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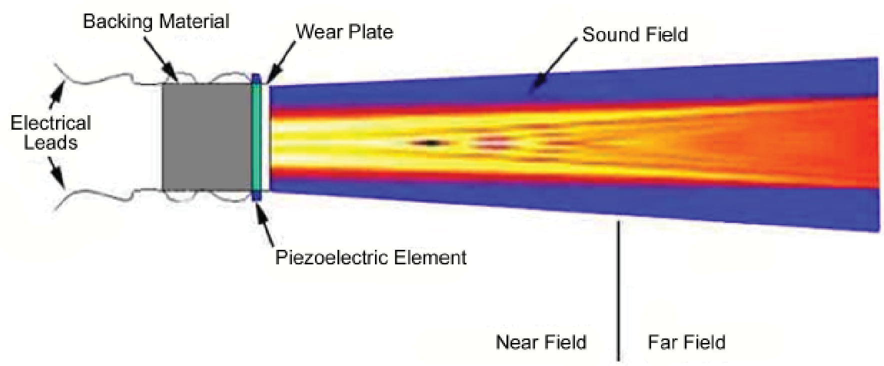

AN INVESTIGATION ON PVDF PIEZOELECTRIC ELEMENTS AND LINEAR ARRAY TRANSDUCERS

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MASTER’S DISSERTATION

AN INVESTIGATION ON PVDF PIEZOELECTRIC ELEMENTS AND LINEAR ARRAY TRANSDUCERS

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Abstract

Ultrasonic waves are widely used in different application e.g. for sonar scanning in water and fetal imaging. Furthermore it is used for doing measurements on different materials to determine the thickness of the material or the velocity of sound inside it. The ultrasonic waves are produced and detected by using piezoelectric elements based on e.g. Polyvinylidene fluoride (PVDF)-film or Lead Zirconate Titanate (PZT)-elements. In this thesis project the aim has been to do measurements on different materials and then develop a linear array transducer based on the use of PVDF-films. Three different methods have been studied to do the measurements on different materials. The first method has been to use a commercial product (ultrasonic (US) key and software from Lecoeur), the second method has been to use the same US-key but in combination with MATLAB. The US-key is an ultrasonic device which is connected to ultrasonic transducer(s) to emit and detect ultrasonic waves. The software was used for displaying plots from the measurements. Finally, the third method involved the use of a generator and an oscilloscope. It has been found that the first and second methods did not work properly to make the linear array transducer because the US-key produced a noise artifact during measurements. The linear array transducer was made by using two industrial ultrasonic transducers of 1-MHz which were connected to the generator and three PVDF-films used as receivers and connected to the oscilloscope. The linear array transducer was built up to use it for examining a specific material-aluminum. It was found that aluminum is the best material to be used to do the ultrasonic testing because of its low attenuation of the ultrasonic waves.

Keywords:

Ultrasonic Transducer, Piezoelectric Element, PVDF, Frequency, Ultrasound Wave Penetration, PZT, Acoustic Impedance, raw data, linear array transducer.

Sammanfattning

Ultraljudsvågor används i många olika tillämpningar, t.ex. som sonar i vatten och för fosterdiagnostik. De kan också användas för att göra mätningar på olika material för att bestämma materialets tjocklek eller ljudets hastighet i materialet. Ultraljudsvågorna produceras och detekteras med hjälp av piezoelektriska element, t.ex. polyvinylidenflourid (PVDF)-film eller så kallade PZT-element (bly-zirconium-titan). I detta projekt har målet varit att göra mätningar på olika material och sedan utveckla en omvandlare av PVDF-film. Tre olika metoder har studerats för att göra mätningarna på olika material. Första metoden har varit att använda en kommersiell ultraljudsutrustning (”US-key” och programvara från Lecoeur), den andra metoden har varit att använda samma hårdvara (”US-key”) i kombination med MATLAB. Hårdvaran är en ultraljudsenhet som ansluts till en eller två ultraljudsgivare för att producera och detektera ultraljudsvågor. Lecoeur-programvaran används för att plotta mätvärdena. Slutligen har en tredje metod provats genom att använda en generator och ett oscilloskop. Det har visat sig att den första och andra metoden inte fungerade bra för att bygga omvandlaren eftersom den kommersiella hårdvaran skapade störningar när mätningarna gjordes. Omvandlaren har därför byggts genom att använda två 1-MHz ultraljudsgivare som har anslutits till en generator och tre PVDF-filmer som mottagare som har anslutits till ett oscilloskop. Omvandlaren har sedan använts för att undersöka ett specifikt material - aluminium. Aluminium har en låg dämpningskoefficient som gör att ultraljudsvågorna inte dämpas för mycket.

Acknowledgments

This master thesis has been carried out at Lund University, Sweden. I want to give many thanks to Stefanos Athanasopoulos and to my supervisor Delphine Bard for their guidance and support in the making of this thesis work.

I also want to thank my family for their support.

Lund, April 19, 2017

Ali Alkhudri

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Chapter 1

Introduction

1.1. Background

The definition of sound is expressed as the variation of the pressure in air particles. There are three types of sound frequencies. The first type is infrasound which is below 20 Hz. The second type is sound hearable by humans (between 20 Hz to 20 kHz). The third type is ultrasonic sound which refer to frequencies above 20 kHz that humans cannot hear [1]. Ultrasound waves (ultrasonic waves) were firstly used in 1917 to detect submarines in the First World War. In 1949, it was firstly used for medical imaging of human organs [2, 3]. Before the 1970's ultrasound machines could only image the outer shell of the examined materials, since that the usage of ultrasound was developed to examine the inner of the examined materials [4].

A well-known application for using of ultrasonic waves is for fetal imaging. It is very common in some countries, 97% in Sweden, although less common in others (20% US) [4, 5]. Here are some benefits of the usage of the ultrasound waves:

- It is an inexpensive, easy, and painless to do ultrasound imaging [6].
- It is not a harmful radiation as like X-ray radiation [6].
- It is a noninvasive method to do imaging. It means there is no need for injections [6].

Apart from medical use, ultrasound is also used in ocean sonar scanning, microphones, motion detectors for measuring distance, welding of plastic, ultrasonic cleaning to get rid of impurity from certain devices and researching purposes. Different frequencies for ultrasonic waves are applied for different applications for imaging of different things. The following table shows the range of used ultrasonic frequencies in some situations:

Table 1. Ultrasound frequencies in sonar, pregnancy scan and animal communication.

Medium	**Frequency range**
Sonar scanning in water [7]	600 kHz
Fetus imaging [1]	5-7 MHz
Communication and navigation by bats or dolphins [8]	20-100 kHz
Rocks	150 kHz

There are different types of ultrasonic transducers and each one is used for a specific application. Some of them are used for measurements on rocks with low ultrasonic frequency of 100-kHz. Other transducers of 1-MHz frequency are used to do measurements on metals e.g. aluminum and steel. The application of the ultrasonic transducer is decided by the shape and frequency of the ultrasonic transducer [9]. In most of the ultrasonic testing, the range of frequencies which are used is 0.1 to 15 MHz with short pulses.

The generation of ultrasonic waves is done by using piezoelectric elements. There are multiple piezoelectric materials which can be used to produce ultrasonic waves. The most common piezoelectric materials include [10]:

- Crystals: e.g. quartz (SiO_2)
- Ceramics: e.g. lead zirconate titanate (PZT)
- Polymers: e.g. polyvinylidenfluoride (PVDF)

In this thesis work, the focus will be to do measurements on metals by using different frequencies of ultrasonic waves. When voltage is applied between the electrodes of a piezoelectric element it vibrates leading to generation of ultrasonic waves, see figures 1, 2. The frequency and wavelength of the produced ultrasonic waves is fixed which means that it cannot be changed during the procedure of the measurement.

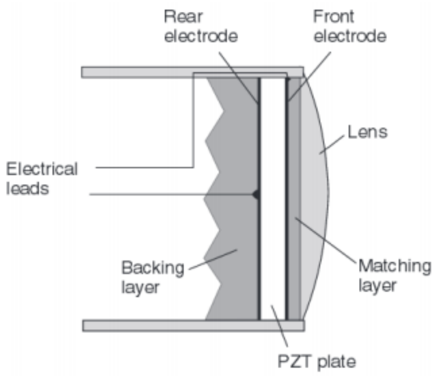

Figure 1. The design of an industrial ultrasonic transducer with PZT-plate [3].

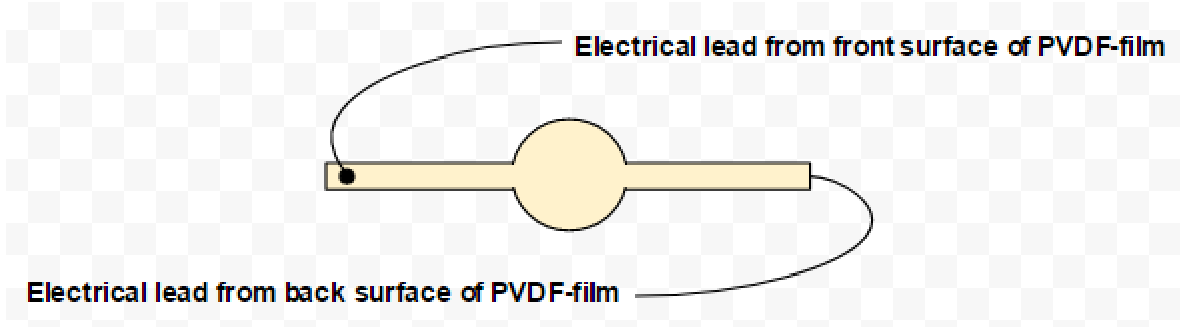

Figure 2. The design of an ultrasonic transducer with PVDF-film.

In this project, PVDF piezoelectric elements will be used to make the linear array transducer. The basic design of the linear array transducer that it will have at least one industrial ultrasonic transducer as emitter and two receivers of PVDF-film. The PVDF-film will be cut in different shapes, see table 2. The purpose of that is to determine the best shape of the PVDF-film to use it in linear array transducer. The PZT-elements were used to make a comparison with the PVDF-film and the industrial transducers.

Table 2. Names of Transducers and Piezoelectric Materials which were used to do measurements.

Transducers and piezoelectric materials	Note
5 MHz-industrial transducer	All can work as emitter, receiver, or both at the same time
500 kHz- industrial transducer	
Two 1 MHz- industrial transducers	
PVDF-film of 110 µm thickness of square form 2*2 cm^2	
PVDF-film of 110 µm thickness and 1*1 cm^2	
PVDF-film of 110 µm thickness and 1.25*1.25 cm^2	
PVDF-film of 110 µm thickness and 1.5*1.5 cm^2	
PVDF-film of 110 µm thickness and 1 cm of diameter	
PVDF-film of 110 µm thickness and 1.25 cm of diameter	
PVDF-film of 110 µm thickness and 1.5 cm of diameter	
PZT of 1 MHz with diameter of 2.45 cm	
PZT of 2 MHz with diameter of 2.45 cm	
PZT of 5 MHz with diameter of 2.45 cm	

The samples which will be used in this thesis work are rock, bright drawn steel, manufactured steel, plastic, aluminum and silicone. All the samples will be examined by different ultrasonic frequencies by using different piezoelectric elements and transducers as shown in the above table.

The main idea of sending ultrasonic waves through a sample is to detect the thickness of the material or detect cracks and flaws in the material. The thickness of the material can be calculated by measuring the time difference between the reflected ultrasonic waves from the front surface of the material and the back surface of the material. The following formula shows how the thickness is calculated:

$$Thickness = ct \quad (1)$$

Where c is the sound velocity in the material and t is the time difference. Ultrasonic waves can also be used to determine the physical properties of the material such as sound speed in the material or the attenuation coefficient of it.

1.2. Thesis goal and research questions

The main goal of this thesis is to make a linear array transducer for testing it on a specific sample. The linear array transducer will have multiple receiving channels for detecting ultrasonic waves. The receiving channels will be made by using PVDF-film to detect the ultrasonic waves. There will be several types of industrial ultrasonic transducers, PZT-elements, circular PVDF-film and square PVDF-film will be tested on several materials, see table 2. The experiments, measurements and theoretical research will be used to answer the following questions:

1) How does a piezoelectric element work?
2) Does the shape of the piezoelectric element affect the measurements?
3) What is the difference between different piezoelectric materials?
4) Does the thickness of the piezoelectric element matter?
5) What is the relation between a transducer's frequency and the attenuation in the examined material?
6) Is it possible to make a simple transducer by using a piece of piezoelectric element?
7) What is the advantage of using ultrasound couplant in ultrasonic testing?
8) Is it possible to make a linear array transducer having multiple receiving channels for detection of ultrasonic waves?

1.3. Report outline

In Ch. 2 the general theory of piezoelectricity and the design of an industrial ultrasonic transducer are explained in detail with figures for clarification. Ch. 3 representation of the tools that have been used in this thesis work. Ch. 4 shows the tables and measurements that have been done in this thesis work. Furthermore, different designs of the linear array transducer are presented in chapter 4. The results of this thesis work are presented in Ch. 5. In Ch. 6 it demonstrates the conclusions of the results of this thesis work. The limitation of this thesis work is also mentioned in this chapter. Last thoughts and future work are also presented in Ch. 6.

Chapter 2

Theory

2.1. Piezoelectric Phenomenon

Piezoelectric elements such as lead zirconate titanate (PZT) or polyvinylidenfluoride (PVDF) are polarized materials which means that they contain positive and negative charges. Generally, all types of piezoelectric elements are aligned electric dipoles so that the positive and negative charges are easily separated from each other. The unit cell of atoms of a piezoelectric element is not symmetrical and the charges of the crystal (element) is always in a neutral state. It means that the positive charges in the piezoelectric crystal cancel out the negative charges. When the piezoelectric element is squeezed, or stretched then the positive charges move to one side and the negative charges move to the other side of the piezoelectric element. That occurs because the structure of the piezoelectric element is deformed and its charges are not neural anymore. The piezoelectric element becomes electrically charged as a battery, see figure 2. In general, voltage potential is produced across the piezoelectric element when it is stretched or squeezed. Same thing happens when voltage is applied across the piezoelectric element, its structure deforms and ultrasonic waves are produced [11, 12, 13], see figure 3.

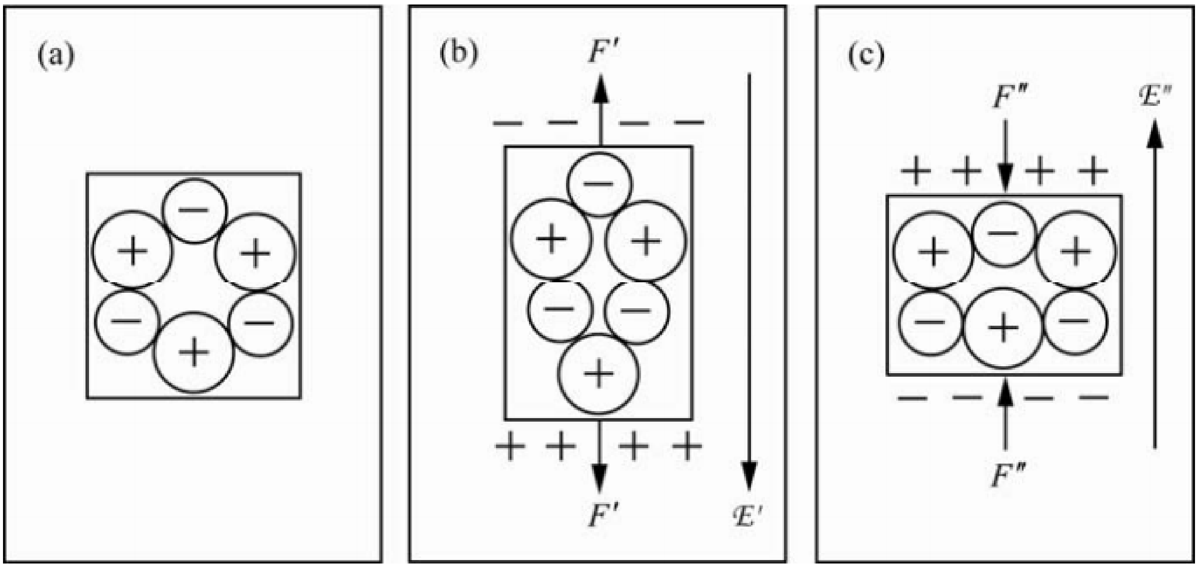

Figure 3. Representation of the piezoelectric material; (a) piezoelectric material in normal condition, (b) generation of negative and positive charges when force F' stretches piezoelectric material or electric field E' is applied across it, (c) inverted poles when force F" compresses piezoelectric element or electric field E" is applied across it [14].

2.2. Generation and Detection of Ultrasonic Waves by Piezoelectric Elements

A piezoelectric element is a mechanical device which can convert energy from one form to another one, see figure 4. It converts electrical energy to mechanical or mechanical energy to electrical [11]. Piezoelectric elements are used in all ultrasonic transducers.

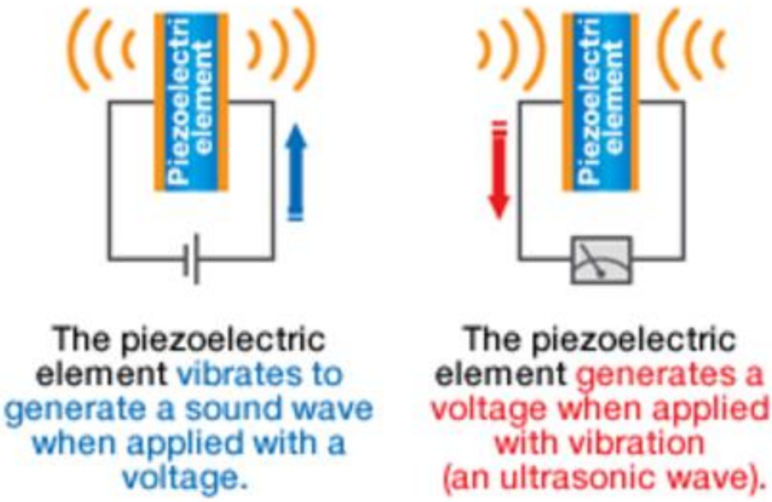

Figure 4. The vibration of the piezoelectric element in two different cases [11].

The above figure shows that the piezoelectric element produces ultrasonic waves when voltage is applied across it. The piezoelectric elements also produce voltage when ultrasonic waves hit its surface. The ultrasonic waves press the surface of the piezoelectric element which can lead to generation of voltage.

A piezoelectric element can generate ultrasound waves when DC voltage is quickly applied and removed from the two electrodes of the piezoelectric element. The applied voltage makes the piezoelectric element change its size and its surface starts to vibrate up and down, at that moment the piezoelectric element will resonate at its resonant frequency [15].

The process of generation of ultrasonic waves from a piezoelectric element is the following:

Electrical pulse → Mechanical vibration → Ultrasonic wave generation

On the other hand, when the ultrasound waves hit the surface of the piezoelectric element at that moment its surface starts to vibrate and that results in generating of electrical pulse, see figure 3. The process of detection of ultrasonic waves in an ultrasonic transducer is the following:

Reflected ultrasonic wave → Mechanical vibration → Electrical pulse

The delivered power from the ultrasonic transducer is expressed in milliwatts and it is dependent on the applied voltage across the piezoelectric element with almost no current is applied to the transducer.

2.3. Speed and Wavelength

The definition of ultrasonic speed through a material is the vibration of the kinetic energy passed from one particle to another particle. The ultrasonic speed is different in various materials, see table 3. When the particles in a material are too close to each other and tighter their bonds then the ultrasonic speed is increased in that material. The studies show that the velocity of the ultrasonic waves in different samples is depending on many factors e.g. size of the sample, elastic properties, density, porosity and how many different minerals are embedded in the sample [22, 23].

The ultrasonic speed in a material affects the beam spread of the ultrasonic waves when it propagates through the sample. A higher ultrasonic speed gives a wider beam spread while a slower ultrasonic speed gives a narrower beam spread.

Table 3. Different speeds of the ultrasound waves in varied materials [24].

Material	Speed of sound in m/s
Dry air	331
Water	1540
Bright drawn steel	6100
Aluminum	6320
Silicone	1485
Rock-Marble	3810
Glass	4540
Gold	3240
Rubber	60

The speed of the ultrasonic wave in a homogenous material is dependent on two factors; the elastic properties of the material and its density as shown in the following formula:

$$c = \sqrt{\frac{C_e}{\rho}} \quad (2)$$

where C_e is the elastic property of the material and ρ is the density [20]. The elastic property describes the stiffness of the material.

Furthermore, the wavelength λ of sound is defined as one cycle of a wave. It is dependent on the frequency of the waves and its velocity. A high frequency gives a short wavelength while a low frequency gives a long wave length. The relation between the ultrasonic wavelength and its speed is expressed in the following formula:

$$\lambda = ct = \frac{c}{f} \quad (3)$$

where t is the period and c is the velocity of the soundwave [20].

2.4. Propagation of Ultrasonic Waves

The propagation of ultrasound waves in a material is dependent on the following factors:

1)The acoustic impedance Z (Rayls) of the material is the ultrasonic waves propagate through it. The formula of the acoustic impedance of a material is calculated by:

$$Z = p_o \cdot c \quad (4)$$

where the p_o is the mean density of the material and c is the velocity of the ultrasonic wave in the material [20]. When the ultrasonic waves penetrate through two different materials with different acoustic impedances then some of the ultrasonic waves reflected to the transducer [17].

The percentage of the reflected ultrasound waves R is calculated by

$$R = \frac{(Z_2 - Z_1)^2}{(Z_1 + Z_2)^2} 100\ \% \quad (5)$$

where Z_2 is the acoustic impedance of the second material while Z_1 is the acoustic impedance of the first material [20]. The percentage of the transmitted ultrasound waves T through the material is calculated by following formula [20]:

$$T = 1 - R \quad (6)$$

2)The attenuation of the ultrasonic wave when it propagates through a material. The propagation leads to loss of energy of the propagated waves because of scattering and absorption in the material, that can cause reducing of the intensity of the propagated ultrasonic waves. The definition of the attenuation is described as scattering of ultrasonic waves plus damping of ultrasonic waves in the examined material. Scattering is the reflection of ultrasonic waves in random directions while absorption is the conversion of ultrasonic energy to other types of energy. The effect of scattering and absorption in a specific material is called attenuation [20].

The internal friction and thermal conductivity of the examined material can lead to energy losses of the propagated waves because of its energy is converted to thermal heat. The scattering of waves is more relevant for metals because they made of randomly oriented grains. If the size of one grain is 20 times less than the wavelength of the ultrasonic wave, then the relation between the attenuation coefficient and the frequency becomes linear [25].

Generally, each material has its own attenuation coefficient, see table 4. The higher the attenuation coefficient, the higher the attenuation of the propagated ultrasonic waves inside the material, see figures 5, 6.

Table 4. Attenuation coefficients for different materials at 1 MHz frequency [18].

Material	Attenuation coefficient (dB/(MHz cm))
Bright drawn steel	$434 \cdot 10^{-7}$
Aluminum	$434 \cdot 10^{-8}$
Marble	9.5
Rock	15

When ultrasonic waves propagate through two materials with different sound velocities, at that moment the amplitude of the ultrasonic waves decrease if the second material has a lower sound velocity than the first material. The lower sound velocity you have, the shorter the wavelength you get, see equation *(3)*. That is why the attenuation is greater in the second material.

Furthermore, the temperature of some materials can give to an increased attenuation. Gases and liquids with hot temperature decrease the velocity of ultrasonic propagation and that causes a higher attenuation but it is vice versa in water [25].

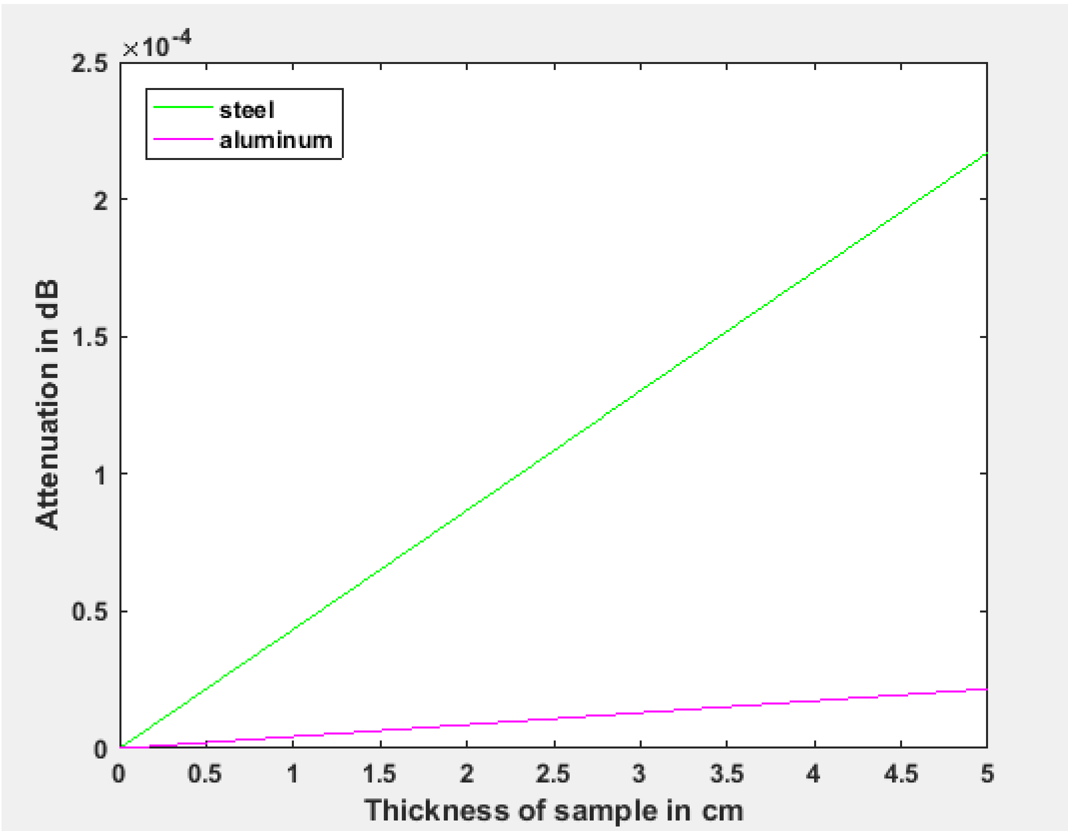

Figure 5. Attenuation in different thicknesses of a bright drawn steel sample and an aluminum sample.

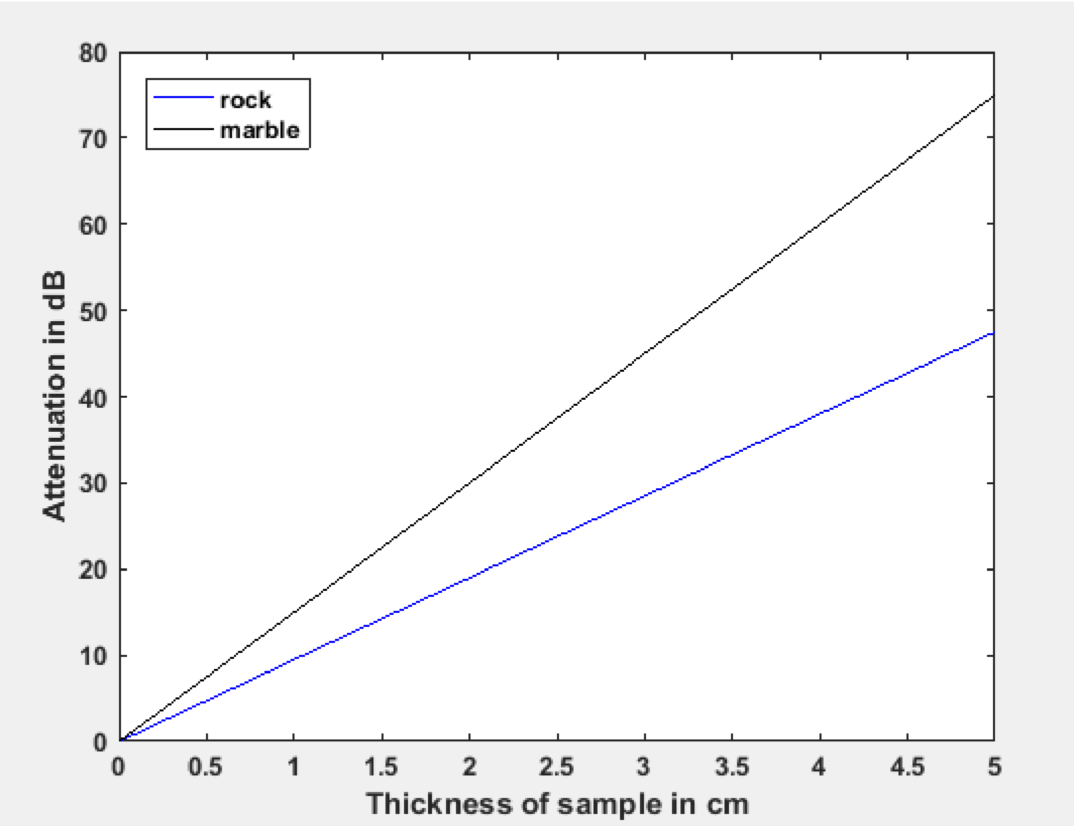

Figure 6. Attenuation in different thicknesses of a rock sample and a marble sample.

3)The frequency of the transducer. As mentioned before that each sample should be examined with a specific frequency to get the purest image results, otherwise the image resolution will be too poor or there will be no detection at all. Every sample should be examined with the correct frequency of the ultrasonic waves. The attenuation coefficient in each sample determines how much the ultrasonic waves are attenuated. High frequency is more attenuated in the materials of high attenuation coefficient because its wavelength is too short.

The usage of high ultrasonic frequencies has some benefits in comparing with low ultrasonic frequencies. High ultrasonic frequencies give a good resolution of the examined material while the penetration of the ultrasonic waves is reduced because the waves are easily attenuated. The reason is that its wavelength become very short and its energy become too low that is why high ultrasonic waves are easily attenuated (absorbed) in the rock and marble, see figure 7, 8. On the other hand, low ultrasonic frequencies are used for examining deep mediums because they are not easily attenuated. The disadvantage of low ultrasonic frequencies that they give inferior resolution when they compared to high ultrasonic frequencies [8]. The next table shows the attenuations of the ultrasonic power in relation with different ultrasonic frequencies for varied materials. The following table is showing the recommended frequencies for doing measurements on different materials:

Table 5. The recommended ultrasound frequencies on varied materials [26].

Material	Recommended frequency	Notes
Metals in general	0.1-15-MHz	It depends on the thickness of the metal. If it is too thick then low frequency is preferred otherwise higher frequency is preferred.
Aluminum	1-MHz	Even higher frequencies give reliable results.
Wood	50-200-kHz	
Silicon in breast	3.5-5-MHz	
Rock	50-700-kHz	High frequencies are disapproved because the attenuation is too high.
Water	1-MHz	Higher frequencies are not highly attenuated in water.
Glass	1-MHz	
Lucite (a transparent plastic)	1-MHz	
Steel	900 kHz	Even with higher frequencies are possible to be applied.

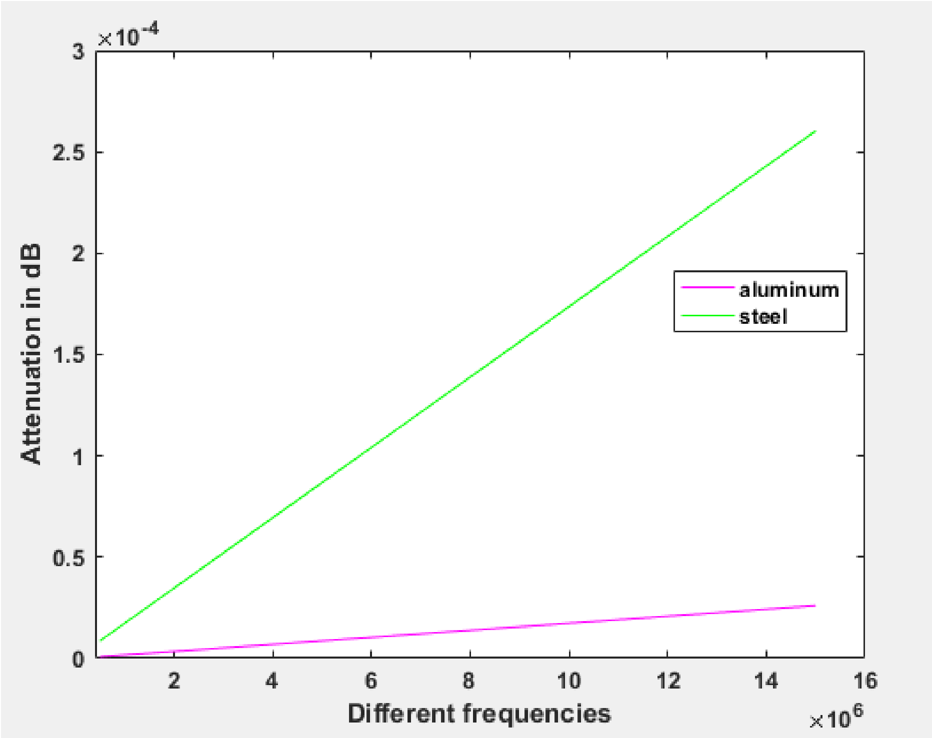

Figure 7. Attenuation with different frequencies in aluminum and bright drawn steel samples.

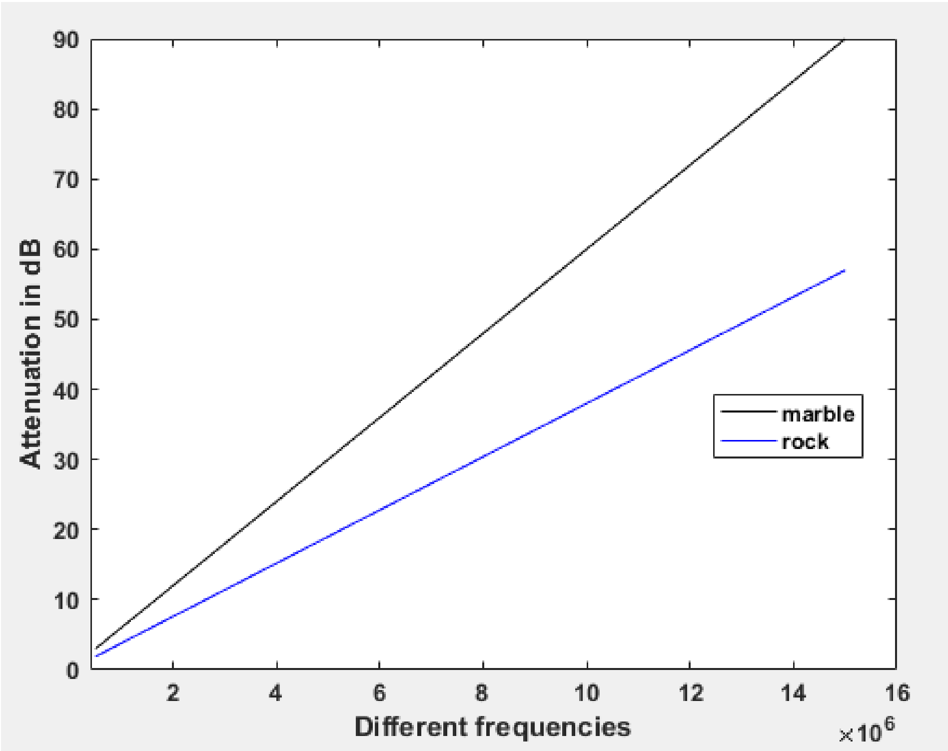

Figure 8. Attenuation with different frequencies in rock and marble samples.

2.5. Basic Design of an Ultrasonic Transducer

The main idea behind the design of ultrasonic transducers is the shape and thickness of the piezoelectric element of the transducer. The shape of the piezoelectric element defines how much is the transmitted ultrasonic waves are focused while the thickness of the piezoelectric element defines the frequency of the transmitted ultrasonic waves, no matter what kind of piezoelectric material it is.

The frequency of the ultrasonic waves determines the spread shape of the ultrasonic waves. A low frequency of ultrasonic waves gives a wider field while a high frequency gives a narrower ultrasonic field [16], see figure 9. If the diameter of the piezoelectric element is large in the transducer, that will provide a better focusing of the transmitted ultrasonic waves.

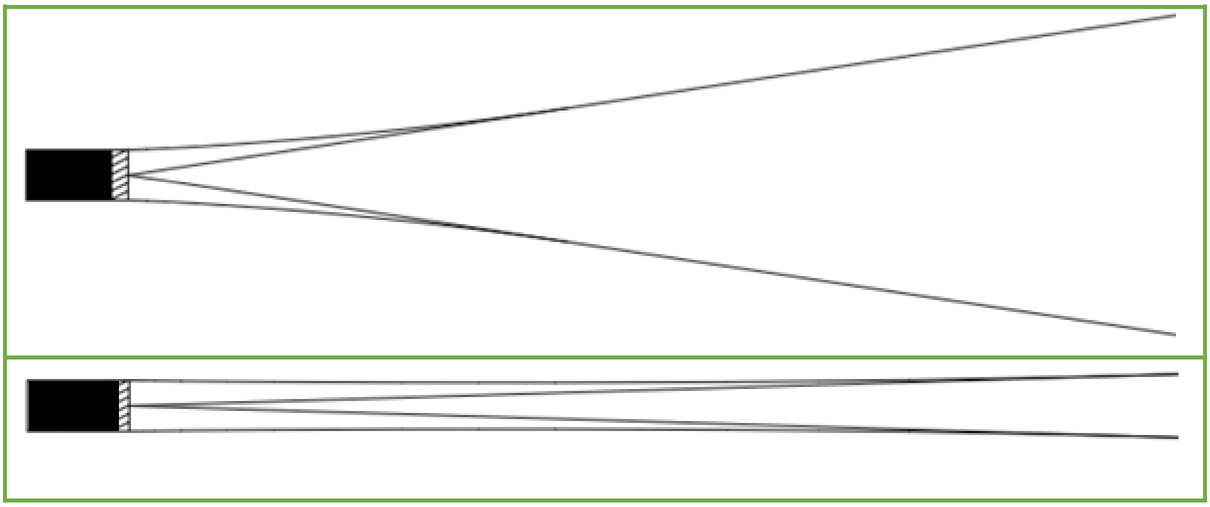

Figure 9. Two beam spread of ultrasound waves for two transducers with the same diameter. The above beam shows the spread of 1-MHz transducer while the below beam shows the spread of 5-MHz transducer.

The beam angle of the ultrasonic waves, see figure 10, can be calculated by using the following formula:

$$\sin(\theta) = 1.2\frac{V}{Df} \qquad (7)$$

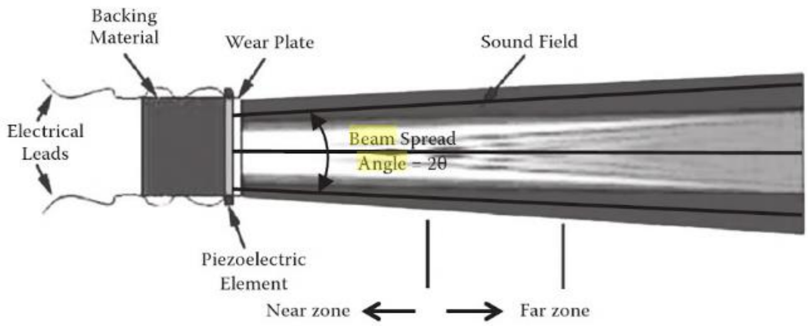

Figure 10. Beam spread of ultrasonic waves from an ultrasonic transducer [16].

where θ is the beam divergence angle as shown in figure 5, V is ultrasound velocity in the examined material, D is the diameter of the ultrasonic transducer and f is the frequency of the transducer [16].

The diameter of the piezoelectric element is important in making of ultrasonic transducers. In figure 11, the shape of the piezoelectric element is in circular form. It shows that a larger diameter of the piezoelectric element gives a better focusing of the transmitted ultrasonic waves in the examined material.

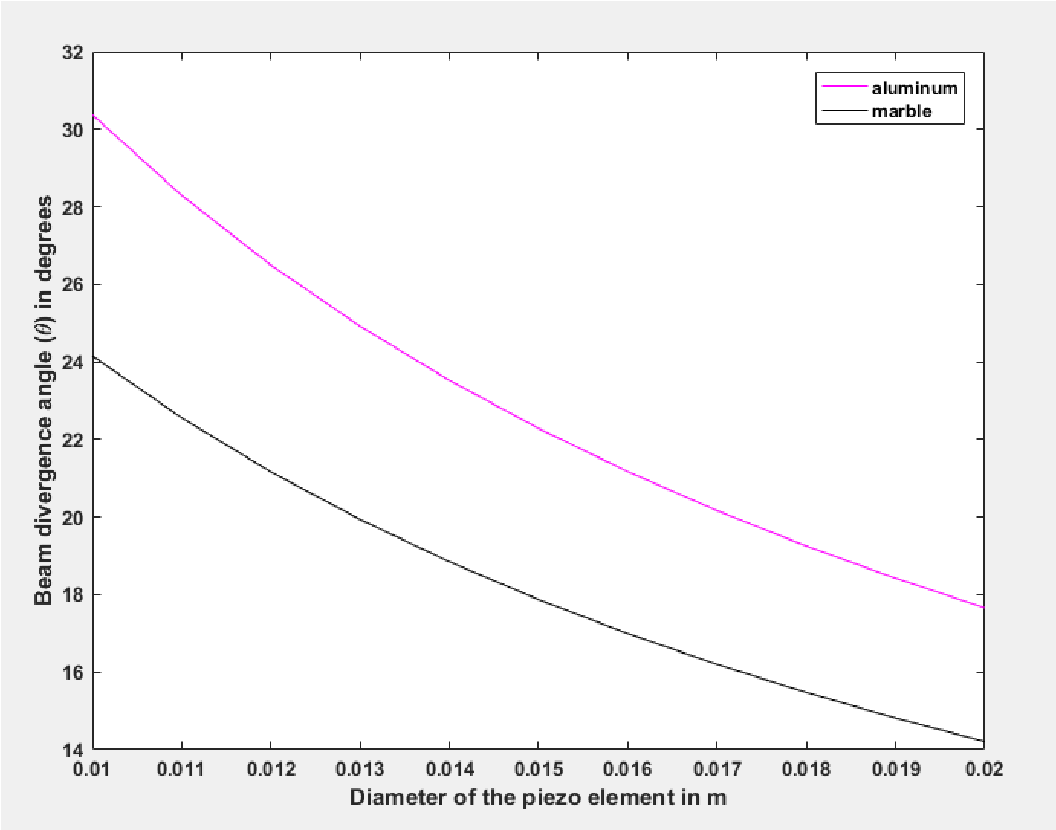

Figure 11. Beam spread angle of the transmitted ultrasound waves. θ shows half the beam spread angle of the transmitted ultrasound waves in aluminum and marble from a transducer of 1-MHz frequency with different diameters of the piezoelectric element.

On the other hand, different thicknesses of piezoelectric elements give rise to different ultrasonic frequencies of ultrasonic transducers. In the below figure, it is obvious that the thickness of 10-MHz transducer is less than the thickness of 1-MHz transducer of PVDF-films. The thickness of the piezoelectric element should be $\lambda/2$ of the transmitted ultrasonic waves to achieve the desired resonance frequency, where λ is the wavelength of the transmitted ultrasonic waves.

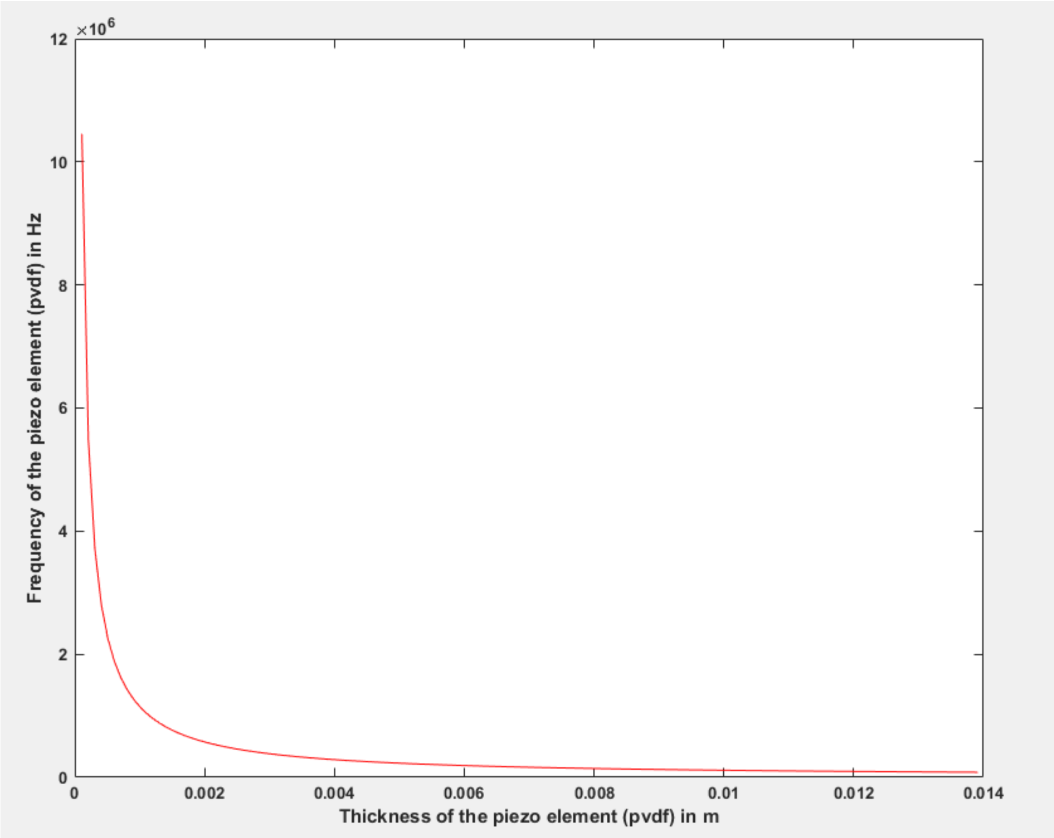

Figure 12. The relation between resonance frequency and thickness of the PVDF piezoelectric element.

Generally, all the ultrasonic transducers consist of the following components:

- A piezoelectric element
- A backing layer
- A matching layer

It should be noted that some transducers have a lens in front of the transducer to give a better focusing of the transmitted ultrasonic waves in the examined material, see figure 1.

The purpose of having a backing layer is to allow the ultrasonic waves to propagate away from the piezoelectric element with as little reflection as possible. It also provides damping to give the transducer a flatter frequency response [17].

The purpose of having a matching layer is to improve the transmission of the ultrasonic waves from the piezoelectric element to the examined material by reducing the matching acoustic impedance mismatch between the piezoelectric element and the examined material. The length of the matching layer should be $\frac{\lambda}{4}$, see figure 13.

The matching acoustic impedance Z_M is calculated by the following formula [18]:

$$Z_M = \sqrt{(Z_p Z)} \quad (8)$$

Where Z_p is the acoustic impedance of the piezoelectric element and Z is the acoustic impedance of the examined material, see figure 13.

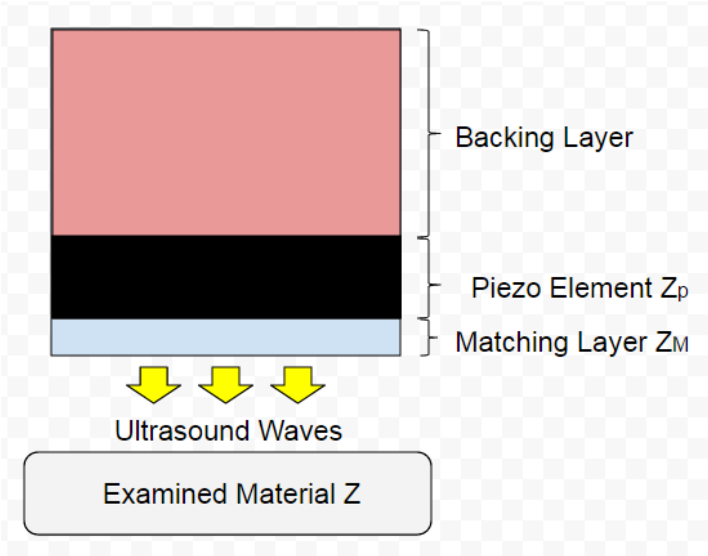

Figure 13. The backing layer and matching layer of an ultrasound transducer. The matching layer should be calculated carefully to allow the most possible ultrasound waves to propagate through it.

2.6. PZT-Element Compared to PVDF-film

Commonly PZT elements of high quality are more common than PVDF-film in the making of ultrasound transducers, because of its high piezoelectric stress coefficient. High piezoelectric stress coefficient produces high acoustic power when a low electrical input is applied across the PZT element, see table 6. This advantage makes it easier for the PZT transducer to detect the reflected ultrasonic waves from the examined material because the amplitudes of the reflected waves are high.

Table 6. The acoustic impedance and stress coefficient of different piezoelectric materials [18].

Material	Acoustic impedance (kg/mm2 s)	Stress coefficient (N/V m)
Quartz	15	0.17
PZT	33	9.2
PVDF	3.9	0.069

On the other hand, PVDF-film has also some benefits e.g. it has a good strength properties, good electrical properties, very thin and it has a homogenous piezoelectric activity. In general, PVDF elements are much more expensive than the PZT elements because of that PVDF elements are used to produce a very high ultrasonic frequency up to tens of megahertz.

On the other hand, the efficiency of all piezoelectric elements is determined by comparing the amount of the input power to the transducer to the amount of the output energy of the transducer. In case when the amount of the output power is close to the amount of the input power, it means that the piezoelectric element is efficient otherwise it is less efficient. Because of low efficiency, the produced image by using such piezoelectric element is less accurate and reliable [15]. The common advantage of all piezoelectric elements that they offer a wide dynamic range and they are broadband materials.

2.7. Frequency Response of Piezoelectric Elements

The Frequency of an ultrasonic transducer is dependent on the thickness of the piezoelectric element. In general terms, a thin piezoelectric element has a higher resonance frequency than a thick piezoelectric element of the same composition material, volume, and shape [15,19]. The following equation calculates the resonance frequency of the piezoelectric element [12]:

$$f = \frac{v}{2th} \quad (9)$$

Where f is frequency of ultrasonic waves, v is the velocity of ultrasonic waves in the piezoelectric element (usually v = 2300 m/s for PVDF) and th is the thickness of the piezoelectric element in meter. A piezoelectric element vibrates with a wavelength that is double its thickness, that is why a piezoelectric element is cut to a thickness that it is half the desired wavelength of the emitted ultrasonic wave [8,13,20]. The relation between resonance frequency of the PVDF piezoelectric element and its thickness is shown in figure 7.

2.8. Circular and Square PVDF-film

The golden coated circular and square PVDF-film will be investigated in this thesis work, see figure 14.

Figure 14. Illustration of circular and square PVDF-film.

The biggest difference between using of circular and square PVDF-films is that the near field length of the piezoelectric element is different in circular and square piezoelectric elements. For a circular piezoelectric element, its near field is calculated by the following formula [21]:

$$N = \frac{D^2 f}{4\,v} \quad (10)$$

Where D is the diameter of the piezoelectric element, f is the frequency of the transducer and v is the sound velocity in the examined sample. While the formula for the near field length of a square piezoelectric element is the following [30]:

$$N = \frac{1.35\,D^2 f}{4\,v} \quad (11)$$

Where D is the side length of the piezoelectric element. The near field defined as the area where it is difficult to evaluate flaws in the examined sample. The fluctuation in sound intensity in this area causes an unordered acoustic oscillation of the ultrasonic waves [21]. The longer is the near field, the worse is the transducer. The following table is showing some values of the near field length for two shapes of piezoelectric transducers:

Table 7. Near field length of circular and square PVDF transducers.

Circular transducers		**Square transducers**	
Diameter in cm	Near field length in cm	Side length in cm	Near field length in cm
1	0.40	1	0.53
1.25	0.62	1.25	0.67
1.5	0.89	1.5	0.80

The above table shows different values of parameter D in the equations (10) and (11). The frequency of the transducers is 1-MHz and the ultrasonic testing was applied on an aluminum piece. It is obvious that the higher the diameter is, the longer is the near field length. It is preferred to use a circular transducer but for much bigger values of parameter D it is more efficient to use a square transducer as emitters, because of its near field length is less compared to the circular ones.

2.9. Ultrasound Couplant

The first enemy of ultrasonic waves is air; Air has a low acoustic impedance as shown in table 8. The ultrasonic waves reflect when they encounter air. The acoustic impedance of the ultrasonic couplant should be close to the acoustic impedance of the transducer beam to allow the ultrasonic waves to propagate through it and them to the examined material. There should be no air bubbles in the ultrasound couplant when doing experiments otherwise it is not efficient to use ultrasound couplant [27]. Here is an example of the reflected ultrasonic waves between air and aluminum boundary.

$$\textit{Reflected waves (air to aluminum boundary)} = \frac{(0.0004-17.33)^2}{(0.0004+17.33)^2} 100\ \% \ = 99.9\%$$

This means that 99.9% of the transmitted ultrasonic waves are reflected when they encounter air between the transducer and the aluminum sample. Ultrasound couplant has a very close acoustic impedance to water. Ultrasound couplant makes the ultrasonic waves easily propagated through the couplant and on to the examined material. It means that the reflected ultrasonic waves are much minimized [27].

$$\textit{Reflected waves (couplant to aluminum boundary)} = \frac{(2.42-17.33)^2}{(2.42+17.33)^2} 100\ \% = 56.99\ \%$$

This means that 56.99 % of the transmitted ultrasonic waves reflect when they go through the ultrasonic couplant before they enter the examined aluminum sample.

Table 8. The acoustic impedance of different materials [28].

Medium	Acoustic impedance Z (MRayls)
Air	0.0004
Water	1.48
Aluminum	17.33
Ultrasound couplant (Glycerin)	2.42

The acoustic impedance of the ultrasound couplant is required to be less than the acoustic impedance of the examined material. When that constraint is satisfied, then the ultrasonic waves easily penetrate through the examined sample otherwise there is no penetration of the ultrasonic waves occurs inside the sample.

The propagation of ultrasonic waves is affected by the attenuation coefficient of the examined sample. The more ultrasonic waves propagate through the sample, the more their amplitude is decreasing, see figure 15. The reason for that is the ultrasonic waves are more attenuated and scattered when they go deeper in the sample.

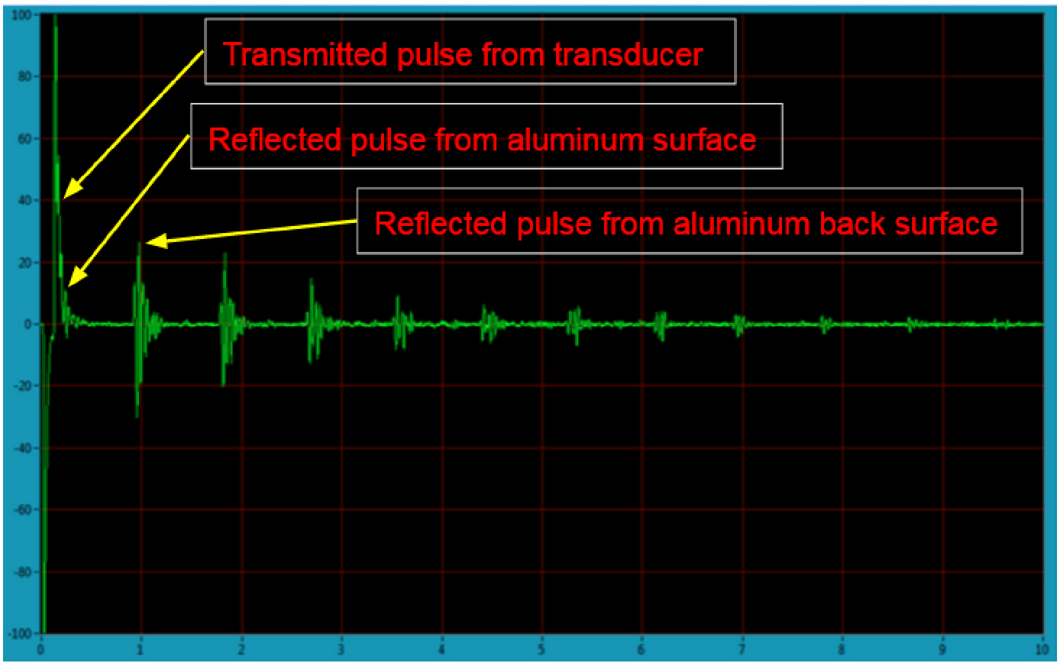

Figure 15. The propagation of ultrasonic waves in an aluminum sample.

Tools and Setups

3.1. Tools from Lecoeur Electrique Company

Lecoeur Electronique is a company which works with ultrasonic testing and producing of ultrasonic devices for researching purposes. US-key is an ultrasound device which is manufactured by Lecoeur Electronique. The US-key can be used to investigate the thickness and physical properties of various materials such as rock, aluminum, plastic, rubber, wood etc. The device has two channels, one for transmitting ultrasonic waves and the other one to receive the reflected waves (echoes) from the examined material. The device is connected to a computer via an USB connector. The power supply from the US-key to the ultrasonic transducer (ultrasound probe) is 5 Voltage DC [29]. Any channel of the US-key could be used in two modes at the same time as a transmitter and a receiver, see figure 16.

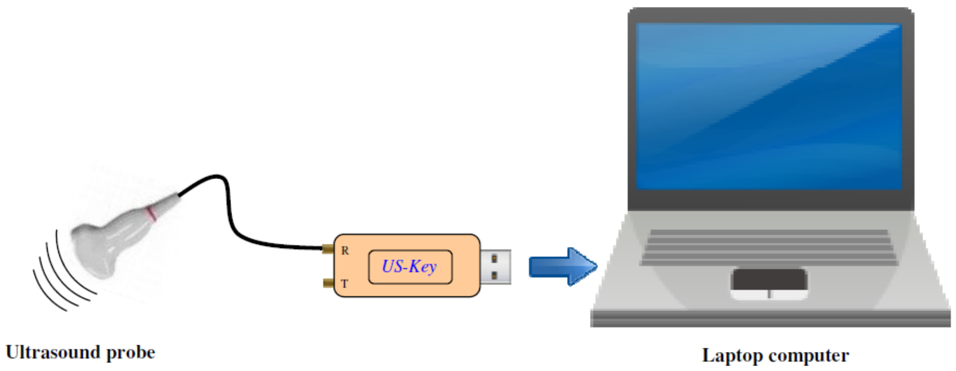

Figure 16. The connection of the US-key to the computer and to the ultrasound transducer (probe) [29].

The basic idea behind the US-key is that it transmits a pulse via an ultrasonic transducer with a specific frequency and plots the reflected pulse in a xy-plane. Different ultrasonic transducers were bought separately from the US-key device. The US-key device can be used with Lecoeur software or with MATLAB. The plotted figures in the Lecoeur software show the amplitude of the reflected pulse on the y-axes while the x-axes represent the distance in mm or the time in µs.

3.1.1. Linear Array Transducer by Using Two US-keys and an Interface Module

The first method for designing of the linear array transducer is by using an interface module and two US-keys. The interface module is a multi-channel block which can be connected to one US-key as shown in the below figure [30].

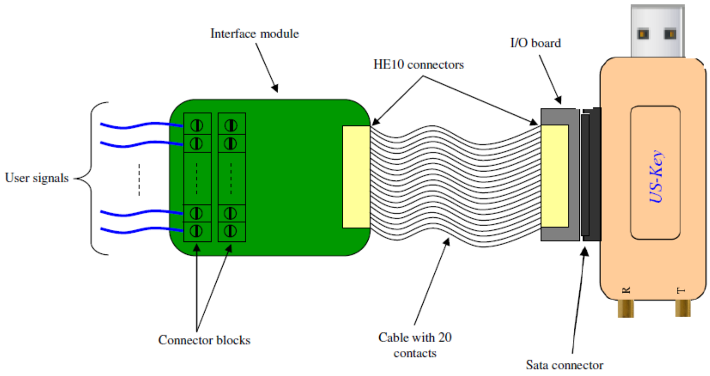

Figure 17. The interface module connected to one US-key [30].

Two US-keys and the interface module are supposed to be used to build up the linear array transducer. The idea of the linear array transducer is shown in the following figure:

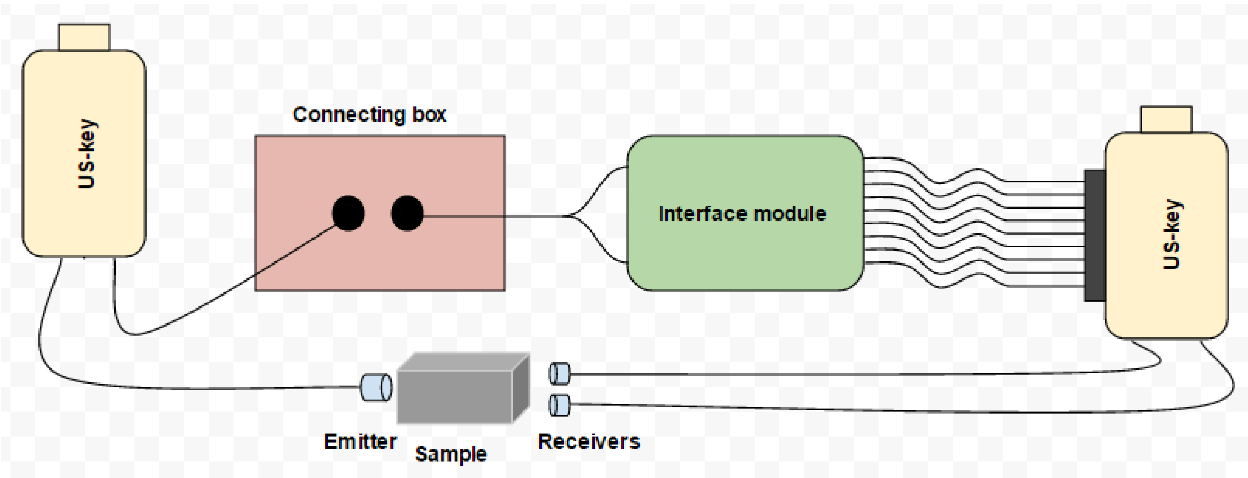

Figure 18. The layout of the linear array transducer with one emitter and two receivers with US-keys.

There the connecting box is an electric circuit with resistors which was designed to connect two US-keys. The connecting box reduces the input voltage from the left US-key to the right US-key.

The linear array transducer is considered to have one industrial transducer as an ultrasonic emitter and two PVDF-films as ultrasonic receivers. The shape of the PVDF- film is decided to be circular of 1 cm of diameter, but then it was changed to be 1.5 cm in diameter. The reason for choosing 1.5 cm in diameter is to detect higher amplitude of the reflected ultrasonic waves when doing measurements. The examined material is decided to be aluminum because it gave readable results.

3.2. Linear Array Transducer by Using a Generator and an Oscilloscope

The second method for designing of the linear array transducer is by using a generator and an oscilloscope. The generator was used to power two industrial 1-MHz transducers. The oscilloscope was connected to three PVDF-film receivers to detect the ultrasonic waves which propagate through the examined sample. The difference between using US-keys compared with generator and oscilloscope is that the oscilloscope does display and save the raw data of the measurements while the US-key does not do that.

The two industrial transducers are connected to two power channels in the generator. Three PVDF-film receivers, each one is connected to a channel in the oscilloscope. Each channel gives its own raw data which can be saved and handled in MATLAB. All the three PVDF-film receivers are made of circular shape with 1.5 cm in diameter. The reason for that is to detect a much signal as possible.

The two industrial transducers transmit ultrasonic waves with same frequency at 1-MHz. The active frequency of the three PVDF-film receivers is at 10-MHz but the PVDF-film could detect even low frequency as 1-MHz without difficulties.

Below is the setup of the linear array transducer:

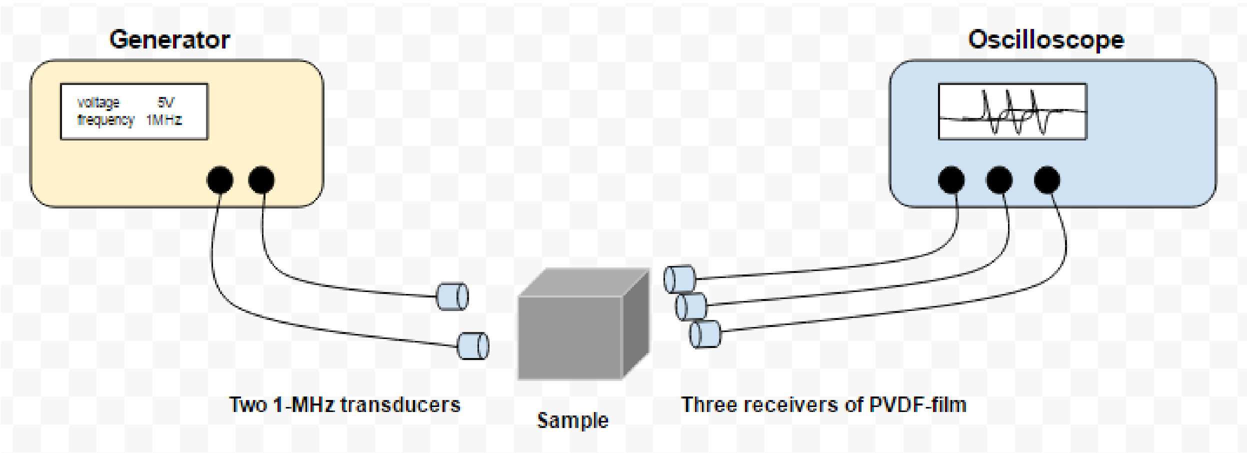

Figure 19. The layout of the linear array transducer with two emitters and three receivers By using generator and oscilloscope.

Chapter 4

Measurements

Here are all the measurements which were done to decide which sample is the most appropriate to be examined in the linear array transducer. The measurements are done with industrial transducers, PZT transducers and handmade transducers of PVDF-films with different shapes and sizes. The results of the measurements are illustrated in the result part of this thesis report.

Initially, greace was used as couplant. It is a good conductive medium to enable a tight bond between the transducer and the sample, but later it was changed to another couplant called Mollas. Mollas couplant was less messy and easier to clean it out.

The meaning of using industrial transducers in some cases is to make sure that the measured results from using PVDF-films are acceptable. The results from PVDF-films were compared to the industrial ones. In the other hand, the meaning of using PZT piezoelectric elements is just to develop acknowledge and experience in different piezoelectric elements.

4.1 Measurements by US-key with Lecoeur Software

All the measurements in this section were done with the Lecoeur software by using a single US-key device. Different transducers and piezoelectric elements were connected to the US-key in different combinations as the tables below show.

Table 9. Measurements on a manufactured steel specimen by using 5-MHz transducer with other combinations. Grease was used as couplant.

Type of test	**Material**
5-MHz transducer as an emitter and a PVDF-film as a receiver	Manufactured steel
5-MHz transducer as a receiver and a PVDF-film as an emitter	
5-MHz transducer as an emitter and as a receiver	
5-MHz transducer as an emitter and a PZT (1-MHz) as a receiver	
5-MHz transducer as a receiver and a PZT (1-MHz) as an emitter	
5-MHz transducer as an emitter and a PZT (5-MHz) as a receiver	
5-MHz transducer as a receiver and a PZT (5-MHz) as an emitter	

Table 10. Measurements on a rock specimen by using 5-MHz transducer with other combinations. Grease was used as couplant.

Type of test	Material
5-MHz transducer as an emitter and a PZT (1-MHz) as a receiver	Rock
5-MHz transducer as a receiver and a PZT (1-MHz) as an emitter	
5-MHz transducer as an emitter and as a receiver	
5-MHz transducer as an emitter and a PZT (2-MHz) as a receiver	
5-MHz transducer as a receiver and a PZT (2-MHz) as an emitter	
5-MHz transducer as an emitter and a PVDF-film as a receiver	
5-MHz transducer as a receiver and a PVDF-film as an emitter	

Table 11. Measurements on an aluminum specimen by using 5-MHz transducer with other combinations. Grease was used as couplant.

Type of test	Material
5-MHz transducer as an emitter and a PVDF-film as a receiver	Aluminum
5-MHz transducer as a receiver and a PVDF-film as an emitter	
5-MHz transducer as an emitter and as a receiver	
5-MHz transducer as an emitter and a PZT (1-MHz) as a receiver	
5-MHz transducer as a receiver and a PZT (1-MHz) as an emitter	
5-MHz transducer as an emitter and a PZT (2-MHz) as a receiver	
5-MHz transducer as a receiver and a PZT (2-MHz) as an emitter	

Table 12. Measurements on a silicone specimen by using 5-MHz transducer with other combinations. Grease was used as couplant.

Type of test	Material
5-MHz transducer as an emitter and a PVDF-film as a receiver	Silicone
5-MHz transducer as a receiver and a PVDF-film as an emitter	
5-MHz transducer as an emitter and a PZT (2 MHz) as a receiver	
5-MHz transducer as a receiver and a PZT (2 MHz) as an emitter	
5-MHz transducer as an emitter and a PZT (5-MHz) as a receiver	
5-MHz transducer as a receiver and a PZT(5-MHz) as an emitter	
5-MHz transducer as a receiver and as an emitter	
5-MHz transducer as a receiver and a PZT (2-MHz) as an emitter	

Table 13. Measurements on a marble specimen by using 5-kHz transducer with other combinations. Grease was used as couplant.

Type of test	**Material**
500-kHz transducer as an emitter and as a receiver	Marble
the 500-kHz transducer as an emitter and a PZT (1-MHz) as a receiver	
500-kHz transducer as a receiver and a PZT (1-MHz) as an emitter	

Table 14. Measurements on a rock specimen by using 5-kHz transducer with other combination. Grease was used as couplant.

Type of test	**Material**
500-kHz transducer as an emitter and a PVDF-film as a receiver	Rock
500-kHz transducer as a receiver and a PVDF-film as an emitter	
500-kHz transducer as an emitter and as a receiver	
500-kHz transducer as an emitter and a PZT (1-MHz) as a receiver	
500-kHz transducer as a receiver and a PZT (1-MHz) as an emitter	

Table 15. Measurements on a metal specimen by using 5-kHz transducer with other combinations. Grease was used as couplant.

Type of test	**Material**
500-kHz transducer as an emitter and as a receiver	Manufactured steel
500-kHz transducer as an emitter and a PZT (5-MHz) as a receiver	
500-kHz transducer as an emitter and as a receiver	
500-kHz transducer as a receiver and a PZT (5-MHz) as an emitter	

Table 16. Measurements on an aluminum specimen by using 5-kHz transducer with other combinations. Grease was used as couplant.

Type of test	**Material**
500-kHz transducer as an emitter and as a receiver	Aluminum
500-kHz transducer as an emitter and a PZT (1-MHz) as a receiver	
500-kHz transducer as a receiver and a PZT (1-MHz) as an emitter	
500-kHz transducer as a receiver and a PZT (5-MHz) as an emitter	

Table 17. Measurements on a silicone specimen by using 5-kHz transducer with other combinations. Grease was used as couplant.

Type of test	**Material**
500-kHz transducer as an emitter and as a receiver	Silicone
500-kHz transducer as an emitter and a PZT (1-MHz) as a receiver	
500-kHz transducer as a receiver and a PZT (1-MHz) as an emitter	

Table 18. Measurements on different specimen by using 5-kHz transducer as emitter and receiver. Mollas was used as couplant.

Type of test	Material
500-kHz transducer as an emitter and as a receiver	Marble
500-kHz transducer as an emitter and as a receiver	Rock
500-kHz transducer as an emitter and as a receiver	Manufactured steel
500-kHz transducer as an emitter and as a receiver	Aluminum
500-kHz transducer as an emitter and as a receiver	Silicone
500-kHz transducer as an emitter and as a receiver	Plastic

Table 19. Measurements on different specimen by using square shapes of PVDF-films as emitter and receiver. Mollas was used as couplant.

Type of test	Material
PVDF (1.5*1.5 cm^2) as emitter and receiver	Aluminum
PVDF (1.5*1.5 cm^2) as emitter and receiver	Manufactured steel
PVDF (1.5*1.5 cm^2) as emitter and receiver	Silicone
PVDF (1.25*1.25 cm^2) as emitter and receiver	Aluminum
PVDF (1.25*1.25 cm^2) as emitter and receiver	Manufactured steel
PVDF (1.25*1.25 cm^2) as emitter and receiver	Silicone
PVDF (1*1 cm^2) as emitter and receiver	Aluminum
PVDF (1*1 cm^2) as emitter and receiver	Manufactured steel
PVDF (1*1 cm^2) as emitter and receiver	Silicone

Table 20. Measurements on different specimen by using square shapes of PVDF-films with other combinations. Mollas was used as couplant.

Type of test	Material
500-kHz transducer as an emitter and as a receiver	Bright drawn steel
PVDF (1*1 cm^2) as emitter and receiver	
PVDF (1*1 cm^2) as receiver and (1.25*1.25 cm^2) as emitter	
PVDF (1*1 cm^2) as receiver and (1.25*1.25 cm^2) as emitter	Aluminum
PVDF (1*1 cm^2) as receiver and (1.25*1.25 cm^2) as emitter	Silicone

Table 21. Measurements on different specimen by using square and circular shapes of PVDF-films. Mollas was used as couplant.

Type of test	Material
PVDF (Diameter of 1.5cm, 1.25cm and 1cm) as emitter and receiver	Aluminum, bright drawn Steel, and Silicone
PVDF (1*1 cm^2) as receiver and (1.25*1.25 cm^2) as emitter	Aluminum

Table 22. Measurements on a silicone specimen by using two circular shapes of PVDF-films as emitter and receiver. Mollas was used as couplant.

Type of test	**Material**
Pvdf (1*1 cm^2) as emitter and receiver	silicone
Pvdf (1.5*1.5 cm^2) as emitter and receiver	silicone

After all these measurements, it was found out that aluminum gave the most readable images compared to the other materials. It was also found out that the US-key device caused a noise artifact when it was used with the Lecoeur software, see figure 20.

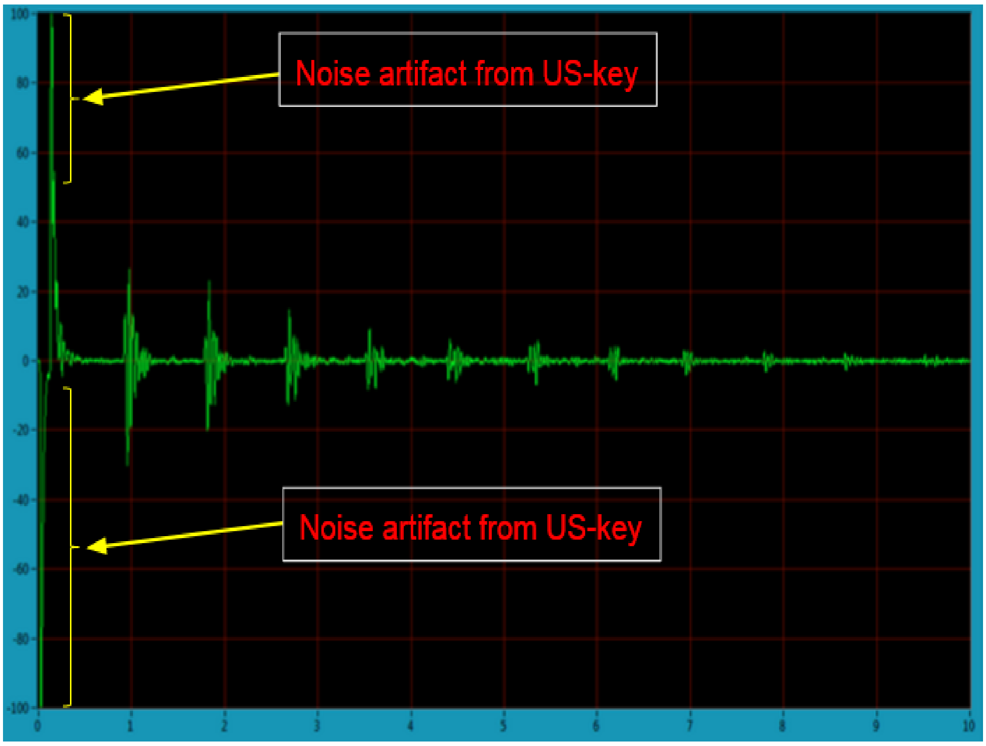

Figure 20. The noise artifact from the US-key by using Lecoeur software. Aluminum was used as sample.

4.2 Measurements by US-key with MATLAB code

It was decided to skip the Lecoeur software and use MATLAB instead to do the plots. The reason for that is to be sure that the noise artifact in the previous figure is really produced by the US-key. The measurements with MATLAB code were done by using one US-key device. The purpose of using MATLAB code is to make a comparison between the plotted values in MATLAB and Lecoeur software.

The measurements by MATLAB code were only applied on aluminum, bright drawn steel and rock samples. It was not advantageous to do measurements on the other samples because they all gave poor plots. The following table shows the ultrasonic testing which were done by using MATLAB code:

Table 23. Measurements on different specimen by MATLAB code.
Measurements were done with Mollas couplant.

Type of test	Material
PVDF (circular of 1 cm in diameter) as emitter and receiver	Aluminum, bright drawn steel and rock
5-MHz transducer as an emitter and as a receiver	
1-MHz transducer as an emitter and as a receiver	
1-MHz transducer as an emitter and 1-MHz as a receiver	
PVDF (circular of 1 cm in diameter) one as emitter and another one as receiver	
PVDF (circular of 1 cm in diameter) as emitter and 5 MHz transducer as receiver and vice versa	
PVDF (circular of 1 cm in diameter) as emitter and 1-MHz transducer as receiver and vice versa	
PVDF (square of 1 cm, 1.25 cm and 1.5 cm in length) as emitter and receiver	
PVDF (square of 1 cm, 1.25 cm and 1.5 cm in length) one as emitter and another one as receiver	

The plots from MATLAB software were quite like the plots from the Lecoeur software. In the following figure, it shows the noise artifact which is created by the US-key device. For the following plot, it was used two industrial transducers of 1-MHz, one as emitter and the other one as receiver.

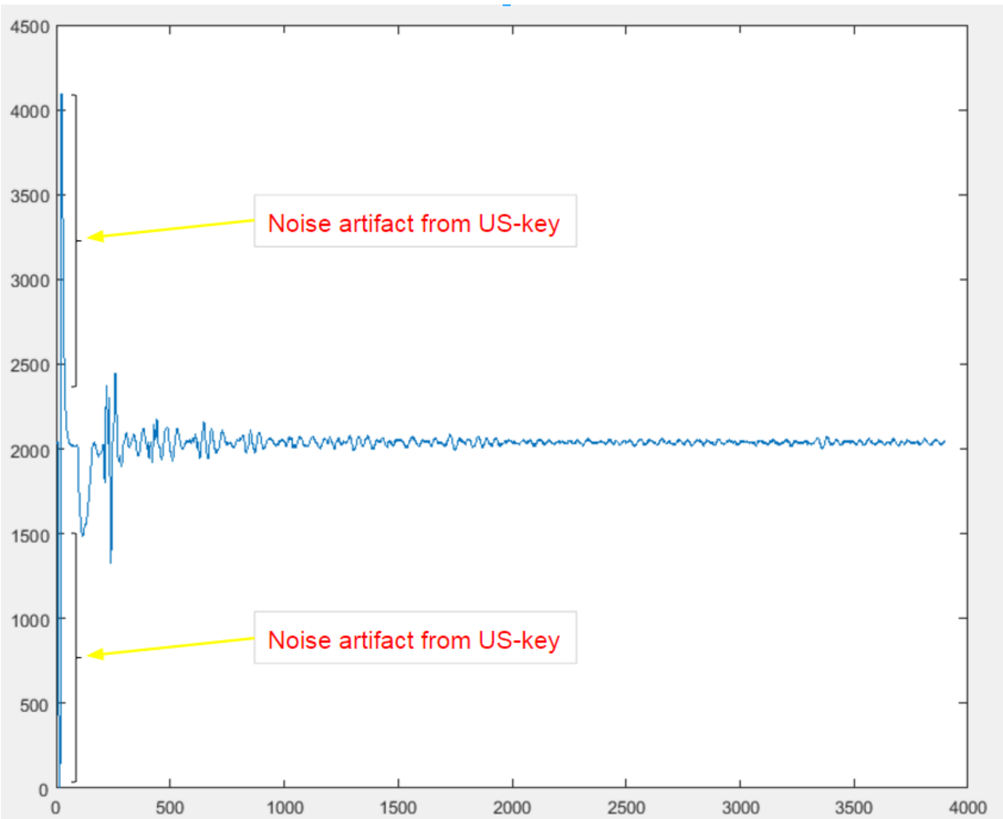

Figure 21. The noise artifact from the US-key by using MATLAB code.
Aluminum was used as sample.

The above picture shows the noise artifact which was produced when one US-key device was used to do plots in MATLAB. Even here, the noise artifact confirms that it is produced by the US-key.

4.3 Measurements by a Generator and an Oscilloscope

Until now it was found that the US-key device is not the proper device to be used to do ultrasonic testing because it creates a noise artifact in the beginning of the plot, see figure 23, 24. The plan of the project was changed to use generator and oscilloscope to do ultrasonic testing.

The advantage of using generator and oscilloscope that there is no noise is creating by these devices and you can save the raw data of each measurement. But at the same time the oscilloscope is very sensitive when it takes measurements.

In the next page, table 24 shows some measurements which were done by using the generator and the oscilloscope. The idea behind these measurements is to determine the best way to connect the PVDF-films to the oscilloscope to achieve as good plots as possible.

Table 24. Measurements on aluminum by using a generator and an oscilloscope. Measurements were done with Mollas couplant.

Type of test	Material	Note
1-MHz transducer as an emitter and 1-MHz as a receiver	Aluminum	
PVDF (circular of 1 cm in diameter) one as emitter and another one as receiver		Big crocodile clips to connect the PVDF and BNC cables
PVDF (circular of 1 cm in diameter) as receiver and 1 MHz transducer as emitter		Big crocodile clips and tape were used to connect the PVDF and BNC cables. Normal electric wires (non-BNC) also were used to do connection between PVDF and BNC cables
PVDF (circular of 1.5 cm in diameter) as receiver and 1 MHz transducer as emitter		Small crocodile clips, big crocodile clips, plastic container, soldering and tape were used to connect the PVDF-film and BNC cables

In these measurements, the PVDF-elements were connected to the BNC cables in several ways. It was found out that small crocodile clips were best solution to connect the PVDF-elements to the BNC cables.

Chapter 5

Results and Discussion

The achieved results in measurements of different samples fit with the theory, because the samples with high attenuation coefficient gave poor images while the samples with low attenuation coefficient gave legible images. The quality of the images which were taken by using the PVDF-films gave better results than the PZT. The PZT-elements which were used in this thesis work have low quality. The low quality of the PZT-elements could be because they were manufactured by using cheap chemical materials. This means that PVDF-film is vibrating more when it detects ultrasonic waves while the PZT does not vibrate as much as the PVDF-film.

The provided images by PVDF-film were quite similar with the images from the industrial transducers and that gave a good sign that the PVDF-film is acceptable. The measurements with the PVDF-films were done with two different shapes. The first shape was square and the second one was circular. The distribution of ultrasound waves is a little bit better in the circular PVDF-films and that is why most of the industrial transducers are in circular shape. The circular ones gave a little bit higher amplitude compared with the square ones as shown in the below figures 22,23,24. The images were recorded by the US-key and Lecoeur software. One transducer of 1-MHz used as emitter while the PVDF-film used as receiver.

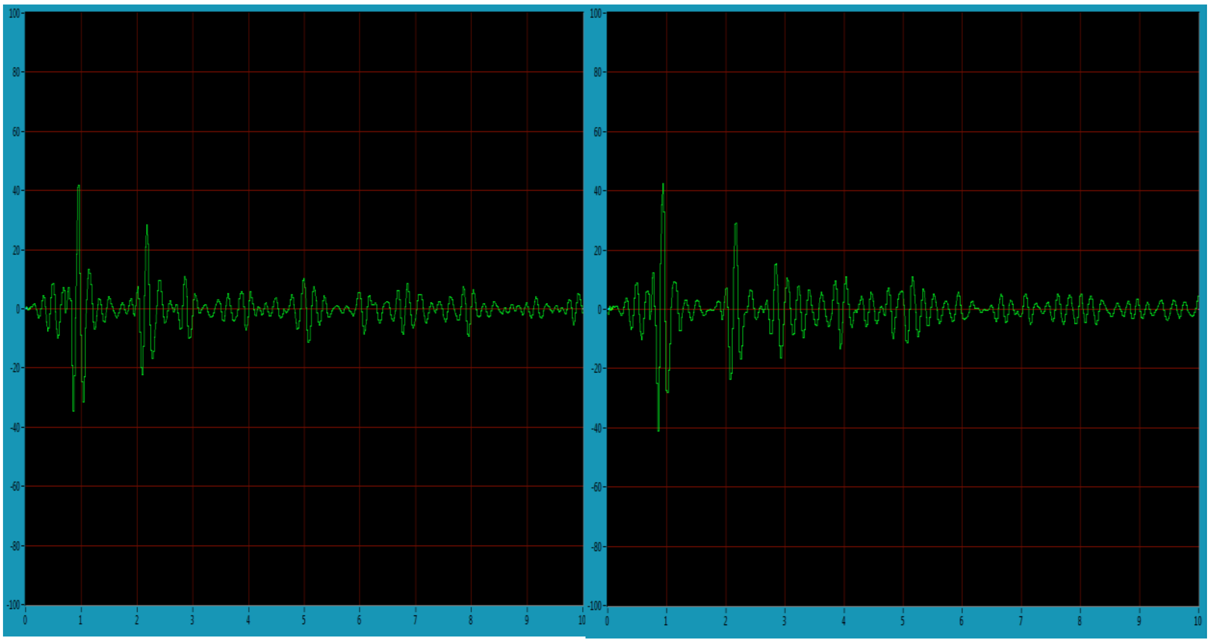

Figure 22. The square PVDF of length 1 cm (to left) and circular PVDF of diameter 1 cm (to right). Ultrasonic testing on an aluminum piece.

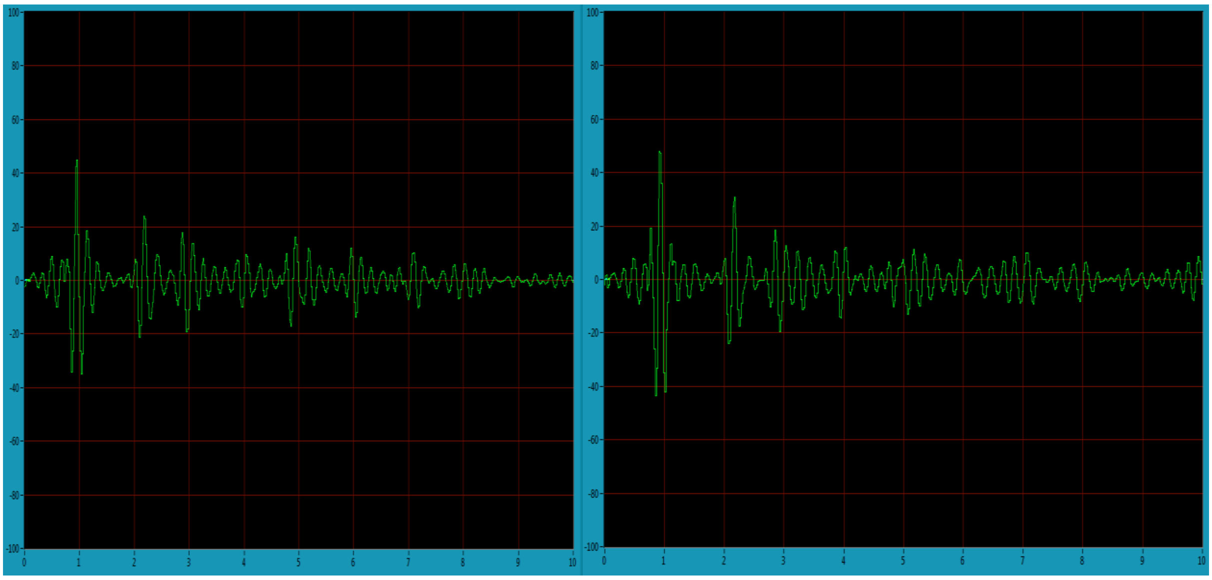

Figure 23. The square PVDF of length 1.25 cm (to left) and circular PVDF of diameter 1.25 cm (to right). Ultrasonic testing on an aluminum piece.

As shown in the above pictures that the received ultrasonic waves have a little higher amplitude with the circular PVDF-films compared to the square PVDF-films.

In the following figure, it shows the differences between circular PVDF-film of 1.5 cm in diameter and square PVDF-film of length 1.5 cm:

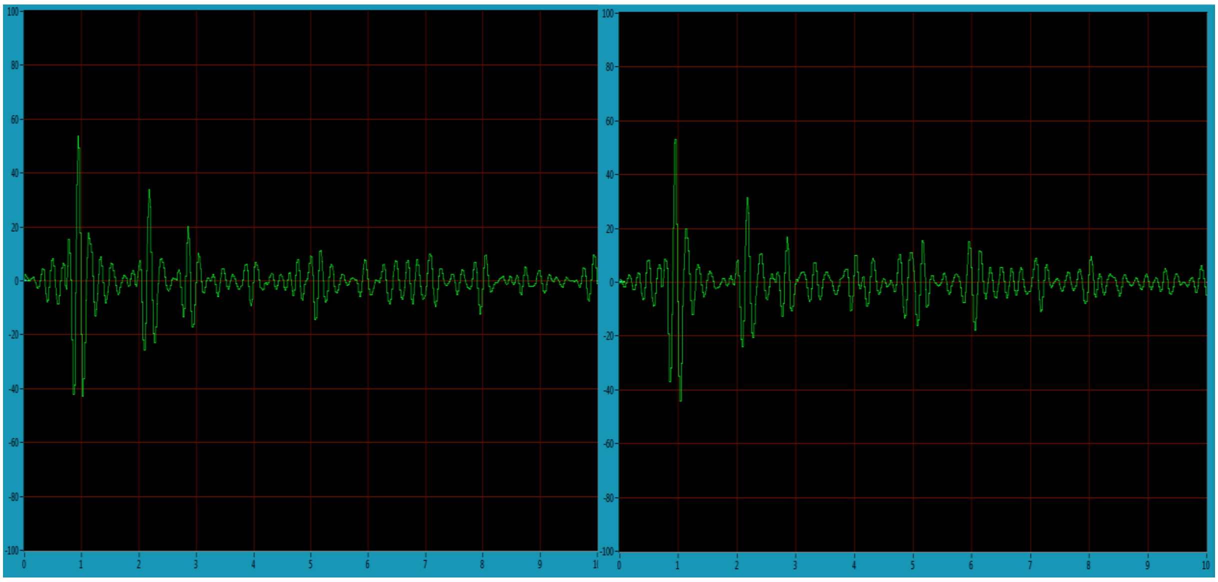

Figure 24. The square PVDF of length 1.5 cm (to left) and circular PVDF of diameter 1.5 cm (to right). Ultrasonic testing on an aluminum piece.

It shows that the both gave almost the same result. It was decided later to choose circular PVDF-films of diameter 1.5 cm as receiver for making of the linear array transducer because it gave a little bit higher amplitude, see figure 25.

The main advantage of using circular PVDF-films of diameter 1.5 cm as receivers instead of 1 cm and 1.25 cm is to detect more ultrasonic waves with higher amplitude, that is why the receivers of the linear array transducer were made of PVDF-films of diameter 1.5 cm. Figure 25, shows that the detected amplitude of the ultrasonic wave is a little higher when the PVDF-film is used as receiver and 1-MHz ultrasonic transducer is used as emitter.

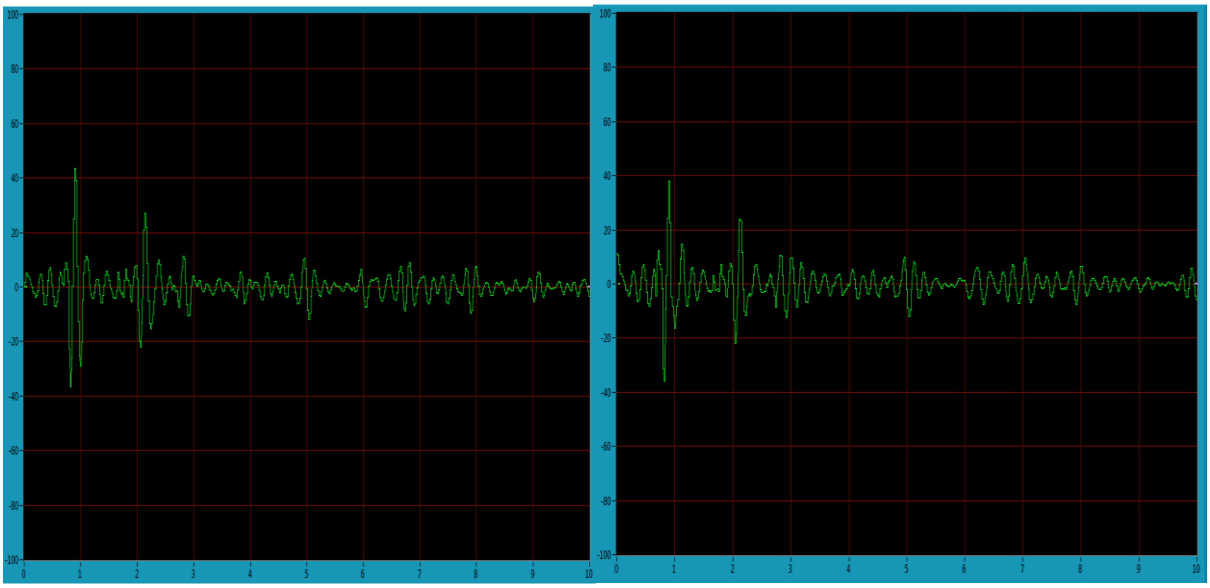

Figure 25. Difference between using PVDF-film as emitter and as receiver. Circular PVDF of diameter 1.5 cm as emitter (to left), 1-MHz transducer as receiver (to left). Circular PVDF of diameter 1.5 cm as receiver (to right), 1-MHz transducer as receiver (to right). Ultrasonic testing on an aluminum piece.

The usage of US-key for making of the linear array transducer did not work because it plots a smooth and a filtered data. The US-key itself designed to filter out the noise and then plot the average of the detected signals. Same thing happens when US-key was used with MATLAB, the plots were smooth and as well filtered. The US-key itself produces a noise artifact when it is used to do ultrasonic testing so that is why the US-key was excluded from the making of the linear array transducer.

On the other hand, the generator and oscilloscope worked well to make the linear array transducer because they gave raw data which was processed in MATLAB to plot the amplitude spectrum/frequency spectrum and the power spectral density of the row data.

During the laboratory work, it was found that BNC cables are best connectors for making of ultrasonic transducers because they were shield so there is less noise in the plots of the raw data. Small crocodile clips gave much less noise when they were connected to the PVDF-films while the other connection manner provided more noise when the raw data was plotted. It would be better if the crocodile clips were as small as possible because the noise would be reduced even more.

The setup for the linear array transducer is illustrated in the following table by using the generator as a power source for the sender and the oscilloscope as a receiving device. Three channels from the connected to the three PVDF-films, see figure 19 and table 25.

Table 25. Measurement on aluminum by the linear array transducer. Measurements were done with Mollas couplant.

Ultrasonic sender	Ultrasonic receiver	Examined sample
Two industrial 1-MHz transducers	Three PVDF-films with circular shape of 1.5 cm in diameter	Aluminum

It was found that PVDF-film with circular shape of 1.5 cm in diameter is the best way to make the linear array transducer. Because the recorded signals were much more readable.

The recorded signal by the oscilloscope is shown in figure 26. First one oscilloscope channel was used to detect the signals from the two transducers then two channels were used and finally three channels were used. The frequency of the industrial emitters was 1-MHz and that is shown in all channels of the multichannel transducer. The quality of the plots for each channel is not the same, as shown in figure 26 that channel 1 gives best image and then channel 2 finally channel 3. The reason is that the PVDF-films are very sensitive and the recorded signal is affected by mixed factors e.g. stability of PVDF-films, interference from ambient and the golden layer of the PVDF-films should not be removed or scratched. The noise from the three channels in the oscilloscope was not identical. In some occasions, it was recorded more noise that than other occasions. The reason for that could be because the PVDF-film detected ultrasonic waves from the surroundings.

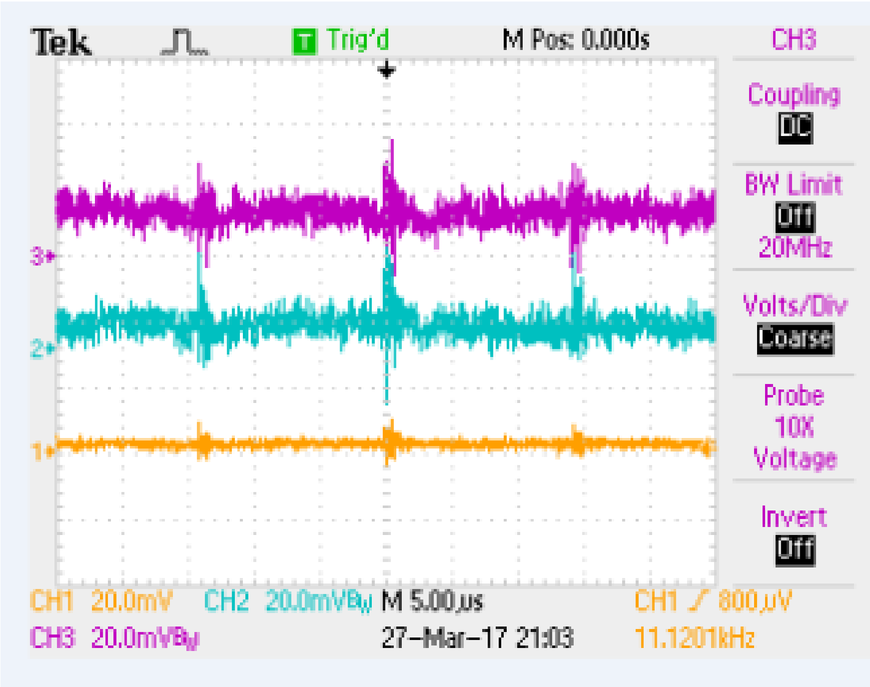

Figure 26. The recorded raw data by oscilloscope from the three PVDF-films.

The raw data recorded signal has noise for the three channels as shown above. The reason for that is already mentioned. The frequency distribution spectrum and power spectral density of each channel in the linear array transducer are not 100% identical to each other as shown below.

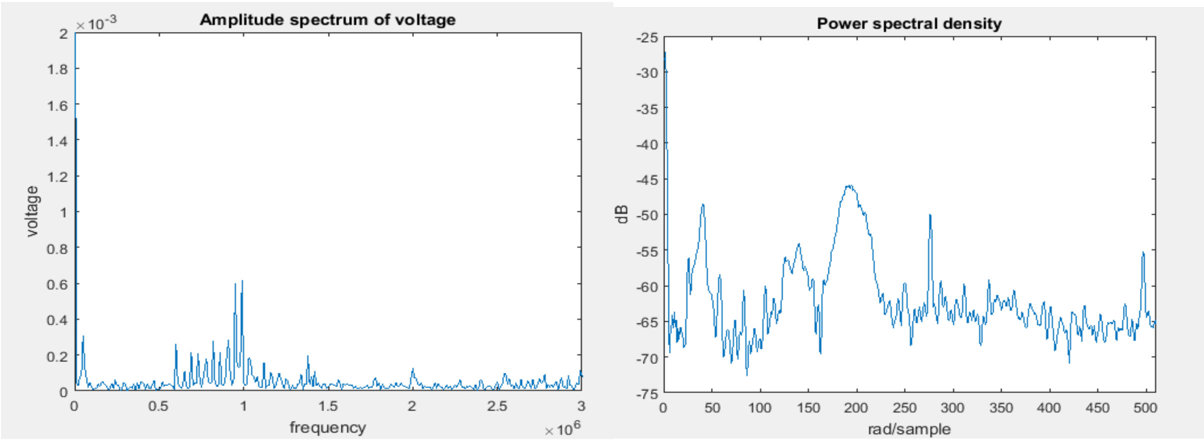

Figure 27. The recorded signal by first oscilloscope channel with its amplitude spectrum and power spectral density. It was plotted in MATLAB.

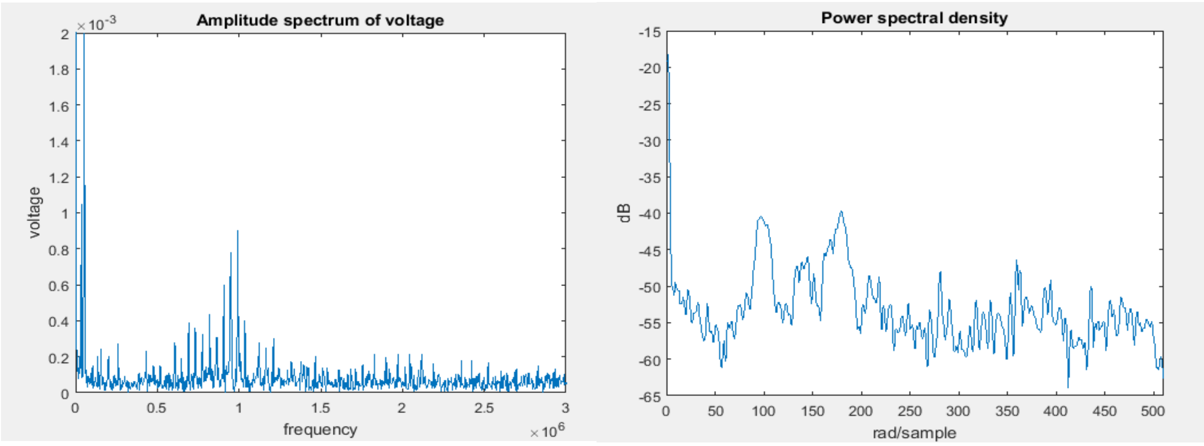

Figure 28. The same recorded signal by second oscilloscope channel with its amplitude spectrum and power spectral density measured in MATLAB.

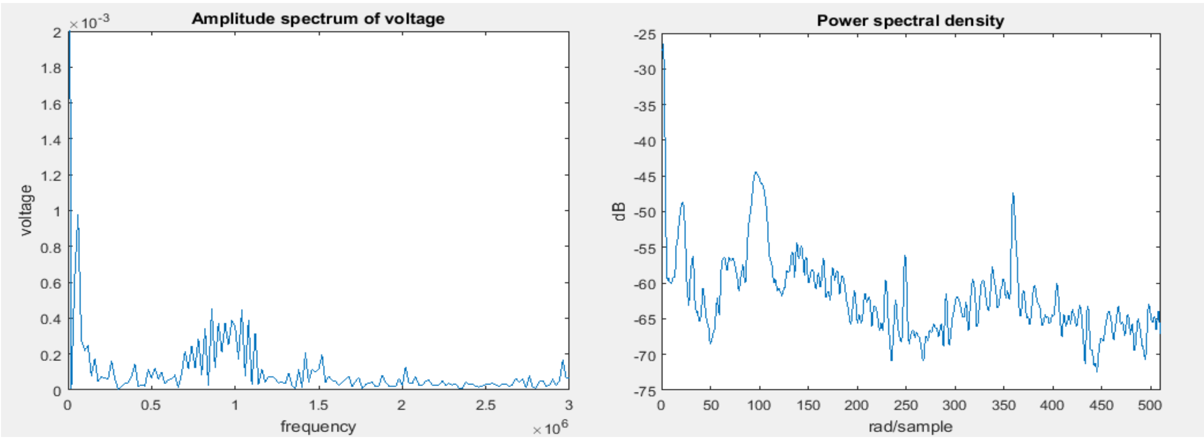

Figure 29. The same recorded signal by third oscilloscope channel with its amplitude spectrum and power spectral density measured in MATLAB.

The frequency spectrum of the three channels is a little bit identical but the power spectral density of all the channels is not the same. The reason for that could be because the connection between the PVDF-films and the BNC cables is not perfect. The frequency spectrums above show that 1-MHz frequency is recorded as it was expected, because the emitters are using 1-MHz frequency. There are also other frequencies are detected which could be frequencies of radio channels.

In conclusion, here is an illustration of different ultrasonic parameters which are calculated in this thesis work. The acoustical parameters are calculated by using some standard equations. Firstly, the velocity of sound in an aluminum piece is calculated by

$$c = \frac{l}{t} \quad (12)$$

There t is time between sending and receiving ultrasonic wave and l is length of the aluminum. The distance between the sender and emitter is called *l*. The time is calculated by the Lecoeur software and the length of the sample is calculated by a ruler.

$$c = \frac{0.0285\ meter}{0.000004676\ second} = 6095\ m/s$$

The theoretical value of sound velocity in aluminum is 6320 m/s. The absorption or attenuation of ultrasonic waves in the aluminum is calculated by

$$Attenuation = a \cdot l \cdot f \quad (13)$$

There a is the attenuation coefficient of the examined material and f is the frequency of the transmitted ultrasonic wave, there f is chosen to be 1-MHz.

$$Attenuation = 0.00000434\ \frac{dB}{MHz\ cm} \cdot 2.85\ cm \cdot 1\ MHz = 0.000012369\ dB$$

The acoustic impedance Z of aluminum is calculated by this formula:

$$Z = p_o \cdot c = 2.7\ gram/cm^3 \cdot 6320000\ cm/s = 17064000\ g/cm^2s$$

Finally, the transmission of ultrasonic waves from the transducer can be called as contentious because the common mode of operation is pulsed at a given period (generally 4 to 5000 times a second), it can be continuous but caution must be taken so the piezoelectric element does not become over temperature of 150 C.

Chapter 6

Conclusions

The conclusion of this thesis work is that the quality of ultrasonic images depends on three main factors. The first factor is the resonance frequency of the transducer, the second factor is type of the piezoelectric element and the third factor is the attenuation coefficient of the examined sample. It is important to use the right frequency when measuring on different samples. The thickness of the piezoelectric material determines the frequency of the transmitted ultrasonic waves. It is also important to use the right couplant when doing ultrasonic testing. The acoustic impedance of the couplant is important to be less than the acoustic impedance of the examined sample.

The PVDF-film of diameter 1.5 cm gave the most accurate images compared to the other PVDF-films of 1 cm and 1.25 cm in diameter when they were used as receivers. But on the other hand, when they were used as emitters, the amplitudes of the images were little bit reduced. The investigated PVDF-film is better to be used for receiving of ultrasonic waves. When the circular PVDF-film of 1.5 cm in diameter was used as emitter or receiver, the images were much better than those with the circular PVDF-film of 1 cm and 1.25 cm in diameter.

Furthermore, the square PVDF-films were not good as the circular ones. The amplitude of the images from the circular ones were a little bit higher compared to the square ones. The square PVDF-films are usually used for testing of weld integrity. It is more applied for angular ultrasonic transducers because it is more appropriate for scanning of large areas.

The aluminum was the best sample of the all examined samples. The attenuation coefficient of the aluminum is much lower compared with the other samples, that made the images from the aluminum much more accurate compared to the other samples. The produced images in different samples ranked from best to worst, are:

- Aluminum
- Bright drawn steel
- Manufactured steel
- Silicone
- Plastic
- Rock
- Marble

On the other hand, the linear array transducer was not successful when it was done by using two US-keys and an interface module. The noise artifact from the US-keys caused us to change the plan by using generator and oscilloscope instead.

The setup for the generator and oscilloscope is also called linear array transducer. Generally, the main benefit of using generator and oscilloscope is that they gave the raw data of the measurements while the Lecoeur Electronique software did not provide the raw data of the measurements.

The aluminum piece was used in all trails in this setup. The reason is its low attenuation coefficient. In the setup, there were two industrial transducers used of 1-MHz frequency used as emitters. 1-MHz transducers provide a wider propagation of ultrasonic waves. It was not efficient to use the PVDF-film as ultrasonic emitter in the setup because the frequency of the PVDF-film is 10-MHz which is too high. High frequencies are less penetrated in the materials. The frequency of the PVDF-film is calculated by equation *(9)* as following:

$$\mathrm{f} = \frac{2300\ m/s}{2*110\ \mu s} = 10\ MHz$$

In the linear array transducer when generator and oscilloscope were used, the best way to connect PVDF-films to BNC cables is by using small crocodile clips. Small crocodile clips gave much less noise when the measurements were done. Here is the order of the connectors that were applied to connect PVDF-films to the BNC cables, ranked from best to worst:

- Small crocodile clips
- Big crocodile clips
- Electricity tape conductor
- Normal electric wires
- Soldering

Finally, the images from the three channels in the oscilloscope did not provide more details about the aluminum sample. There was a wide variance between the recorded raw data from each channel in the oscilloscope. The reason for that may be that the connections between the PVDF-films and BNC cables were not enough good or the PVDF-film is too sensitive which makes the measurements too difficult to proceed.

6.1. Future work

This thesis work was made to do an experimental work of how to design a linear array transducer by using two US-keys. When this setup did not work, which was not expected with Lecoeur Electronique software, then MATLAB was used instead. The MATLAB code from Lecoeur company was improved to make the linear array transducer. Because of the artifact that the US-key did create then it was decided to move on and use generator and oscilloscope to extract the raw data in MATLAB instead of using US-keys and Lecoeur software. The future work can be summarized in the following points:

- Different thickness of PVDF -films can be tested on different samples. Each thickness is related to a specific frequency, that means it will be more informative if the PVDF-films with low frequency are used to measure on rocks or marble

- Use LABVIEW instead of generator and buy the required equipment for that

Chapter 7

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Appendix I

Abbreviated MATLAB code:

```
clc;
clear;

% Attenuation in steel and aluminum
alfa=0.0000434/1000000; % Attenuation constant (dB/(MHz*cm))
of steel
l=[0:1:5]; % Sample length in mm from 0 cm to 5 cm
f=1000000; % Frequency at 1 MHz
Attenuation = alfa*l*f; % Attenuation formula
plot(l,Attenuation,'g')
% title('Attenuation in different thickness of steel');
set(gca,'FontName','Arial','FontSize',10,'FontWeight','Bold');
xlabel('Thickness of sample in cm');
ylabel('Attenuation in dB');
set(gca, 'XLim',[0 5]);

hold on
alfa=0.00000434/1000000; % Attenuation constant (dB/(MHz*cm))
of aluminum
l=[0:1:5]; % Sample length in mm from 0 mm to 5 cm
f=1000000; % Frequency at 1 MHz
Attenuation = alfa*l*f; % Attenuation formula
plot(l,Attenuation,'m')
% title('Attenuation in different thickness of aluminum');
set(gca,'FontName','Arial','FontSize',10,'FontWeight','Bold');
xlabel('Thickness of sample in cm');
ylabel('Attenuation in dB');
set(gca, 'XLim',[0 5]);
legend('steel','aluminum','Location','northwest')


alfa=9.5/1000000; % Attenuation constant (dB/(MHz*cm)) of rock
l=[0:1:5]; % Sample length in cm from 0.10 cm to 4 cm
f=1000000; % Frequency at 1 MHz
Attenuation = alfa*l*f; % Attenuation formula
figure(7)
plot(l,Attenuation,'b')
% title('Attenuation in different thickness of rock');
set(gca,'FontName','Arial','FontSize',10,'FontWeight','Bold');
xlabel('Thickness of rock in cm');
ylabel('Attenuation in dB');
set(gca, 'XLim',[0 5]);
```

```
alfa=15/1000000; % Attenuation constant (dB/(MHz*cm)) of
marble
l=[0:1:5]; % Sample length in mm from 0 cm to 10 cm
f=1000000; % Frequency at 1 MHz
Attenuation = alfa*l*f; % Attenuation formula
figure(8)
plot(l,Attenuation,'k')
% title('Attenuation in different thickness of marble');
set(gca,'FontName','Arial','FontSize',10,'FontWeight','Bold');
xlabel('Thickness of marble in cm');
ylabel('Attenuation in dB');
set(gca, 'XLim',[0 5]);


clc;
clear;
alfa=15/1000000; % Attenuation constant (dB/(MHz*cm)) for
marble
l=0.4; % Sample length in cm
f=[500000:500000:15000000]; % Frequencies
Attenuation = alfa*l*f; % Attenuation formula
plot(f,Attenuation,'k')
hold on
alfa=9.5/1000000; % Attenuation constant (dB/(MHz*cm)) for
rock
l=0.4; % Sample length in cm
f=[500000:500000:15000000]; % Frequencies
Attenuation = alfa*l*f; % Attenuation formula
plot(f,Attenuation,'b')
hold on
alfa=0.00000434/1000000; % Attenuation constant (dB/(MHz*cm))
for aluminum
l=0.4; % Sample length in cm
f=[500000:500000:15000000]; % Frequencies
Attenuation = alfa*l*f; % Attenuation formula
plot(f,Attenuation,'m')
hold on
alfa=0.0000434/1000000; % Attenuation constant (dB/(MHz*cm))
for steel
l=0.4; % Sample length in cm
f=[500000:500000:15000000]; % Frequencies
Attenuation = alfa*l*f; % Attenuation formula
plot(f,Attenuation,'g')
hold on
set(gca, 'XLim',[400000 16000000]);
% title('Frequency attenuation in different materials');
xlabel('Different frequencies');
ylabel('Attenuation in dB');
legend ('aluminum','steel')
set(gca,'FontName','Arial','FontSize',10,'FontWeight','Bold');
legend('marble','rock')
```

```
clc;
clear;

dt=1/8000;                              % seconds per sample
st=0.004;                             % stop time in second
t = (0:dt:st-dt)';                   % time interval
f = 500000;                         % frequency at 500 kHz
x = cos(2*pi*f*t);
figure;
plot(t,x,'b');
xlabel('Time in seconds');
ylabel('Wave amplitude')
set(gca,'FontName','Arial','FontSize',10,'FontWeight','Bold');
title('Signal with short wavelength at 500 kHz');
zoom xon;

dt=1/8000;                            % seconds per sample
st=0.004;                           % stop time in second
t = (0:dt:st-dt)';                 % time interval
f = 50000;                         % frequency at 500 Hz
x = cos(2*pi*f*t);
figure;
plot(t,x,'r');
xlabel('Time in seconds');
ylabel('Wave amplitude')
set(gca,'FontName','Arial','FontSize',10,'FontWeight','Bold');
title('Signal with long wavelength at 500 Hz');
zoom xon;

% the piezo element is a pvdf
clc;
clear;
th=[0.00011:0.0001:0.014]; % thickness of the piezo element in
meter
c=2300;                   % acoustic velocity of the crystal
(piezo element)
f=c./(2*th);             % frequency of the piezo element in Hz
plot(th,f,'r')
set(gca,'FontName','Arial','FontSize',10,'FontWeight','Bold');
xlabel('Thickness of the piezo element (pvdf) in m');
ylabel('Frequency of the piezo element (pvdf) in Hz')
% title('The relation between resonance frequency and
thickness of the piezo element');
%zoom xon;

clc;
clear;
f=1000000; % frequenct at 1 MHz
c=[300:100:1800]; % ultrasound speed
```

```
l = c./f; % wavelength formula
plot(c,l,'b')
set(gca,'FontName','Arial','FontSize',10,'FontWeight','Bold');
% title('Relation between wavelength and ultrasound speed');
xlabel('Different ultrasound speeds in m/s');
ylabel('Wavelength in m');
xlim([250 1850])
ylim([0 0.002])

clc;
clear;

v=6320; % velocity in aluminum in m/s
f=1000000; % % Frequency at 1 MHz
d=[0.015:0.001:0.025]; % diameter of the piezo element in m
theta=asind((1.2*v)./(d*f)); % theta is the beam divergence
angle from centerline to point where signal is at half
strength
plot(r,theta,'m')
xlabel('Diameter of the piezo element in m')
ylabel('Beam divergence angle in degrees')
hold on

v=5115; % velocity in marble in m/s
f=1000000; % % Frequency at 1 MHz
d=[0.015:0.001:0.025]; % diameter of the piezo element in m
theta=asind((1.2*v)./(d*f)); % theta is the beam divergence
angle from centerline to point where signal is at half
strength
plot(r,theta,'k')
xlabel('Diameter of the piezo element in m')
ylabel('Beam divergence angle (\theta) in degrees')
set(gca,'FontName','Arial','FontSize',10,'FontWeight','Bold');
legend('aluminum','marble')



L=2500; %signal length
variable = dlmread('C:\Users\ali\Desktop\Oscillo\exCh33.csv');

% Access the time variable
time = variable(: , 1);

% Access the voltage which measured on the oscilloscope
voltage = variable(: , 2);

figure(1)
plot (time,voltage)
title('Recorded signal by one PVDF-plate')
xlabel('time')
ylabel('voltage')
```

```
ylim([-0.015 0.025]); % just interested in frequencies between
0 and 3 MHz

% Fast fourier transform of the voltage to plot different
frequencies
Y = fft(voltage);
P2 = abs(Y/L);
P1 = P2(1:L/2+1);
P1(2:end-1) = 2*P1(2:end-1);

Fs=1/(time(2,1)-time(1,1));
f = Fs*(0:(L/2))/L;
figure(2)
plot(f,P1)
xlim([0 3000000]); % just interested in frequencies between 0
and 3 MHz
ylim([0 0.002]);
title('Amplitude spectrum of voltage')
xlabel('frequency')
ylabel('voltage')

figure(3)
powerspectral= pwelch(voltage);
plot(10*log10(powerspectral));
title('Power spectral density')
ylabel('dB')
xlabel('rad/sample')
xlim([0 510]);




% propagation of ultrasonic waves in the linear array
transducer
with two US-keys

plot([1 4.2], [2 2.5],'w')
hold on
plot([1 4.2], [2 1.5],'w')
ylim([0 4]);
xlim([0 5]);
scatter(1,2,80,'filled')
scatter(4.2,2.5,60,'filled','k')
scatter(4.2,1.5,60,'filled','k')
set(gca,'xtick',[])
set(gca,'ytick',[])
title('Propagation of ultrasonic waves');

th = linspace( pi/7, -pi/7, 10);
R = 0.35;  %radius of the circle
```

```
x = R*cos(th)+0.95;
y = R*sin(th)+2;
plot(x,y,'g'); axis equal;

th1 = linspace( pi/6, -pi/6, 10);
R = 0.75;  %radius of the circle
x = R*cos(th1)+1.35;
y = R*sin(th1)+2;
plot(x,y,'g'); axis equal;

th2 = linspace( pi/6, -pi/6, 10);
R = 1.3;  %radius of the circle
x = R*cos(th2)+1.75;
y = R*sin(th2)+2;
plot(x,y,'g'); axis equal;

th3 = linspace( pi/5, -pi/5, 10);
R = 1.6;  %radius of the circle
x = R*cos(th3)+2.45;
y = R*sin(th3)+2;
plot(x,y,'g'); axis equal;

text(0.2,2.5,' One ultrasonic emitter','FontSize',10)
text(3.3,0.8,' Two ultrasonic receivers','FontSize',10)


% the MATLAB code for the linear array transducer by using US-
key

clear all;

loadlibrary('C:\DLL_USKEY_x64\Ap_int_usb.dll','C:\DLL_USKEY_x6
4\Ap_int_usb.h','alias','ApintUsb')

Err_Code(1) = int16(1);
Product = uint32(1);
Channel = uint32(0);
Out1(1) = uint16(1);
Out2(1) = uint16(1);
Out3(1) = uint16(1);
Out4(1) = uint16(1);
Out5(1) = uint16(1);
Out6(1) = uint16(1);
Len(1) = int16(3900);
Array(Len) = uint16(0);

%Function = 'RunExeX32';

Err_Code=calllib('ApintUsb','ApintUsb',Product,Channel,'RunExe
X32',0,0,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array,Len);
% Loading x32 to x64 resident
```

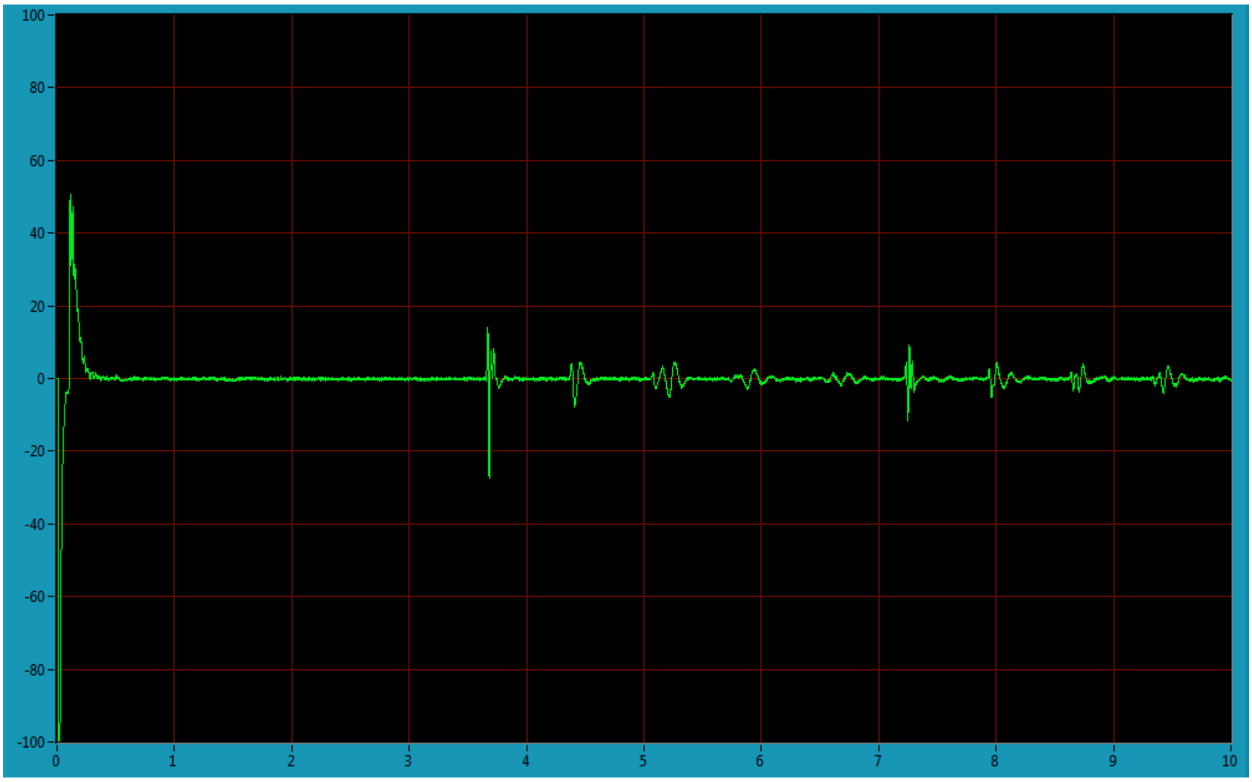
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Loading DLL and Init US-key %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


calllib('ApintUsb','ApintUsb',Product,Channel,'Init
usb',0,0,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array,Len)
% Loadind DLL
calllib('ApintUsb','ApintUsb',Product,Channel,'load
configuration',1,0,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array
,Len)                              % Init US-Key


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% US-Key Transmitter management   %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

PRF = 0.5;
% PRF (KHz)

% special value PRF = 0.07 (external sync)

Tension = 120;
% Voltage (Volts)

% from 30 to 230 Volts

Largeur_Pulse = 5;

Retard_Pulse = 0;
% Pulse

calllib('ApintUsb','ApintUsb',Product,Channel,'Prf',PRF,0,0,0,
0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array,Len)
calllib('ApintUsb','ApintUsb',Product,Channel,'voltage',Tensio
n,0,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array,Len)
calllib('ApintUsb','ApintUsb',Product,Channel,'width',Largeur_
Pulse,0,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array,Len)
calllib('ApintUsb','ApintUsb',Product,Channel,'pulse
delay',Retard_Pulse,0,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Ar
ray,Len)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% US-Key Receiver management       %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Filtre = 2;
% Filters
```

```
Mode = 0;
% Mode

Gain = 20;
% Gain 0

Retard_Num = 0;
% Scale

Freq_Num = 1;                                                    %
Sampling frequencies


calllib('ApintUsb','ApintUsb',Product,Channel,'filter/mode',Fi
ltre,Mode,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array,Len)
calllib('ApintUsb','ApintUsb',Product,Channel,'Gain',Gain,0,0,
0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array,Len)
calllib('ApintUsb','ApintUsb',Product,Channel,'scale
delay',Retard_Num,0,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Arra
y,Len)
calllib('ApintUsb','ApintUsb',Product,Channel,'samplingfreqmod
e',Freq_Num,Mode,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array,L
en)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% US-Key Gates management                     %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Num_Porte = 1;
% Gate

Pos_Porte = 10;
% Gate
Larg_Porte = 5;
% Gate

Seuil_Porte = 30;
%Threshold (%)

calllib('ApintUsb','ApintUsb',Product,Channel,'gate
position',Num_Porte,Pos_Porte,0,0,0,0,Out1,Out2,Out3,Out4,Out5
,Out6,Array,Len)
calllib('ApintUsb','ApintUsb',Product,Channel,'gate
width',Num_Porte,Larg_Porte,0,0,0,0,Out1,Out2,Out3,Out4,Out5,O
ut6,Array,Len)
calllib('ApintUsb','ApintUsb',Product,Channel,'gate
hight',Num_Porte,Seuil_Porte,0,0,0,0,Out1,Out2,Out3,Out4,Out5,
Out6,Array,Len)
calllib('ApintUsb','ApintUsb',Product,Channel,'relays',bin2dec
('000'),0,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array,Len)%
Alarms (On appearence or vanish)
```

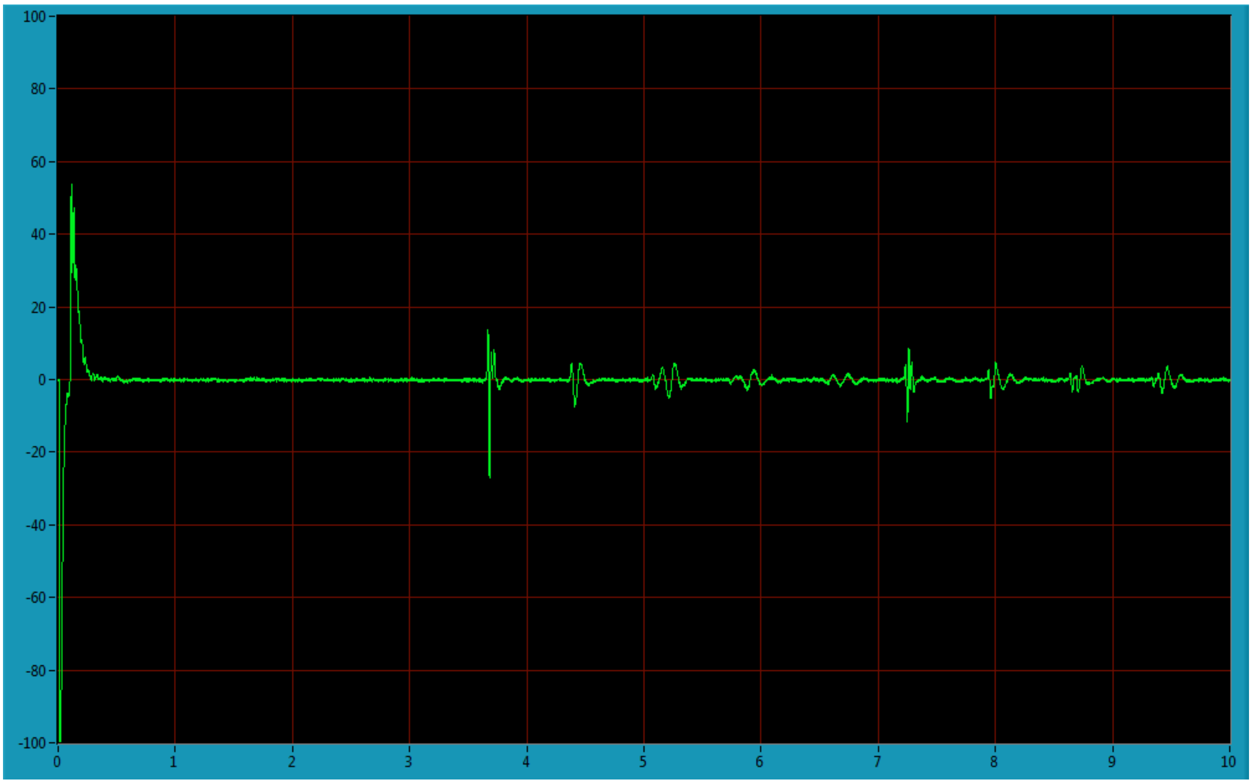
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% US-Key A-scan                                 %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Type_Donnees = 0;

Nb_Echantillons = 3900;                                           %
Number of samples

Forme_Onde = 0;

%%%
calllib('ApintUsb','ApintUsb',Product,Channel,'Ascan',Type_Don
nees,0,Nb_Echantillons,Forme_Onde,0,0,Out1,Out2,Out3,Out4,Out5
,Out6,Array,Len)

calllib('ApintUsb','ApintUsb',Product,Channel,'Scale A-scan
counter',Nb_Echantillons/2,0,0,0,0,0,Out1,Out2,Out3,Out4,Out5,
Out6,Array,Len)
tic
matrix=zeros(100,3900);
for i=1:100
[Err_Code Function Out1 Out2 Out3 Out4 Out5 Out6 Array Len] =
calllib('ApintUsb','ApintUsb',Product,Channel,'A-
scan',Type_Donnees,0,Nb_Echantillons,Forme_Onde,0,0,Out1,Out2,
Out3,Out4,Out5,Out6,Array,Len);
matrix(i,:)=Array;
pause(5/1000);
figure(1)
plot(Array(1:Len));drawnow;
end
toc
%%plot(Array)
xlabel('Echantillons');
ylabel('Valeur');

calllib('ApintUsb','ApintUsb',Product,Channel,'KillExeX32',0,0
,0,0,0,0,Out1,Out2,Out3,Out4,Out5,Out6,Array,Len)
```

Appendix II

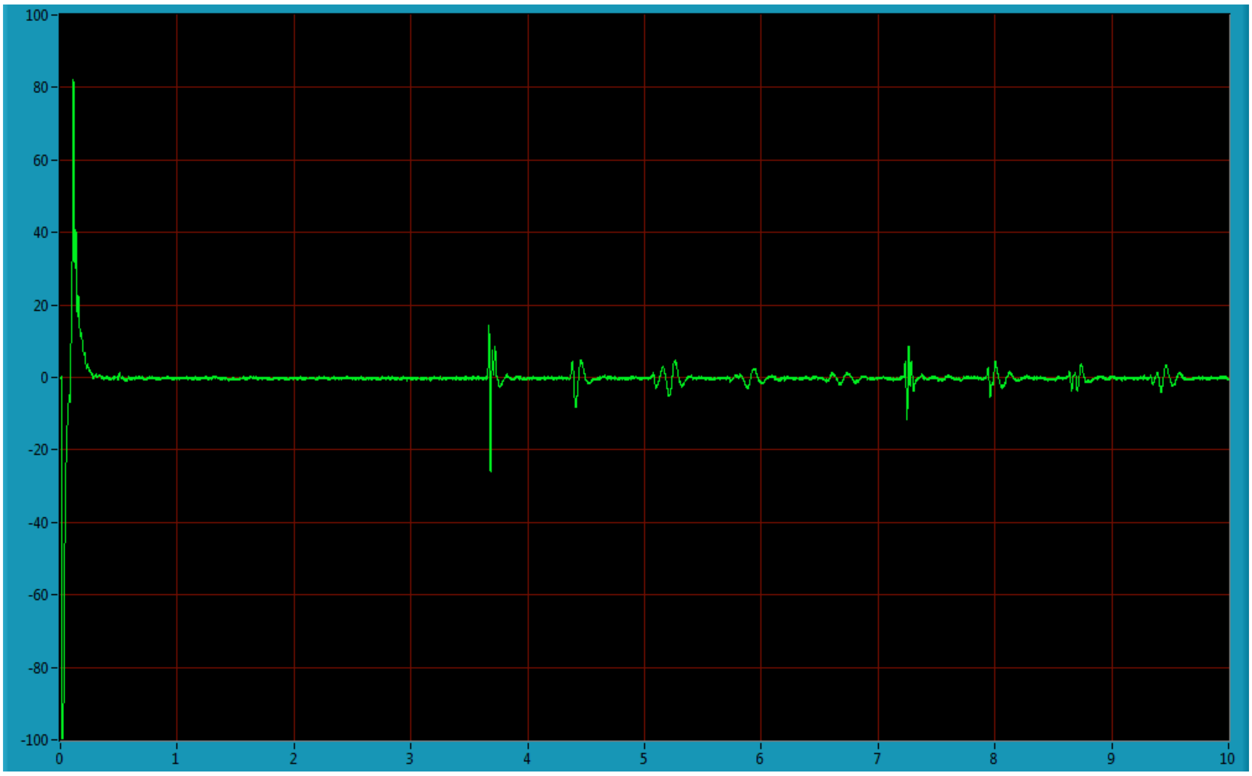
Here are some selected pictures of the measurements which were done by using a single US-key and Lecoeur software.



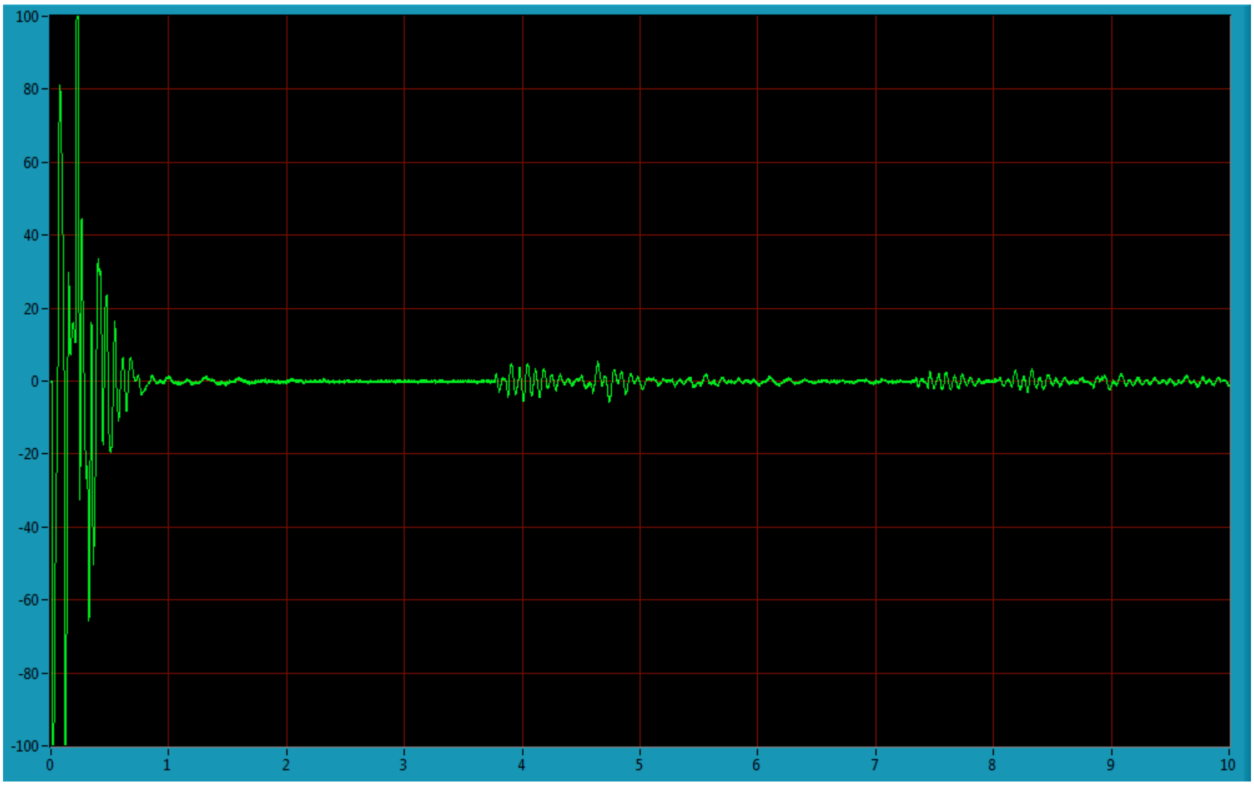
Manufactured steel: Measurements with 5 MHz transducer as emitter and circular PVDF-film of diameter 1 cm as receiver.



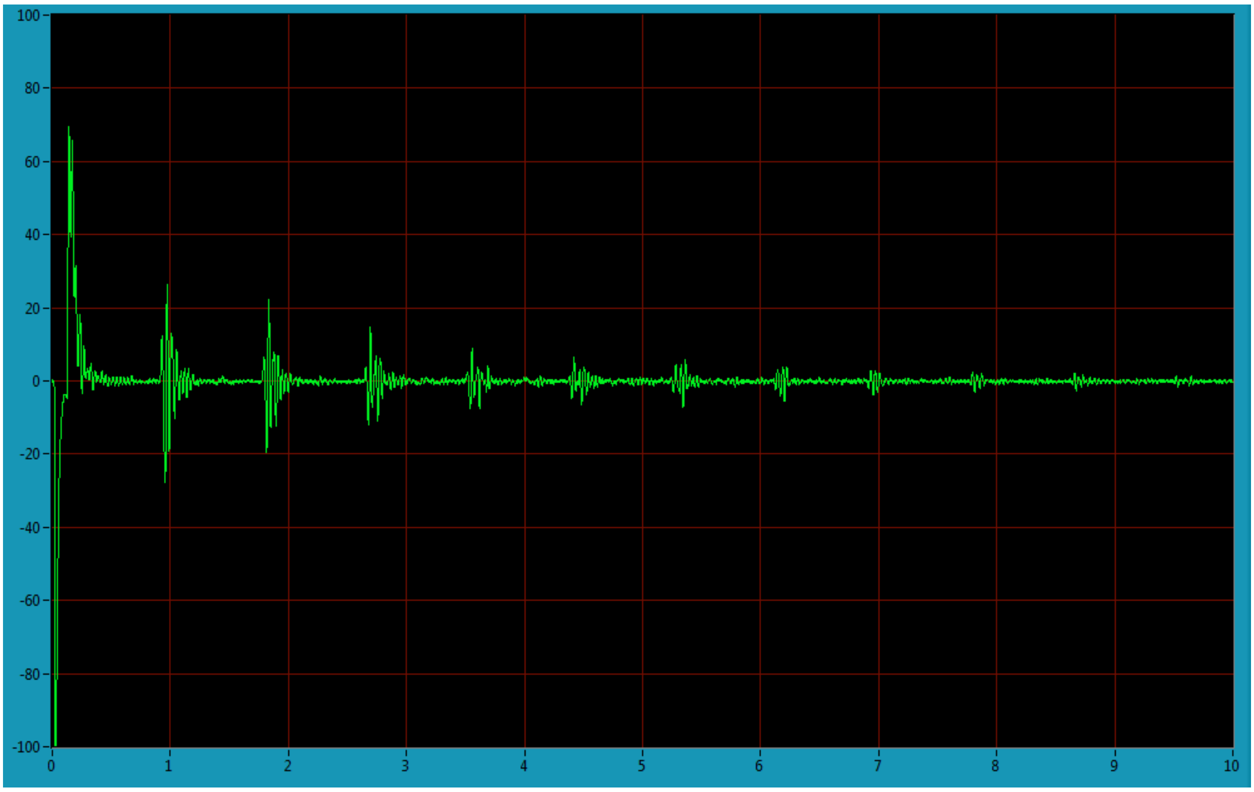
Manufactured steel: Measurement with 5 MHz transducer as receiver and circular PVDF-film of diameter 1 cm as emitter.



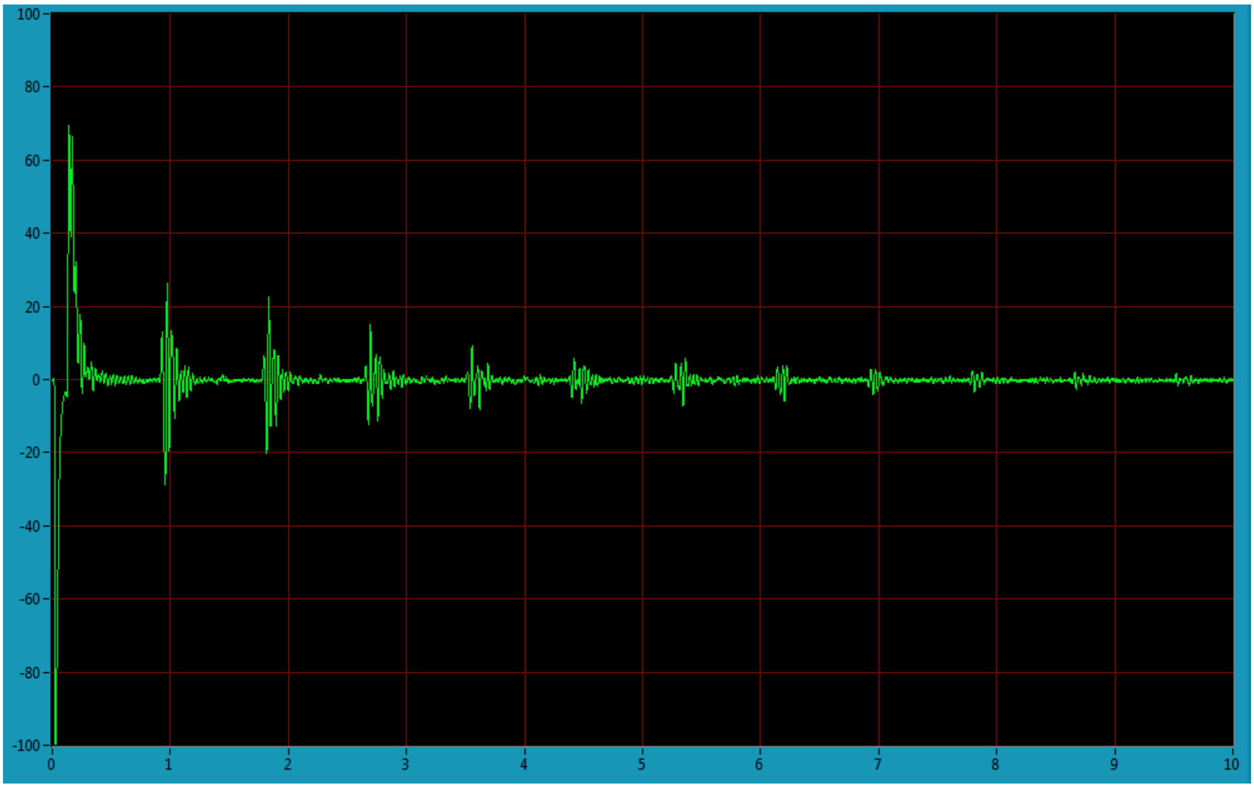
Manufactured steel: Measurement with 5 MHz transducer as emitter and as receiver at the same time.



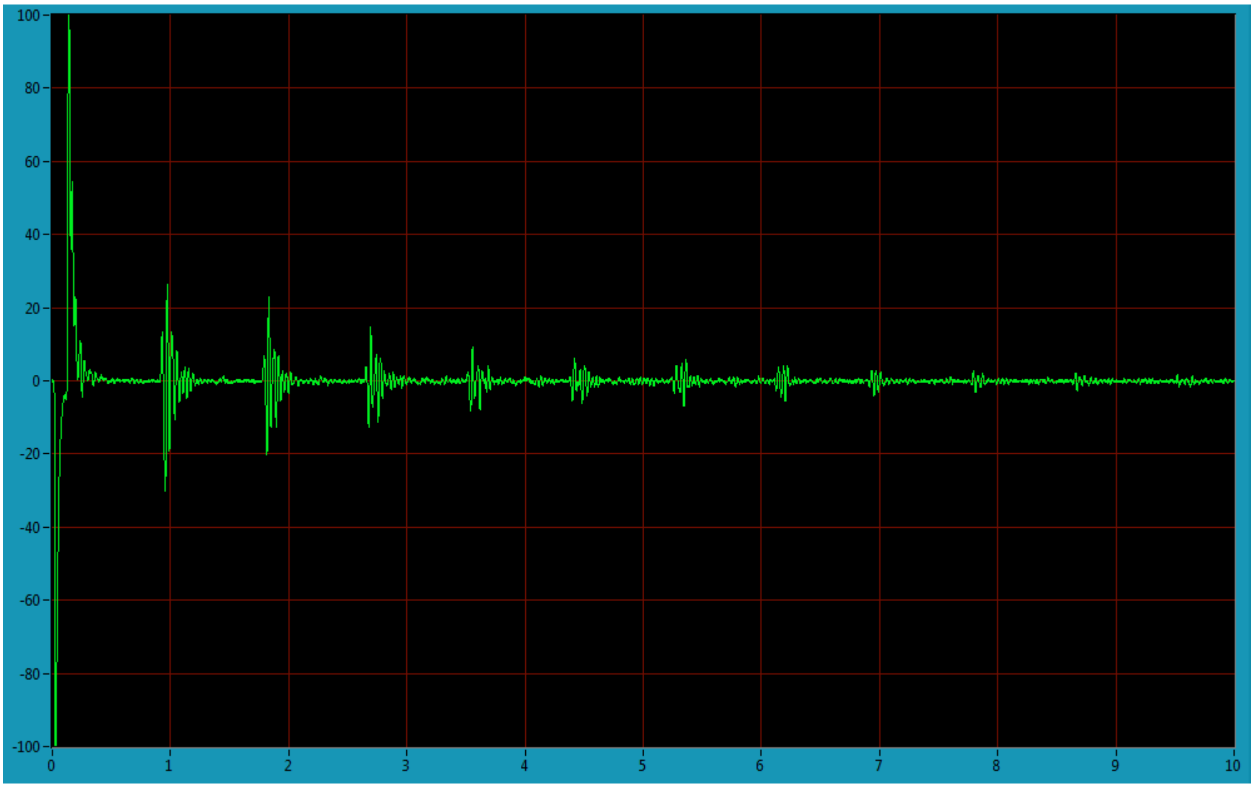
Manufactured steel: Measurement with 500 kHz transducer as emitter and as receiver at the same time.



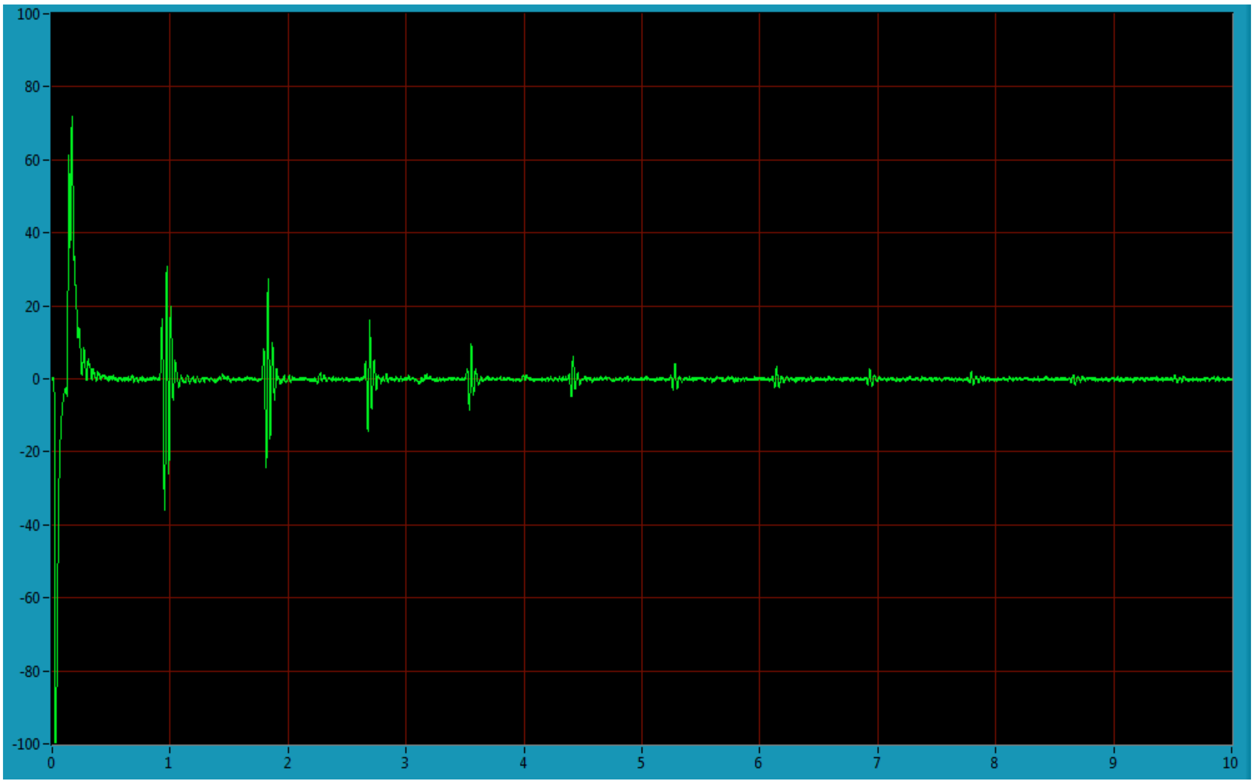
Aluminum: Measurement with 5 MHz transducer as emitter and PVDF-film of diameter 1 cm as receiver.



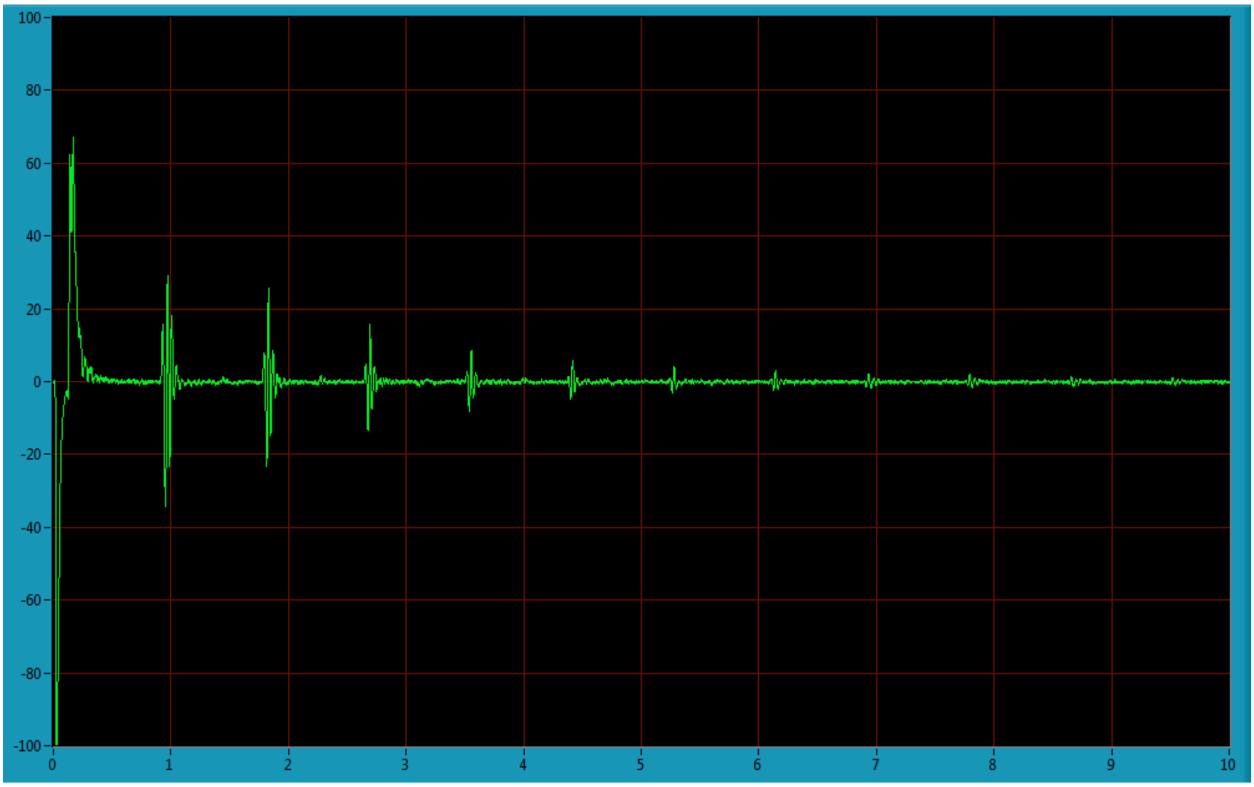
Aluminum: Measurement with 5 MHz transducer as receiver and circular PVDF-film of diameter 1 cm as emitter.



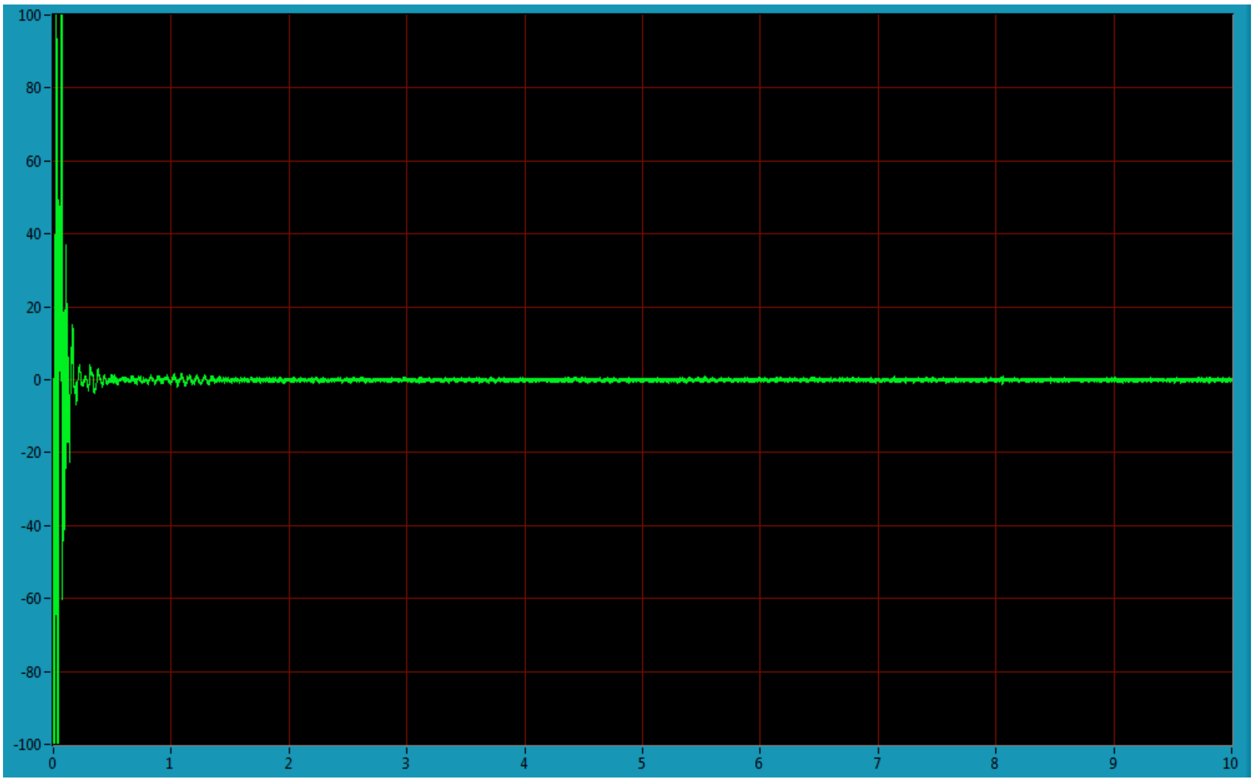
Aluminum: Measurement with 5 MHz transducer as emitter and as receiver at the same time.



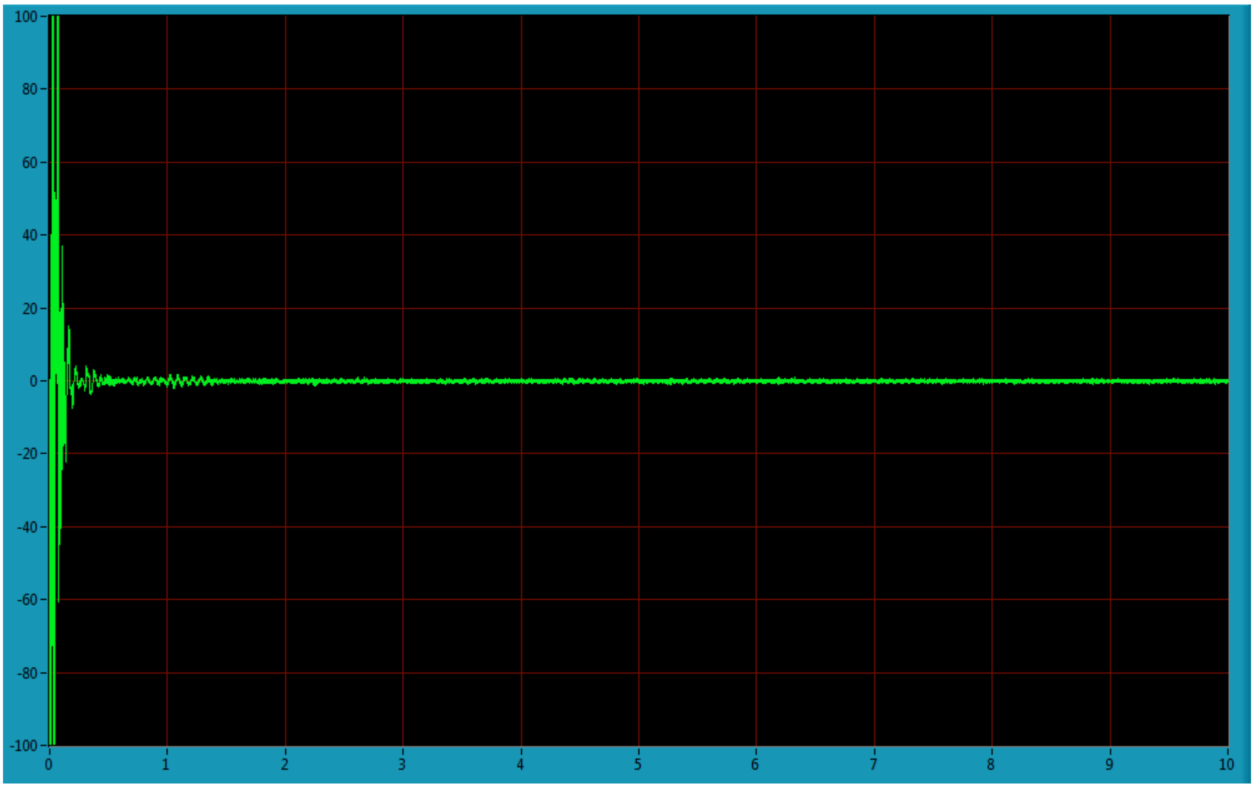
Aluminum: Measurement with 5 MHz transducer as emitter
and PZT-element (2 MHz) as receiver.



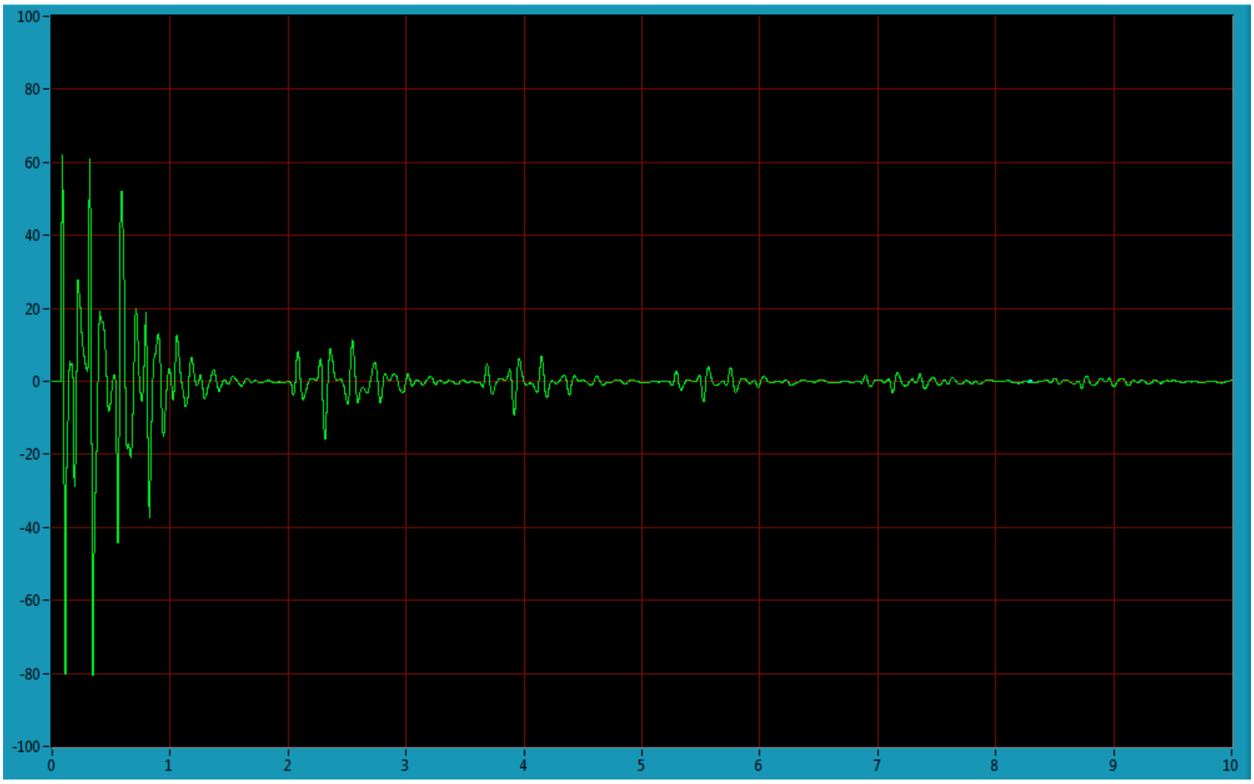
Aluminum: Measurement with 5 MHz transducer as receiver
and PZT-element (2 MHz) as emitter



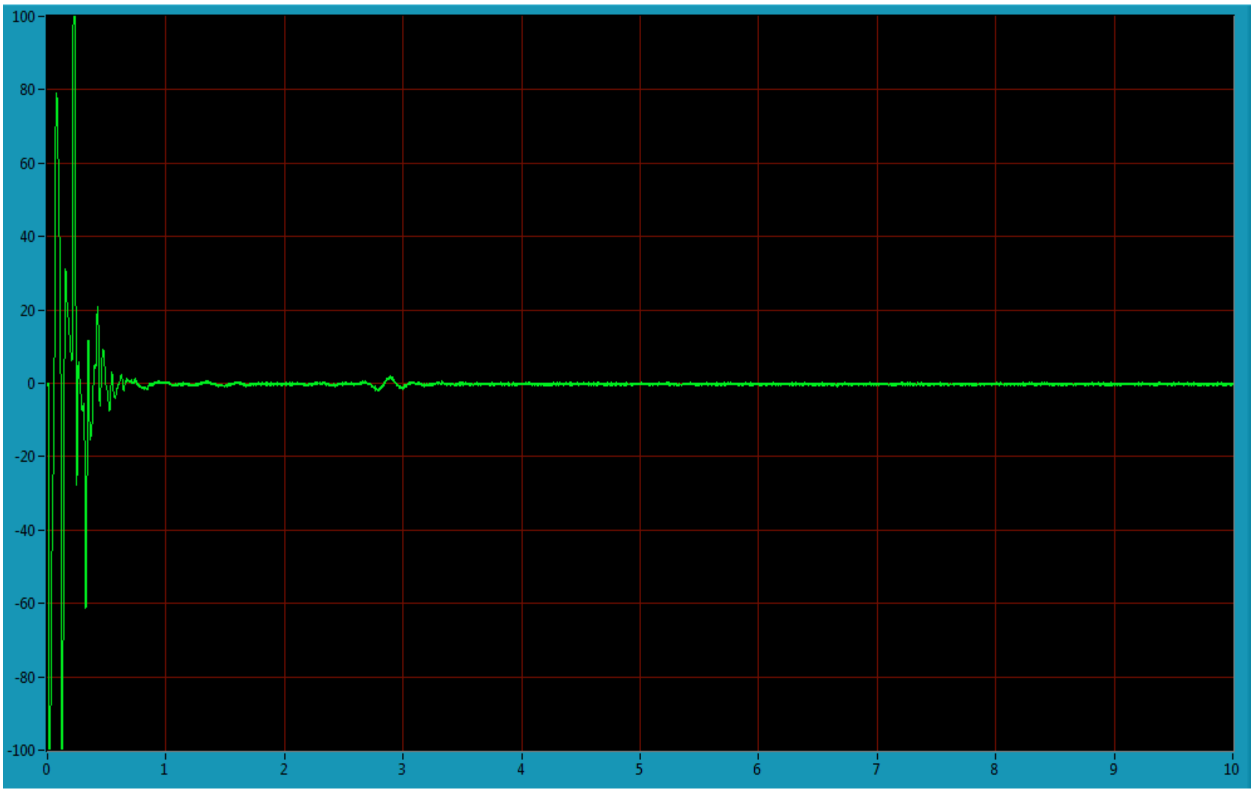
Aluminum: Measurement with 500 kHz transducer as emitter and PZT-element (1 MHz) as receiver.



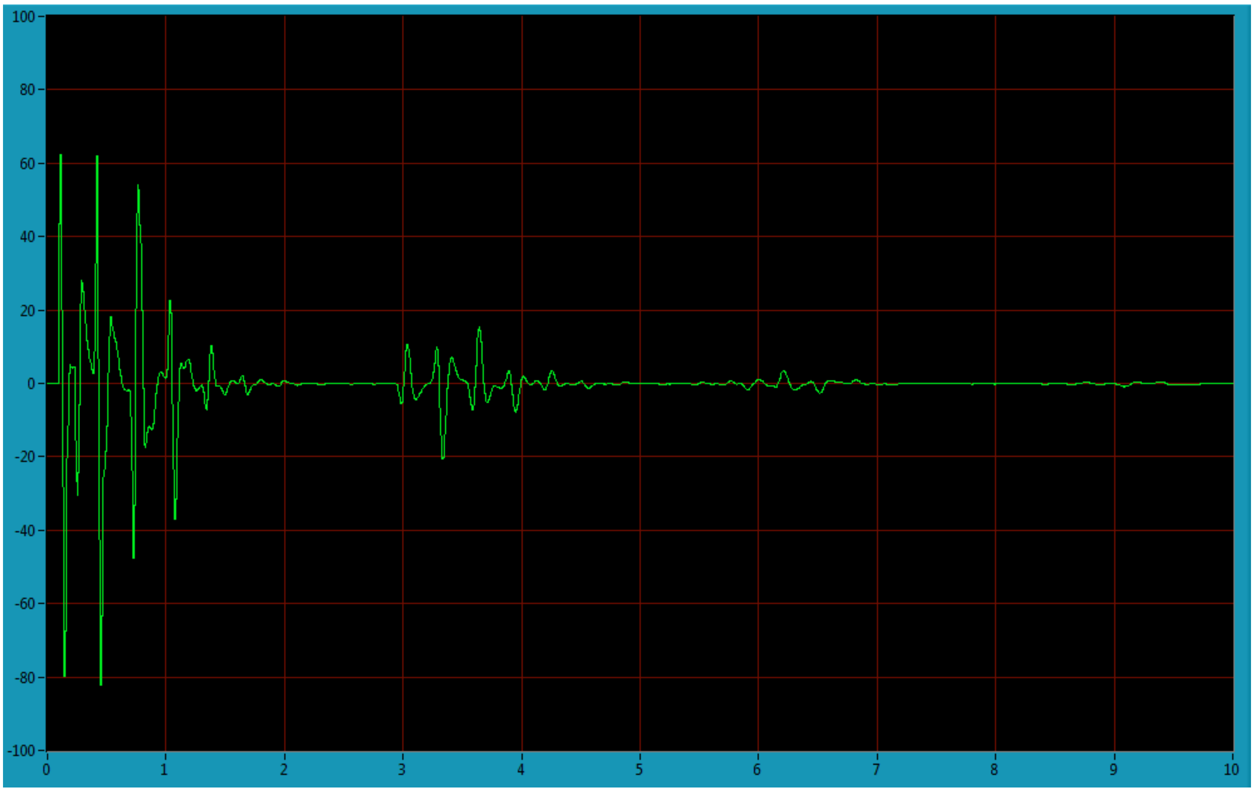
Aluminum: Measurement with 500 kHz transducer as receiver and PZT-element (1 MHz) as emitter.



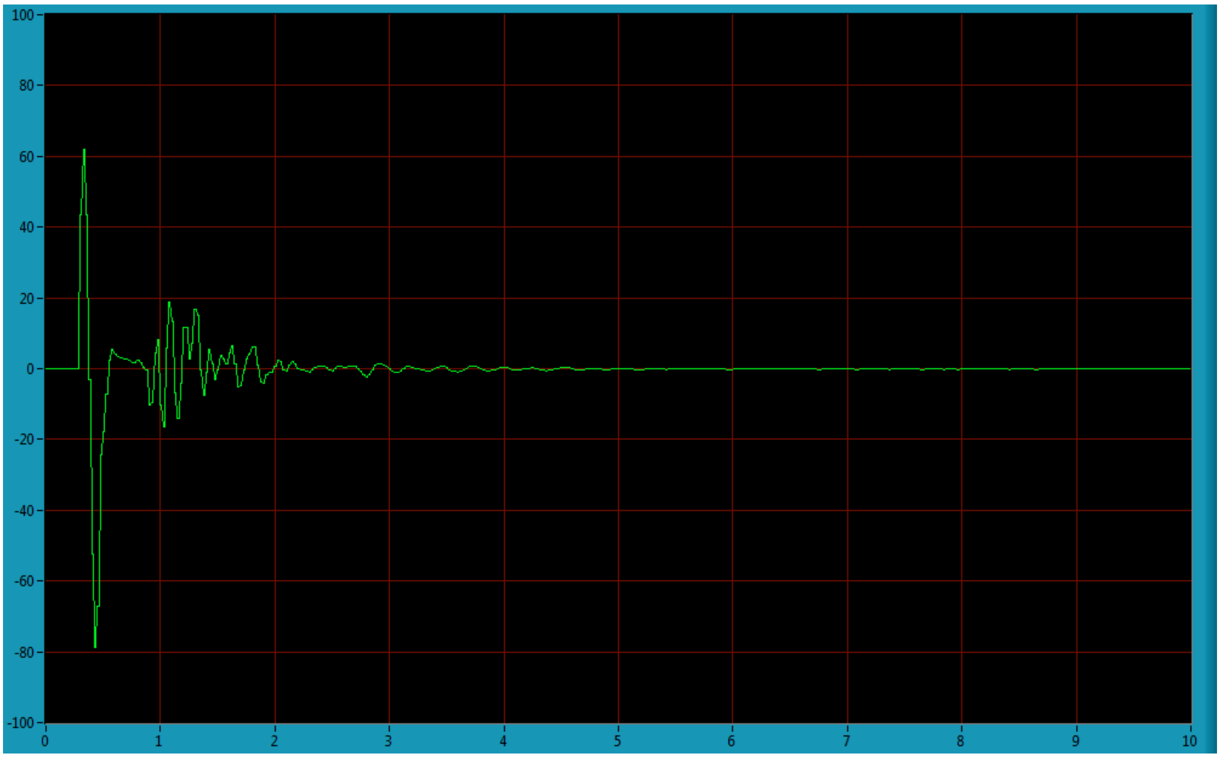
Aluminum: Measurement with 500 kHz transducer as emitter and as receiver at the same time.



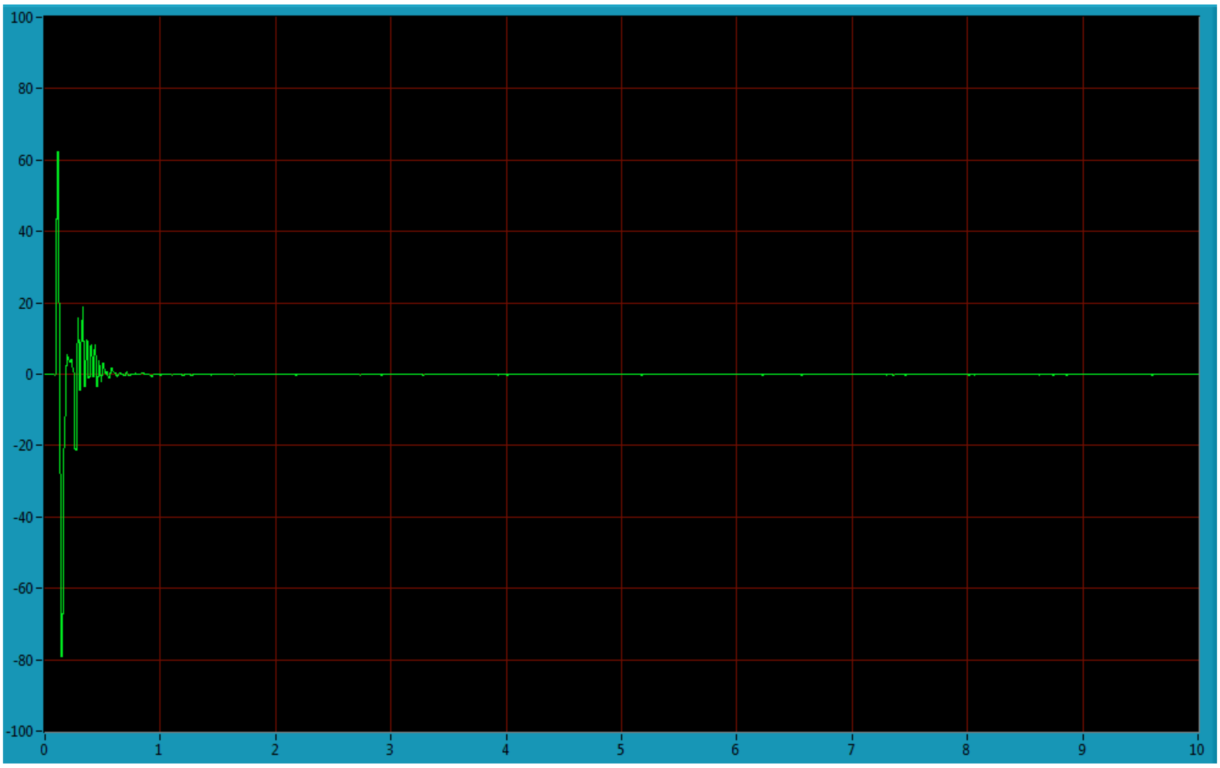
Rock: Measurement with 500 kHz transducer as emitter and as receiver at the same time.



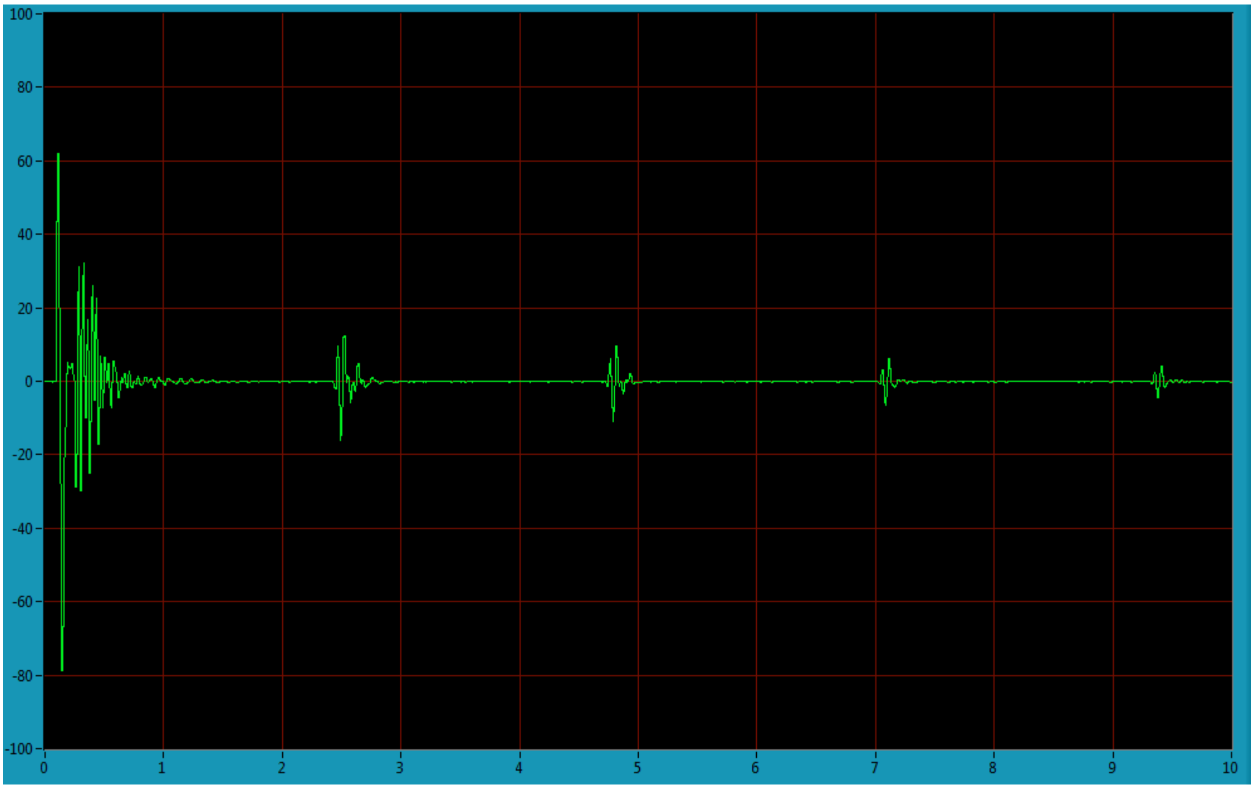
Plastic: Measurement with 500 kHz transducer as emitter and as receiver at the same time.



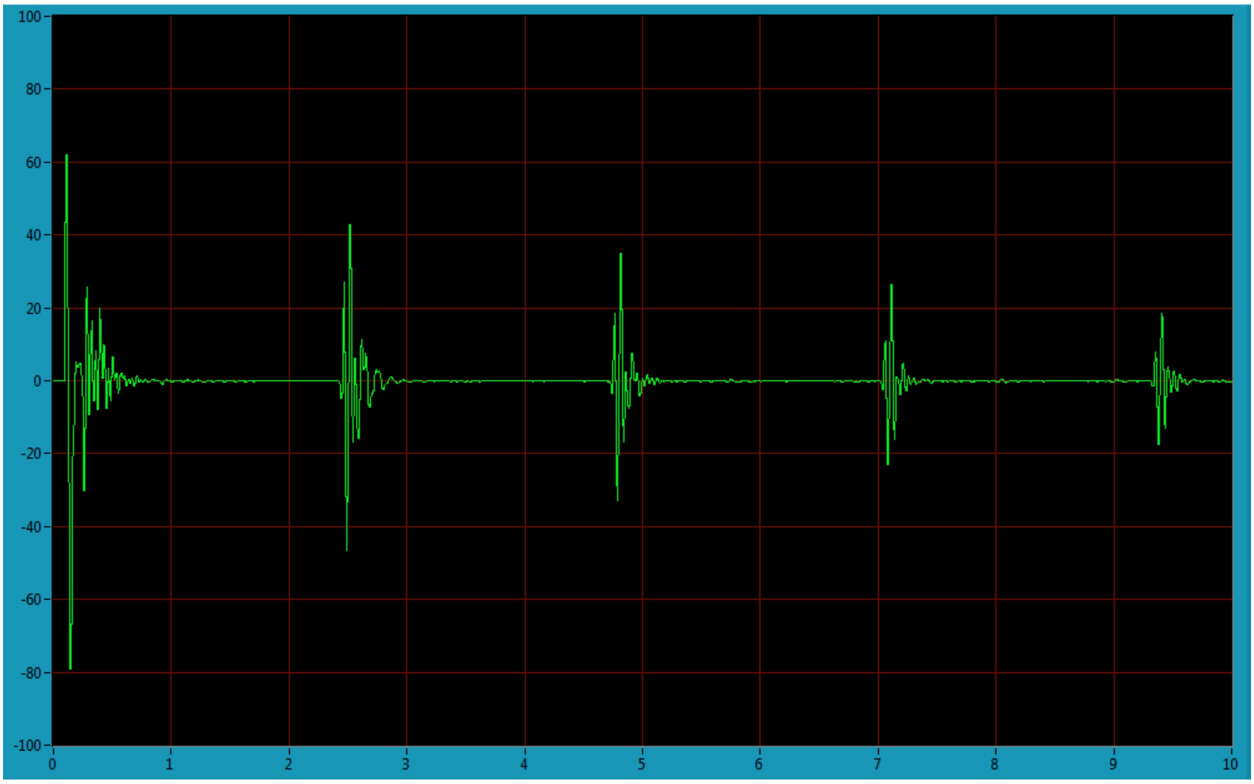
Silicone: Measurement with square PVDF-film (side length 1.5 cm) as emitter and as receiver at the same time.



Silicone: Measurement with circular PVDF-film (diameter 1.5 cm) as emitter and as receiver at the same time.



Bright drawn steel: Measurement with circular PVDF-film (diameter 1.25 cm) as emitter and as receiver at the same time.



Bright drawn steel: Measurement with circular PVDF-film (diameter 1.5 cm) as emitter and as receiver at the same time.