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Faculty of Mechanical Engineering

Study of Energy Harvesting Capabilities using Piezo-Electric Components of Different Geometries

Master Thesis

Study programme: N2301 Mechanical Engineering
Study branch: Machines and Equipment Design

Author: **Mustafa Halis Ozkaptan**
Thesis Supervisors: prof. Ing. Karel Fraňa, Ph.D.
Department of Power Engineering Equipment

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Zadání diplomové práce

Study of Energy Harvesting Capabilities using Piezo-Electric Components of Different Geometries

Jméno a příjmení:	**Mustafa Halis Ozkaptan**
Osobní číslo:	S18000454
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Studijní obor:	Machines and Equipment Design
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Zásady pro vypracování:

Piezo-Electric materials is a class of smart materials that can produce electric charges in response to applied mechanical pressure and vice-versa. This phenomenon has found applications in the field of acoustic energy harvesting.

1. Introduction of the various materials which can be used for energy harvesting from energy source such as vibration or acoustics type energy.
2. A study the effect of geometry of the piezo-electric component on the efficiency of energy harvesting process.
3. Experimental measurement of electric energy harvested from piezo components of different geometries. (Flate Plate-Cylinder-Bending Element).
4. Analysis of experimental results.
5. Accuracy of the measurement, measurement if the acoustics resources.

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Seznam odborné literatury:

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2. KANG, Min-Gyu, Woo-Suk JUNG, Chong-Yun KANG a Seok-Jin YOON, Recent Progress on PZT Based Piezoelectric Energy, 2016
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Vedoucí práce:	prof. Ing. Karel Fraňa, Ph.D. Katedra energetických zařízení
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prof. Dr. Ing. Petr Lenfeld
děkan

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doc. Ing. Petra Dančová, Ph.D.
vedoucí katedry

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To my Family…

Acknowledgement

I would like to express my gratitude to my supervisor, **Prof. Ing. Karel Frana Ph.D.** for his guidance during this work. I would like to express my gratitude to **Mr. Ing Shehab Ashraf Salem**, who always supports me in laboratory studies and my thesis process. I would also like to express my gratitude to all my teachers, who supported me throughout my education. Finally, I would like to thank my family and my dear wife, **Şenel Etingü ÖZKAPTAN**

ABSTRACT

This study is about the research and development of mechanical vibration obtained from sound waves, obtaining energy with ambient energy in an acoustic sense. Piezoelectric material has been used to generate electrical energy. In order to create mechanical vibration, the sound is produced from the speaker, the sound produced is induced on a piezoelectric material, the frequency of the sound is propagated as a sinus wave, and the results are examined on the computer. The experiment series is then carried out by the piezoelectric transducer. The piezoelectric transducer passes through the full rectifier circuit; the results are measured with a voltmeter and oscilloscope. Experiment from three cases is studied, in different geometries; in other words, by keeping the position of a piezoelectric transducer constant, is evaluating the effect of distance and temperature changes.

Keywords: Piezoelectric, Acoustic, Frequency, Sinus wave.

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List of Variables and Abbreviations

PVDF = Polyvinylidene fluoride

PZT ($PbZrO_3$) = Lead zirconium titanate

MHW = Mass acoustic waves

SAW = Surface acoustic waves

F = Force

˚C = Celsius

˚K = Kelvin

cm = Centimetr

mm = Milimetr

Ø = Diameter

λ =Lambda

φ = Maximum power angle

V = Volt

mV = Milivolt

AC = Alternating current

DC = Direct current

Hz = Hertz

kHz = Kilohertz

MEMS= Micro electro Mechanical System

$d_{i\lambda}$ = Piezoelektric material coefficient

$S_{\lambda\mu}$ = High mechanical stiffness

Li = Lithium

Al = Aluminium

Mg = Magnesium

Ti = Titanium

Na = Sodium

$BaTiO_3$ = Barium titanate

TiO_2 = Titanium dioxide

MgO = Magnesium Oxide

CaO = Calcium oxide

SrO = Strontium oxide

BaO = Barium oxide

$CaTiO_3$ = Calcium titanate

$SrTiO_3$ = Strontium titanate

$PbTiO_3$ = Lead titanate

Fe_2O_3 = Iron (III) oxide

$CaCO_3$ = Calcium carbonate

NaCl = Sodium chloride

CO_2 = Carbon dioxide

CHAPTER 1

1. Principle of Piezoelectricity

1.1. Discover of Piezoelectric

The name "Piezo" means "to press" from Greek; in more contemporary terminology, we say that the effect confuses electric and elastic phenomena. Explore by Curie brothers [1], the piezoelectricity quickly grew as a new field of investigative in the last quarter of the nineteenth century. In 1880, Pierre and Jacques Curie found that in zinc blende, some materials such as topaz and quartz, mechanical voltages were accompanied by the production of macroscopic polarization and, therefore electrical surface charges. The piezoelectric was discovered by the Curie, Pierre (1859–1906) and Jacques (1855–1941), brothers in 1880. In their experiment, positive and negative charges were observed on the surface of the crystals compressed in certain directions. These loads are proportional to pressure and have observed that when pressure is terminated, it returns to its original state. It was not discovered as a result of luck. It was found as a result of Pierre Curie's earlier work on pyro electricity and symmetry of crystals. He discovered that polar electricity is produced only in a certain direction depending on the symmetry of certain crystal classes. There is a close relationship between piezoelectric effect and the pyroelectric effect. The relationship between pyroelectric and piezoelectric is fundamental. All pyroelectric materials are inherently piezoelectric. We now know that pyroelectric materials form a subset of piezoelectric materials. The words "piezo" and "pyro" mean "pressing" and "fire" in Greek, respectively. [2].The following year, Lippmann [3] predicted the reverse effect through his experimental work: a voltage loaded on the material causes mechanical deformation or forces the material. The piezoelectric effect kept a concern until the early 1920s, when its asset in quartz was used to perform crystal resonators for the stabilization of oscillators, thus to begin the field of frequency control [4]. With quartz control, humankind expanded the areas of piezoelectric applications and devices by producing piezoelectric materials. These expanded areas were sonar, hydrophone, microphones, piezo-ignition systems, accelerometers and ultrasonic transducers. After the discovery of piezoelectric effect in polyvinylidene fluoride (PVDF) polymer by Kawai in 1969 [5], mechanical flexibility added many applications. Today, piezoelectric has brought innovation in many areas.

These areas,

- Aviation applications of flexible surfaces
- sensors we use in many places
- sports equipment to reduce vibration (tennis racquets and snowboards)

1.2. Direct and Reverse Piezoelectric Effect

The piezoelectric effect is, as shown in Figure 1.1. Electricity generation occurs as a result of the force applied to the material.

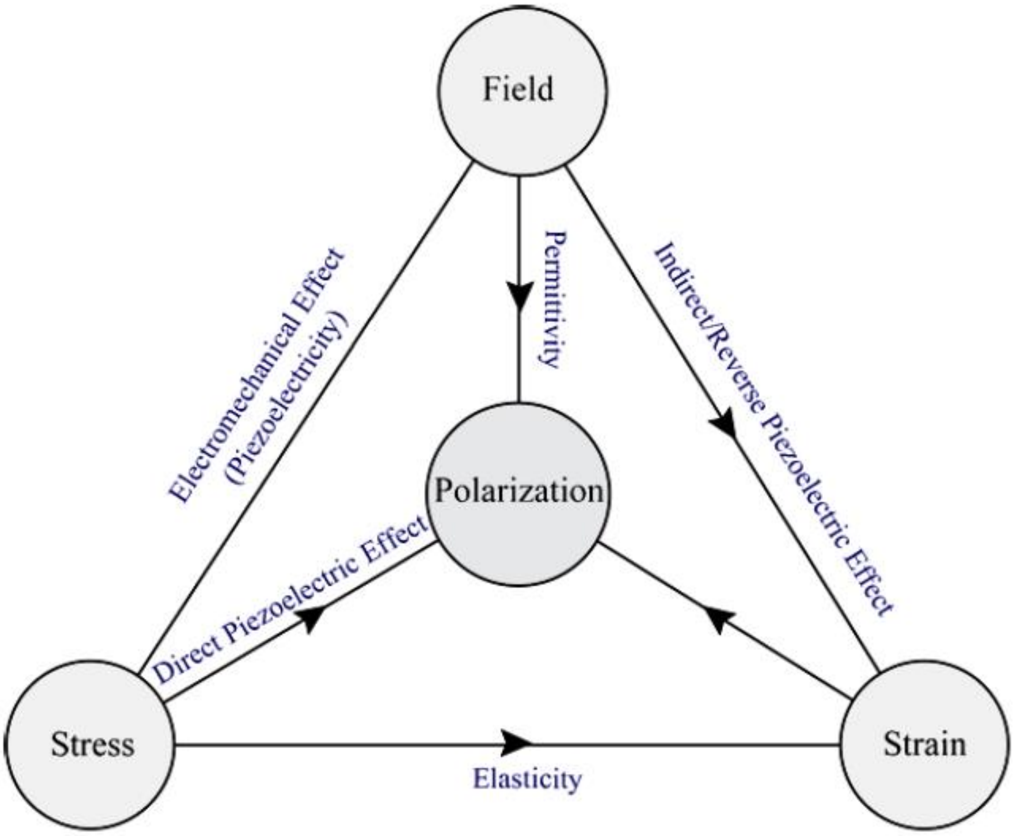


Figure 1.1: Piezoelectricity—an intermingling of electric and elastic phenomena

Before exposing the material to external stress, the negative and positive charges of each molecule coincide - leading to an electrically neutral molecule, as indicated in 1.2 (a). However, in the presence of external mechanical tension, the internal reticular can be deformed so that the positive and negative centers of the molecule are separated and small dipoles are produced as shown in Figure 1.2 (b). As a result, the opposite poles of the material cancel each other out, and constant loads appear on the surface. This is shown in

Figure 1.2 (c). Namely, the material is polarized and this effect is called direct piezoelectric. This situation creates an electric field that can be used after converting mechanical energy into electrical energy as a result of the deformation of the material.

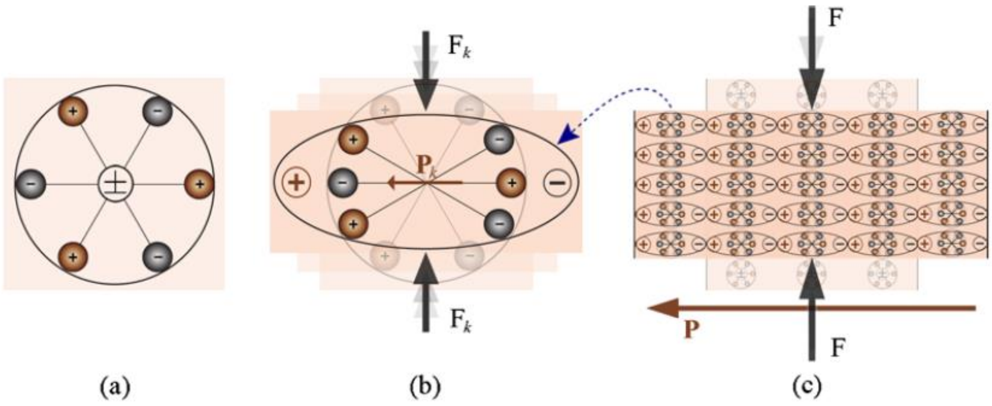


Figure 1.2 Piezoelectric effect explained with a simple molecular model: (a) An unperturbed molecule with no piezoelectric polarization (though prior electric polarization may exist); (b) The molecule subjected to an external force (Fk), resulting into polarization (Pk) as indicated; (c) The polarizing effect on the surface when piezoelectric material is subjected to an external force

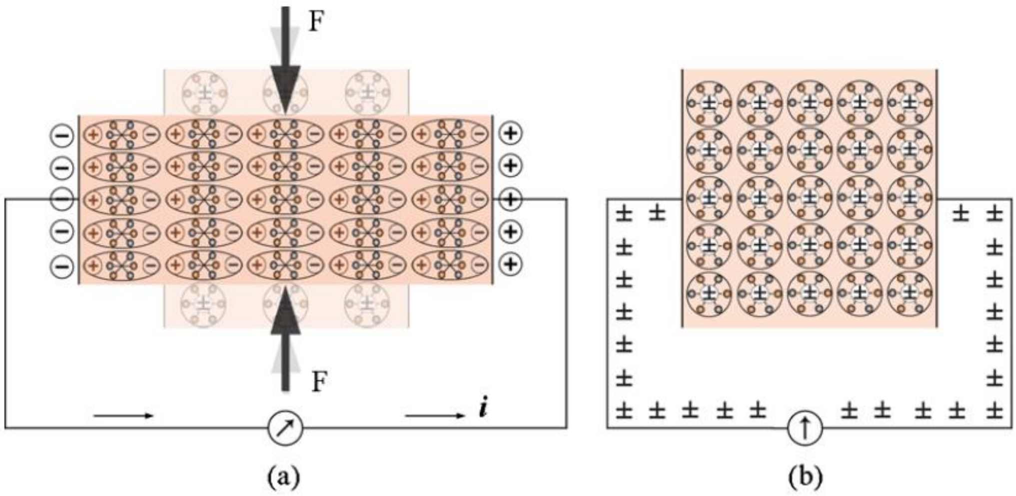


Figure 1.3: Piezoelectric phenomenon: (a) The neutralizing current flow when two terminal of piezoelectric material, subjected to external force, are short circuited; (b) The absence of any current through the short-circuit when material is in an unperturbed state

Figure 1.3 (a) shows two metal electrode-piezoelectric materials deposited on opposite surfaces. Electrodes short-circuit externally with a galvanometer connected to the short circuit wire and if force is applied to the surface of the piezoelectric material, a constant charge density is created on the surfaces of the crystal electrodes that come into contact with the electrodes. This polarization creates an electric field that causes the flow of free charges that form a conductor field. Depending on their markings, the free loads will move to the ends where the fixed loads produced by polarization are the opposite sign. This free load flow continues until the free load neutralizes the polarization effect, as shown in Figure 1.3 (a). This means that no load flows in steady or intact state, regardless of the presence of external force. When the force on the material is removed, the polarization also disappears, the flow of free loads reverses, and finally the material returns to the original stopping state indicated in Figure 1.3 (b). This process will be displayed on the galvanometer, pointing to two opposite signs current peak. If the short-circuit wire was replaced with a resistance / load, it flows through the current and the mechanical energy is converted into electrical energy. This scheme is the basis for various energy harvesting techniques that touch mechanical energy such as vibrations [6] and transform it into usable electrical form.

Some materials also have an inverse piezoelectric effect, i.e., when a voltage is applied across the electrodes, mechanical deformation or strain occurs in the material. The strain produced in this way can be used, for example, to displace a combined mechanical load. This way of converting electrical energy into usable mechanical energy is essential for applications such as Nano-positioning devices.

1.3. Applications of Piezoelectric

The practical application of piezoelectricity went ahead at an irregular speed. Slow progression periods were replaced by rapid development. The first third of the time elapsed since the discovery of piezoelectric materials is quite limited. In "Oeuvres" Pierre and Jacques Curie describe several piezoelectric devices designed for static measurements of various parameters. Piezoelectric makes it possible to convert electricity into acoustic signals. Using piezoelectric crystal, it is possible to produce the required amount of electrical charge very accurately. This is necessary in the construction of sensitive electrometers. This kind of devices have used for measurement of capacitance, voltage, pyroelectric and piezoelectric effects, and radioactivity measurements.

In 1917, the National Research Council sponsored a conference moderated by Robert A. Millikan. W. G. Cady was invited for his interest in detecting submarines by ultrasonic waves. Paul Langevin reported that ultrasonic waves were produced through transducers using quartz and steel sandwiches. This device, called Langevin's transducer, is a unique piezoelectric application in ultrasonic engineering. He used both direct and reverse piezoelectric effects of a large quartz plate to emit underwater sound waves first and then detect. This device opened the doors of the ultrasonic and hydroacoustic field. Sonar exists thanks to Paul Langevin.

The conference convinced Cady to turn his interest into piezoelectricity. In 1919, Cady launched the resonators study, and the first report on the piezoelectric resonator was presented to the American Physical Society in 1921. He recommended the piezoelectric quartz resonator as a frequency standard or filter. Cady showed how to connect a resonant quartz crystal to an electric oscillator and thereby achieve frequency stability. Studies on the characteristics of the crystal resonator, represented by the equivalent electrical circuit, were done by Butterworth, Boya, Van Dyke and Mason. They provided a better understanding of the crystal resonators used in filters and oscillators. The next important step is linked to the development of publishing. Quartz crystal oscillators were first used as frequency standards by the US National Bureau of Standards. For the first time a quartz oscillator was used to stabilize the frequency of a transmitter around 1926. The father of modern piezoelectricity is considered Cady. (Cady 1964). He died the day before his 100th birthday (Lang 1975). [2].

Piezoelectric materials have benefited humanity in many areas from past to present. These areas have been both beneficial and harmful to humanity. When we examine the historical process of human beings, piezoelectric materials started to be developed further with the start of the First World War. In this war, piezoelectric materials were developed and used in many areas. After the war, some scientists accelerated the development of piezoelectric materials and developed some materials for use in the Second World War or discovered a new piezoelectric material.

Piezoelectric materials, parking sensors, lighting and even some night clubs, which are in the military and social life today, have benefited from generating this material on the ground and producing their own electricity. Piezoelectric materials, which direct scientific studies, some devices have designed to facilitate scientific studies. As a result of using these devices in scientific studies, it has been provided to progress more quickly and reliably.

Piezoelectric devices are used in the following areas: Measurement of pressure, measurement of vibrations, stress gauge, strain gauge and measurement of acceleration, impact detector and position sensors. There are a wide variety of material types and shapes that are actively piezoelectric. Many have the ability to convert mechanical forcing into electrical load when used as a sensor and reversing when used as an actuator. Studies on piezoelectric semiconductors, nonlinear effects and surface waves have led to the construction of useful devices. More examples of this type can be given.

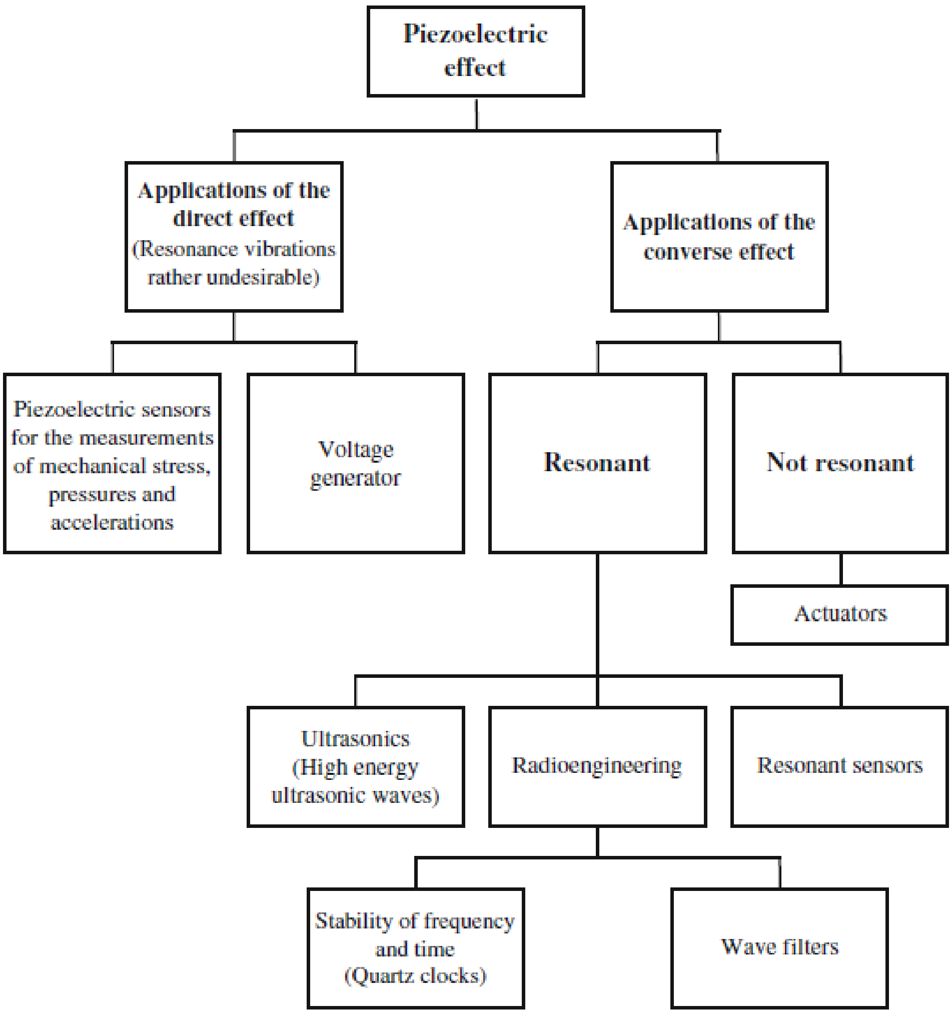
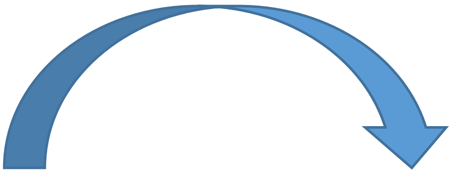


Figure 1.4: Technical applications of piezoelectricity

1.3.1. Applications of the Direct Effect

Applications of direct piezoelectric effect can be distinguished by electrical energy or an output by an electrical signal. An overview of such applications is given in Table 1.1. [7]



electro-mechanical transducers: - switches, keys - sensors
sound and ultrasound transducers: - microphones
high voltage generators: - igniters - cigarette / gas lighters

Table 1.1: Overview of applications of the direct piezoelectric effect

1.3.1.1. Gas lighter (output: electric energy)

The best known application of direct piezoelectric effect is probably a cigarette or gas lighter, where a force application induces an electrical voltage across a piece of piezoelectric material and then causes an electric spark to ignite the gas. This is an example of the direct piezoelectric effect used to produce electrical energy (converted from mechanical energy). [7]

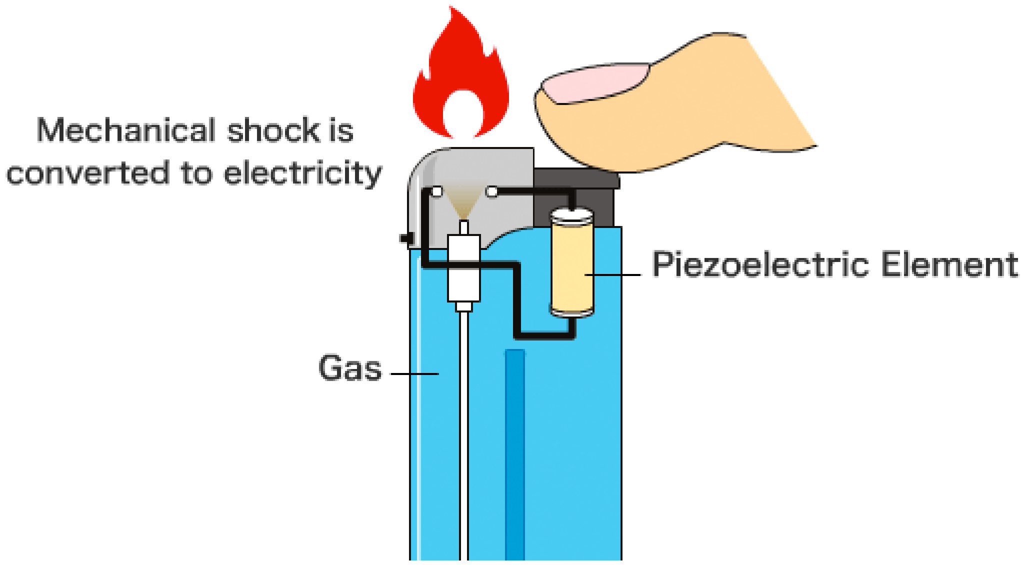


Figure 1.5: Piezoelectric gas lighter

1.3.1.2. Electronic pick-up (output: electric signal)

The direct piezoelectric effect is also used in piezoelectric sensors to produce an electrical signal representing information from or collected from the mechanical field. The first application is in the collector part of early electronic phonographs (Figure 1.6). Here the mechanical movement of the needle in the grooves of the (vinyl) record created a stress with the piezoelectric component, which induced an electrical voltage that can be further processed and converted into music or other types of sound. [7]

Figure 1.6: Phonograph

1.3.1.3. Airbag sensor (output: electric signal)

Another example is the automotive industry airbag acceleration sensor, which can also be made of piezoelectric material. In a car accident, the sensor detects a sudden slowdown and sends a trigger to inflate the bag car. All within one second. [7]

Figure 1.7: Piezoelectric acceleration sensor

1.3.2. Applications of the inverse effect

Applications of the inverse piezoelectric effect can be heard from DC and can even be distinguished by the desired output with power or deformation or motion or vibration ranging from ultrasound frequencies. An overview of such applications is given in Table 1.2. [7]

electro-mechanical transducers: - motors - actuators
sound and ultrasound transducers: - loud speakers / buzzers - cleaning / welding / drilling
resonators: - vibration generators

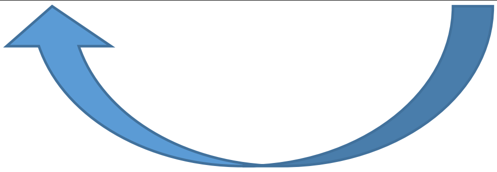


Table 1.2: Overview of applications of the inverse piezoelectric effect

1.3.2.1. Position actuator (output: deformation)

The inverse effect allows it to be used as a position actuator in piezoelectric material. Operation is typically limited to a few microns, but with practically limitless resolution and bandwidth up to a few kHz, e.g. for use in atomic force microscopy.

With the special design of the piezoelectric actuator or surrounding mechanical structure, effective stroke can be enlarged. The application, called piezoelectric benders, provides a stroke in the range [mm], it can find application in Braille keyboards. [7]

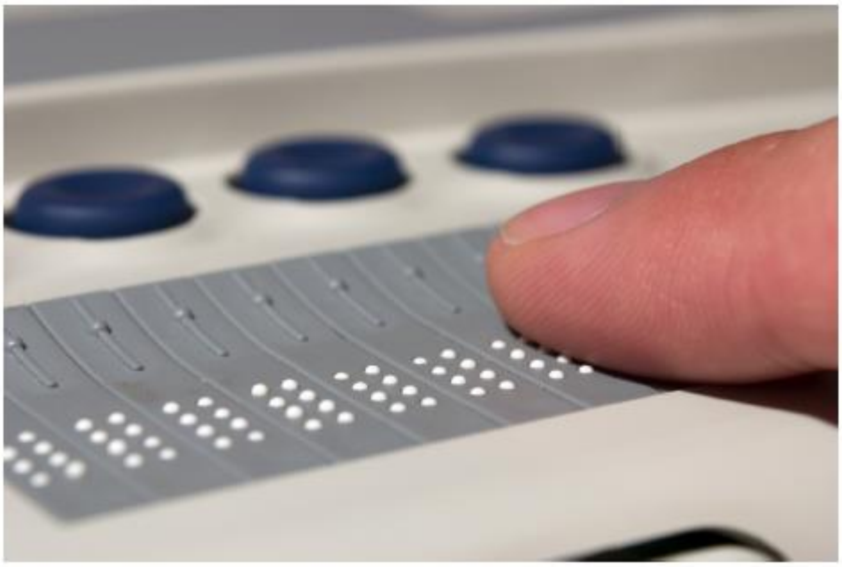


Figure 1.8: Braille keyboard based on piezoelectric bending actuators

1.3.2.2. *Acoustic transducers (output: sound or ultrasound)*

With the appropriate mechanical design, piezoelectric materials can also be used for acoustic 'actuation' converters. Such examples are sonic transducers for audio stimuli. In liquid ambiences, ultrasonic (or ultrasound) transducers are used for applications such as cleaning, mixing and emulsification. Another application is ultrasonic source. [7]

Figure 1.9: Piezoelectric transducer for ultrasonic cleaning

1.3.3. Applications of the combined effect

In addition to the above-mentioned applications of direct or inverse piezoelectric effect, various applications in which both effects are combined are known, see Table 1.3. [7]

electro-mechanical transducers: - motors - actuators
sound and ultrasound transducers: - loud speakers / buzzers - cleaning / welding / drilling
resonators: - vibration generators

Table 1.3: Overview of applications of the combined piezoelectric effect

1.3.3.1. Ultrasonic transducers

The examples to be given for ultrasonic transducers are used in both airborne (e.g. in parking sensors) and underwater sonar applications as well as in solid materials (non-destructive testing). [7]

Figure 1.10: Parking sensors at the back of a car

1.3.3.2. Indication of time (output: electric signal)

Quartz crystal oscillators based on mass acoustic waves (MAW), in which waves propagate through the material, are known for their stable resonance frequencies that allow high accuracy timing in an electrical circuit. For this reason, quartz crystals are used not only in wrist watches, but also in almost all microprocessors.

In addition to bulk acoustic waves, a wide diversity of piezoelectric applications are based the use of alleged surface acoustic waves (SAW) where waves spread along the surface of the piezoelectric material. Known examples include SAW filters applied on mobile phones and other communication devices, and extremely good SAW sensors. [7]

1.4. During First and Second World War

1.4.1. First World War

With the start of the First World War in 1914, many countries have made real investments in technologies to change the course of the war. For example, an investment in ultrasonic technology has been made to search for German U-boats at sea. The main reason for these investments was political. Dr. Paul Langevin, together with Albert Einstein, Pierre Curie and Ernest Ratherford, conducted experiments in Paris in collaboration with the French navy on how to transmit ultrasonic signals under the sea in Paris. In 1917, Langevin managed to make an ultrasonic pulse to the sea on the southern coast of France. Langevin first chose the 40 kHz sound wave frequency. Since increasing the frequency would provide shorter wavelengths, the targets would be better tracked and travelled the distance faster. Since the speed of sound in quartz is approximately 5 km/h, it means that the wavelength in 40 kHz quartz is 12.5 cm. If we use mechanical resonance in piezoelectric materials, a single crystal part quartz with a thickness of 12.5 / 2 = 6.25 cm is required. However, it has not possible to produce such a high quality single crystal quartz in the mentioned period. [8]

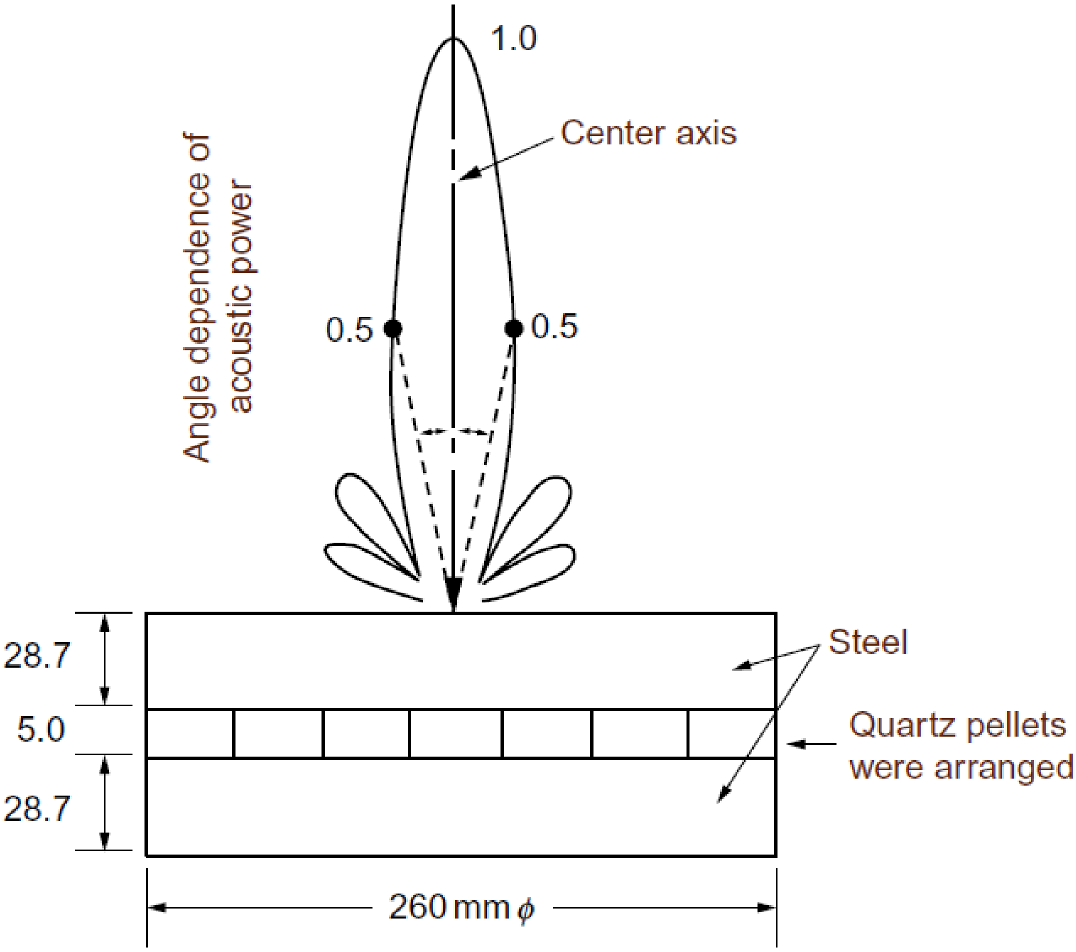


Figure 1.11: Original design of the Langevin underwater transducer and its acoustic power directivity

To overcome this situation, Langevin decided to make a new converter. Small quartz crystals arranged in a transformative mosaic were sandwiched between two steel plates. Since the sound velocity in steel was similar to that of quartz with a total thickness of 6.25 cm, it managed to adjust the thickness to the resonance frequency, i.e. around 40 kHz. This sandwich structure is called Langevin and is still popular today.

Furthermore, Langevin used a 26 cm diameter (more than twice the wavelength) sound radiation surface to provide a sharp orientation for the sound wave. So he wanted to evaluate the maximum-power angle "φ".

$$\Phi = 30 \times (\lambda/2a) \quad [\text{Degree}]$$

Here, lambda (λ) is the wavelength in the transmission medium (except steel). a, radiation surface radius. If λ = 1500 [m / s] / 40 [kHz] = 3.75 [cm], a = 13 [cm], Φ = 4.3 degrees is obtained for this design. In his experiment, Langevin managed to detect the U-boat at a distance of 3000 m. Langevin made some observations during the experiments and saw that there were many bubbles in the experiment. This shows that after 60 years, there is a cavitation effect for ultrasonic cleaning systems. [9]

1.4.2. Second World War

The barium titanate ($BaTiO3$, BT) ceramics were found during the independent experiments of the countries during the Second World War. It was found by the USA, Japan and Russia, respectively. During the Second World War: In 1942, Wainer and Salomon [10], Ogawa [11] and Vul [12] in 1944. A variety of oxides have been added as their commonly used "titacon", consisting of TiO2-MgO, wanted a higher permeable material by their researchers. According to the article written by Ogawa and Waku [13], they explored three dopas over a wide fraction range. These are CaO, SrO and BaO. They found the maximum permeability around the compositions of CaTiO3, SrTiO3 and BaTiO3 (all defined as perovskite structures). Especially BaTiO3 has very high permeability. This situation can be seen in Figure 1.12.

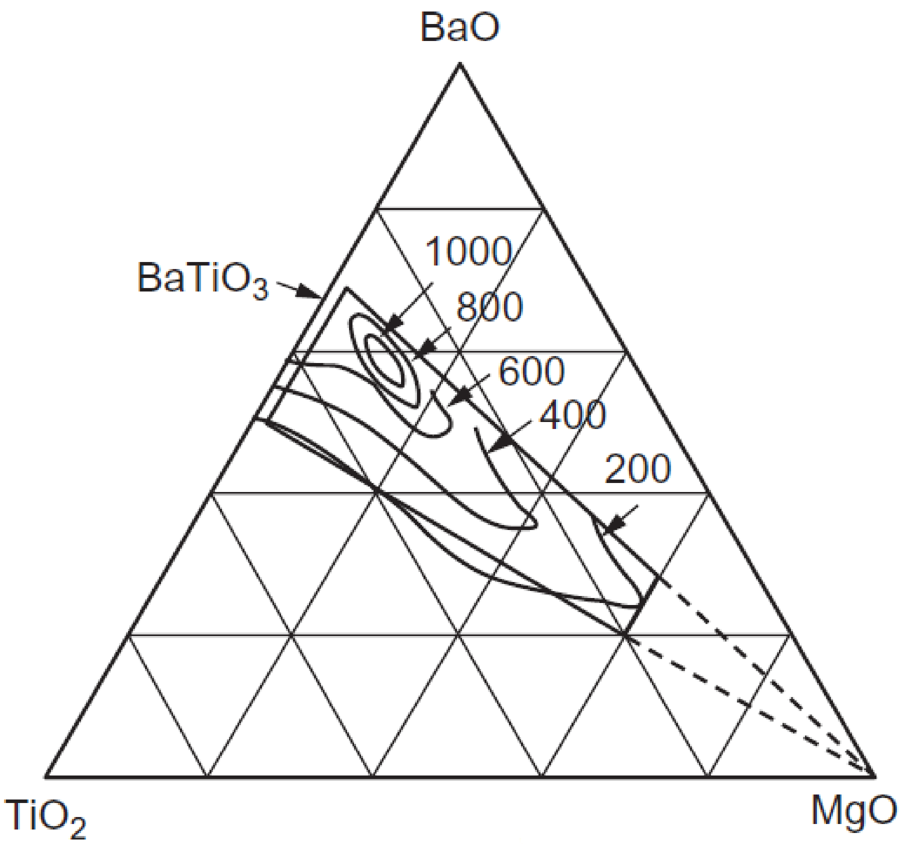


Figure 1.12: Permittivity contour map on the MgO-TiO2-BaO system, and the patent coverage composition range (dashed line). [13]

It should be noted that the original discovery of BaTiO3 was not on piezoelectricity. Equally important, R. B. Gray filed a patent application in Erie Resister in 1946 [14] and independently discovered the "piezoelectricity" situation at MIT by Shepard Roberts in 1947 [15], regulating the effect of electrical polarization on BT. The researchers at that time were not focusing on the first effect, "piezoelectricity", but on the secondary effect, "electrostriction." Ease of choice and manufacturability of BT ceramics, according to Mason and others, led to the study of transducers in electroceramics. Finally, the piezoelectric material multilayer capacitor was used in the nuclear bomb dropped on Hiroshima in the Second World War.

1.5. Factors Affecting Piezoelectric Property

Many factors affect the piezoelectric property of the materials. These factors can be shown as aging, mechanical limitations, electrical limitations, and thermal limitations. The effect of each factor on the piezoelectric property of the materials is described separately below.

1.5.1. Aging

Aging can be defined as the loss or decrease in piezoelectric properties of the material depending on the time. Aging is an expected phenomenon in a piezoelectric material used under normal conditions or in service. The speed of aging depends on the composition of the piezoelectric material and the production method used for the piezoelectric material. Using piezoelectric material over mechanical, electrical and thermal requirements will increase the aging rate of the material and shorten the life of the material. [16]

1.5.2. Mechanical limitations

In a piezoelectric material, the piezoelectric property varies according to the mechanical load applied to the material. If the mechanical stress size applied to the piezoelectric material is large enough to distort the orientation of the regions, this will have a negative effect on the piezoelectric property of the material. Consequently, this will cause the piezoelectric property to be added to the material by polarization wholly or partially. Piezoelectric material's mechanical stress resistance limit differs from material to material. [17]

1.5.3. Electrical limitations

If a polarized piezoelectric material is exposed to a strong electric field in the opposite direction to the polarization direction after polarization, the material becomes depolarized.

The degree of depolarization; the reverse electric field to which the material is exposed depends on the application time, ambient temperature and environmental factors. Electric fields in the range of 200-500 V/mm or more, cause significant depolarization in piezoelectric materials. Alternating current also affects the piezoelectric properties of the materials. The depolarization effect of the alternating current occurs on each half cycle where the loop is opposite to the polarization field. [17]

1.5.4. Thermal limitations

The piezoelectric property of the materials is directly dependent on the operating temperature. As the operating temperature increases, the piezoelectric properties decrease with increasing temperature. If a piezoelectric material is heated to Curie temperature, which is the critical temperature value for piezoelectric materials, the regions within the material will disappear, and the material will be depolarized. After this process, even if the piezoelectric material is brought to room temperature or appropriate operating temperature, it will not show a piezoelectric property. For this reason, operating temperatures of piezoelectric materials should be below Curie temperatures. The top recommended operating temperature for piezoelectric ceramic materials is half the Curie temperature. Changes in the arrangement of material domains are reversible for use at recommended temperatures. Besides, sudden temperature fluctuations can distort the piezoelectric properties of the materials. A piezoelectric ceramic element can generate relatively high voltages that can depolarize itself in sudden temperature changes. [17]

CHAPTER 2

2. Piezoelectric Materials

The piezoelectric materials known to date have been used in test and measurement devices and technical applications. Nowadays, many piezoelectric materials are applied to transducers, actuators, and ceramics, and if these are given as examples, ceramics, crystals, polymer sheets, etc. Piezoelectric (Ferroelectric) materials are increasing rapidly after the Second World War. Piezoelectric (Ferroelectric) materials were integrated with the new technology with micro-electro-mechanical systems (MEMS), and the development of the materials was achieved. It is possible to find ferroelectric ceramic materials on the market, and it is preferred today because it is good material with balanced prices. [2]

Piezoelectric materials are a type of dielectric material polarised by applying both in the electric field and mechanical stress [18]. Piezoelectric materials can be found in nature or can be produced by human hands. Minerals such as tourmaline, quartz, sugar cane, and Rochelle salt; Some organic structures such as wood, bone, hair, silk can be given as examples of piezoelectric materials. The Figure 2.1 below shows the structure of the oxygen atoms and the silicon atom in the quartz mineral. As seen in the figure, each oxygen atoms are equidistant to the silicon atom and the oxygen atoms are equally distant from each other. Along with the applied stress, the positions of the atoms change and this leads to the formation of net dipole moments that cause polarization and electric field formation [19].

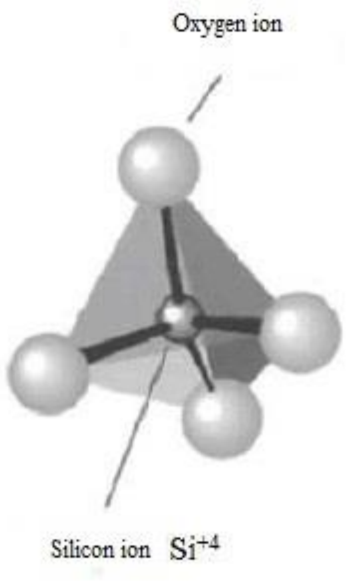


Figure 2.1: Molecular structure of quartz mineral [19]

Artificial piezoelectric materials, that is, those produced by human hands, have much more piezoelectric effect than natural piezoelectric materials. These materials can generally be classified as ceramic, polymer, and composite piezoelectric materials.

2.1. Desired Properties of Piezoelectric Materials

Generally, material properties requirements depend on like sensors, actuator or transducers. When switching to the application part, not only the form of the selected material but also the material to be applied must be selected specially. As an example, the desired properties in the application areas of force, pressure or accelerator sensors are listed below:

- Low production costs (Mass Production)
- High piezoelectric coefficients (i.e. sensitivity)
- High mechanical resistance and stiffness as well as secure processing
- High insulation resistivity
- High time stability of material properties important in the specific application as well as their low dependence on other factors (mainly on the temperature and external stress)
- The linear relation between mechanical stress and electric polarization (electric displacement)

Low production costs are significant generally for any product. Manufacturing and processing technology is chosen concerning the marketing needs of the product. Pricing plays a crucial role in material and technology selection.

The high piezoelectric sensitivity is governed by the piezoelectric material coefficients symbolized as $d_{i\lambda}$ [CN^{-1}]. Although piezoelectric is limited to anisotropic materials, piezoelectric coefficients depend on a particular crystal cutting direction, not point group symmetry. If device performance is in question, the piezoelectric coefficients should be high.

High frequency, symbolized by $S_{\lambda\mu}$ [m^2N^{-1}], which is the constant of high mechanical stiffness and elastic stiffness, is required. The high-pressure plane causes anisotropy of radial stresses. Due to this anisotropy, errors will occur in the measurement results made with the piezoelectric element. High mechanical toughness belongs to the important prediction in measuring force, pressure and acceleration. Element toughness is positive for the durability of the device based on the magnitude of the mechanical impacts. Thanks to its easy machinability, it is a convenience for the production of the piezoelectric element.

Kaastatic measurements are carried out using high insulation resistivity, piezoelectric sensors. The situation to be considered is not only the specific resistance of the piezoelectric material but also the surface quality is important. Surface conductivity varies depending on the processes performed on the material surface. In piezoelectric element applications, the relationship of insulation resistance with temperature is very important.

At the temperatures where the phase transition occurs, the surface conductivity can be strictly temperature-dependent.

Time stability is governed by aging in piezoelectric ceramics or by ferroelastic coupling in α-quartz. The measurement of third-order material constants updates the mechanical stress in polarization and quartz. One of the physical and technical problems is the design of element efficiency independent of temperature and pressure. Besides material selection, crystallographic element orientation can also eliminate this problem.

2.2. Quartz Crystals

Nowadays, many power tools contain quartz crystal devices. Quartz crystal; electrical polarization is observed when pressure is applied to some piezoelectric materials. An example of these materials is PZT and LiNbO3. This was first found by the Curie brothers in 1880.

The formula of quartz is SiO2, and it contains 46.5% Si and 53.3% O2 in pure form. It is one of the minerals with a hardness of 7 in Mohs scale, a specific gravity of 2.65 g / cm3, a melting temperature of 1785 ° C, and very common in the earth crust. Available as a solid solution in natural quartz main elements; Li, Na, AI, Ti, and Mg. It is generally colorless but can be seen in many different colors. Colourful formations are formed by gas, liquid, and solid inclusions. These inclusions are some minerals such as CO2, H2O, Hydrocarbon, NaCl, CaCO3, rutile. Although quartz minerals are not dissolved, they are soluble only in hydrofluoric acid. It shows piezoelectric and pyroelectric properties.

Quartz varieties are divided into two groups: coarse crystal (milk quartz, amethyst, blue quartz, pink quartz, etc.) and cryptocrystalline quartz (chalcedony, agate, onyx, agate, collapse stone, sard tripoli, etc.). Smooth and clean crystalline quartz is used in frequency control oscillators, frequency filters, and as an ornamental stone in the optical and electronics industry. It is also used in the glass, detergent, paint, ceramics, metallurgical industries, and as an abrasive and filling material following milk quartz and glassy quartz grinding and ore preparation processes. Although quartz mineral is mostly found in igneous rocks, it can also be formed by sedimentation or metamorphism. The quartz in an igneous rock or in sandstone cannot be characterized as a quartz mine, but quartz crystals or amorphous structures that have formed secondarily as veins in faults and cracks have economic value. The GTiP of quartz can be given as (250.610.000.011)[-19].

The largest quartz deposits in the world are located in Brazil. Known, natural, ultra-pure quartz reserves are found in Brazil, the U.S., Namibia, Angola, Madagascar, China, and India. These reserves are either primary or secondary formations and are not continuous. This kind of quartz is good enough to be used in the electronics industry. The best and biggest amethysts in the world are also available in Brazil. Amorphous or cryptocrystalline quartz deposits are located in Argentina, Austria, Belgium, Luxembourg, Hungary, Republic of South Africa, Spain and Norway. Reliable resources on world quartz reserves It could not be reached. Pure quartz crystals are used in the optical and electronics industry and as an ornamental stone.

In the chemical industry, it is consumed in the production of crystalline silicon metal and crucible. Ultra-pure quartz is used in the optical, electronic, and electrical industries. In addition, quartz is ground and consumed in the glass, detergent, and paint, ceramic, sanding, filling, and metallurgical industries. Quartz is generally produced by an open-pit method. The crust on it is very thin and it is subjected to triage after the explosive material bursts. Clean and quality ones are collected by hand and stored. Fe_2O_3 at the end of grinding is reduced by ore preparation methods. Sometimes quartz, which is broken and extracted, is washed with water to make it cleaner. The quartz crystals used in the optical and electronics industry are required to contain 99.99% SiO_2 [20].

2.3. Barium Titanate (BaTiO3)

Barium titanate (BaTiO3) is an inorganic compound with a chemical formula ABO3, which is attached to the peroxide family, the colour of which varies from white to grey.

Barium titanate is a material that has attracted more than 60 years. The first reason for the interest is that it is chemically and mechanically stable. Another reason is that Ferro can maintain its electrical feature at room temperature and above. It is soluble in many acids, including sulfuric, hydrochloric and hydrofluoric acids. Alkali and insoluble in water. It is electrically insulating in its pure form. But when it is added with a small amount of metal, mostly metals such as scandium, yttrium, neodymium, samarium, it becomes a semiconductor. The doped barium titanate has wide application in semiconductors, PIK thermistors and piezoelectric devices.

Metal oxides such as $BaTiO_3$ and Pb (Zr, Ti) O_3 (lead zirconium titanate, PZT) are widely used in different electronic applications due to their unique ferroelectric, pyroelectric and piezoelectric properties. Barium titanate is one of the most important Ferro electrical materials studied in a wide range. One-dimensional (1D) barium titanate nanomaterials such as nanofibers, nanotubes and nanostrips attract attention due to their developable properties and potential application areas in nanodevices.

Barium titanate can be used as a piezoelectric material in microphones and other transducers. The ferroelectric and piezoelectric properties of this material are used to produce some uncooled sensors used in thermal cameras. High purity barium titanate powder is used in the production of barium titanate capacitor energy storage systems used in electric vehicles. It is used in nonlinear optical devices. Used in multi-functional structural capacitors where material elements need to carry and store loads simultaneously [21].

2.4. Lead Zirconate Titanate (PZT)

PZT; given its physical, chemical, mechanical and piezoelectric properties, it has more high-efficiency properties than natural piezoelectric materials. In addition, their chemical stability is better than other piezoelectric ceramics. PZTs are resistant to moisture and atmospheric conditions. They provide easy adaptability to special applications, easy and inexpensive production for applications requiring complex geometry or large volume [22].

For the production of PZT, PbZrO3 and $PbTiO_3$ metal oxides in powder form are mixed by measuring in specific proportions, and a homogeneous mixture is obtained. By adding some binders to this obtained powder mixture, different geometries can be obtained, or they can be stored in powder form. Ceramic parts with different geometries are fired using suitable firing programs for appropriate times. This process is called sintering. The purpose of sintering is to connect the dust particles to obtain a dense crystal structure. Piezoelectric properties are obtained by applying various electrical processes to the crystal structure obtained after sintering [22] [23].

As with many ferroelectric materials, PZT has a perovskite crystal structure. In this structure, there are oxygen atoms on the surfaces and titanium and zirconium atoms in the centre. In these crystal structures, as a result of the merger of unit cells in the same direction, regions called "domain" are formed. In these regions, there are grains oriented among themselves, these grains can settle in different directions within themselves, but they can be located in the same direction as in single crystals.

Curie temperature of hard PZT is over 300 ˚C. The polarisation process of hard PZT at room temperature is not easy. Curie temperature of soft PZT is below 200 ˚C, and they can be polarized under a strong electric field at room temperature [24]. Comparison of soft and hard PZT is given in Table 2.1.

Properties	Soft Piezoelectric Ceramics	Hard Piezoelectric Ceramics
Piezoelectric d constant	High	Low
Dielectric constant	High	Low
Dielectric loss	High	Low
Hysteresis	High	Low
Mechanical quality factor	Low	High
Coupling constant	High	Low
Electrical resistance	High	Low
Breakdown voltage	Low	High
Elasticity constant	High	Low
Ageing effect	Low	High

Table 2.1: Comparison of soft and hard PZT properties

The crystal structure of PZT differs according to how much $PbZrO_3$ and $PbTiO_3$ powders are combined. The crystal structure that varies according to temperature and composition can be cubic, rhombohedral or tetragonal. The phase diagram of PZT is shown in Figure 2.2. The solution does not show ferroelectric properties in the region "a". It has rhombohedral in the "b" region, cubic in the "c" region and tetragonal in the "d" region. The vertical line drawn from the middle is a special phase boundary and is known as the morphotropic phase boundary.

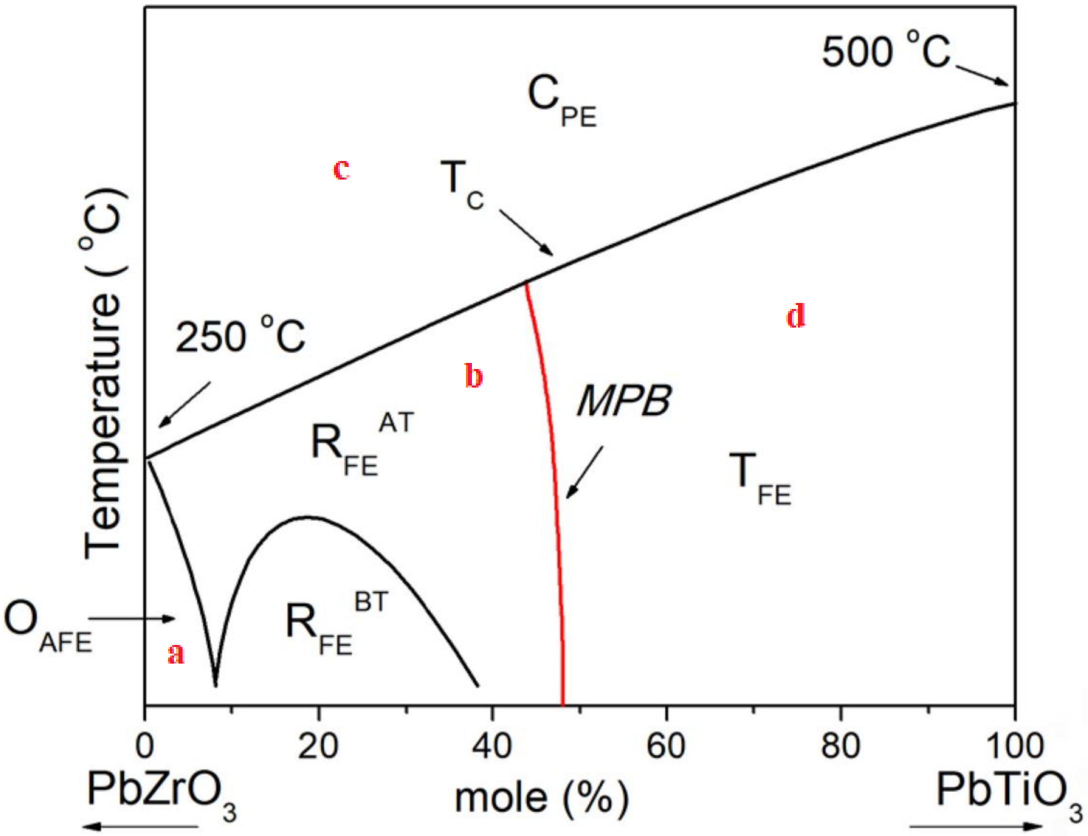


Figure 2.2: PZT phase diagram; Phase diagram of the $PbTiO_3$-$PbZrO_3$ system. The line denoted by MPB ("Morphotropic Phase Boundary") separates the ferroelectric tetragonal region (T_{FE}) from the ferroelectric rhombohedral region ($R_{FE}{}^{BT}$: low temperature rhombohedral modification; $R_{FE}{}^{AT}$: high temperature rhombohedral modification). O_{AFE} refers to the orthorhombic antiferroelectric region, while the Tc line indicates the Curie temperature behavior separating the FE and AFE phases of the parabolic cubic phase (C_{PE}). [25]

When a high-temperature PZT is cooled, a phase conversion takes place in PZT. During this phase transformation, approximately 0.1A˚ atomic movements occur. In titanium-rich PZT compositions, the Curie temperature transitions from cubic m3m to 4mm tetragonal structure. In this way, the polarization in line with the tetragonal structure [001] protects itself between the Curie temperature and 0 K [5]. These structural transformations are also shown in Figure 2.3.

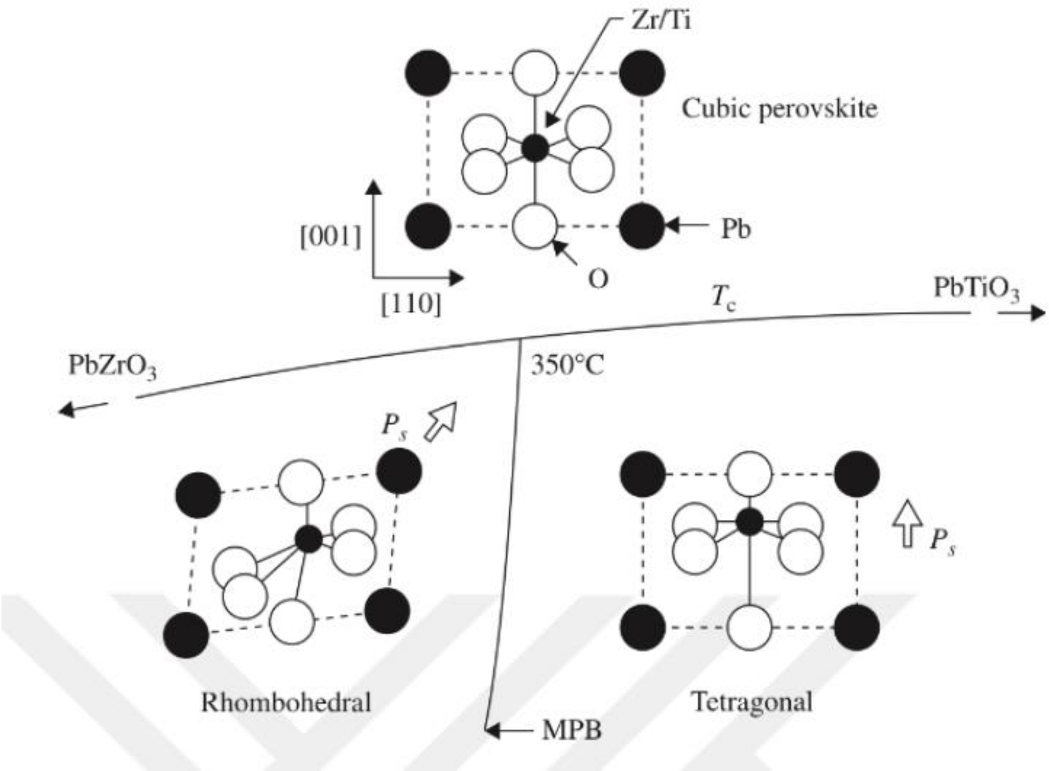


Figure 2.3: Cage structures seen in the phase diagram [26]

When it is desired to create a PZT solution with certain features, Pb 52-48 ratio is generally used. However, PZT with different compositions will have different piezoelectric properties. In Figure 2.4, the effect of the change of $PbZrO_3$ amount on the piezoelectric load constants is given.

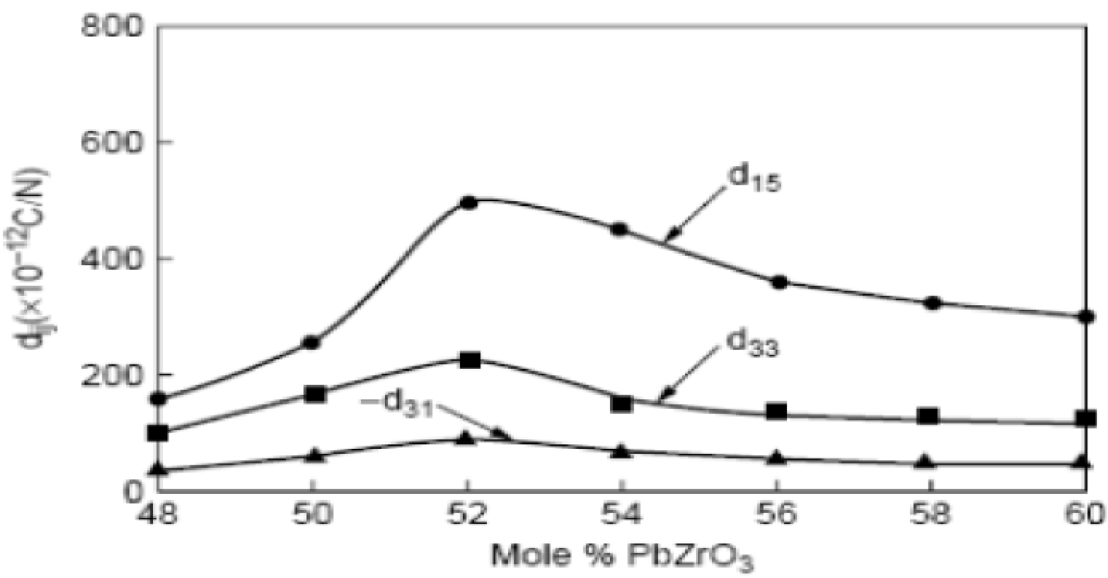


Figure 2.4: Piezoelectric load constant changes of PZT in different compositions

PZT has different properties according to ceramic materials composition. The properties of PZT ceramics in different compositions are shown in Table 2.2. Elements such as Ba, Sr, Ca and La, which is used as additives to PZT, affect the characteristics of the material such as Curie temperature, material stability and strength, and provide a wider range of work [22].

Type of PZT	Curie Temp (˚C)	d_{33} (pc/N)	d_{31} (pc/N)	K^{T}_{33}	k_{33}	k_{31}
PZT-2	370	152	-60	450	0,63	-0,28
PZT-4	325	285	-122	1300	0,7	-0,33
PZT-4D	320	315	-135	1450	0,71	-0,34
PZT-5A	365	374	-171	1700	0,71	-0,34
PZT-5B	330	405	-185	2000	0,66	-0,34
PZT-5H	195	593	-274	3400	0,75	-0,39
PZT-5J	250	500	-220	2600	0,69	-0,36
PZT-5R	350	450	-195	1950	-	-0,35
PZT-6A	335	189	-80	1050	0,54	-0,23
PZT-6B	350	71	-27	460	0,37	-0,15
PZT-7A	350	153	-60	425	0,67	-0,3
PZT-7D	325	225	-100	1200	-	-0,28

Table 2.2: Properties of PZT ceramics [22]

2.5. PVDF

PVDF belongs to the category of semi-crystalline fluoropolymer. They show the characteristic stability of fluoropolymers, especially when exposed to extreme thermal, chemical and ultraviolet environments. This polymer has two important properties. The first is the polymorphism of the polymer and the second is the piezoelectric properties (crystals produce electrical energy when mechanical pressure is applied). Its second feature is what makes this polymer ideal for touch-sensitive arrays, low-cost strain gauges, and light-weight audio converters.

Very high purity PVDF is chemically inert to most acids, aliphatic and fragrant organic ingredients, chlorinated solvents and alcohols. Compared to polyamides, it is very resistant to abrasion, and its friction coefficient is low. PVDF can be used at many temperatures (excellent fire resistance), unaffected by ultraviolet rays and very resistant to radiation. PVDF has a high thermal forming capacity and can be easily combined by welding.

In 1069, Dr Heiji Kawai was the name that discovered the features of PVDF. In 1981, Furakawa and Johnson approved the piezoelectric structure of PVDF and determined Curie point as 103 °C.

PVDF can be used in fields such as aviation and space, biotechnology, electronics industries, robot technology, sensors, electrical cable insulation, etc.). It is also used in the production of PVDF hollow fibres, flat sheets, tubular membranes used in the medical and food-beverage industries.

PVDF (polyvinylidene fluoride) is obtained by polymerizing vinylidene difluoride. PVDF exists in four crystalline phases: alpha, beta, gamma and delta. The PVDF molecular structure is shown between Figure 2.5 and 2.8 [27].

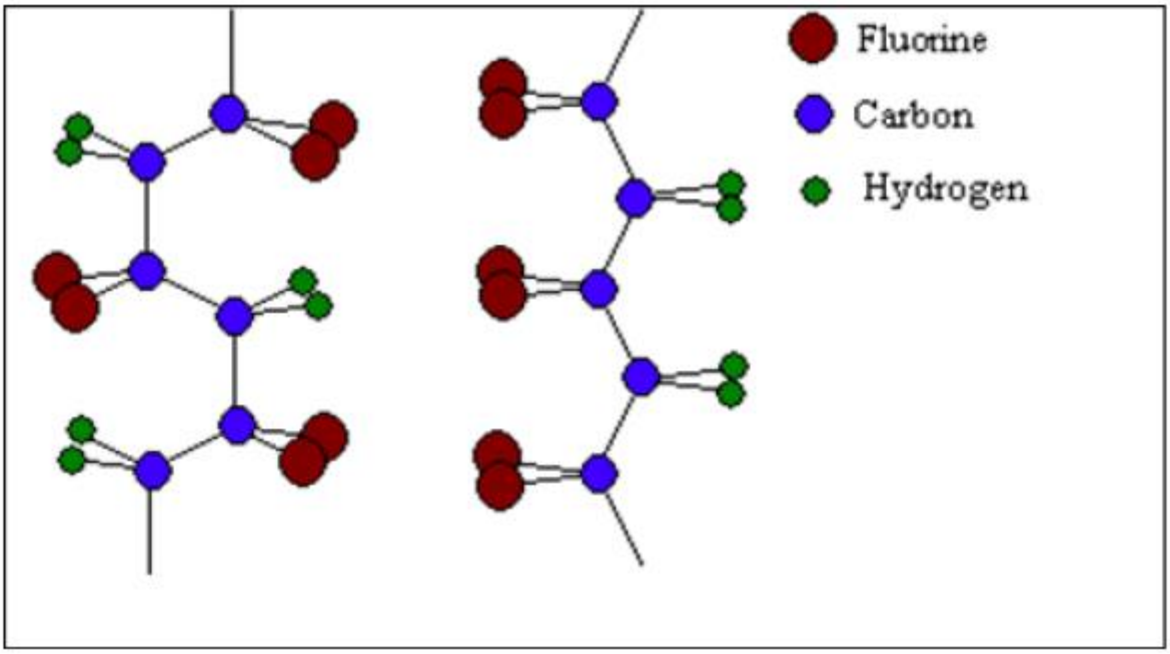


Figure 2.5: Alpha PVDF (left) and Beta PVDF (right) structure [27]

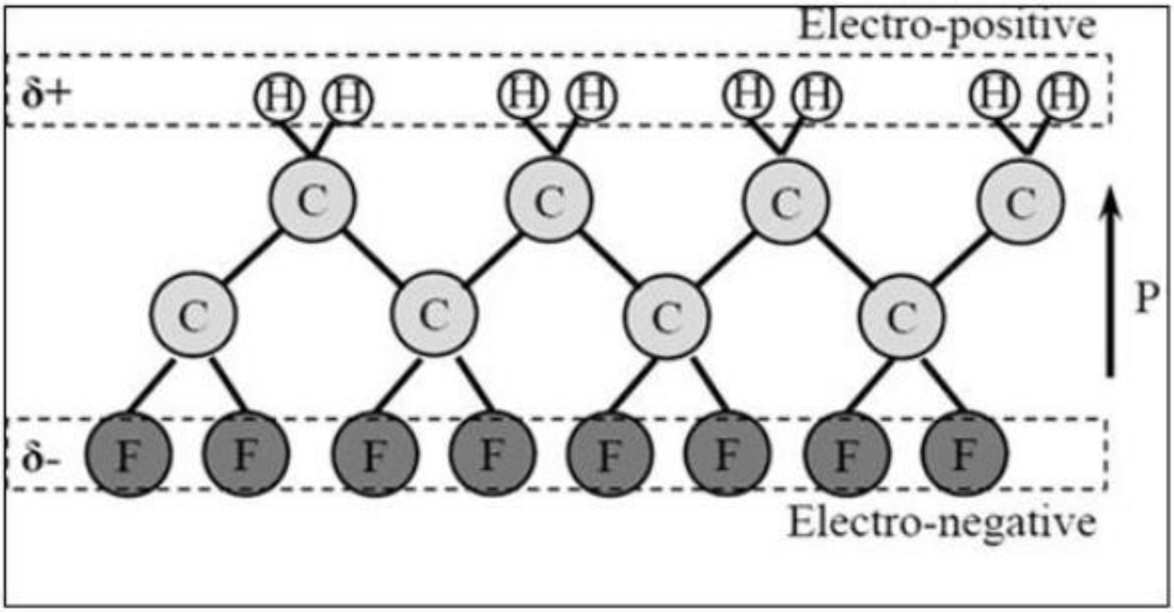


Figure 2.6: Schematic diagram of the atomic order in the PVDF molecule [27]

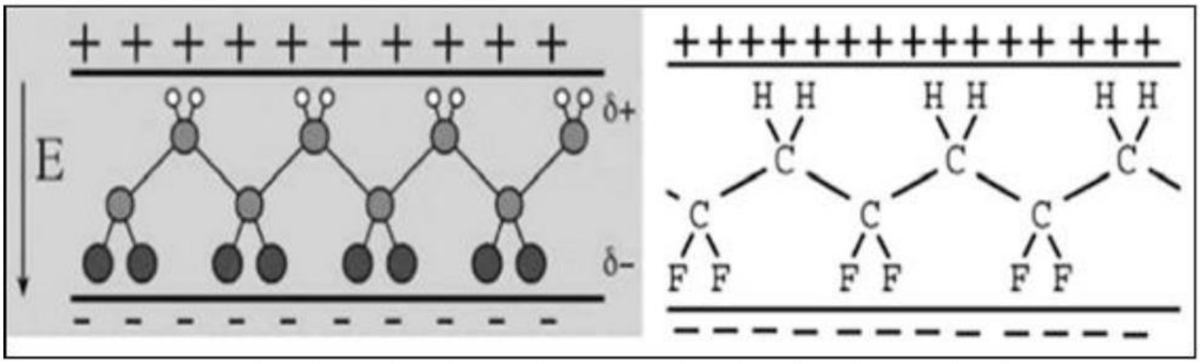


Figure 2.7: Electric field direction and polarisation at the moment of printing of PVDF ceramics [27]

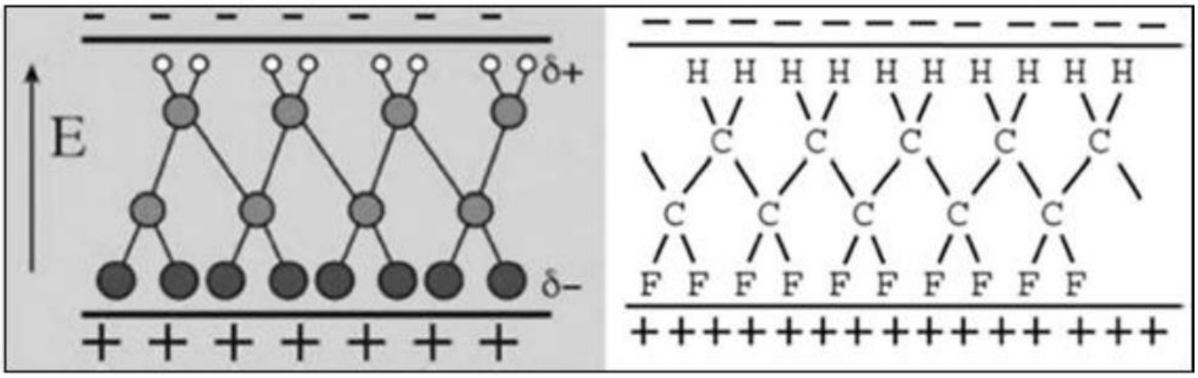


Figure 2.8: Electric field direction and polarization at the moment of relaxation of PVDF ceramics [27]

CHAPTER 3

3. Design of Experiment

The experiment aims to discuss in which frequency range, the piezoelectric material will be more efficient with the help of sound waves in the free or specific frequency range of piezoelectric materials in different geometries and shapes. In this experiment, the sound is sent to the piezoelectric material in the frequency range determined with the help of a speaker. In exchange for this frequency, the voltage generated by the transducer of the piezoelectric material was measured by voltmeter with the help of the full-wave rectifier circuit.

The above-mentioned situation is called "case 1" and freelance work. In case 1, two different piezoelectric materials were examined. These are plate and bending elements. The setup of the experiment is as shown in Figure 3.1 and the actual situation in the Laboratory is shown in Figure 3.2.

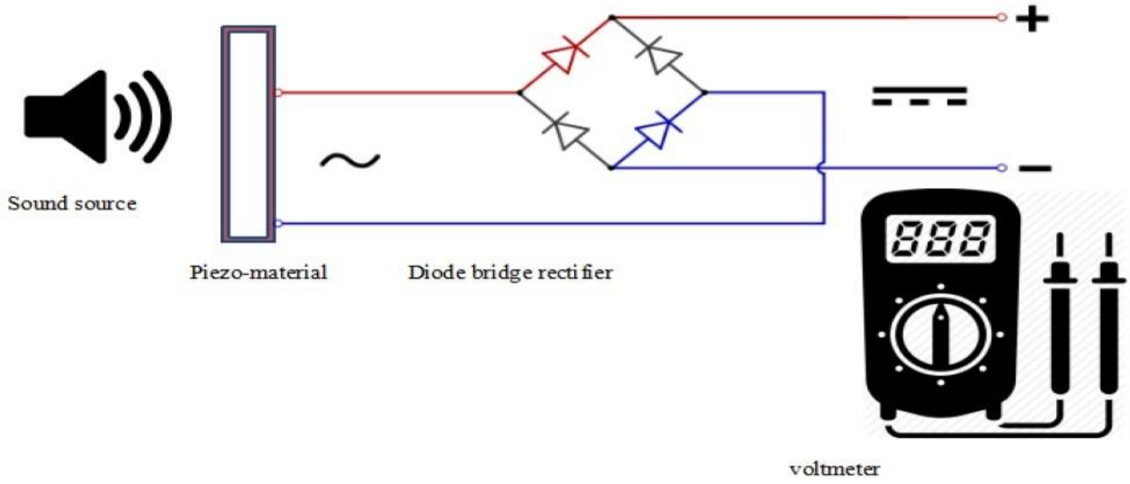


Figure 3.1: The experimental setup

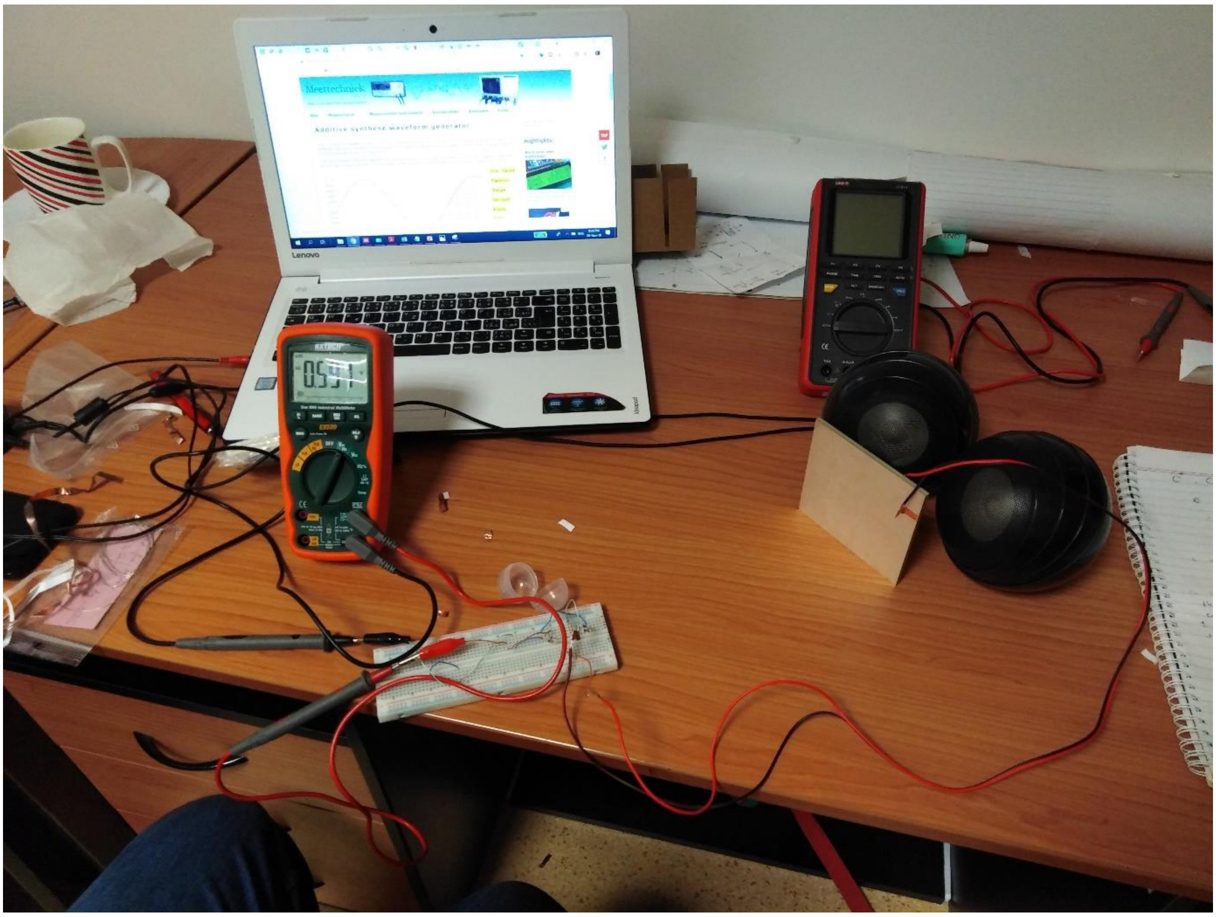


Figure 3.2: Real Experiment setup for case 1

In case 2, the same experimental set up as above was established. In this case, an oscilloscope was used instead of a voltmeter. In this experiment setup, data were obtained from the oscilloscope by placing the speaker at the calculated distances. This is shown in Figure 3.3. Also, four different piezoelectric materials will be used in this experiment. These materials are plate, bending element, buzzers with codes 641-003, and 641-017. A full rectifier circuit was used in all experiments.

In Case 3, the relationship of two different piezoelectric materials with temperature was investigated. In this experiment, buzzer with code 641-017 and plate were used. The experiment setup is the same as for other experiments. The difference from other experiments is the effect of temperature on the piezoelectric material.

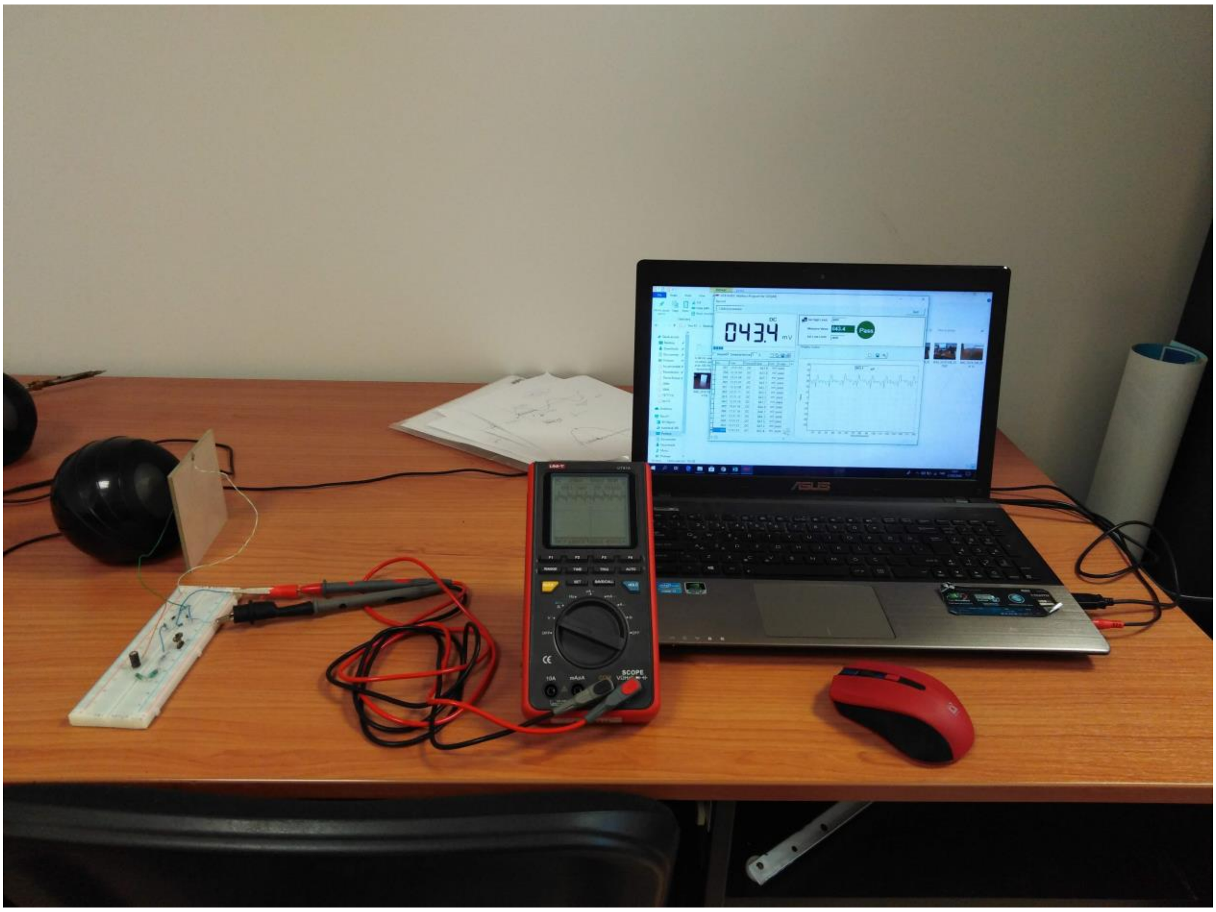


Figure 3.3: Real Experiment setup for case 2

3.1. Full Rectifier Circuit

When the AC signal is applied to the Full Wave Bridge Rectifier Circuit input, the DC signal is received from the output. The Full Wave Bridge Rectifier Circuit converts the AC signal into a DC signal. As shown in Figure 3.4, the Full Wave Bridge Rectifier Circuit contains four diodes and one capacitor.

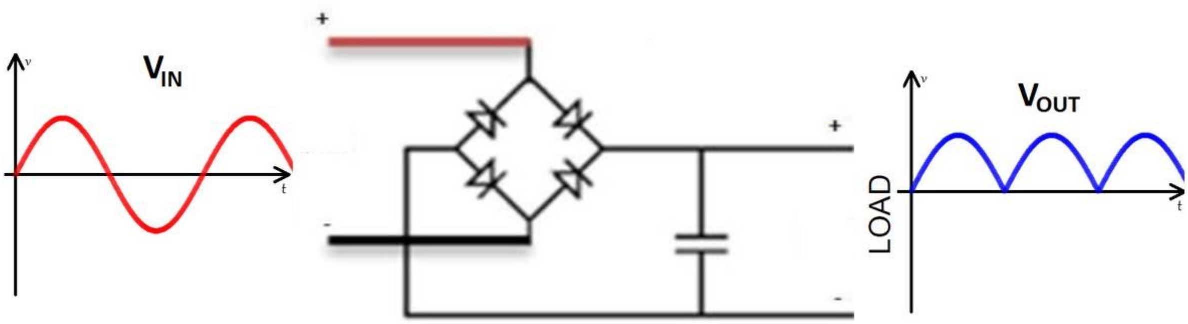


Figure 3.4: Full Wave Rectifier Circuit

3.2. Experiment Method

As mentioned earlier, using a laptop, the frequency sound is output via the help of a speaker. This sound hits the piezoelectric material and generates a certain amount of electricity. That means a different rate electricity generation at different frequencies. In this case, the performance of the materials used depends on the frequency of the incoming sound. As stated below, the experiments were examined in two different ways.

3.2.1. Case one (1):

These experiments were tried freely, and distance, angle, or other situations were ignored. In other words, in the experiments, the sound is provided at a very close distance without any obstacle between the piezoelectric material and the speaker. Which frequency produces better electricity is examined. In these experiments, only the plate and bending element were examined. As an example is shown in Figure 3.5.

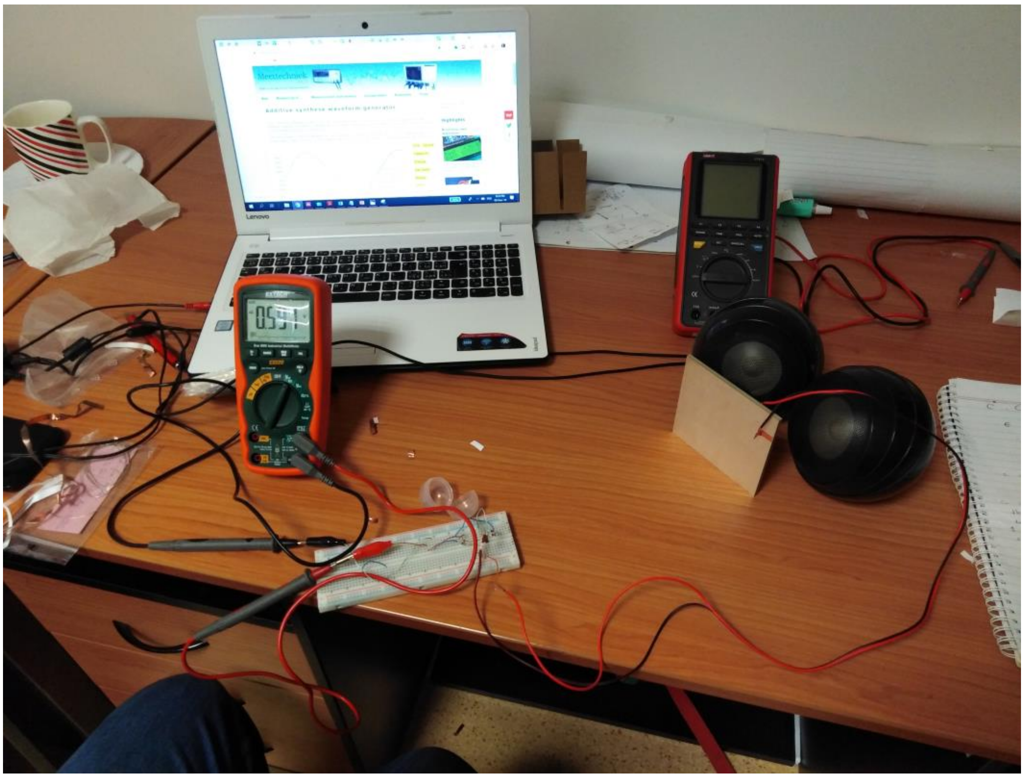


Figure 3.5: Plate experiment setup for case1

3.2.2. Case two (2):

In this experiment, four different piezoelectric materials were examined. These are plate, bending element, buzzers with codes 641-003, and 641-017. The primary purpose of the examinations is how much electricity the piezoelectric materials specified at the calculated distances can produce. In other words, the effect of distance on the material was investigated. The calculated distances are found with the help of the specified frequency and are shown in Table 3.1 below. In these calculations, the sound velocity in the air is taken as 343 m/s. Also, sound of periodic time was calculated. Because the oscilloscope was requested to make a more accurate examination by using the appropriate time interval. As a result of the examinations made with the oscilloscope, it was investigated in which frequency range the materials in different geometry are more efficient. As an example, Figure 3.6 below is given.

Frequency [Hz]	Wavelength [m]	Distance between material and speaker [cm]	speed of sound in air [m/s]	sound of periodic time [sec]
2000	0.1715	4.2875	343	0.0005
4000	0.08575	2.14375	343	0.00025
6000	0.057166667	1.429166667	343	0.000166667
8000	0.042875	1.071875	343	0.000125
10000	0.0343	0.8575	343	0.0001
12000	0.028583333	0.714583333	343	8.33333E-05
14000	0.0245	0.6125	343	7.14286E-05
16000	0.0214375	0.5359375	343	0.0000625
18000	0.019055556	0.476388889	343	5.55556E-05
20000	0.01715	0.42875	343	0.00005

Table 3.1: Distance for frequency

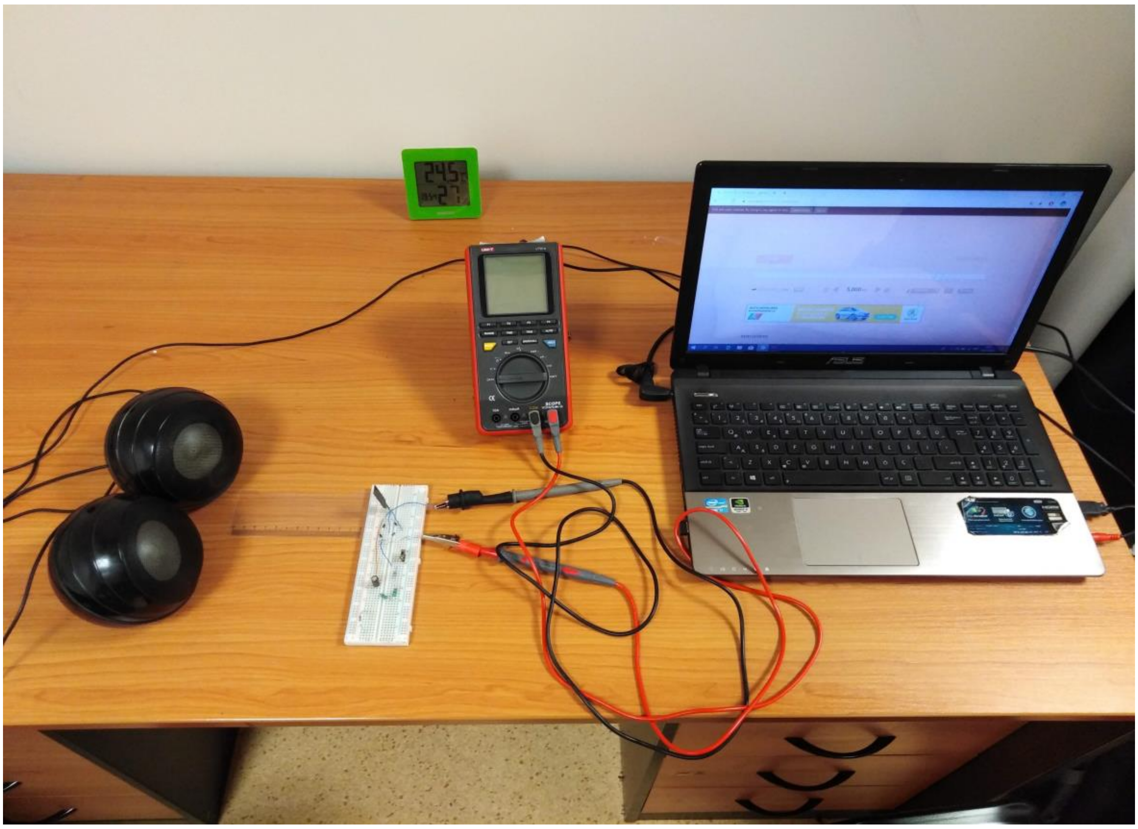


Figure 3.6: Experimental setup with the oscilloscope

3.2.3. Case Three (3)

In this experiment, how much electricity the piezoelectric material, whose temperature is changing, produced at 20000 Hz was examined. Temperatures between 30-70 ˚C were used in the examinations. After the materials were heated in the oven for 15 minutes, they were connected to the experimental setup for measurements. The distance corresponds to 20000 Hz specified in Table 3.1.

CHAPTER 4

4. Results

4.1. Case One (1)

4.1.1. Bending element

The results for the bending element are shown in table 4.1 below. Based on the results from the data, a frequency and voltage graph was created and shown in Figure 4.1. As a result of the experiments, it is seen that as the number of frequency increases, the amount of electricity produced increases. The reason for this is that as the frequency increases, as a result of the decrease in the wavelength and the sound wave hits the material more; it increases the amount of electricity produced.

1. Measurement		2. Measurement		3. Measurement	
Frequency [Hz]	Voltage [mV]	Frequency [Hz]	Voltage [mV]	Frequency [Hz]	Voltage [mV]
1000	2.5	1000	3.8	1000	13
5000	30.5	5000	25.3	5000	75.3
8000	45.9	8000	36.9	8000	109.7
10000	53.9	10000	43.7	10000	129.8
12000	57.5	12000	49.1	12000	146.8
15000	64.2	15000	56.7	15000	165.7
17000	70.1	17000	61.3	17000	175.2
20000	80	20000	70.2	20000	199.2

Table 4.1: Some data for Bending Element

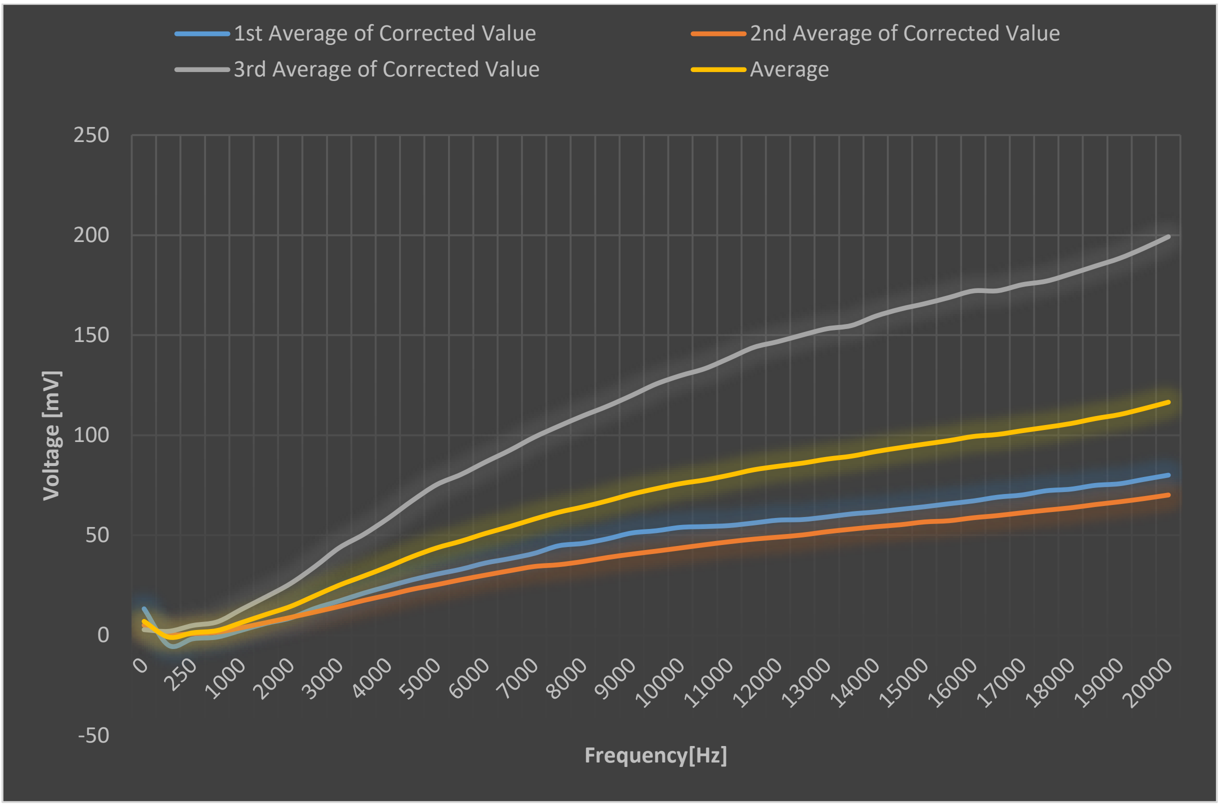


Figure 4.1: Average of Corrected Value in Bending Element

The figure above shows the frequency-voltage relationship of the experiment that has been done to us. As seen in the graph, the average of three experiments performed was taken.

The average curve shows us the range of this material that can be used with the best efficiency, and this range is between 17 kHz and 20 kHz. In this case, if we want to use this piezoelectric material, it can be used with high efficiency in the specified frequency range.

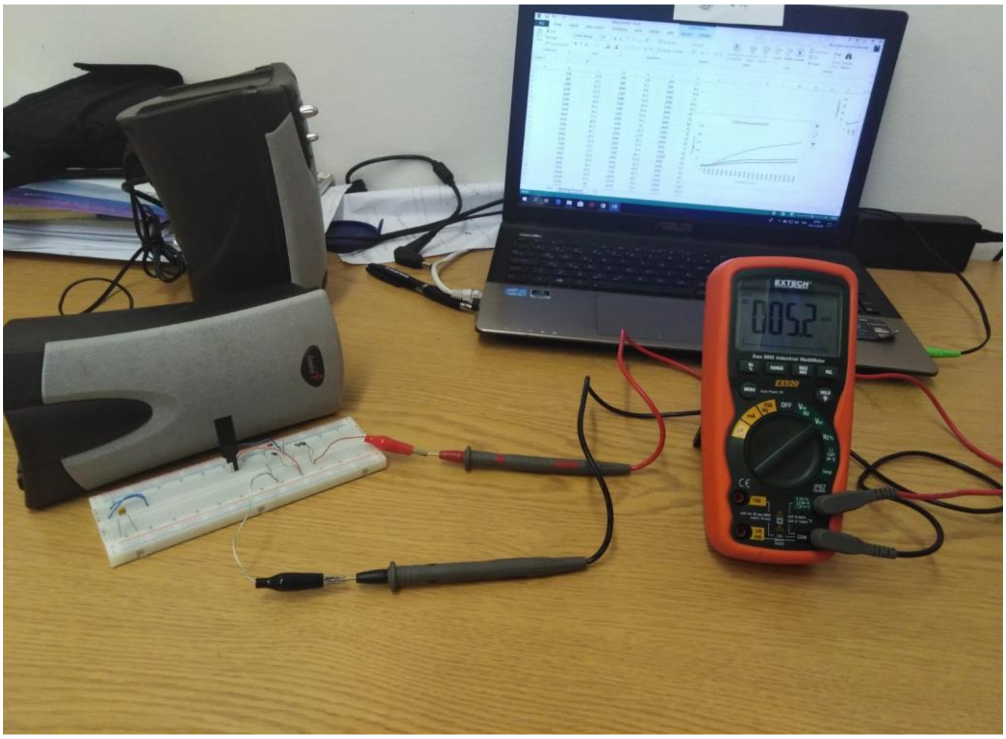


Figure 4.2: Bending element experiment setup for case1

4.1.2. Plate

Similar results have been approached, such as the previous piezoelectric material. In other words, the energy obtained with frequency has been found to be directly proportional. Some data on the plate are shown in table 4.2 below. As seen in the graph, there are fluctuations in some measurements. The reason is that the experiments are not realized in an isolated environment. Therefore, moisture, ambient temperature, solder quality on the speaker and material may be the reason for the fluctuation. In order to obtain precise and clear results, it must be done in an isolated environment.

1. Measurement		2. Measurement		3. Measurement	
Frequency [Hz]	Voltage [V]	Frequency [Hz]	Voltage [V]	Frequency [Hz]	Voltage [V]
1000	0.047	1000	0.014	1000	0.013
5000	0.082	5000	0.05	5000	0.056
8000	0.093	8000	0.076	8000	0.081
10000	0.107	10000	0.085	10000	0.092
12000	0.122	12000	0.096	12000	0.106
15000	0.142	15000	0.112	15000	0.123
17000	0.152	17000	0.124	17000	0.134
20000	0.147	20000	0.144	20000	0.155

Table 4.2: Some data for Plate

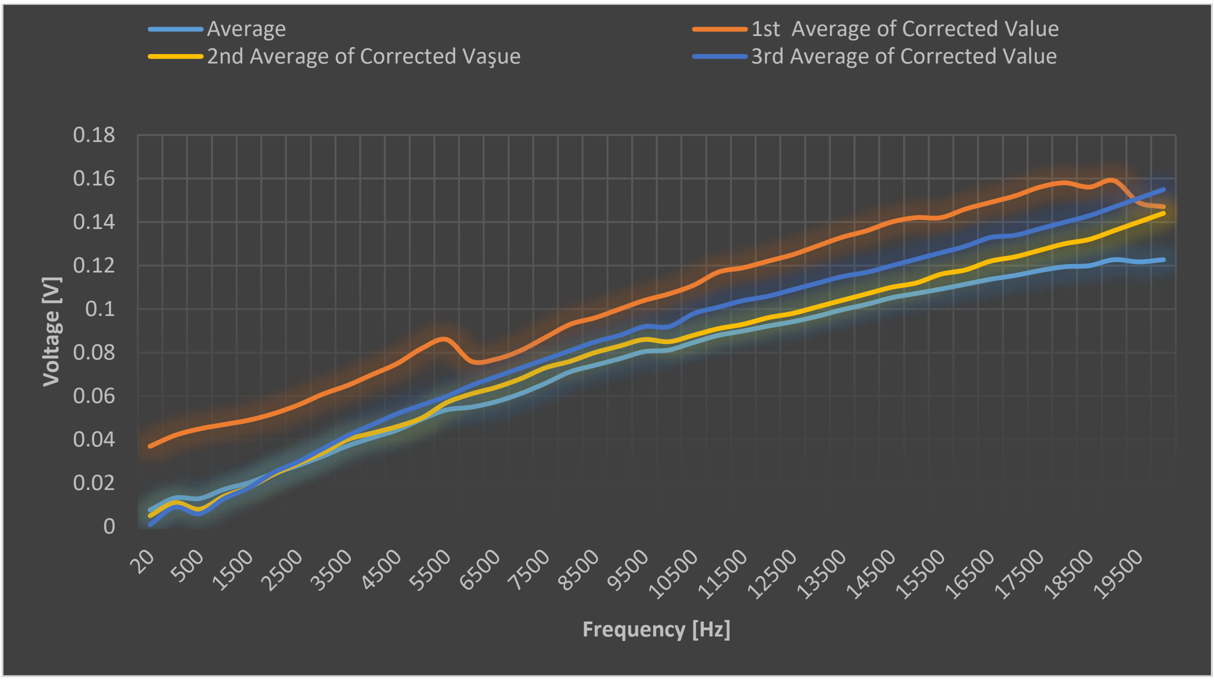


Figure 4.3: Average of Corrected Value in Plate

It is prepared according to the data from three measurements made on average. When looking at the average curve, it is seen that the energy obtained increases with increasing frequency. The piezoelectric plate material is dimensionally larger than the bending element for this reason large energy is obtained. In other words, a different amount of energy is obtained from materials with different geometries. However, their efficiency can be discussed according to the areas in which they are used.

4.2. Case Two (2)

As mentioned earlier, this section will examine four different piezoelectric materials. These materials are plate, bending element and two different buzzers. The oscilloscope was used for the experiment. The necessary examination will be done on the graphic taken from the oscilloscope device. The examination of this graph will vary according to each frequency and will find out which frequency range is more suitable for the materials. Besides, the frequency range examined is not desired to be 50 kHz. Because electric lines emit a fixed wave frequency of 50 kHz. Therefore, examinations should be done very carefully from the oscilloscope.

4.2.1. Bending Element

As mentioned in the first explanation, the experimental setup is placed according to the calculated frequency distances. The first measurement was set at 20 kHz and the distance 0.428 cm. After first the measurement, 18 kHz and distance were set as 0.476 cm for the second measurement. The amount of energy produced for these two measurements is 10.3 mV and 5.2 mV, respectively, and is indicated in the graphs below. This situation reduces the amount of electricity produced as the distance changes. The most efficient frequency for this piezoelectric material is 20 kHz. Because it was seen that the amount of electricity produced with the change in distance decreased.

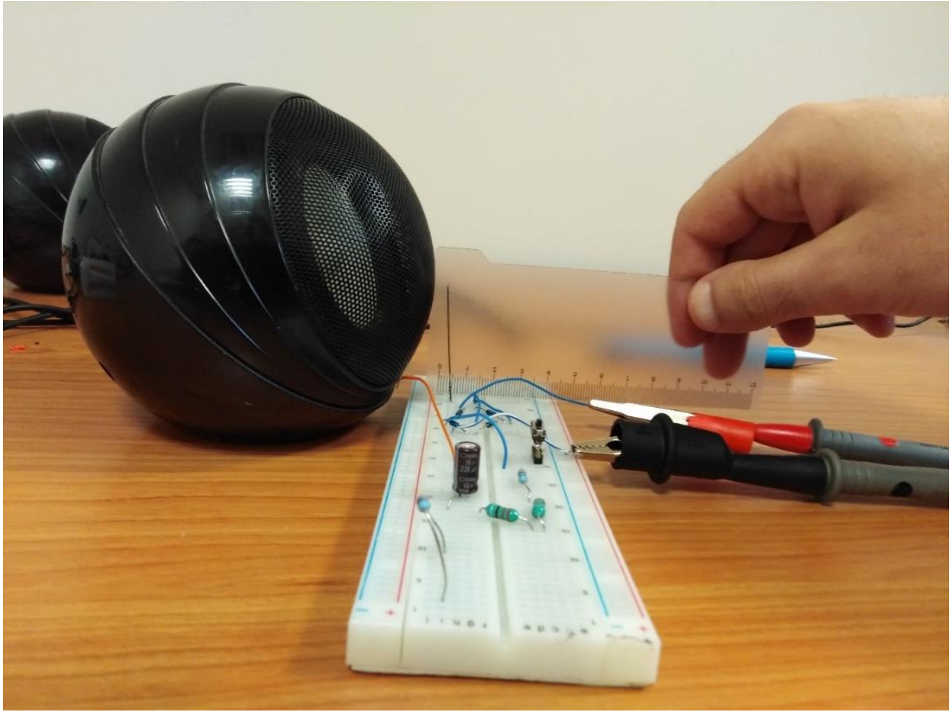


Figure 4.4: Experiment setup for bending element

Below are shown the graphs created after converting AC (alternating current) to DC (direct current). The Vertical (y) axis of the graph shows the amplitude, that is, the intensity of the measured signal. The horizontal (x) axis shows the time. The time in the chart was calculated as follows.

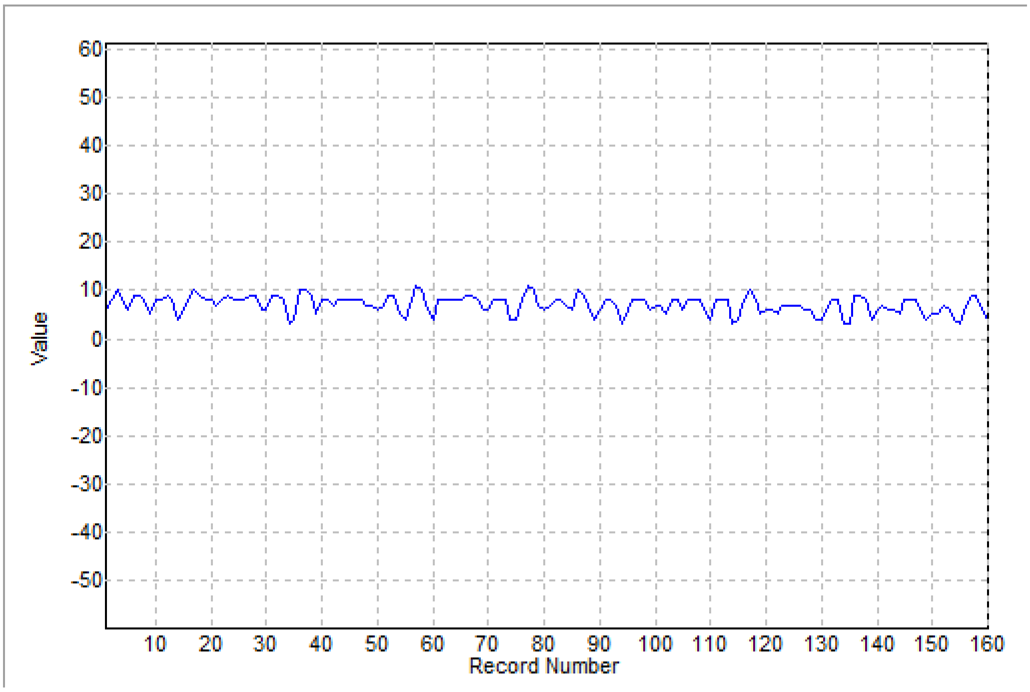


Figure 4.5: For distance 0.428 cm and 20000 Hz

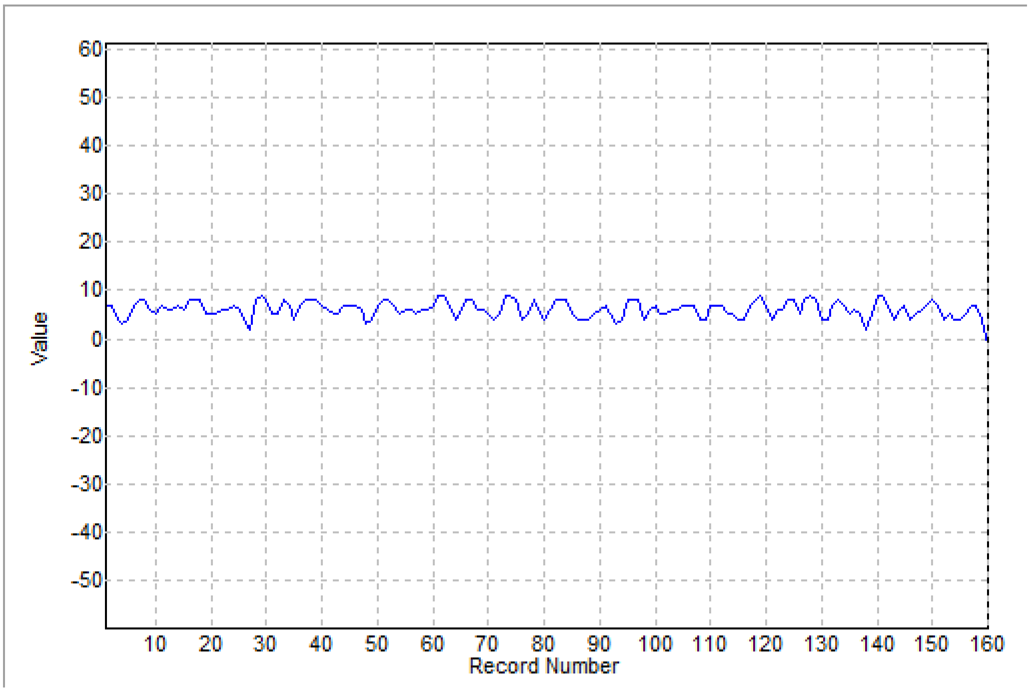


Figure 4.6: For distance 0.476 cm and 18000 Hz

2 Sq → 50 µsec

1 Sq → 25 µsec

10 Record → 25 µsec

1 Record → 2.5 µsec

=160 Sq x 2.5 µsec = 400 µsec

4.2.2. Plate

The piezoelectric material used is larger than other materials. Therefore, the amount of electricity produced will be larger than others. The experiments were realized according to the frequency-distance relationship, as stated in Table 3.1. By looking at the results obtained according to this relationship, the electricity produced decreases as the distance increases. However, the size of the material used in this experiment has increased importance. Because the larger the material used, the amount of energy produced will grow.

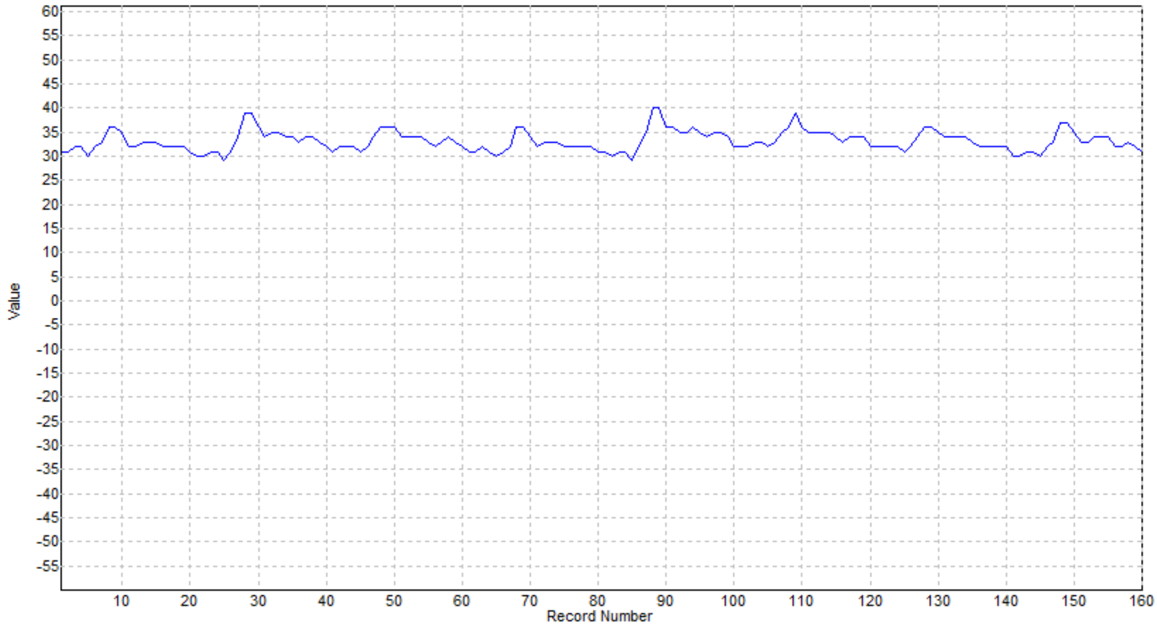


Figure 4.7: For distance 0.428 cm and 20000 Hz

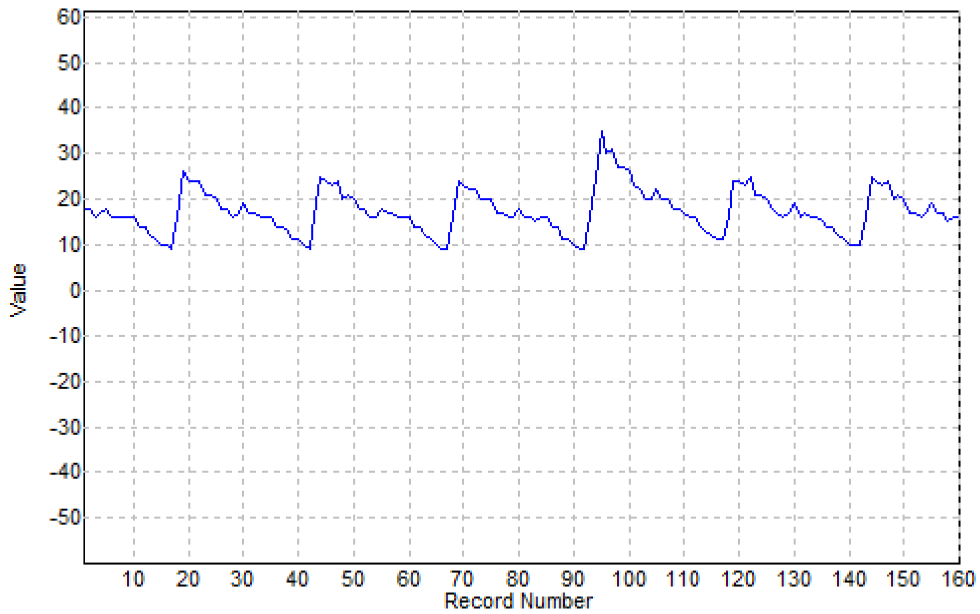


Figure 4.8: For distance 1.071 cm and 8000 Hz

4.2.3. Buzzer 641-003

In the experiments conducted for the piezoelectric material used, apart from Table 4.3 mentioned above, four different frequencies were selected, and the natural frequency was examined. As a result of the examinations, it was found which natural frequency is more efficient by looking at the frequency-distance relationship.

Frequency [Hz]	Wavelength [m]	Distance between material and speaker [cm]	Speed of sound in air [m/s]	Sound of periodic time [sec]	Code
713	0.481065919	12.02664797	343	0.001402525	641-003
2310	0.148484848	3.712121212	343	0.0004329	
7650	0.044836601	1.120915033	343	0.000130719	
19326	0.017748111	0.443702784	343	5.17438E-05	

Table 4.3: Natural Frequency for buzzer 641- 003

Figure 4.9: The longest distance for buzzer 641-003

For 641-003, the lowest usable one (1) mV electricity production was provided at 800 Hz. To produce electricity in this material, a frequency of 800 Hz and above must be applied. If a frequency lower than the specified frequency is applied, electricity will be produced under one mV and will take neglect. In this study, experiments between 20000 Hz and 800 Hz were done and they were efficient at a high frequency according to the frequency-distance relationship. This situation is shown in the two graphs shown below.

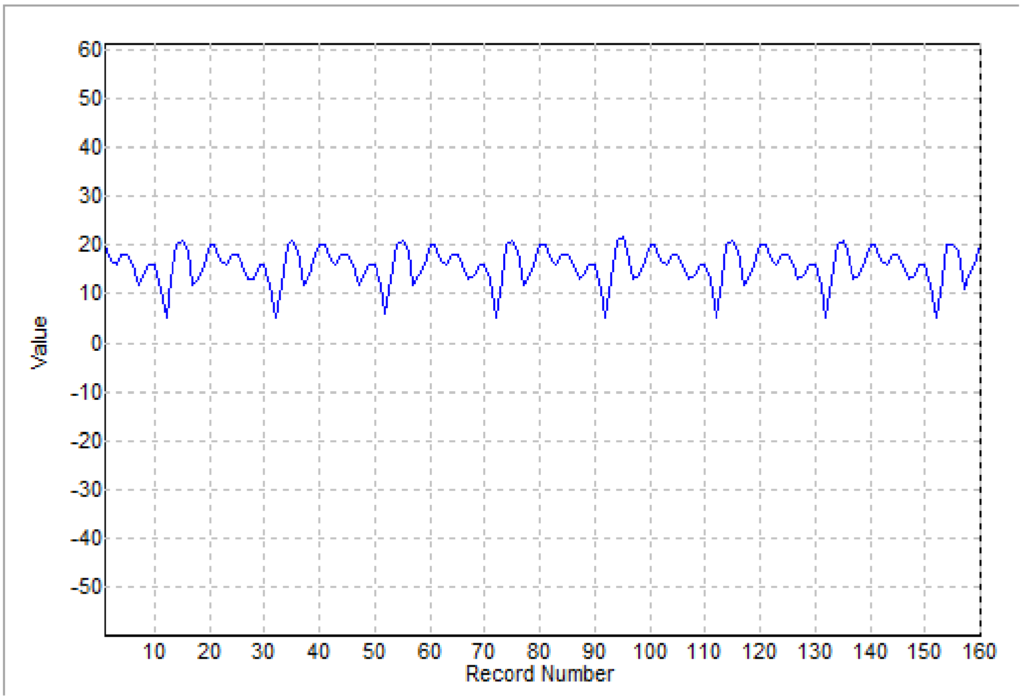


Figure 4.10: For distance 0.428 cm and 20000 Hz

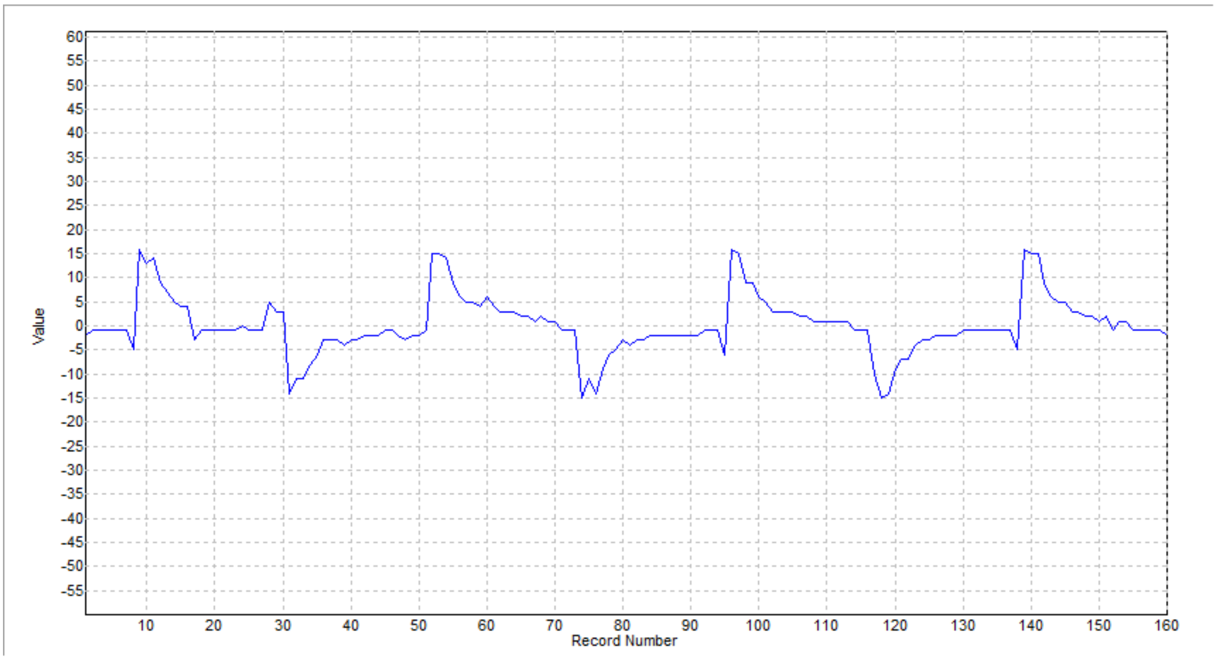


Figure 4.11: For distance 3.71 cm and 2310 Hz in special frequency

4.2.4. Buzzer 641-017

The same path has been followed with the previous measurement, and almost very close results have been obtained. However, a different result was obtained in this experiment compared to other experiments. This exception is obtained high electricity at low frequency. In other words, electricity production between 30 and 35 mV was provided at 688 Hz. This situation may be due to the fact that the measuring chamber is not insulated, voltage changes in the electrical lines during measurement, or from devices in the room.

Frequency [Hz]	Wavelength [m]	Distance between material and speaker [cm]	Speed of sound in air [m/s]	Sound of periodic time [sec]	Code
688	0.498546512	12.46366279	343	0.001453488	641-017
2110	0.162559242	4.063981043	343	0.000473934	
6028	0.056901128	1.422528202	343	0.000165893	
8323	0.041211102	1.030277544	343	0.000120149	

Table 4.4: Natural Frequency for buzzer 641- 017

Frequency	Distance	mV
8323	12.4636	15
6023	4.0639	13
2110	1.4225	11
688	1.0302	30-35

Table 4.5: Relationship between Frequency and Distance

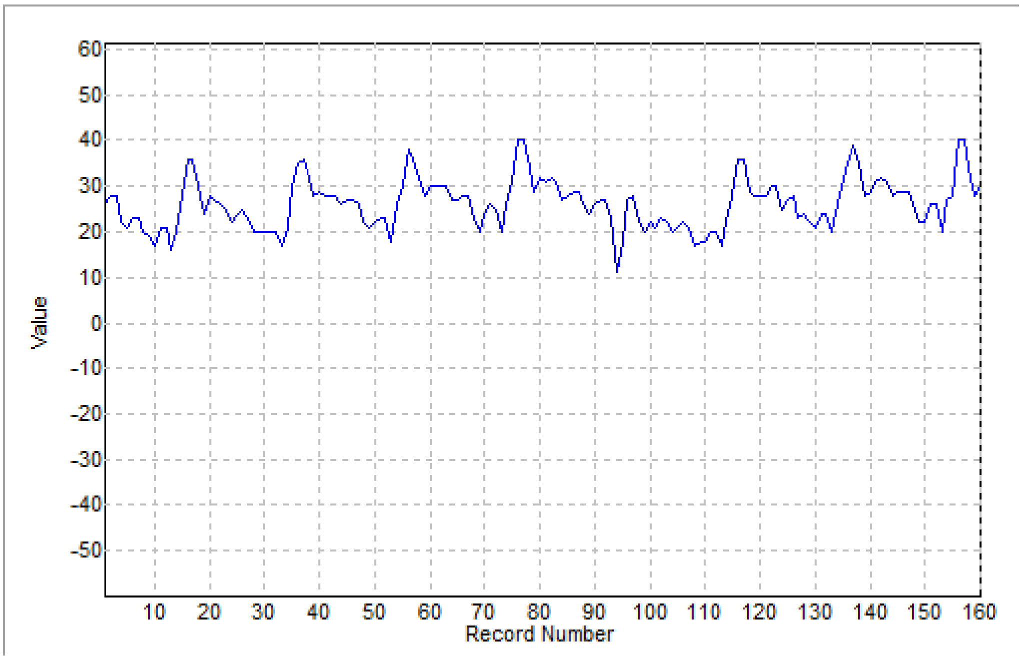


Figure 4.12: For distance 0.428 cm and 20000 Hz

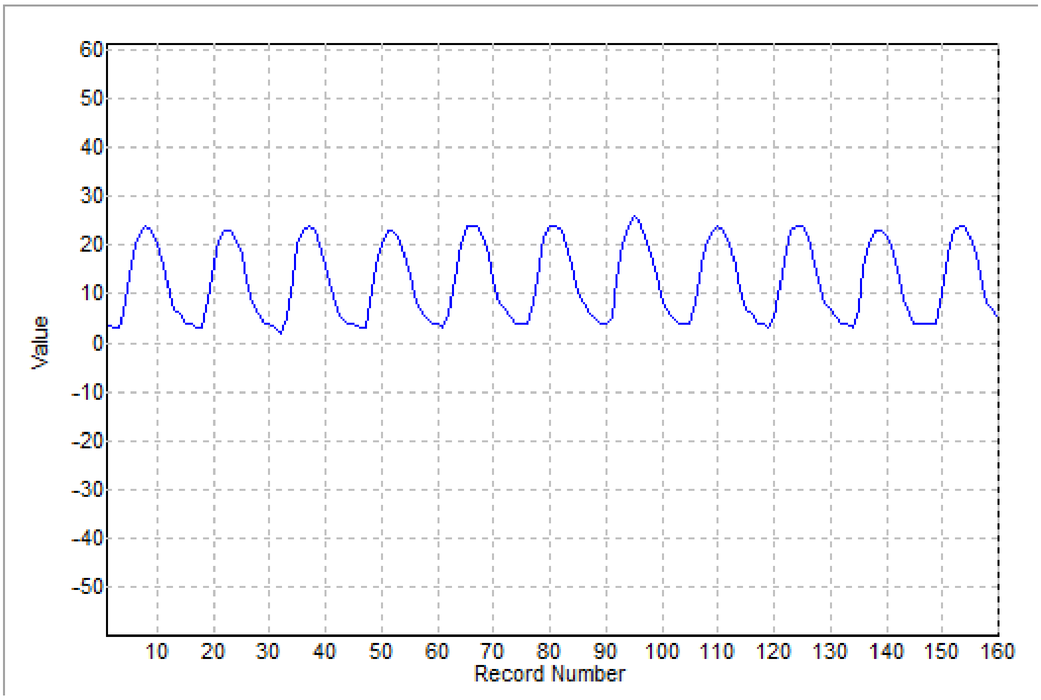


Figure 4.13: For distance 12.4636 cm and 688 Hz

4.3. Case Three (3)

As a result of the experiment, the effect of temperature on piezoelectric material was examined. In the review, some of the piezoelectric materials increase the energy produced with the increase of the temperature. Still, in some materials, the rise in the heat causes the decrease of the produced energy. It is shown in Figure 4.14 below. As seen in the figure, it is understood that the energy produced by the plate material increases with the increase in temperature. The energy produced decreases with increasing temperature in Buzzer. Temperature rise is not suitable for every material.

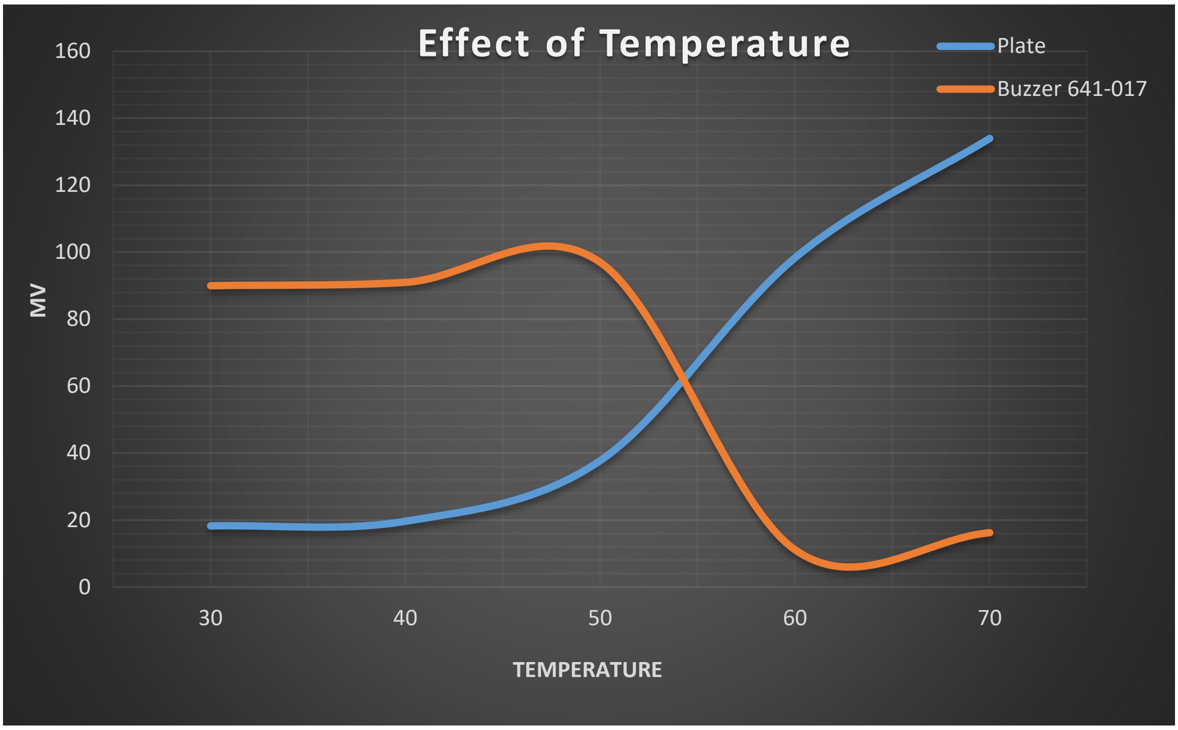


Figure 4.14: Effect of Temperature

The temperature was not used more than 70 ° C. Because the plate material becomes irregular at temperatures above 70 ° C. So this irregular is called pyroelectric. It can be defined as temporarily generating a voltage when a pyroelectric material is heated or cooled. The change in temperature becomes such that the positions of the atoms in the crystal structure change, the polarization of the material. This polarization change creates a tension between the crystals. If the temperature remains constant, the pyroelectric will slowly disappear due to leakage current.

Temperature [˚C]	Plate	Buzzer	Unit
30	18.2	90	mV
40	19.6	91	mV
50	37.7	97	mV
60	98.3	11.1	mV
70	134	16.2	mV

Table 4.6: The amount of voltage produced with temperature.

CHAPTER 5

5. Conclusion and Future Work

5.1. Conclusion

Energy has been used in different forms since the day it was discovered and has progressed to the present day. Energy mechanical, kinetic, potential, electricity, etc. available in forms. Human beings will need these forms of energy during their lifetime. For example, it has generated electricity by leaving the water from a certain height. In other words, it transformed mechanical energy into electricity and gained people's lives easier. One of these conveniences is the piezoelectric material discovered by the Curie Brothers in 1880. Piezoelectric materials have many places in the military field, vehicles, and even in our daily life.

In this thesis, the energy collection capabilities of piezoelectric materials with different geometries have been investigated. Three different ways were followed in the experiments. The first experiment was studied with free methods. At the end of this study, plate material has higher efficiency than the bending element. Because the plate material is PZT. So handmade is a material with higher efficiency. Therefore, if it is to be worked freely, high efficiency is obtained from the plate material.

In the second experiment, the effect of distance on piezoelectric materials was examined. Measurements were made between 0- 20 kHz. Since the data received from 20 kHz at the end of the experiment was obtained with higher energy, the data from other frequencies were ignored. One hundred data records were entered for each material and averaged these data. According to the calculated average, the highest efficiency material was determined as plate material at a rate of 70.4%. For the two buzzers used, the buzzer code 641-017 was determined as 13.5% and the buzzer code 641-003 was determined as 13.2%.In this case, the efficiency of these two buzzers can be considered equal. Finally, the efficiency of the bending element was determined as 2.9%. Although their distances are equal, the efficiency of the material is important to their type and size.

In the third experiment, the effect of temperature on piezoelectric material was examined. Two different size materials were used in this experiment. The first is the plate and the second is Buzzer. These two materials were chosen because the efficiency of these two materials is higher than the others. Buzzer material provides better electricity production at

30 ˚C than plate material. However, this situation changes after 50 - 55 ˚C. The plate material at 60 ˚C and 70 ˚C produces better electricity than the buzzer.

The best efficiency of piezoelectric materials with four different dimensions examined was taken from the plate. However, the geometry and dimensions of these materials may be different, but the desired efficiency may vary depending on where they are used.

5.2. Future Work

The work of this thesis in the future is a beginning for conducting experiments on the use of piezoelectric materials with acoustic effect in different fields. These works can be in military, space and our daily lives. For example, friction occurs due to air during the rotational motion of satellites in space. Piezoelectric materials can be used in suitable places on the satellite by generating energy with the friction that occurs. Along with the noise of vehicles in traffic, piezoelectric materials generate energy and can be used for lighting. Finally, there is nobody in the world who doesn't like football. If these devices are placed in the stadiums, when the fans cheer, energy is produced along with the acoustic effect and this energy can be used there.

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