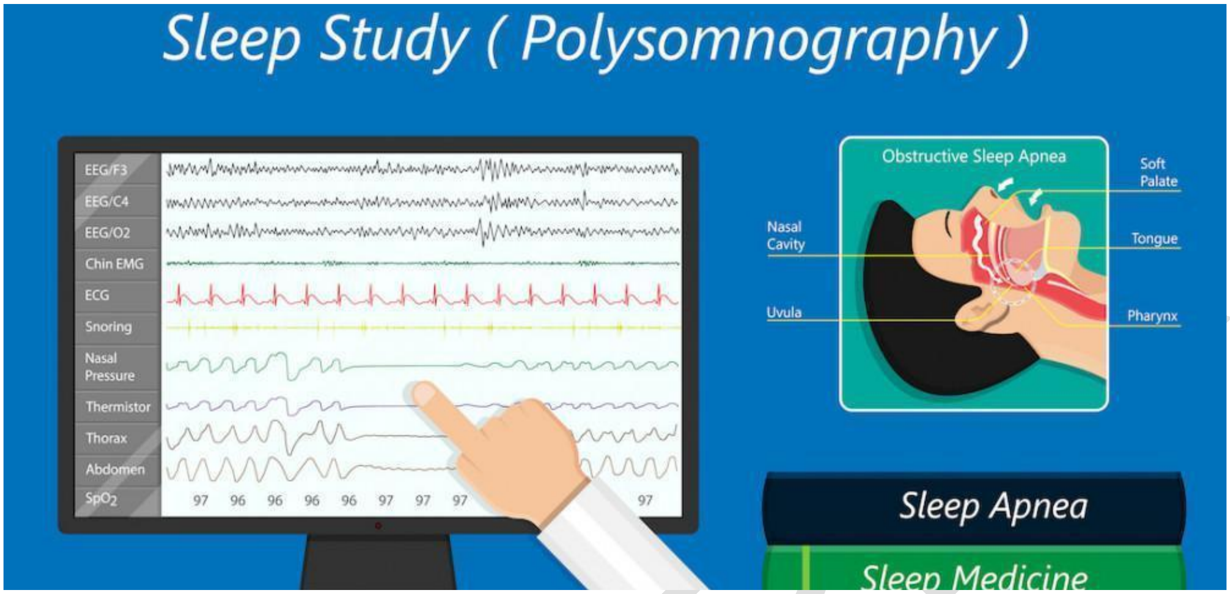


Fig.14: Polysomnography

(Source: https://images.app.goo.gl/KTpiZ5fdZq1frVfPA)

- A better choice is using Piezoelectric ceramic sensors deployed under the mattress to capture the pressure data. The appropriate sensor that captures respiration and heartbeat sensitively is selected by the proposed channel-selection algorithm.
- The piezoelectric ceramic sensor has many advantages for physiological information detection:
    a. First, it can capture the pressure changes caused by small vibrations and convert them into electrical signals. Thus, signals caused by breathing and heartbeat can be obtained.
    b. Second, it has a much lower cost than other sensors.

04. PIEZOELECTRIC SURGERY:

- Piezoelectric surgery is a procedure that uses an ultrasound device that creates micro-vibrations to cut the bone. This surgical procedure is also called piezo surgery.
- The piezo surgery device has a tip that vibrates in different frequencies which enables cutting of the bone without damaging structures like the nerves
- Unlike implanted devices, piezoelectric devices needed for surgery do not need to be biocompatible, because they do not encounter human cells.
- The typical piezo-surgical devices will consist of stacked rings which are given an applied voltage. The resulting vibration will be transduced to the tip, which is installed in such a way that it will amplify vibrations, because traditionally ceramics are more brittle and do not display much displacement.

- In surgery, piezoelectric devices, such as the ultrasonic lancet, are used for delicate operations to preserve surrounding tissue. By controlling the micromovements of the oscillating device, damage to soft tissues can be avoided, and the separation between interfaces is easily accomplished.
- It is the treatment of choice whenever bone removal or bone shaping is needed in a surgical procedure and is more used in dental treatments such as: Placement of dental, Crown lengthening, Orthodontic surgery, Root canal treatment etc.
- Piezo-surgery has some other applications in neurosurgery and orthopedic surgery; however, it is limited in equipment fragility and associated expenses. The tip of the device fractures, creating the need for replacements. It also takes longer to perform operations, and can damage tissue through heating. Irrigation is required to keep the area cool, and larger scale devices are used for macro-sized surgeries.

05. DENTAL SCALING:

- A piezoelectric dental scaler also has piezoelectric ceramic rings on the inside to induce axial vibrations, and operates at ultrasonic frequencies.
- Its purpose is to remove accumulated biofilms from the tooth surface and for treatment of root canals. The vibrations of the tip break down the calculus (tartar) and plaque which have formed on the tooth's enamel surface.

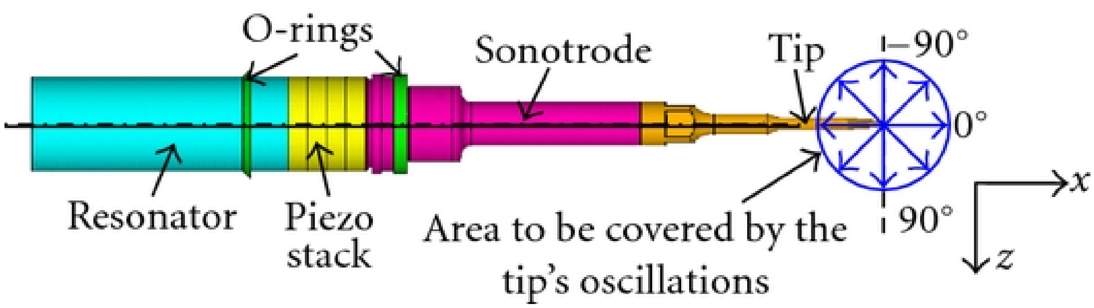


Fig.15: A dental scaling device

(Source: Reprinted from Engelke et al.)

- Ultrasonic dental scalers operate in the range of 25–50 kHz, and oscillate parallel to the tooth surface over a range of 10–100 μm.
- Because of the tip's quick speed, when the irrigation water passes over the scalar, micro- and nanosized bubbles form around its curve and tip. When bubbles collapse, cavitation forces create shock waves cleaning the tooth.
- The oscillation pattern of the scalar depends on the type of tip chosen and the effectiveness of the scaler varies depending on how it is used.
- Influencing factors can be the lateral force, tip angle, and power setting. Increasing the power on the ultrasonic scaler too much will scratch a tooth's protective enamel surface, increasing the tooth's surface roughness and causing damage to the surrounding tissues.

06. COCHLEAR IMPLANT:

- The destruction of inner ear cells results in severe hearing loss and is most treated by cochlear implants.
- Though the current technology allows for recovery from deafness, it is incompatible with water and has very high-power requirements.
- Piezoelectric materials can be used for creating an artificial basilar membrane (ABM). The membrane performs mechanical frequency selectivity for the cochlea.

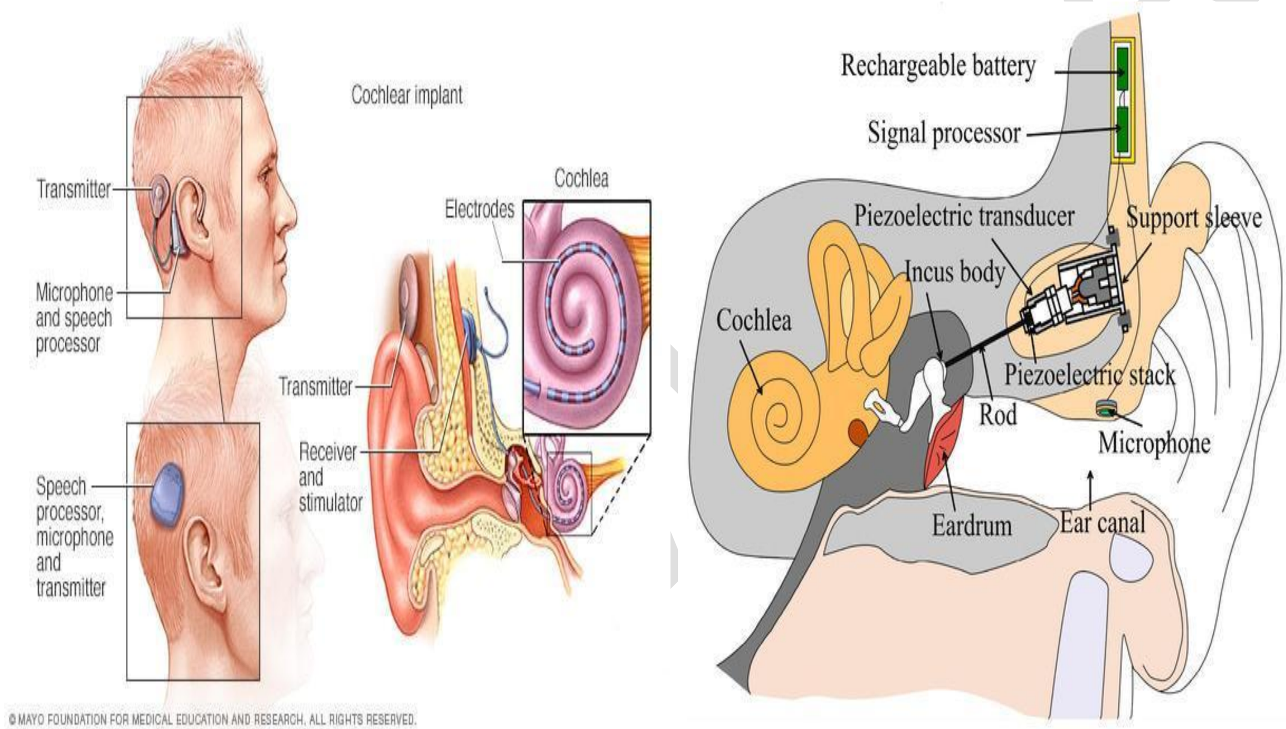


Fig.16: Cochlear implant surgery and device

(Source: https://images.app.goo.gl/DTk8xaZceT7JgtwX9)

- Cochlear implants use a sound processor that fits behind the ear.
- The processor captures sound signals and sends them to a receiver implanted under the skin behind the ear.
- The receiver sends the signals to electrodes implanted in the snail-shaped inner ear (cochlea).
- The signals stimulate the auditory nerve, which then directs the signals to the brain. The brain interprets those signals as sounds, though these sounds will not be just like natural hearing.
- Varying physical rigidity and thickness of the basilar membrane allows it to perform its duty, and likewise piezoelectric materials can filter out frequency based on their physical properties.

Ceramics, such as PZT, can be fabricated in beam or cantilever arrays with lengths corresponding with different resonance frequencies.

07. Electronic Stethoscope

The electronic stethoscope has a very thin diaphragm connected to the Piezoelectric material. The diaphragm is made of metal or plastic because it is a good conductor of sound. When the sound waves hit the diaphragm it oscillates, making compressions or expansions inthe piezoelectric material. This produces voltage across the material proportional to the amount of deflection.

The voltage is then transferred to an amplifier and filter circuit to get the desired output. A foam spacer is connected to the piezo material and a steel plate to enhance the vibrations which in turn results in generating more voltage.

08. Pulse Measurement

Arterial pulse wave velocity is a measure of the elasticity (or stiffness) of peripheral arterial blood vessels. The principle of the PWV measurement is based on simultaneous measurement of two pulse waves at two different positions.

V is the piezoelectric sensor's volume ; S is the section area; L is the displacement length of the skin movement of the pulse. The internal pressure change ΔP of the pressurized sensor is the sum of the pressure PA before being pressurized and the pulse wave pressure Pa. of the skin movement of the pulse. The proportional relationship involves the ratio of specific heats γ, which is about 1.4 for air.

09. Anaesthesia Machines

In anesthesia machines, piezoelectric materials are primarily employed in flow sensors. Flow sensors are essential components of anesthesia machines that monitor the flow rate of gases such as oxygen and anesthetic agents. These flow sensors help regulate the delivery of gases to the patient, ensuring that the right amount of anesthesia is administered throughout the procedure. In the case of flow sensors in anesthesia machines, piezoelectric materials can detect changes in gas flow as pressure fluctuations cause mechanical deformation in the material. When the gas flows through the sensor, it causes mechanical deformation in the piezoelectric material, resulting in the generation of an electric charge. This charge is then measured and converted into a corresponding flow rate, providing real-time information to the anesthesia machine's control system.

Here's how the piezoelectric flow sensor works:

Sensor Construction: The piezoelectric flow sensor typically consists of a piezoelectric material, which is a crystal or ceramic that exhibits the piezoelectric effect. The material is usually sandwiched between two metal electrodes.

Gas Flow: When the anesthesia machine is in operation, gases such as oxygen and anesthetic agents flow through the sensor. The gas flow exerts pressure on the piezoelectric material, causing mechanical deformation or stress within the crystal or ceramic.

Generation of Electric Charge : As the piezoelectric material experiences this mechanical deformation, it generates an electric charge across its electrodes. The amount of charge generated is directly proportional to the applied stress or pressure. The charge is a measure of the gas flow rate.

Charge Measurement : The electric charge generated by the piezoelectric material is then measured by the sensor's electronics. This charge measurement is converted into an electrical signal, which is proportional to the gas flow rate.

Flow Rate Calculation: The electrical signal is sent to the anesthesia machine's control system, where it is processed and converted into a flow rate value. The control system uses this flow rate information to regulate the delivery of gases to the patient, maintaining the desired anesthesia level throughout the medical procedure.
Real-Time Monitoring: As the gas flow continuously changes during the anesthesia administration, the piezoelectric flow sensor's real-time monitoring helps the anesthesia machine make rapid adjustments to maintain precise gas delivery.
The piezoelectric flow sensor's mechanism enables accurate and responsive monitoring of gas flow rates, ensuring that the anesthesia machine delivers the appropriate amount of anesthesia to the patient. This level of control and feedback is crucial in medical procedures to provide safe and effective anesthesia administration.

10. Detection of Disease
Piezoelectric materials have shown potential for various applications, including the detection of diseases. Piezoelectric materials generate an electric charge in response to mechanical stress or pressure. This property can be harnessed to create sensors and devices for detecting certain diseases or biomolecules. Here are a few ways piezoelectric materials are used in disease detection
1)Biosensors & Microfluidics
•Piezoelectric materials can be functionalized with specific biological molecules such as antibodies or DNA probes. When the target biomolecule (like a specific protein or nucleic acid) binds to the functionalized surface, it causes a change in mechanical stress, leading to a change in the electrical output of the material. This change can be measured and quantified, providing a means to detect the presence of the disease-related biomolecule.
•Microfluidic devices use tiny channels to manipulate small volumes of liquids. Piezoelectric materials can be integrated into these devices to precisely control the movement of fluids and particles. In disease detection, microfluidic devices can be designed to process and analyze small samples of bodily fluids like blood, urine, or saliva. Piezoelectric actuators can aid in pumping, mixing, and separating these fluids for analysis.
2)Acoustic Wave Sensors & Breath Analysis
•Piezoelectric materials can be used in surface acoustic wave sensors. These sensors utilize acoustic waves that propagate along the surface of a piezoelectric material. When the surface is coated with a sensing layer that interacts with specific biomolecules, changes in the propagation of these waves occur. This change can be detected and correlated with the presence of disease markers.
•Certain diseases can cause changes in the composition of a person's breath due to metabolic processes. Piezoelectric gas sensors can be used to detect volatile organic compounds present in breath. The interaction of VOCs with the sensor's surface causes a change in its piezoelectric properties, which can be used to identify specific disease-related compounds.
3)Implantable Sensors & Urinary Infections
•In some cases, piezoelectric materials can be used in implantable sensors. These sensors can monitor physiological parameters like pressure, strain, or even chemical composition within the body. For example, they can be used to monitor intraocular pressure for glaucoma patients or to detect changes in tissue mechanics that might indicate the presence of tumors.
•Piezoelectric sensors have been explored for the rapid and label-free detection of bacteria in urine samples. The mechanical stress caused by bacterial attachment to the sensor surface can lead to changes in its piezoelectric properties, allowing for the detection of UTIs without the need for time-consuming culturing methods.

11. Developing Synthetic Skin

Piezoelectric materials have indeed been explored for use in developing synthetic skin or electronic skin (e-skin) due to their ability to convert mechanical energy (such as pressure or vibration) into electrical signals. This characteristic makes them suitable for mimicking the sensory functions of human skin and enhancing the interaction between humans and machines or devices.

Prosthetics and Robotics: Piezoelectric sensors integrated into synthetic skin for prosthetic limbs or robots can provide feedback about pressure, touch, and even temperature. This can allow for more natural and intuitive interactions between the user and the device.

Health Monitoring: E-skin with piezoelectric elements can be used for health monitoring by detecting subtle changes in pressure or vibrations on the skin's surface. This could enable wearable devices to track vital signs like pulse and respiration rate.

Gesture Recognition: By detecting pressure and deformation patterns, e-skin can enable gesture recognition without requiring external cameras or sensors. This can be useful for applications like virtual reality, gaming, and controlling smart devices.

Human-Machine Interfaces: E-skin could be integrated into wearable devices to create more immersive human-machine interfaces. For example, users could feel vibrations or pressure changes that correspond to notifications or alerts on their devices.

Sensitive Robotics: Robots equipped with e-skin could have improved tactile perception, allowing them to handle delicate objects or interact with humans more safely.

Some piezoelectric materials commonly used in developing synthetic skin include:

•Polyvinylidene fluoride: This is a popular piezoelectric polymer that can be fabricated into thin films. It's flexible and can conform to various shapes, making it suitable for e-skin applications.

•Lead Zirconate Titanate: PZT is a ceramic material with strong piezoelectric properties. It offers high sensitivity and is often used in applications where a higher level of performance is required.

•Flexible Composites: Researchers have also explored combining piezoelectric materials with flexible substrates to create composite materials that can better mimic the properties of human skin.

While the concept of e-skin using piezoelectric materials holds great potential, there are also challenges to overcome, such as maintaining the durability and stability of the materials over time, ensuring compatibility with human skin, and developing effective methods for integrating these materials into devices. Ongoing research is focused on addressing these challenges and unlocking the full capabilities of synthetic skin with piezoelectric materials.

APPLICATION OF PIEZOELECTRIC MATERIALS IN SONAR SYSTEMS

INTRODUCTION

• Have you ever wondered how submarines are able to navigate underwater? Or how scientists are able to study the depths of the ocean? The answer lies in piezoelectric materials and sonar technology, two fascinating areas of science that we'll be exploring today.

• Piezoelectric materials are unique in their ability to convert mechanical energy into electrical energy, and vice versa. This property has made them incredibly useful in a wide range of applications, including sonar technology. By using piezoelectric transducers, sonar systems are able to detect and analyze sound waves in water, allowing us to map the ocean floor and study marine life. But the potential uses for these materials go far beyond just sonar technology.

WHAT IS SONAR TECHNOLOGY?

• Sonar technology is a method of using sound waves to detect and locate objects underwater. It works by emitting a pulse of sound, which then travels through the water and reflects off any object it encounters. The reflected sound wave is then detected by a receiver, which can determine the distance, size, and shape of the object based on the time it takes for the sound to travel back and the strength of the reflected signal.

• Sonar technology has been used for a variety of purposes, including navigation, communication, and military operations. It is particularly useful in underwater environments where visibility is limited and other forms of detection are impractical. By using sonar technology, scientists and engineers can explore the depths of the ocean and discover new species, while also improving our understanding of the world around us.

HOW DO PIEZOELECTRIC MATERIALS ENHANCE SONAR TECHNOLOGY?

• Piezoelectric materials are used in sonar technology to enhance its performance in various ways. One of the main benefits of using piezoelectric materials is their ability to convert electrical energy into mechanical energy and vice versa, which makes them ideal for use in transducers. In sonar technology, transducers are used to generate and receive sound waves, and piezoelectric materials can be used to create highly sensitive and efficient transducers.

• Another way that piezoelectric materials enhance sonar technology is through their durability. These materials are able to withstand high levels of stress and strain without losing their properties, which makes them ideal for use in harsh environments such as underwater. This means that sonar systems that use piezoelectric materials can operate reliably and effectively in a wide range of conditions.

PIEZOELECTRIC TRANSDUCERS

• Piezoelectric transducers are a key component of sonar technology, converting electrical signals into mechanical vibrations and vice versa. These transducers consist of a piezoelectric crystal sandwiched between two electrodes, which generates an electric field when subjected to mechanical stress. This electric field can be used to detect sound waves in the water or to produce sound waves for echolocation.

• The role of piezoelectric transducers in sonar technology is crucial, as they allow for accurate detection and measurement of underwater objects and phenomena. By carefully controlling the frequency and amplitude of the electrical signals applied to the transducer, sonar systems can create detailed images of the underwater environment, including the location and movement of marine life, geological features, and man-made structures.

• Piezoelectric transducers also function as projectors in Sonar Systems. When an electrical signal is applied to the piezoelectric material, it experiences mechanical deformation, causing it to emit acoustic waves into the water. These acoustic waves can be used to transmit sound signals for various purposes, such as underwater communication or active sonar systems.

BENEFITS OF PIEZOELECTRIC TRANSDUCERS

• Piezoelectric transducers offer a number of benefits when used in sonar technology. One of the main advantages is their high sensitivity, which allows them to detect even slight changes in pressure or vibration. This makes them ideal for use in underwater applications, where small signals can be easily lost or distorted. In addition, piezoelectric transducers are extremely durable and can withstand harsh environments without losing their performance. This makes them ideal for use in marine applications, where they may be exposed to salt water, extreme temperatures, and other challenging conditions.

• One practical application of piezoelectric transducers in sonar technology is in the detection of submarines. By using an array of transducers placed on the hull of a ship, it is possible to create a detailed picture of the underwater environment and detect any objects that may be present. This technology has been used by navies around the world for many years and has proven to be highly effective in detecting submarines and other underwater threats.

UNDERWATER ACOUSTIC SENSORS

Piezoelectric materials are used as sensitive underwater acoustic sensors. They can detect and convert even faint underwater sounds and vibrations into electrical signals with high fidelity. These sensors are employed in passive Sonar Systems, which listen for sound signals emitted by other sources, like submarines or marine life. Their sensitivity allows for effective long-range detection and monitoring.

SONAR IMAGING

Sonar systems equipped with arrays of piezoelectric transducers can create sonar images of underwater environments using a technique called side-scan sonar. By controlling the timing and amplitude of signals sent to different transducers, the system can focus on specific areas and generate detailed images of the seafloor or underwater structures. The reflected sound signals are then analysed to produce visual representations of the underwater terrain, aiding in underwater exploration and mapping.

NAVIGATION AND MAPPING

Piezoelectric sensors are crucial for underwater navigation and mapping applications. By emitting acoustic waves and measuring the time it takes for them to return after reflecting off underwater objects or the seabed, Sonar Systems can determine distances and depths with great precision. This data is used for safe navigation, obstacle avoidance, and mapping underwater terrains, which is especially essential for maritime operations and research.

FUTURE OF PIEZOELECTRIC MATERIALS AND SONAR TECHNOLOGY

• As we look to the future, there is no doubt that piezoelectric materials and sonar technology will continue to play a critical role in many industries. With ongoing research and development, we can expect to see even more innovative applications of these materials in the years ahead.

• One exciting area of potential growth is in the use of piezoelectric materials in energy harvesting. These materials have the ability to convert mechanical energy into electrical energy, making them ideal for use in renewable energy systems. In the coming years, we may see piezoelectric materials being used to power everything from wearable devices to entire buildings.

Application of Piezoelectric Materials in Automobile Industry
As today’s vehicles incorporate more and more sophisticated sensing technology. Industrial piezoelectric components are becoming increasingly important to manufacturers. In fact, the automotive Industry is currently the second-largest market for piezoelectric ceramic products.

Types of Piezoelectric materials Used:
Piezoelectric materials find dual applications in the automotive sector, manifesting both direct and indirect roles, each exerting a substantial influence on the manufacturing and functioning of automobiles. However, these two applications exhibit notable distinctions in their utilization.
Direct: Incorporated within vehicles for a multitude of purposes, directly utilized piezoelectric materials serve as versatile components. They serve as actuators, injectors, and sensors, facilitating control, adjustment, and monitoring of diverse systems. These materials enable precise, dependable manipulation, maintaining consistency and precision even after enduring billions of operational cycles.
Indirect: In the automotive sector, piezoelectric materials find application in a variety of indirect capacities, such as their utilization in machinery and robotics for tasks related to vehicle design, production, and testing.

Applications in Automobile industry:
Car Actuators: Piezoelectric automotive actuators are integral to various vehicle components, serving as a crucial mechanism for translating electrical signals into precise physical motions. They excel in tasks such as fine-tuning lenses, adjusting mirrors, and controlling various components. Additionally, they can function as a compact volume pump or initiate hydraulic valve actions. Piezo-based automotive actuators are indispensable in applications that demand simplicity and dependability. Furthermore, they offer the advantage of being maintenance-free and capable of enduring billions of operational cycles without suffering from wear or degradation.

Fuel Injectors: Incorporating piezoelectric technology in fuel injectors is reputed to enhance precision compared to traditional counterparts. By harnessing piezoelectric components, the fuel injector's pintle can achieve faster and more precise opening and closing motions, leading to a finely controlled fuel spray. Extensive research has demonstrated that the adoption of piezo technology yields superior fuel efficiency and reduced emissions.

Piezoelectric Sensors: In the realm of automotive technology, sensors represent a crucial category of piezoelectric products, serving diverse functions across various applications. These sensors exhibit the capacity to convert external stimuli such as pressure or acceleration into electrical signals, which in turn convey essential data to a vehicle's onboard computer system. Noteworthy instances of these sensors encompass piezoelectric tire pressure sensors, engine knock sensors, and a plethora of other safety features that have become integral components of contemporary automobiles.

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APPLICATIONS OF PIEZOELECTRIC MATERIALS IN AEROSPACE

Introduction :- In recent years, space exploration has made large strides in the implementation of piezo sensors and piezo actuators in aerospace applications.

Operating and data gathering in space presents an array of difficulties in an uncontrollable environment; however, piezoelectric sensors are favoured for their immediate response time and low power consumption. Here we will discuss some of its applications.

1. **Micro-thruster for Satellite:-** Piezos are used in micro-thruster for satellites in many ways.Piezoelectric materials are used to generate thrust through piezoelectric effect which is used to position and stabilize the satellite. Piezoelectric micro-thruster can provide precise control over a satellite's attitude (orientation) in space.

Working:- Micro thruster can use different technologies such as when a voltage is applied to a piezoelectric material it deforms creating mechanical vibrations and oscillations and these oscillations can be used to expel propellant to produce thrust, making them suitable for micro thrusters the technology cold - gas micro thrusters used to generate a very small and controlled force by expelling a jet Nitrogen gas stored in a high pressure tank, piezo actuators integrated into valves can ensure both an accurate control of the pressure of the propellant and fast and precise dispensing.

Piezo Material used for micro-thruster for satellite:-The material used for micro-thruster in satellite are often called piezoelectric actuators or piezo stacks. The materials that can be used for micro thrusters in satellites are PZT which offers good piezoelectric properties making it suitable for precise and controlled movements. PVDF (polyvinylidene fluoride) its flexibility and low mass can be advantageous for satellite applications. Ferroelectric single crystals can be considered for specialised satellite micro-thrusters design.

2. **Active vibration Damping :-** Piezoelectric materials can be used for active vibrations damping in mechanical structures to reduce vibrations and oscillations which are undesirable . It is used to reduce noise, power and fuel consumption. Recently the reduction of sound level in helicopters has drawn a great interest while this technology can be applied to other areas such as planes, wind turbines, motor machine tools, laboratory tables etc.

Working:- There are two methods of damping the undesired vibrations and oscillations: the first one is passive vibrations damping and second is active vibrations damping. In the first method of vibrations damping, vibrations are converted into electrical energy by the help piezo effect and then stored or dissipated into heat for example by means of resistors. While in the second method the piezo actuators are used to generate a counter loop, it actively dampens the vibrations by introducing forces that counteract the structural motion. It is a more preferable method, however it requires power and a complex controller.

Piezo Material used for Active vibration Damping:- Active vibrations damping in the aerospace sector usually focuses on high amplitude, low frequency vibrations, which require powerful large stroke actuator, Lead Zirconate Titanate (PZT) and other similar ceramic materials are used because they can actively generate forces to counteract vibrations in aircraft and other aerospace structures. Stakes multilayer piezoelectric actuators are preferred for their high strain and are often integrated in amplifying structures.

2.1. Application of piezoelectric material for Aircraft propeller blades vibrations damping:- Piezoelectric materials can be used for aircraft propeller blades vibrations damping through an active vibrations control system.

Piezoelectric materials used as sensors are attached to the propeller blades or to the surrounding structure to detect vibrations and dynamic forces generated during the operation of the propeller. Based on the analysis of vibration data the controlling system sends messages to actuators placed on propeller blades.

The piezoelectric actuators exert forces on the propeller blades to counteract the vibrations by adjusting timing and magnitude of the external forces. Using these materials we can minimize vibrations and contribute to a smoother and quieter flight experience for crew.

Active vibration control can adapt to changing conditions, optimizing propeller performance throughout the flight.

3. Structural Health Monitoring:- Piezoelectric materials have found widespread application in structural health monitoring . This is highly relevant where safety is a very important issue. The continuous monitoring also holds an obvious financial advantage to traditional inspection, for example an airplane that requires a planned interruption of service and even a dismantling of selected parts.

Working:- Piezoelectric material, often in the form of piezoelectric transducers or sensors, are attached to or embedded within a structure. When the structure undergoes mechanical vibrations or deformations, these sensors generate electrical charges in response to mechanical strain. This electrical signal can be used to monitor the structural integrity and health.

SHM can be Active or Passive. A passive system only “listens” to eventual noise. The Active system generates a sound wave in the material. There are different methods for active SHM, the most common ways to analyse the transmission between two transducers or to listen to the reflected sound. The detection localisation, characterization and assessment of flaws, requires complex signal processing and analysis.

Piezo Material used for Structural health monitoring:- SHM applications are typically constructed with monolayer piezo transducers providing low power, high sensitivity and wide frequency range. Lead Zirconate Titanate (PZT) is commonly used for SHM. It is favoured because it has ability to generate and detect ultrasonic waves, making it valuable for monitoring the integrity of aircraft structures by analysing change in wave propagation caused by structural damage or defects.

Applications of Piezoelectric Materials in Various Defense Equipments

Piezoelectric materials have several important applications in the defense industry due to their unique properties. Piezoelectric materials exhibit the piezoelectric effect, which means they can generate an electric charge when subjected to mechanical stress or, conversely, undergo mechanical deformation when exposed to an electric field. These materials have proven to be valuable in various defense-related technologies. Here are some notable uses of piezoelectric materials in defense:
1.Smart Combat Suit
2.Sonar Systems
3.Acoustic Sensors
4.Energy Harvesting
5.Shock and Impact Sensors
6.Unmanned Aerial Vehicles (UAVs)
7.Acoustic Weapons
8.Underwater Communication
9.Smart Munitions
10.Shockwave Generation
11.Airbag initiation
12.Pyroelectric Infrared Sensors

Smart Combat Suit
A smart combat suit, also known as an intelligent or high-tech combat suit, integrates advanced technologies to enhance the capabilities and survivability of military personnel. Piezoelectric materials can be utilized in various ways within a smart combat suit to provide additional functionalities and advantages. Here are some potential applications:

1. Energy harvesting: Piezoelectric materials can be integrated into the fabric of the combat suit to capture and convert mechanical vibrations generated during movement into electrical energy. This harvested energy can then be used to power various electronic components of the suit, such as sensors, communication devices, or even small displays, reducing the reliance on external power sources and extending the operational duration of the suit.

2. Body motion sensors: Piezoelectric sensors can be strategically placed on the suit to detect and measure the wearer's movements and biomechanics. This data can be used for real-time monitoring of the soldier's physical condition, tracking fatigue levels, and providing valuable insights into their health and well-being during missions.

3. Impact detection: By incorporating piezoelectric impact sensors into critical areas of the suit, it can record impacts from projectiles or other objects. This data can be crucial for post-mission analysis, injury assessment, and performance evaluation.

4. Active camouflage: Piezoelectric materials can be utilized in smart camouflage systems to actively change the suit's appearance and blend it with the surroundings. By applying an electric field to the piezoelectric elements in the camouflage fabric, the suit's color or pattern can adapt to match the environment, providing effective concealment.

5. Vibration damping: In combat situations where soldiers may encounter intense vibrations, such as during vehicle rides or explosions, piezoelectric materials can be used to dampen these vibrations and reduce the impact on the wearer's body, increasing comfort and potentially preventing injuries.

6. Communication systems: Piezoelectric transducers can be integrated into the helmet or collar of the combat suit to serve as bone conduction speakers. Bone conduction technology allows for clear communication while keeping the wearer's ears free to listen for external sounds, making it easier to maintain situational awareness.

7. Health monitoring: Piezoelectric sensors can measure vital signs such as heart rate, respiratory rate, and body temperature. The data collected can be sent to a central monitoring system, providing real-time health updates for each soldier in the field. This can be particularly crucial for identifying injuries or health issues early on.

Mechanism of smart combat suit for energy harvesting-
The basic concept involves converting the mechanical energy generated during the soldier's movement into electrical energy, which can be used to power various electronic components of the suit. Here's how the mechanism works:

1. Integration of Piezoelectric Materials: Piezoelectric materials, such as certain ceramics, crystals, or polymers, are embedded or integrated into the fabric or structure of the combat suit in strategic locations. These locations are chosen based on areas of the suit that experience frequent mechanical vibrations or deformations during the soldier's movements.

2. Mechanical Stress Generation: As the soldier moves, the combat suit's fabric experiences mechanical stress, deformations, and vibrations. For instance, during walking, running, or even breathing, the fabric of the suit undergoes these mechanical movements.

3. Piezoelectric Effect: When subjected to mechanical stress or vibrations, the embedded piezoelectric materials generate electric charge across their surfaces. This is a result of the piezoelectric effect, which causes the crystal structure of the material to produce a voltage in response to mechanical deformation.

4. Energy Conversion: The generated electric charge from the piezoelectric materials is in the form of small electrical signals. However, these signals can be collected and aggregated to form usable electrical power.

5. Energy Storage and Utilization: The harvested electrical energy is typically stored in batteries or capacitors within the smart combat suit. These energy storage components ensure that the energy can be stored and utilized as needed, even when the soldier is not in continuous motion.

6. Powering Electronics: The harvested energy can be used to power various electronic components integrated into the combat suit. These components may include sensors, communication devices, heads-up displays, health monitoring systems, or any other electronic gadgets that enhance the suit's functionality and the soldier's situational awareness.

Mechanism of Body Motion Sensors using Piezoelectric Materials:

1.Piezoelectric Material Integration: Piezoelectric materials are strategically integrated into specific areas of the combat suit where motion data needs to be captured. These materials are flexible and can be embedded into the fabric without significantly affecting the overall flexibility and comfort of the suit.

2.Deformation during Motion: When the wearer moves, the deformation and mechanical stress applied to the piezoelectric materials change. This occurs because the piezoelectric elements in the suit experience strains and stresses as the fabric stretches or contracts during different movements.

3.Generation of Electrical Signals: The mechanical stress applied to the piezoelectric material causes a separation of positive and negative charges within the material. This separation generates an electric charge, creating an electrical signal across the material.

4.Signal Processing: The electrical signals generated by the piezoelectric materials are collected by sensors or conductive pathways integrated into the smart combat suit. These signals carry information about the wearer's movement patterns and biomechanics.
5.Data Interpretation: The collected electrical signals are then processed and analyzed by electronic components within the combat suit. Signal processing algorithms interpret the data to extract meaningful information about the wearer's movements.

6.Motion Monitoring: The processed data allows the smart combat suit to monitor and track the soldier's motion in real-time. The suit can detect various activities such as running, walking, crawling, or specific gestures.

7.Health and Performance Insights: By continuously monitoring the wearer's body motion, the combat suit can provide valuable insights into the soldier's health and physical condition. It can track fatigue levels, detect unusual or irregular movement patterns, and assess potential injuries or overexertion.

8.Integration with Systems: The data from the body motion sensors can be integrated with other components of the smart combat suit. For example, the suit's heads-up display (HUD) could show real-time movement data or health status to the soldier, providing them with important feedback during missions.

Active Camouflage

The key components involved in the mechanism of active camouflage using piezoelectric materials are:
1.Piezoelectric materials
2.Camouflage fabric
3.Power source and control circuitry

Here's how the mechanism works:
1.Sensing the environment: The combat suit's active camouflage system utilizes sensors, such as cameras or other types of environmental sensors, to detect the color and pattern of the surrounding environment. These sensors collect data about the background, including the colors and textures of the terrain, vegetation, or structures.

2.Signal processing: The data collected by the sensors are processed by the control circuitry. Advanced algorithms analyze the information to determine the optimal camouflage pattern that the combat suit should adopt.

3.Electric field generation: Based on the analyzed data, the control circuitry determines the required pattern and color changes for the piezoelectric elements in the camouflage fabric. It then applies an electric field to these elements, causing them to change shape or deform accordingly.

4.Changing camouflage: The deformation of the piezoelectric elements in the fabric results in a change in the suit's appearance. The surface of the fabric may shift its colors and patterns to match the background, effectively blending the wearer with the environment.

Unmanned Aerial Vehicles (UAVs): commonly known as drones, have various components that enable their functionality. While piezoelectric materials can be incorporated into UAVs, they are usually used for specific purposes and not for the primary propulsion or control mechanisms. Here's how piezoelectric materials can be integrated into UAVs:

1.Energy Harvesting: Piezoelectric materials can convert mechanical vibrations or deformations into electrical energy. In UAVs, they can be placed in areas where there are dynamic forces, such as the wings or the body, to harvest energy from vibrations caused by flight or turbulence. This harvested energy can be used to power low-energy components such as sensors, communication systems, or even recharge the UAVs batteries.

2.Vibration Damping: Piezoelectric materials can also act as vibration dampers by absorbing and converting mechanical vibrations into electrical energy. This helps reduce vibrations that might affect the stability or performance of the UAV, contributing to smoother flight.

3.Structural Health Monitoring: Piezoelectric materials can be integrated into the structure of the UAV to act as sensors. They can detect stress, strain, and other mechanical parameters by measuring changes in electrical output due to deformation. This information can be used for real-time structural health monitoring, helping to detect potential failures or damages early.

4.Aerodynamic Control: While not commonly used for primary propulsion, piezoelectric materials can be used to induce small changes in the shape of certain components, such as wings or control surfaces. By applying voltage to the piezoelectric actuators, these components can undergo controlled deformations, enabling fine adjustments in flight control and aerodynamics.

5.Communication and Sensing: Piezoelectric materials can also be used for acoustic and ultrasonic sensing. By sending and receiving acoustic waves, UAVs can detect obstacles, measure distances, and gather environmental data. This can be particularly useful for applications like terrain mapping or search and rescue missions.
6. Autonomous Landing and Perching: Piezoelectric materials can be used to enable certain autonomous landing or perching capabilities. By generating controlled vibrations, the UAV can effectively attach itself to a surface, facilitating stable landings on challenging terrain.

Acoustic weapons- also known as sonic weapons or sound weapons, are devices that use sound waves to harm, incapacitate, or deter individuals or groups. The concept of using sound as a weapon is not new, but it's important to note that the development and use of such weapons raise significant ethical and humanitarian concerns. Piezoelectric materials can potentially play a role in the creation of acoustic weapons, though the use of such materials in this context is controversial and subject to international regulations.
Here's how piezoelectric materials could be incorporated into the mechanisms of acoustic weapons:

1.Sound Generation: Piezoelectric materials can be used to generate high frequency sound waves. When a piezoelectric material is subjected to an electric field, it undergoes mechanical deformation, which can create pressure waves in the surrounding air. By rapidly changing the electric field applied to the material, it's possible to generate sound waves at specific frequencies.

2.Directional Sound Emission: Piezoelectric transducers can be designed to emit sound waves in specific directions. This can be achieved through the arrangement of multiple transducers or by using specialized acoustic waveguides. By focusing sound in a particular direction, the weapon's effectiveness can be enhanced.

3.Variable Frequencies: Different frequencies of sound can have varying effects on humans and animals. For instance, certain frequencies can cause discomfort, pain, nausea, or disorientation. Piezoelectric materials can be used to produce a range of frequencies, allowing the weapon operator to select frequencies that elicit the desired physiological response.

4.Non-Lethal Applications: Acoustic weapons using piezoelectric materials have been proposed for non-lethal crowd control and perimeter security. The intense sound waves can create discomfort, pain, or disorientation, potentially deterring individuals from entering a restricted area.

5.Long-Range Capabilities: Piezoelectric-based acoustic weapons could potentially produce sound waves that travel over long distances. This could be useful for creating acoustic barriers or zones where access is restricted due to the discomfort caused by the sound waves. It's important to emphasize that the use of acoustic weapons, especially those causing pain or harm, raises serious ethical concerns.

These weapons have the potential to cause physical and psychological harm, and their use may violate international human rights standards and conventions Overall, while piezoelectric materials can be used in the generation of sound waves for various applications, the use of such technology for acoustic weapons requires careful consideration of the potential harm they can cause and adherence to international legal and ethical standards.

CONCLUSION

The variety of applications for piezoelectric materials in the biomedical industry is promising, however much of this technology is still in the research and development phase. They seem to have a certain developing future. Before reaching the market, these devices need to have scalable manufacturing and guaranteed quality for every device.

The automotive industry's increasing reliance on piezoelectric materials, both directly and indirectly, underscores their pivotal role in shaping the design, functionality, and performance of contemporary automobiles. These versatile materials have revolutionized key components and systems, contributing to enhanced precision, efficiency, and sustainability in the automotive sector.

We can strongly say that piezoelectric materials have several important applications in the aerospace industry due to their ability to convert mechanical stress into electrical voltage and vice versa . Piezoelectric materials are used in sensors and transducers for spacecraft and space probes. Because of their extreme quality to withstand any condition of space and to provide critical data for navigation and scientific experiments they are highly recommendable.

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