EXCITATION SETUP FOR ULTRASONIC HYPERTHERMIA

A dissertation submitted in partial fulfillment of the requirements

for the degree of

Master of Technology

by

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Dissertation Approval

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Abstract

Ultrasound is one of the modalities of hyperthermia treatment for cancer in which the temperature of the cancerous tissue is to be raised by 4-5 degrees above the normal body temperature. Heating of the target tissue by ultrasound should be more than that of the surrounding areas. This project involves developing and testing a system for directing ultrasound from multiple transducers on a target in a water bath. Water immersible transducer probes for continuous wave excitation were made using piezoelectric crystals. Four such transducers probes were mounted on a circular disc and oriented such that their beams direct at the target. They were then excitation sequentially to deliver more energy at the target than at the surrounding regions. Hardware used such as power amplifier, switching circuit using microcontroller and relays was implemented and tested for switching and exciting the transducers in different sequences. The experiments for field measurement during various modes of excitation are described and the results are analysed.

Contents

List of Abbreviations

Abbreviation	**Term**
RF	radio frequency
EMF	electro motive force
EM	electro magnetic
LED	light emitting diode
N/W	network
PZT	lead zirconate titanate
PVDF	poly (vinylidene fluoride)
TRM	time reversal mirror

List of Symbols

Symbol	**Explanation**
(γ, θ)	coordinates of the source points in the plane of transducer
(r, ϕ)	coordinates of point away from transducer surface
dS	size of incremental point source on surface of transducer
r'	distance between source points and the point of observation
z	distance along central axis of transducer
E_z	electric field along the thickness of crystal
V	voltage
l	thickness of crystal
I_z	field intensity of tranducer along central axis at a distance z from surface of transducer
I_o	maximum field intensity of transducer
d	diameter of crystal
λ	wavelength
ψ	beam spread angle of transducer
t	time
τ	time interval
α	attenuation coefficient
f	frequency
P_s	absorption per unit volume at skin surface
P_t	absorption per unit volume at target area

μ_s	absorption coefficient of the tissue at skin surface
μ_t	absorption coefficient of target tissue
R	ratio of absorption at the skin surface and at the target
n	number of transducer excited
R_d	intensity desity ratio
D	diameter at the skin surface
k	thermal conductivity of tissue
T	tissue temperature
T_a	arterial blood temperature
W	blood perfusion rate
C_p	tissue specific heat
Q_p	local power deposition
ρ	density of tissue
TX1	transducer 1
TX2	transducer 2
TX3	transducer 3
TX4	transducer 4
RL1	reed relay 1
RL2	reed relay 2
RL3	reed relay 3
RL4	reed relay 4
V_s	supply voltage to power amplifier
S1	switch cell 1
S2	switch cell 2
S3	switch cell 3
S4	switch cell 4

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Chapter 1

Introduction

1.1 Hyperthermia

Hyperthermia is a treatment modality for cancer, where the temperature of cancerous tissues is elevated to 4 to 5^0C more than the normal body temperature. It has been found that the rapidity of cell division at the affected tissue decreases when subjected to elevated temperature over a period of time [1]. The heated cells are then more permeable to other modalities of treatment like chemotherapy and radiation. It is imperative at the same time not to overheat other surrounding healthy tissues. Research is going on in various parts of the world for designing and developing of hyperthermia systems. The following are the important considerations in designing hyperthermia system.

1. It should be non-invasive.
2. It should provide proper focus and directivity of the heating media on the target tissue with minimum heating of surrounding tissues.
3. It should provide the required heat input to elevate the temperature of target to the required levels.

1.2 Historical development of hyperthermia

The history of heat therapy is both ancient and extensive. As far back as 5,000 B.C., Egyptian doctors treated tumors with heat. The Greeks recognized the value of heat in some medical treatments. Pre-Christian Jews, and Romans all used thermal baths for their curative properties. The rareness of rheumatism in Japan has been thought to be a result of the custom of taking regular, extremely hot baths from infancy. These hot baths were the basis for many successful treatments of syphilis and leprosy. Native Americans have a long tradition of using "sweat lodges" for treating diseases, particularly acute fever [2].

In modern times, interest for hyperthermia as an antitumoral therapy began in 1866 with the discoveries made by a German physician, W. Busch. He observed that the sarcoma disappeared when the patient, who had a highly-contagious skin disease called erysipelas, fell into a high fever. After having studied the effect of these fever flashes, Busch wrote the first scientific report on the effects of heat on tumoral tissues. Near the end of the 1800's, other European and American physicians noted that, when the patient had a very high fever, some malignant tumors receded spontaneously. Researchers like the surgeon W. B. Coley of New York, extracted toxins from the bacteria that causes erysipelas and they inoculated it in patients with inoperable sarcomas. Clearly, modern hyperthermia has long worked alongside of immunotherapy. It is difficult to determine exactly what long-term results were obtained with the treatment of total hyperthermia in the last century. Subsequently, however, experimentation became more frequent and eventually, local hyperthermia was used on tumors. The first in the field to do this was the Swedish gynecologist Westermark. In 1898 Westermark observed the beneficial effects of the local application of heat to inoperable carcinomas in the uterine cervix [3].

Number of investigators in the first quarter of next century who were studying cancer in the laboratory found that tumors were killed by heat more rapidly than were normal benign tissues and that heat acted synergistically with X-irradiation to destroy cancer. Thus people in the early part of this century moved there attention from whole body hyperthermia to regional hyperthermia where in a particular region or part of the body was heated and care was taken not to heat the normal benign cells. This diversion from the earlier methods of heating made people to think of new methods which would deliver the heat only to the targeted region of the body. This lead to the development of methods like capacitive heating, Inductive heating, Microwave heating and ultrasonic heating which are explained in following section.

1.3 Heating techniques

Various techniques can be used for heating in hyperthermia are capacitive, inductive, microwave and ultrasonic. These are briefly described here :

1. Capacitive heating [4][5]: In this method the patient is placed between two capacitor plates. Alternating current with frequencies in the range of 13.56 to 27.12 MHz are used in order to produce parallel field patterns. The dielectric losses of the capacitor manifest themselves as heat in the intervening tissues and the thus heating is obtained. This form of heating may produce heating patterns that are difficult to predict because the current will follow the path of least resistance, perhaps bypassing intended target tissues, if these have low conductivity and are parallel to adjacent high conductivity tissue. Also, the subcutaneous fat layer is a high resistance pathway in series which produces more heat and dissipates it poorly because of low thermal conductivity and low vascular perfusion.

2. Inductive heating [5][6]: This method involves placing the patient within a coil or coils. When RF current is passed through such a coil an electrostatic field is set up between its ends and a magnetic field around its center. In this situation, deeper heating can be produced in a segment of body, the length depending on the number of coils used. Induction has poor coupling efficiency, but the treatment appears to be well tolerated by patients and presumably should be able to produce heating of deep tumors such as in lung and pancreas, with less trauma and stress to the patient than whole-body hyperthermia. However, inductive heating of the body tends to favour superficial tissues with attenuation at increasing depths. Focusing or heat deposition at deep tissues is difficult in this method.

3. Microwave heating [5]: It consists of irradiating tissues of the patient's body with very short wavelength waves having frequency in the microwave range. Typically, the frequency used is 2450 MHz. Heating effect is produced by the absorption of the microwaves in the region of the body under treatment. Various microwave antennas are used as the source of microwave. The disadvantage of microwave heating is that regardless of the frequency chosen, the energy density in the locally applied EM beam decays rapidly because of absorption, divergence, and fringe effects of the fields. Also if a number of small applicators of microwave are used, the beams are not convergent and hence the heating is not efficient. Microwave heating is superficial and cannot be used for deep seated tumors in the body.

4. Ultrasound heating [5]: Ultrasound by definition are sound waves above 20 kHz. In diathermy the frequency is usually around 1 MHz. At this frequency the wavelength is about 1.5 mm in tissue. Since many anatomic structures are large as compared with this wavelength, reflection of ultrasound from tissue interfaces is a problem. Up to 30 percent of energy is reflected from a muscle/bone interface, while bone absorbs ultrasonic energy 10 times more readily than muscle. Advantage of ultrasound is that since absorption is proportional to the protein content of tissue, relatively little ultrasonic energy is absorbed in fat. Another advantage of ultrasound is its small angle of divergence -6.5^0 for a 2 cm. diameter transducer, less for larger transducers. This makes it possible to focus energy into small tissue volumes, especially with multiple applicators. Multiple applicators also decreases the hazard of gaseous cavitation in the intervening normal tissue.

There is no "best" hyperthermia method. Microwave, radio frequency, and ultrasound treatments are appropriate in different situations. It is more difficult to direct and focus microwave and radio frequency energy. This sometimes results in the heating and damaging of normal cells. Ultrasound can be more easily focused, which eliminates these problems. Also, ultrasound can be used for tumors at those deeper locations at which microwave and radio frequency cannot reach. On the other hand, ultrasound is not appropriate for most tumors involving bone or behind gas-filled cavities, such as bowel or lung. In these situations, microwaves would be more useful [1].

1.4 Scope of project

This project involves carrying out experiments in vitro to obtain pressure profiles at target points. A system is to be developed which can direct the ultrasound at a target area in a water bath from multiple transducers. To achieve heating of the target area to a temperature of 4 to 5^0C above the normal body temperature without heating the surrounding area, sufficient heat need to be delivered at the target and less at the surrounding areas. Single transducer cannot serve this purpose. So, a number of transducers whose pressure waves are directed towards the target area are used. These transducers are excited in sequence such that the target area receives continuous pressure waves, while the surrounding medium will have intermittent pressure waves. The number of transducer elements to be used as source of ultrasound will depend on the frequency of excitation and the ratio of pressure amplitudes obtained at the area of interest and the surrounding parts.

The transducer probes (sources) will be mounted on a circular disc of aluminium which will hold the transducers and then can be tilted such that the direction of the ultrasonic output of all the excited transducers is on the target area. The system developed will facilitate the selection of sequence and period of excitation of different sources to get continuous ultrasonic energy at the target for the required amount of time to get sufficient heating. The related hardware will be developed for experiments in vitro.

1.5 Report outline

Project involves the field measurement of ultrasonic transducers excited by continuous wave excitation, so it is important to mention some fundamental aspects regarding the ultrasound generation and wave propagation. Chapter 2 of the report discusses the basic theory related to the ultrasound propagation. It describes the transducer beam characteristics and the transducer selection. It also gives a brief account of various techniques for focusing and directing the ultrasound.

To carry out the experiments in the laboratory, an experimental setup has been developed. Chapter 3 describes the setup used for experiments to be carried out. It also explains the sequence of excitation of ultrasonic transducers.

Chapter 4 reports about the hardware which is used for the experimental purposes. It describes a method of switching of different transducers.

The experimental process and their results are given in next chapter. Chapter 5 describes the experiments which were carried out and presents the results obtained from the experiments.

Every experiments has some limitations, and there are some difficulties which are encountered during the course of experiments. Chapter 6 brings into light the limitations which were encountered during course of this project. This chapter gives some suggestions on how the system can be improved in future, and proposes a scheme for mounting of transducers around the body of a patient in real situation. Conclusions are also presented in this chapter.

Chapter 2

Ultrasound generation, directivity and focusing

2.1 Introduction

This chapter describes the basic concepts related to transducers and their field patterns. It also covers the ultrasonic field distribution at various points of interest. This chapter also includes an account of various techniques used in focusing of ultrasound and describes the criteria for selection of number of transducers and their placement for obtaining optimum intensities at the target.

2.2 Ultrasonic radiation

The emitting surface of a transducer of any shape and size is considered to be represented by small areas, each of which acts as source which radiates or receives energy in the manner appropriate for the application of Huygen's principle. At any given point in space (r, ϕ) away from the transducer surface, the ultrasonic field at any time is made up from all the separate contributions of each of Huygen's sources. This is shown in Fig 2.1. When these contributions are in phase, they interfere to form amplitude maxima; but where they are out of phase, destructive interference occurs and there are corresponding minima. The phase variations arise because of the differences in the path lengths between different points on the surface of the transducer and any given point in space. The field of an ultrasonic transducer consists of maxima and minima along the central axis of the transducer surface [10].

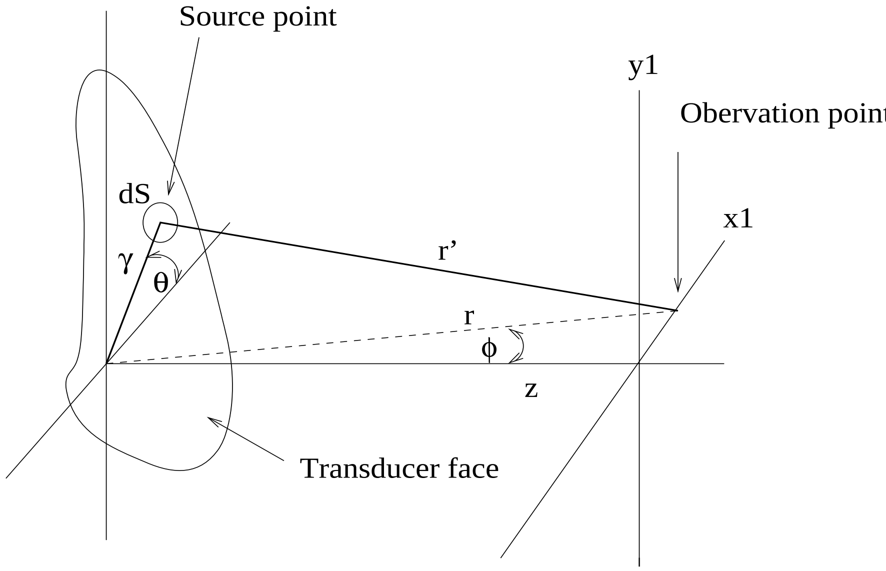


Figure 2.1: The general coordinates for the radiation pattern from an ultrasonic transducer [9].

2.3 Plane disc transducer

A key ingredient of any ultrasonic hyperthermia system is the means of generating and detecting the acoustic waves. Ultrasound is a sound wave of frequencies higher than 20 kHz. In the lower frequency range ($<$ 20kHz), the sound waves have less directivity, while at higher frequency ($>$ 10 MHz) attenuation is more. Thus as a compromise the most effective range of frequencies for hyperthermia applications is between 1 MHz to 10 MHz. There are various ways for producing ultrasound such as induction coil loudspeakers, magnetostrictive devices. These can be used at a lower frequency range i.e. below 500 kHz. But, by far the most convenient transducer at ultrasonic frequencies are piezoelectric crystals and ceramics. Piezoelectric transducers have many advantages over other ultrasonic transducers for hyperthermia applications, such as:

i) easy to manufacture in any shape.

ii) easy to excite using electrical signal.

iii) makes the process of focusing more simple.

2.4 Transducer field distribution and excitation

There are different piezoelectric materials cut and oriented for use as an ultrasonic transducers. The materials might be quartz, barium titanate, lead zirconium titanate

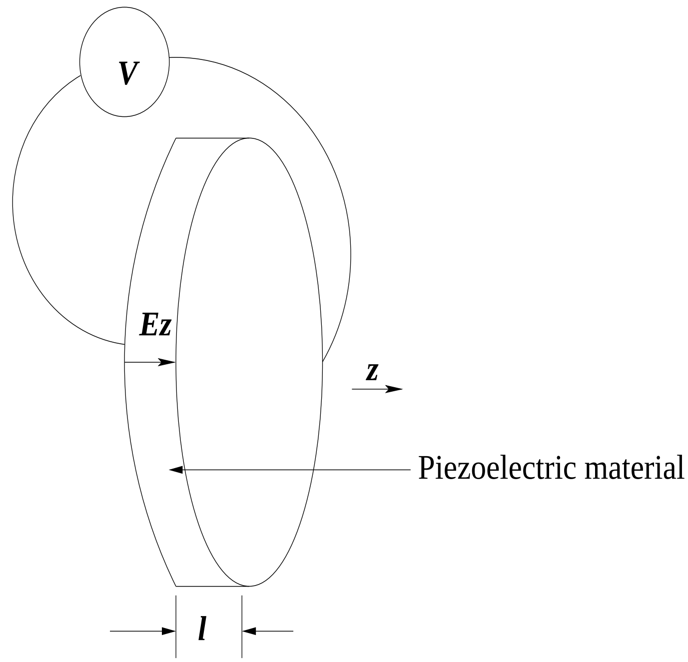


Figure 2.2: Piezoelectric material as a transducer with opposing electrodes [9]

(PZT), or poly vinylidene floride (PVDF). Two opposite faces of the transducers are plated with conductive metal films(generally silver); a voltage generator V, is attached to the electrodes to produce an electric field E_z across the thickness of the transducer whose magnitude is given by (assuming the diameter is much larger than l) $E_z = \frac{V}{l}$ as shown in Fig. 2.2 [9].

Due to this applied electric field the crystal faces develop compressional stresses which makes them vibrate and a piston like action will set up the desired compressional wave. The vibration amplitudes will depend upon various factors such as applied voltage, its frequency, orientation of crystal, the piezoelectric coefficients etc. The ultrasonic field of the transducer is as shown in Fig 2.3.

As shown in the Fig. 2.3 (b) as we move along the central axis z of the transducer the relationship which applies to the distribution of beam is [10]

$$\frac{I_z}{I_o} = sin^2 \frac{\pi}{\lambda} \left\{ \left(\frac{d^2}{4} + z^2 \right)^{1/2} - z \right\} \tag{2.1}$$

where I_o is the maximum intensity, I_z is the intensity at distance z from the transducer surface, $d = 2$a is the diameter of the transducer and a is the radius, λ is the wavelength in the propagation medium. Particular solutions of Equation. 2.1 gives the central axial positions respectively of the maxima as:

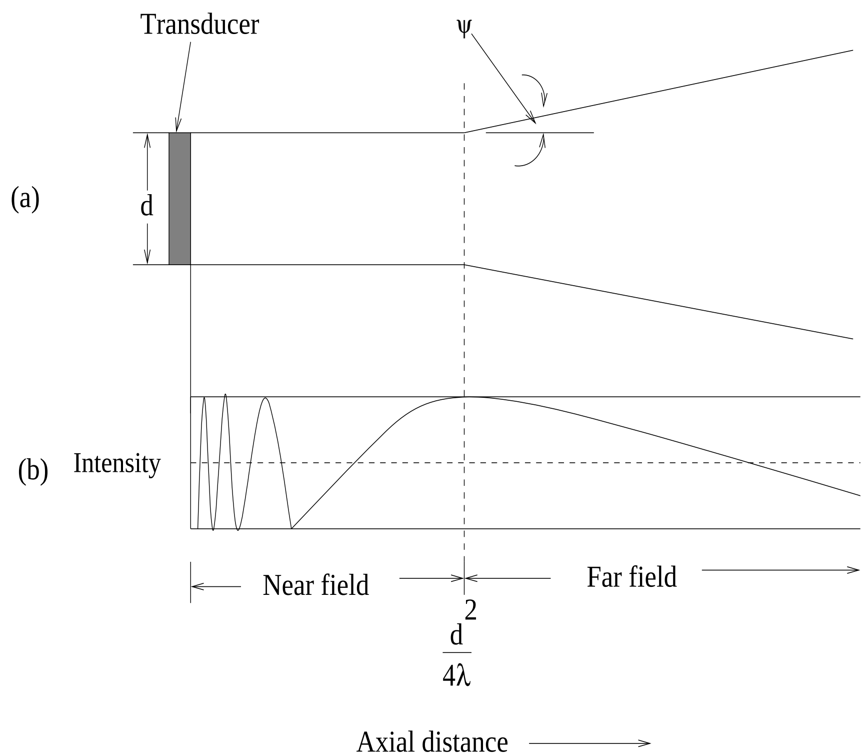


Figure 2.3: The ultrasonic field of a plane disc transducer (a) Spread of beam; (b) relative intensity distribution along the central axis of the beam [10]

$$z_{max} = \frac{4a^2 - \lambda^2 (2m+1)^2}{4\lambda (2m+1)} \tag{2.2}$$

and the minima as:

$$z_{min} = \frac{(a^2 - \lambda^2 n^2)}{2n\lambda} \tag{2.3}$$

where $m = 0, 1, 2$, etc., and $n = 1, 2, 3$, etc.

Moving along the central axis away from the source, the position of the last maximum occurs at a distance given by

$$z'_{max} = \frac{(4a^2 - \lambda^2)}{4\lambda} \tag{2.4}$$

If $a^2 \gg \lambda^2$, this expression can be simplified to become

$$z'_{max} = \frac{a^2}{\lambda} \tag{2.5}$$

The position z'_{max} corresponds to the beginning of the transition between the Fresnel zone (the near zone) and the Fraunhofer zone (the far zone). The field in the far zone may be considered to be plane over distances comparable with λ. In the region where $z \gg z'_{max}$, the intensity follows the inverse square law, and $I_z \propto 1/z^2$.

Also it can be seen from Fig. 2.3(a) that in the near field the beam is confined to in an envelop whose width is same as the diameter of the crystal and as one moves along the central axis the beam starts spreading in the far field. The angle of spread is given by [5]

$$\psi = sin^{-1} \left(\frac{0.61\lambda}{2d} \right) \tag{2.6}$$

Two types of electrical excitation could be given to the ultrasonic transducers, continuous wave or pulsed. Since we want that the pressure amplitudes should be sufficient to heat, we are mostly concerned with the continuous wave excitation and this report deals with the continuous wave excitation only.

2.5 Focusing and directing techniques

There are various techniques used for focusing such as direct ultrasonic beam focusing, Timer Reversal Mirror method and Multitransducer technique. These are briefly described below.

1. Direct ultrasonic beam focusing : In this focusing method [11], the ultrasonic beam is focused with the help of (a) mirror, (b) an acoustic lens, (c) geometric structure of the transducer. Focusing is not accurate for small targets in this method. Moreover, for use in short ranges a short wavelength is needed, which results in an aperture limitation. Geometric design of this technique is simple, but difficult to manufacture. Also the required ratio of intensity levels of the targeted and non-targeted regions cannot be achieved in this method.

2. Time reversal mirror (TRM) technique : This technique [17] based on the concept of time reversal of ultrasonic field. A TRM consists of one-or-two dimensional transducer array. In this technique the properties of piezoelectric transducers such as their transmit and receive capabilities, their linearity, and the capability of instantaneous measurement of the temporal pressure waveforms are used. The pressure field $p(r_i, t)$ detected with a set of transducer elements located at positions r_i is digitized and stored during time interval τ. The pressure field is then retransmitted by the same transducers in a reversed temporal chronology (last in, first out). This is equivalent to the transmission of $p(r_i, \tau - t)$. Such a time-reversed procedure converts a divergent wave issued from an acoustic source into a convergent wave focusing on the source. This process can be used to focus on a reflective target that behaves as an acoustic source after being insonified in an inhomogeneous medium. Very high intensities of ultrasound is focused on the target and hence this method cannot be used in the region of soft tissues. Also the electronic circuitry required (receiving amplifier, A/D converter, storage memory, programmable transmitter, etc) is complex.

3. Multi-transducer technique: The basic principle of this method, proposed by Lele [12] is that the directed pressure waves from the transducers reach the target simultaneously. This gives more heating at the target and less in the surrounding medium. So in this technique the target is focused using number of transducers revolving around a circular path and providing continuous heating at the target and intermittent heating at the surrounding areas.

Shin-ichiro Umemura and Cain [16] have also used the same idea of transducer array for focusing. They constructed a phased -array applicator using special lead-titanate ceramic transducer elements of 16 sectors and two tracks attached on a disk-shaped aluminium shell with spherical curvature. These transducer element were excited with a phase rotation of the excitation to produce an annular focal field at the target area. This method of phased excitation is fast and allow complex spot-focus scan paths for precise synthesis of acoustic power deposition patterns. Moreover, this can directly synthesize, without scanning, complex acoustic field patterns that overlay tumor geometry. The acoustic power into the focal region was measured by plate deflection and it was demonstrated that the applicator was capable of producing sufficient focal acoustic power.

2.6 Selection of the number of transducers

The intensities of the ultrasonic plane wave propagating in the positive z direction is given by [18]

$$I\left(z\right) = I_0 e^{-2f\alpha z} \tag{2.7}$$

where,

$I\left(z\right)$ = acoustic intensity at a distance z into the tissue

α = attenuation coefficient $(nepers/cm/MHz)$

I_0 = acoustic intensity at surface of the tissue $(z = 0)$ (W/cm^2)

z = distance (cm)

f = frequency (MHz)

The absorption per unit volume at the skin surface and the target area can be expressed as [13]

$$P_s = \mu_s I_0 \tag{2.8}$$

$$P_t = \mu_t I_0 e^{-2\alpha f z} \tag{2.9}$$

where,

μ_s = absorption coefficient of the tissues at the skin surface.

μ_t = absorption coefficient of the target tissues. If n number of transducers are used and all of them are excited simultaneously then,

$$P_{tn} = n\mu_t I_0 e^{-2\alpha f z} \tag{2.10}$$

The ratio of absorption at the skin surface and the target is

$$R = \frac{P_{tn}}{P_s} \tag{2.11}$$

For $R \geq 1$, we should have

$$n \geq \frac{\mu_s}{\mu_t} e^{2\alpha f z} \tag{2.12}$$

As an example for, $\alpha = 1 nepers/cm/MHz$, $f = 2.8MHz$, $z = 6\ cm$ and assuming $\mu_s = \mu_t$,

$$n \geq e^{2\times1\times2.8\times6} = 3.911 \times 10^{14}$$

which is obviously impractical. Another method of achieving the objective would be to scan the transducers sequentially i.e., to excite the transducers sequentially. If each transducer is excited for a period of time t from equations 2.8 & 2.9 it is seen that

$$nt\mu_t I_0 e^{-2\alpha f z} \geq t\mu_s I_0 \tag{2.13}$$

$$n \geq \frac{\mu_s}{\mu_t} e^{2\alpha f z} \tag{2.14}$$

where the value of n is same as earlier.

In the first method, all the n transducers were excited simulateously and in the second method each transducer is excited sequentially. In the second method of excitation a single power amplifier is sufficient as it can be used to sequentially switch ON all the transducers as compared to the first method in which n amplifiers would be required for obtaining the same acoustic power at the target. Also the surrounding medium coming in the path of beams of transducers will receive power only during the time of excitation t. This gives the tissues of the normal surrounding areas adequate time for cooling. This is not the case when transducers are excited as in first method, since the normal tissues coming in the path of beam of all the transducers will receive the acoustic power simultaneously for the time the target is insonified. Thus first method of simultaneous excitation may damage the surrounding normal tissues.

Further, if d is the diameter at the target and D, the diameter at the skin surface. The intensity density ratio at the target and the skin surface would be

$$R_d = \frac{P_{tdn}}{P_{sd}} = \frac{\mu_s}{\mu_t} e^{-2\alpha f z} \frac{d^2}{D^2} \tag{2.15}$$

Substituting the values in the above example and assuming $d = 1\ cm$ and $D = 6\ cm$,

$$n \geq \frac{e^{2\times1\times2.8\times6}}{6^2} \times 1^2 = 1.086 \times 10^{13}$$

The three dimensional transient bioheat transfer equation can be written as follows [15][14].

$$\rho C_p \frac{\partial T}{\partial t} + W C_b \left(T - T_a\right) - k\nabla^2 T = Q_p \tag{2.16}$$

Here, k is thermal conductivity in tissue (W/m/^{0}C), T is the tissue temperature (^{0}C), W is the blood perfusion rate (kg/m^3/s), C_p is the corresponding tissue specific heat (J/kg/^{0}C), T_a is the arterial blood temperature (^{0}C), Q_p is the local power deposition. (W/m^3) and is a function of intensity and duration. ρ is the density of the tissue (kg/ m^3) and t is time in seconds. Blood perfusion rate W is less at the cancerous tissue.

From the above equation it can be seen that the temperature rise at the skin surface increases exponentially with a time constant, which is proportional to $\frac{\rho C}{W}$ much greater than at the target.This time constant is hence less at the target than at the skin.

If the time period of excitation of each transducer is taken, much less than the thermal time constant of the surrounding media and a large number of transducers are excited sequentially then it can be ensured that the surrounding media are not elevated to the same temperature rise as the target. The actual number of transducers to be used could be determined from the solution of bioheat equation and the knowledge of the thermal parameters.

Chapter 3

System setup

3.1 Introduction

In the previous chapter, it was shown that the use of multiple transducer is necessary so that the target area is heated more than the surrounding medium. This chapter describes the system used for the experimentation purpose. The transducers are mounted on a disc and they are then excited in different modes which will be explained in this chapter. The pressure profile for different modes of transducer excitation at various points in water is measured with this setup. Experiments were carried out for the ultrasonic field measurements in water at various depths from the transmitting transducer in both near and far field.

3.2 System block diagram

The system block diagram is shown in Fig. 3.1. It consists of water tank with a bridge, excitation transducers, signal generator, amplifiers, hydrophone, preamplifier. In this setup the tank is manufactured by Physical Acoustic Corporation, Princeton Junction, NJ, USA. It is provided with a bridge on which the hydro-phone or the sensing transducer can be fixed using a holder. This bridge has the facility of moving the sensing element (hydrophone or transducer) along the length (X-axis), width (Y-axis) and height (Z-axis) of the tank both manually or by stepper motor control operated by a software provided by the manufacturer. The motion of the bridge in various directions was obtained manually by moving the screws provided for manual operations as the software was not functioning properly.

A hydrophone was used to measure the field of the ultrasonic transducers. Hy-

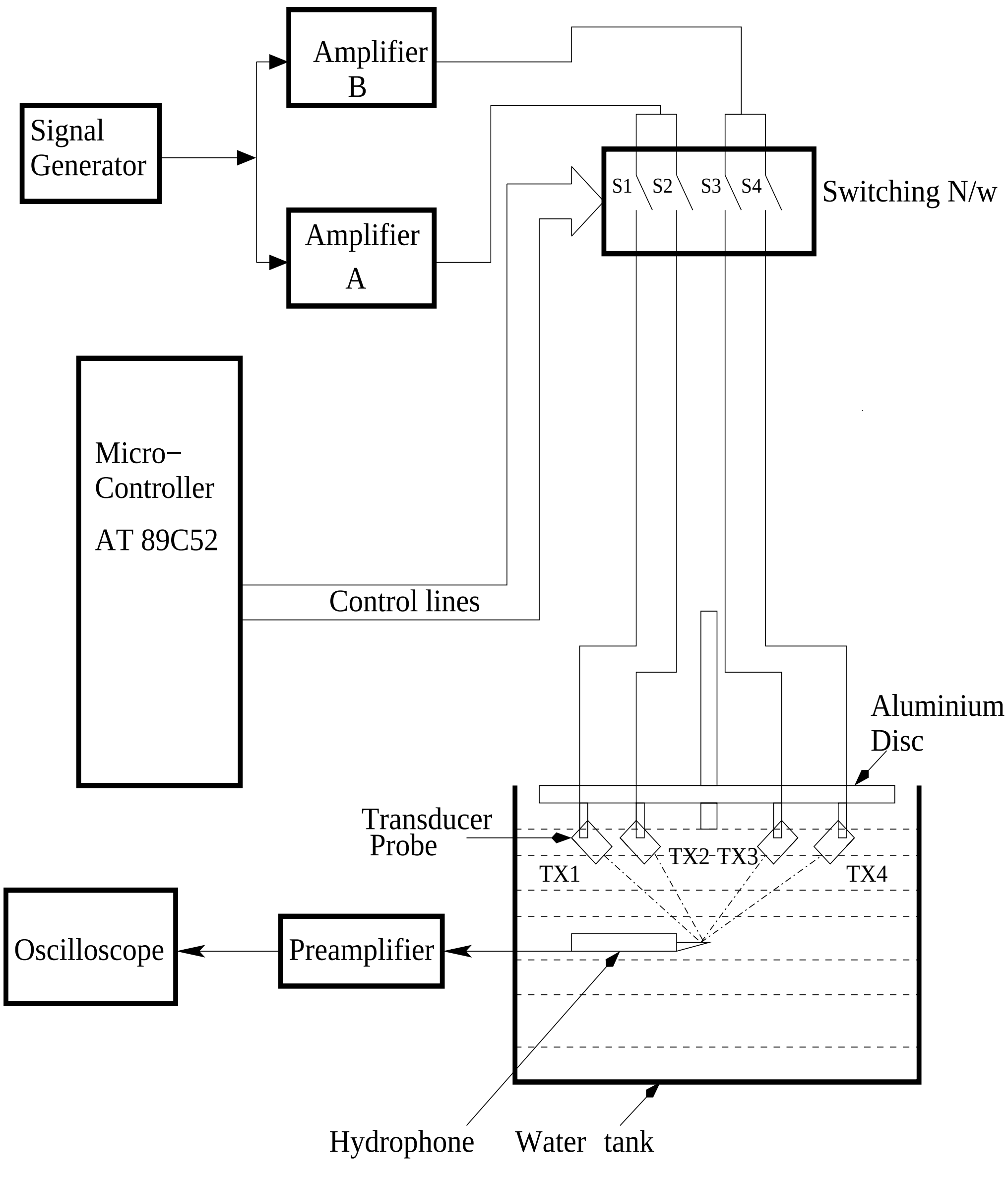


Figure 3.1: System block diagram

drophones are detectors based on transducers which respond directly to the ultrasonic field. The output of a hydrophone is an electrical signal which follows the instantaneous value of the ultrasonic field at the ultrasonic frequency. The hydrophone used is PZT-Z44-0400-S/N H639, manufactured and supplied by Speciality Engineering Associates, North Porter Street-Soquel, CA, USA. It uses PZT material as the sensing element. It is capable of operating in the frequency range of 1 to 10 MHz which is sufficient for the experiments.

A transducer was also used as the sensing element for field measurement which integrates the pressure wave over an area. The transmitting transducer was excited by a continuous wave sinusoidal excitation generated by a push-pull power amplifier. The frequency of excitation was adjusted by adjusting the input frequency to the amplifier.

3.3 Assembly of transducers

To direct the beam of ultrasound from the transducers, it is important that the orientation of the emitting source should be towards the target. It is necessary to have transducer assembly which would hold the transducers and give the required directivity. For this, an aluminium disc of thickness 3 mm and diameter 26 cm was used. The transducer probes were positioned symmetrically as shown in Fig. 3.2. A holder was designed to hold the probes on the disc. The probes were hinged to the holder bracket and were made free to tilt on the hinges. A screw was used to push the probe and tilt it inwards so that the beams of all the four transducers are directed towards target. The position of the point of convergence of the beams from all the transducers can be adjusted by changing the angle of tilt using the screws. This is important as the intensity changes considerably with a slight deviation from proper direction. For additional intensity at the target a focusing lens can be used. This whole assembly was placed in the water tank with the help of a stand. The sensing element (hydrophone/transducer) was fixed on the bridge of the tank with the help of a holder. This sensing element was moved below the disc to measure the field intensity at the target.

3.4 Sequential excitation

In this exploratory work, the pressure intensities when transducers are excited in sequence one by one, were measured. To increase the intensity at the target, experiments were carried out with a pair of transducers excited in sequence (mode 1 & mode 2). Also experiments were carried out using multiple transducers in the disc. Four trans-

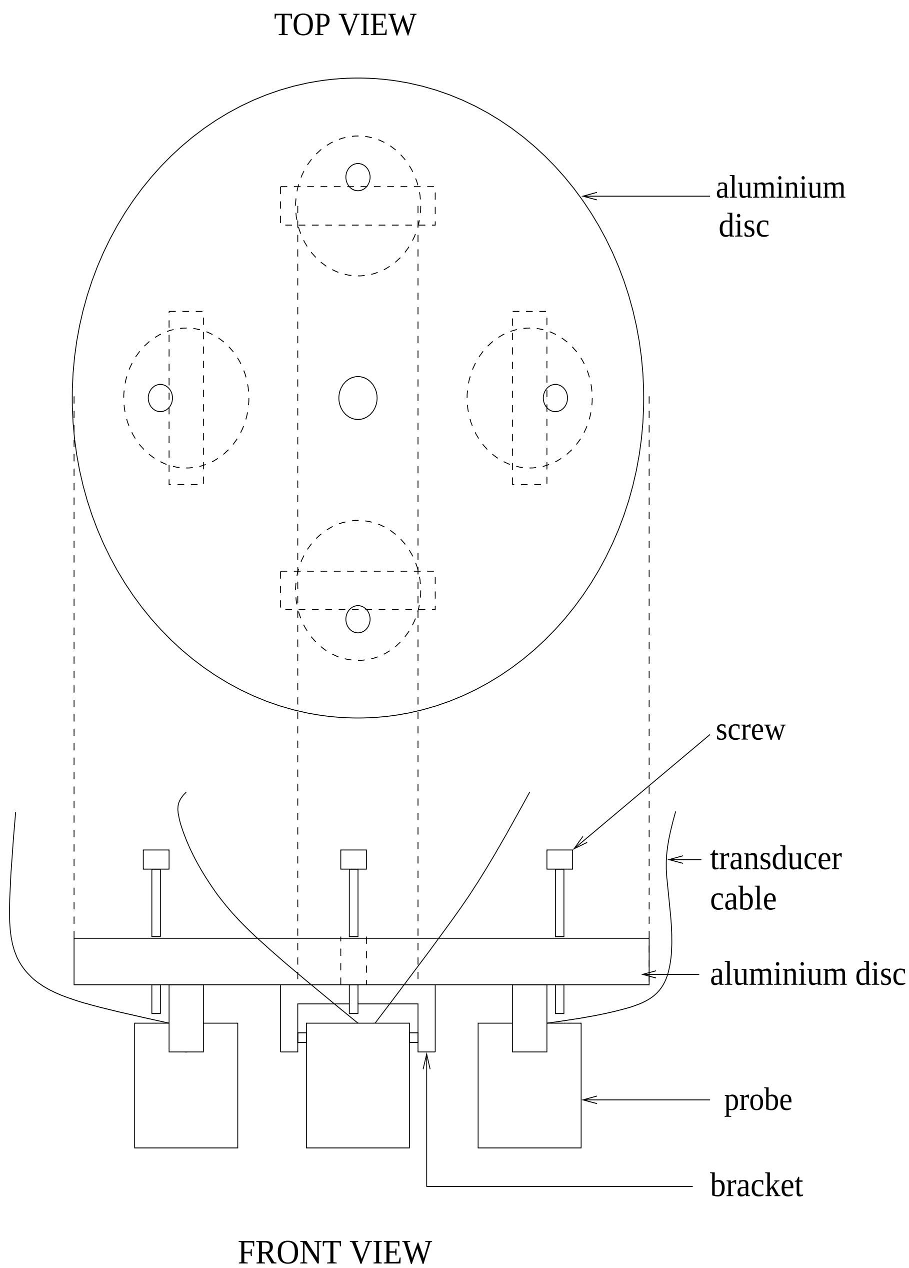


Figure 3.2: Assembly of transducer on disc.

ducers were used in this experiment. Two power amplifiers were used to excite the four transducers in various modes. The four transducers were connected to the two amplifiers through a switching network as shown in Fig. 3.1. Transducer TX1 and TX2 are excited by amplifier A and TX3 and TX4 are excited by amplifier B. Square pulses driving the amplifiers were given from a signal generator. The frequency of excitation was adjusted by varying the frequency of the driving signal. Since a single transducer was loading the amplifier, in each mode of excitation care was taken that not more than one transducer was excited by any amplifier at a given instant. The micro-controller was used to control the switching network and period for which the transducers are excited. The port 2 pins of the micro-controller were polled to select the period of excitation and the mode of excitation of the transducers. The periods for which each transducer was excited are t_1= 1 sec., t_2=1 min. and t_3=5 mins. So, first the duration of excitation is selected and then the modes of excitation are selected. Various modes of excitation are as follows:

Mode 0: In this mode each transducer was excited one after the other for the selected period of time t_s. First, switch S1 was closed and TX1 was connected to amplifier A for the period t_s and readings of the output of the sensing element were taken. After that duration switch S1 was opened and S2 was closed and TX2 was connected to amplifier A and readings were taken. Similarly readings were taken for transducers TX3 and TX4. Thus only one transducer was connected to one amplifier during a given time period. The sequence of switching was repeated after all the four transducers were excited.

Mode 1: In this mode two transducers were excited simultaneously for the selected period t_s. During first time interval S1 and S3 were closed and transducer TX1 and TX3 were connected to the amplifier A and B respectively. After this time interval t_s switches S1 and S3 are opened and S2 and S4 are closed so that transducer TX2 and TX4 are connected to amplifier A and B respectively. This sequence of excitation is repeated.

Mode 2: In this mode again two transducers are excited simultaneously for a selected period of time, but the combination of transducers is changed. During the first time interval t_s switch S1 and S4 are closed and TX1 and TX4 are excited by amplifier A and B respectively. In the next time interval S1 and S4 are open and S2 and S3 are closed such that TX2 and TX3 are connected to the amplifiers A and B respectively.

Chapter 4

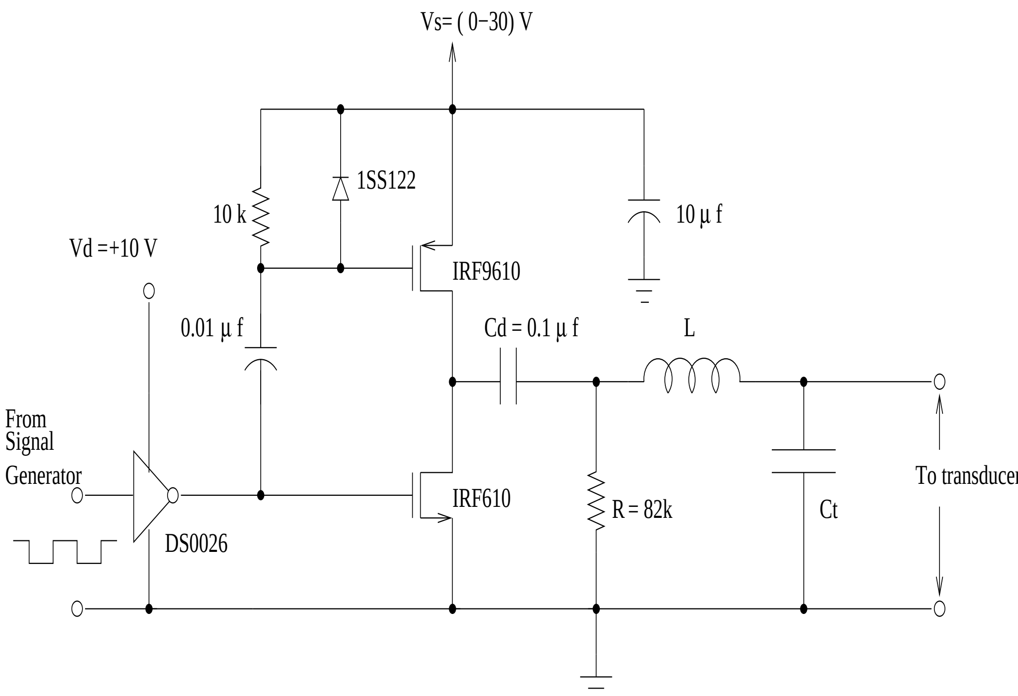
System hardware

4.1 Introduction

The transducers are excited by a continuous sine wave of frequency in the range of 1 to 3 MHz. This chapter describes the electronic hardware that has been designed, implemented and tested for the system. Also it is required to excite the transducers in various modes as described in the previous chapter. This lead to the development of a switching circuit controlled by microcontroller. The switching circuit is also described in this chapter. Different blocks used in the setup are power amplifier, switching elements and switching circuit.

4.2 Power amplifier circuit

The transducers used in the experiments were excited with continuous sine wave. As shown in the system block diagram (Fig. 3.1, Chapter 3) two amplifiers (A and B) are used for exciting a pair of transducers. Fig. 4.1 shows the circuit diagram of the amplifiers used [16]. This amplifier circuit use complementary pair of power MOSFET's. Two amplifiers were used to excite four transducers. As shown in Fig. 4.1. the MOSFET's in this circuit are operated in switching mode. A high- speed MOS driver, DS0026 is used as the driver for the amplifier circuit. Negative square pulses from signal generator are given to the input of the driver IC. These negative square pulses are inverted and given to the gates of MOSFET's. Thus during the period of negative square pulse, the P-channel MOSFET is ON and N-channel MOSFET is OFF and supply voltage V_s appears at the drains of the two MOSFET's. During 0 Volts period of the input square pulse P-channel MOSFET is off and N-channel MOSFET is



For Amplifier A: L = 7.2 µH, Ct = 10.82 pf

For Amplifier B: L = 1.66 µH, Ct = 1.86 pf

Figure 4.1: Power amplifier circuit [16]

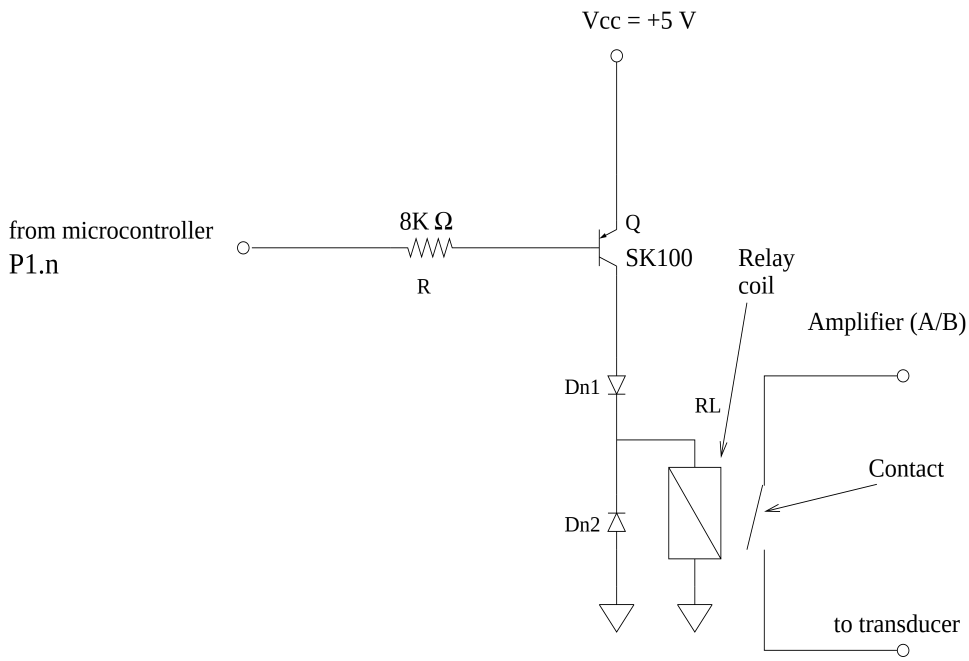


Figure 4.2: Switching cell S_n of switching N/W

ON, which pulls the drains of two MOSFET's to ground during this period. Thus for continuous negative square pulses as input to the amplifier from the signal generator, continuous square wave is obtained at the drains of the two MOSFET's of amplitude same as V_s. The absolute maximum rating of V_{GS} for both the MOSFET's is ±20 V. The switching frequency of the MOSFET's can be varied by varying the input square pulse frequency. This square wave is then passed through a series-parallel combination of L and C_t. This combination of inductance and capacitance acts as a tuned $L - C$ filter. After proper tuning a sinusoidal output is obtained. At resonance the amplitude of the resulting sine wave is more than the input voltage V_s. This sinusoidal output of the amplifiers is used to excite the transducers.

4.3 Switching network

During the three modes of excitation of the transducers as explained in chapter 3 the output of the two amplifiers A & B are connected to four transducers in different sequence. This change in the sequence in different modes is made possible by a switching network which is controlled by the microcontroller as shown Fig. 3.1, Chapter 3. This switching network consists of four switching cells S1, S2, S3, S4 as shown in Fig. 4.2. Each switching cell consists of a high speed reed relay. A transistorized switch is used to make the reed relay ON and OFF which are controlled by the microcontroller pins (p1.0 to p1.3). Diodes D1 and D2 are used to protect the circuit from large back EMF produced during switching.

4.4 Switching circuit

As discussed in Chapter 3 the transducers are excited in different modes by continuous sine wave generated from the two power amplifiers.

A switching circuit using reed relays and microcontroller is used to connect the transducers to the amplifier output in different modes. Fig 4.3 shows the switching circuit using microcontroller AT89C52 (Intel MCS-51 family compatible) and relays. The output of amplifier A is connected to transcducer TX1 and TX4 through the contacts of reed relays RL1 and RL4 respectively. Similarly the output of amplifier B is connected to Transducer TX2 and TX3 through the contacts of relays RL2 and RL3 respectively. Depending on the mode of operation selected, the relay coils are excited using the microcontroller. The sequence of excitation in different modes is indicated by four LEDs. Four pins, p1.0 - p1.3 of port 1 of the microcontroller are used to switch the relays RL1, RL2, RL3 and RL4 respectively and pins p1.4 - p1.7 are used to glow the LEDs L1, L2, L3 and L4 respectively. Here LED L1 corresponds to relay RL1, L2 corresponds to RL2, L3 to RL3 and L4 to RL4. A switching cell S_n is used to switch the relay ON/OFF. The relay coil is energized by giving a low at the base of the corresponding transistor (Q1, Q2, Q3 or Q4) which closes the contacts the relay. LED corresponding to this relay is turned ON by giving a high at the base of respective transistor (Q5, Q6, Q7 or Q8) which glows the same instant the relay coil is energized. In this way the contacts and closed and the amplifier output is connected to the transducers in different modes, the sequence of which is indicated by the corresponding LEDs. The microcontroller is programmed to select the period of excitation of transducers as well as the mode of excitation. The microcontroller generates the different time delays using the two internal timers which are used as the period of excitation. These time delays are $t_1 = 1$ sec, $t_2 = 1$ min and $t_3 = 5$ min. These times are selectable. Port 2 of the microcontroller is polled to select the period and mode of switching. An 8-switch DIP switch is connected to port 2 to select the period and mode. A table showing the selection process using the switch is given in appendix B.

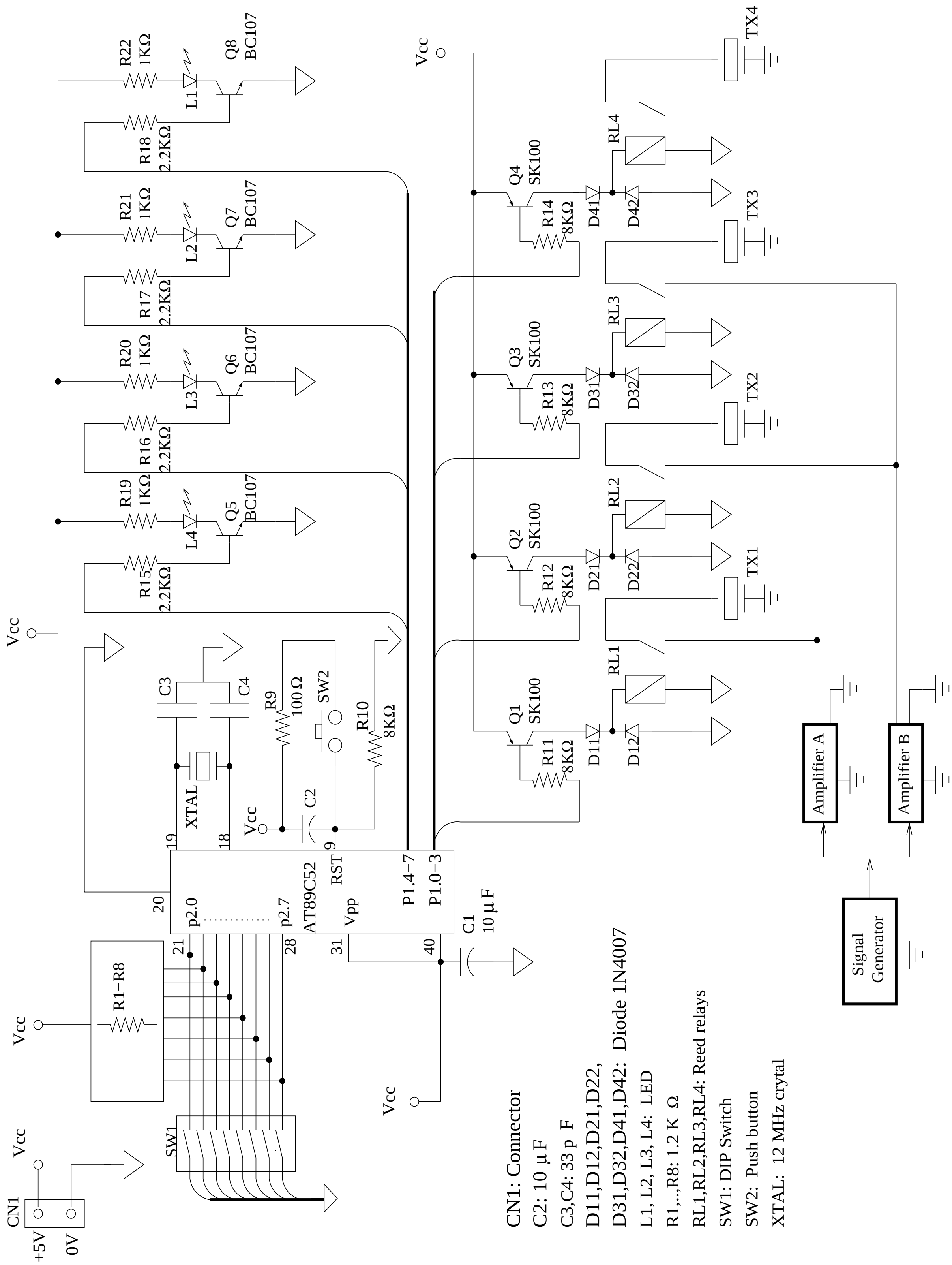


Figure 4.3: Switching circuit

Chapter 5

Experiments and results

5.1 Introduction

In chapter 3, methods for directing ultrasonic beams were discussed. Experiments were performed using the system and hardware as explained in Chapters 3 & 4 respectively. The resulting ultrasonic field patterns discussed in this chapter.

5.2 Experiments with damped probes

Initially field measurement experiments were carried out with ultrasonic transducers that are in the laboratory. These probes manufactured by M/s Roop Ultrasonix Ltd. are provided with a backing material. The backing material provides sufficient damping and hence are more suitable for pulsed excitation. The diameter of these probes is 15 mm and central frequency is 2.5 MHz. Thus the maximum near field distance from the transducer (as described in Chapter 2) equals $\frac{d^2}{4\lambda} = 9.4\ cm$. The field of these probes was observed in both near and farfield.

5.2.1 Near field

In this case hydrophone was kept at a distance z = 8 cm from the emitting surface of the probe. The transducer was excited at f = 2.6 MHz and peak to peak excitation of 10 V. The hydrophone was moved in a horizontal plane along the X-Y axes and readings were taken. For the same z, the readings were repeated three times. The pressure amplitudes recorded are shown in Fig. 5.1, Fig. 5.2 and Fig. 5.3. In these figures, the brightness of the boxes is proportional to the intensity of the hydrophone output. That is, the brightest box represents the maximum intensity point on the plane and the decrease in the intensity measured by the hydrophone is shown by the decrease in the brightness of the boxes. During the first set of readings, the coordinates of the maximum intensity point is (1.2, 0.6) on the plot. In the next set of readings, the maximum intensity point shifts to (0.9, 0.7), keeping all conditions same. In the third set of readings it shifted to (1.3, 0.6). Thus it can be seen that in the near field the maximum intensity point obtained for three sets of readings is not coming at the same point but it shifts. This may be due to the following reasons:

1. The motion along the axes was obtained manually using the screws. The steps taken to move along the axes in each repetation may not be the same, due to backlash of the screw.
2. The dimensions of the hydrophone is greater than λ which creates disturbance in the field.
3. The orientation of the hydrophone with respect to the transducer is also important since a slight change in it might produce large variations in the field measured.
4. As discussed in Chapter 2, the field pattern in the near zone varies.
5. There is scattering and reflection of the ultrasonic field from the tank surface. This has been taken care of to some extent by placing a pad of foam as an absorbing surface at the bottom of the tank.

5.2.2 Far field

In this case all the conditions were identical to the experiment for near field except the distance of the sensing element (hydrophone) was increased to z = 10.6 cm. The readings were taken in the same manner as in near field. The plots are shown in Fig. 5.4, Fig. 5.5 and Fig. 5.6. From these plots it can be seen that the maximum intensity point remains almost at the same position (1.1, 0.7) in the three sets. This indicates that in the far field, the field remains steady and the field intensity reduces symmetrically away from the highest intensity point.

Thus the results obtained are nearly as expected and comply with the theory.

5.2.3 Two transducer beams directed at target

In this experiment two transducers (A and B) were oriented to direct their beams at a target point in the farfield (z = 10.5 cm). Two amplifiers were used to excite the transducers. Both the transducers were excited with excitation frequency of 2.6 MHz and amplitude 10 V peak-peak. The excitation voltage of both the transducers were in phase. The sensing element (hydrophone) was moved along the width (Y- axis) of the

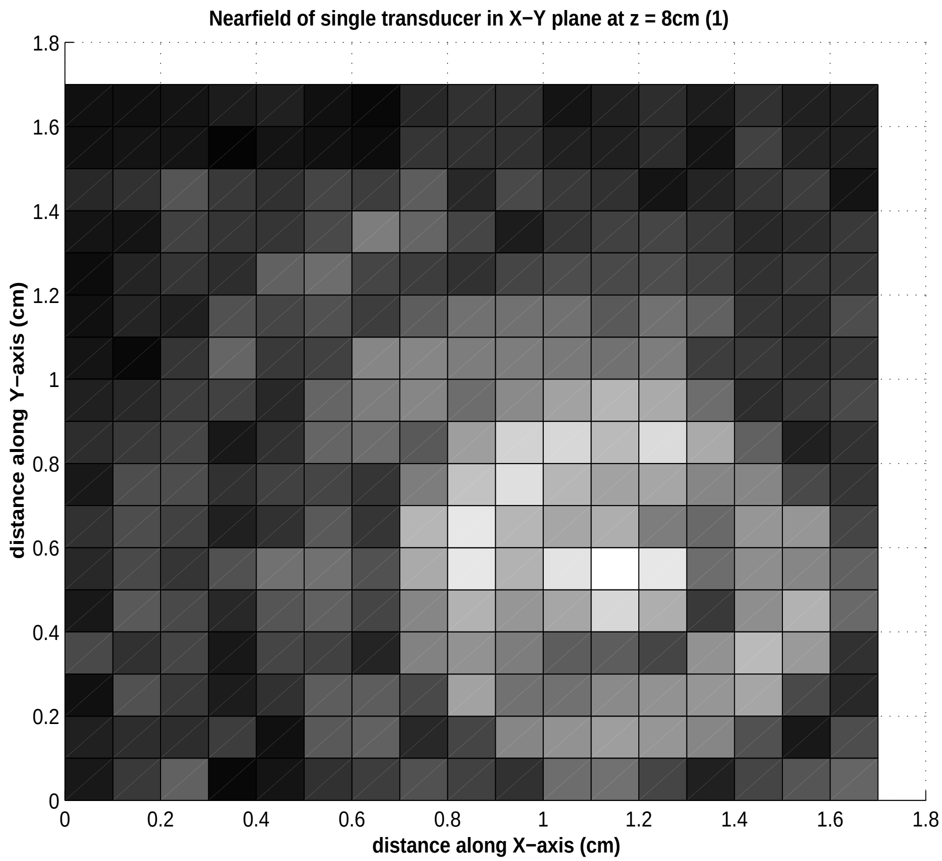


Figure 5.1: Plot of near field (set 1).

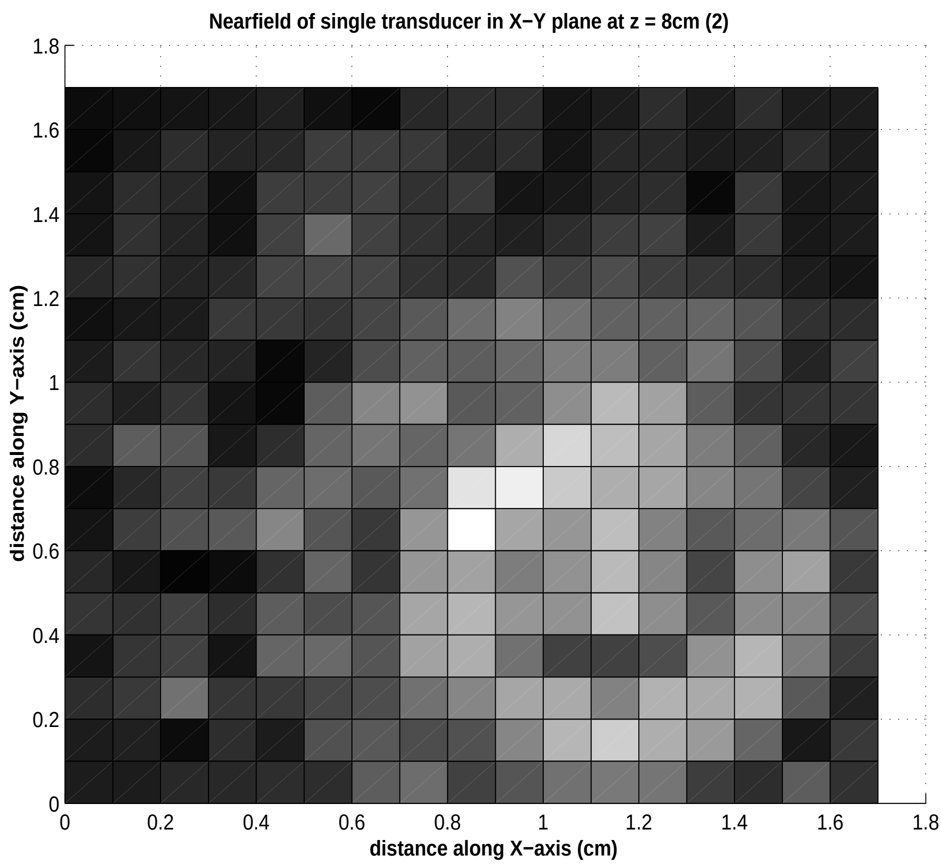


Figure 5.2: Plot of near field (set 2)

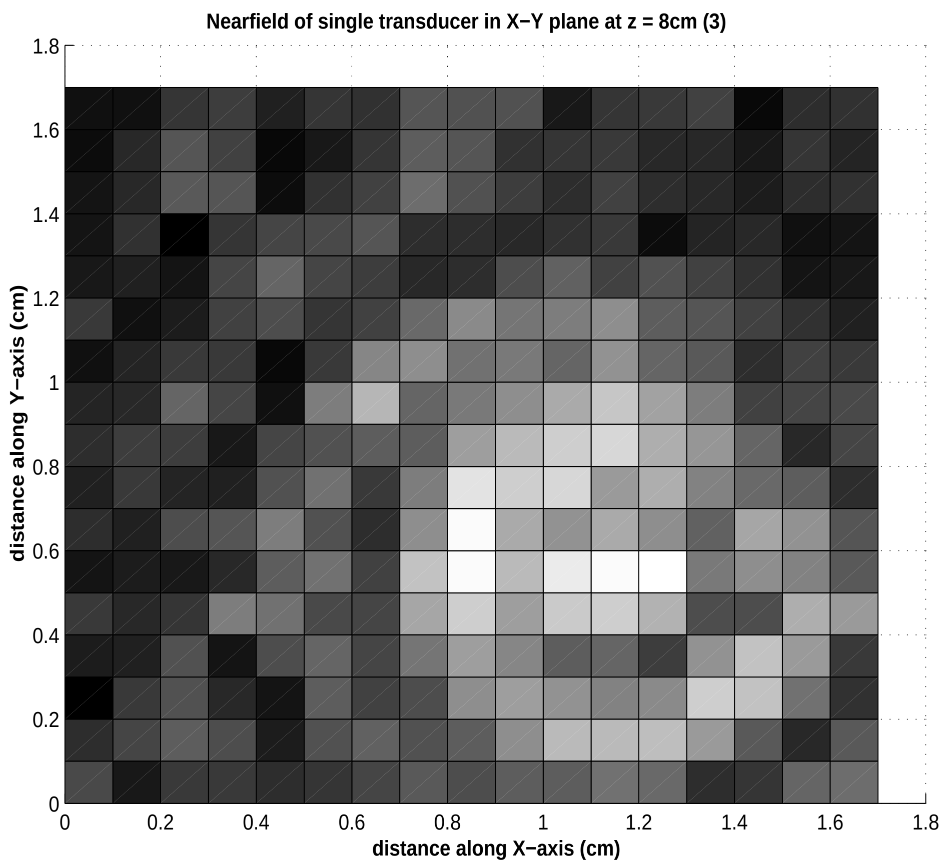


Figure 5.3: Plot of near field (set 3)

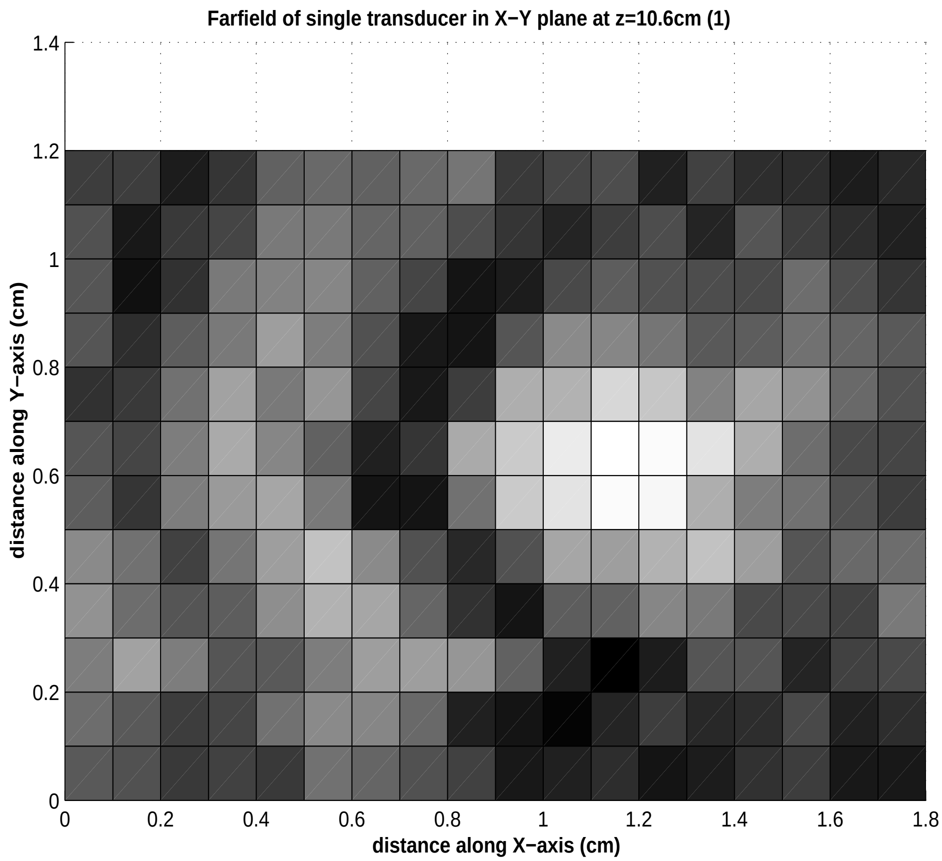


Figure 5.4: Plot of far field (set 1)

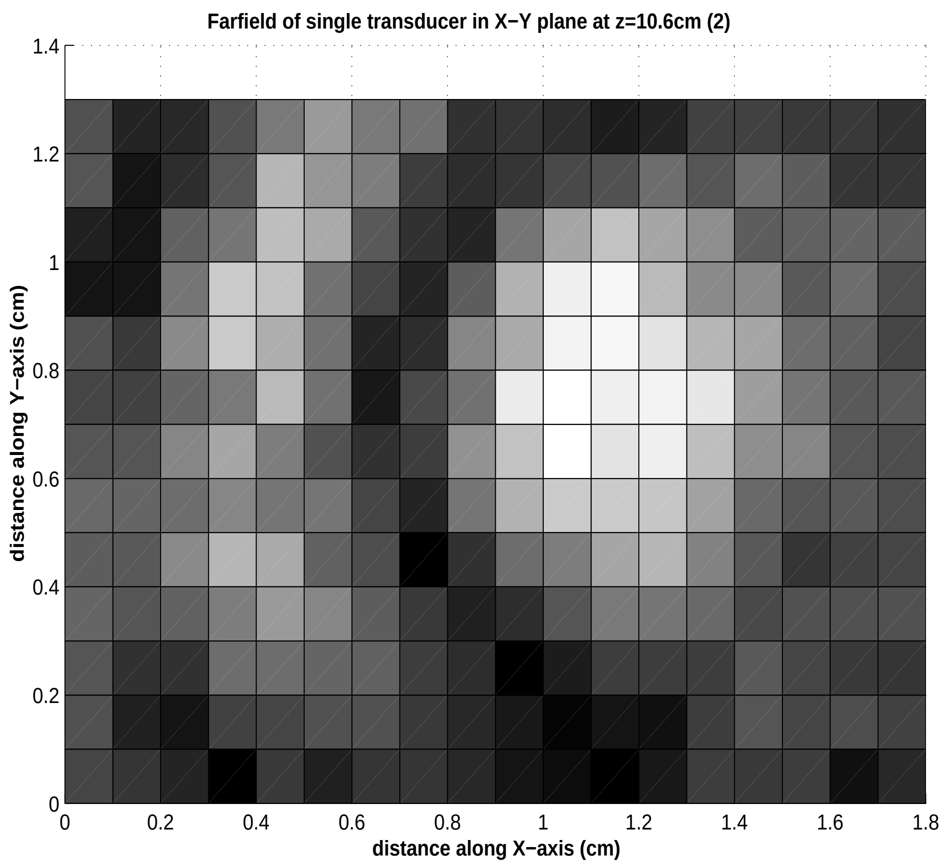


Figure 5.5: Plot of far field (set 2)

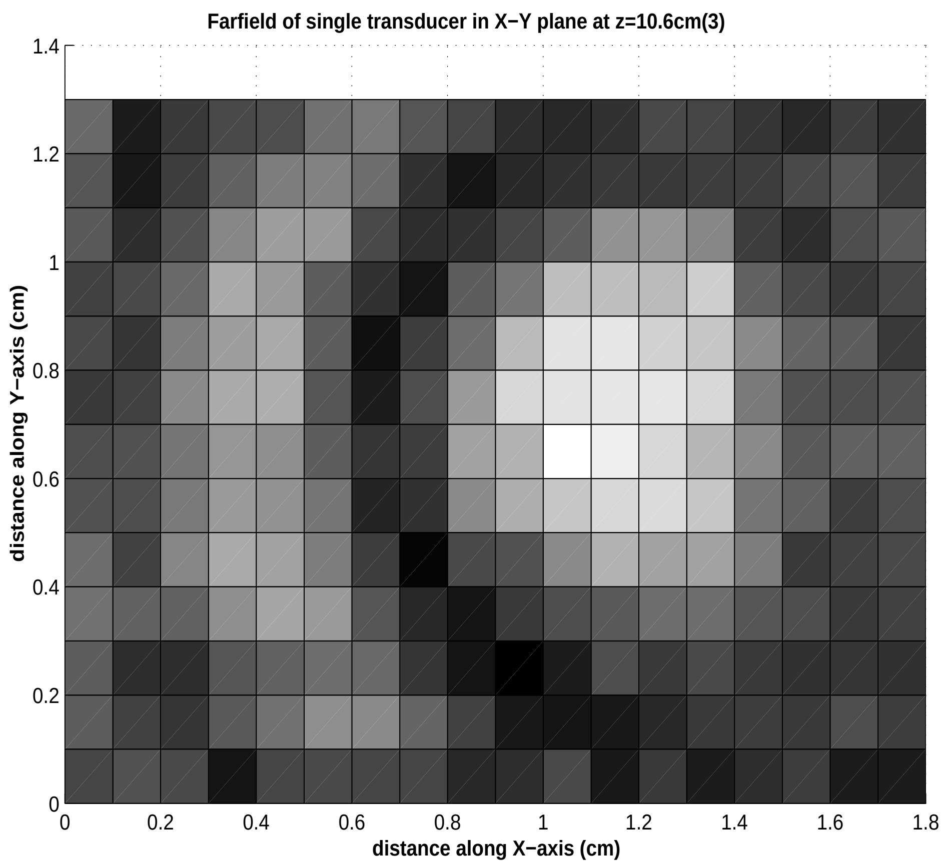


Figure 5.6: Plot of far field (set 3)

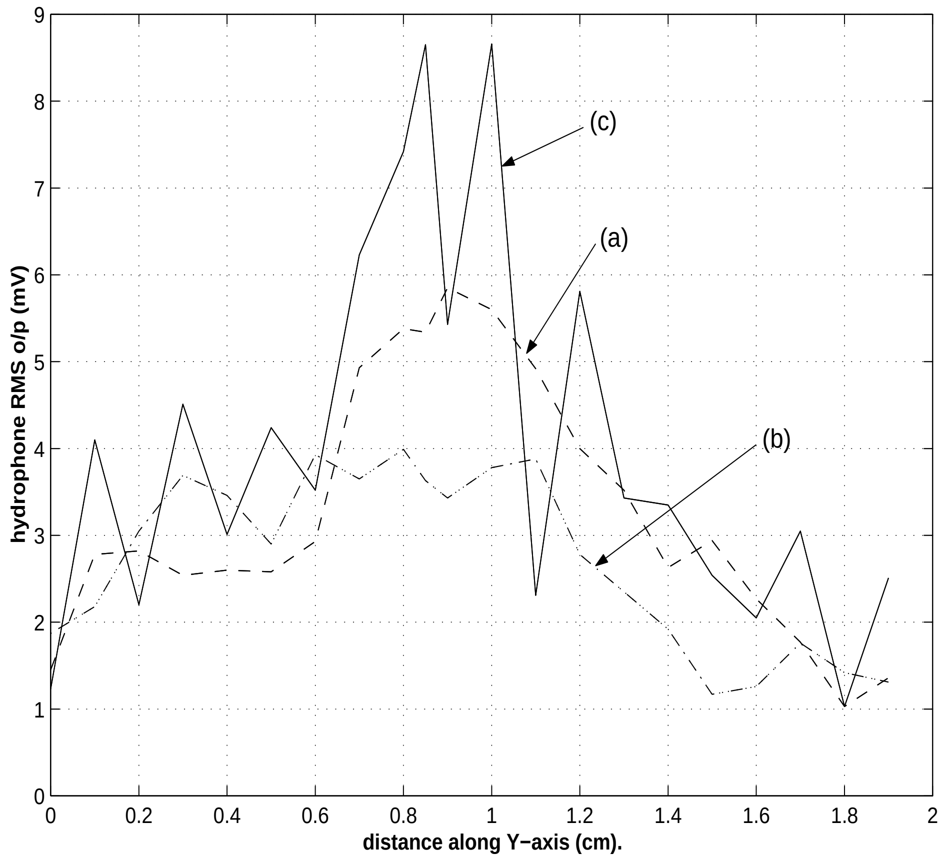


Figure 5.7: Plot of field of two transducers beams directed towards target along Y-axis of the tank. Curve (a): Transducer A excited; Curve (b): Transducer B excited; Curve (c): Both transducers A and B excited simultaneously.

tank and readings of the hydrophone output (RMS) were obtained using an oscilloscope.

First, transducer A was excited and readings were taken. Curve (a) of Fig. 5.7 shows the plot of the field along the Y-axis.

Next, transducer B was excited and readings were taken by moving the hydrophone along the same path. Curve (b) in Fig. 5.7 shows the plot of the readings with transducer B excited. After this both transducers A and B were excited simultaneously and readings were taken in similar manner as with transducer A and B alone. The plot of field when two transducer were excited simultaneously is shown by curve (c) in Fig. 5.7

Though the transducers were excited with the same voltage and frequency there is difference in the field measured, due to the two as seen from curve (a) and (b) of Fig. 5.7. This difference in the measured field is because placement of two transducers from the hydrophone, exactly at the same distance, is difficult with the available stands. Also the orientation of the two transducers may be different with respect to the hydrophone. Curve (c) of Fig. 5.7 shows the output of the hydrophone moved along the Y-axis when both the transducers are excited simultaneously. It can be observed that there is increase in the output of hydrophone as compared to the field, when either transducer A or B is excited. The curve also shows multiple peaks and valleys. This shows that there is interference of peaks between the waves of the two transducers.

5.3 Experiment with undamped probes

Four undamped probes made in laboratory with a crystal of central frequency 2.5 MHz and diameter 2 cm (Appendix A) were mounted on the circular disc as described in Section 3.3, Chapter 3. The assembly (Appendix B) was then fixed in the water tank. The four transducers were excited sequentially in different modes as mentioned in section 3.4 of Chapter 3. The output of the sensing element (transducer probe) placed at the target was observed and recorded. The excitation voltage and frequency of transducer for different modes is shown in these figures. The excitation signal of the transducers was observed on channel 1 of the oscilloscope and the output of the sensing element was observed on channel 2. The frequency of excitation selected in this experiment was 2 MHz.

Mode 0: Fig. 5.8 to Fig. 5.11 shows the output of the receiving probe for this mode of operation. As shown in Fig. 5.8 channel 1 of the oscilloscope displays the peak to peak excitation voltage. The amplitude and frequency of signal of each channel is displayed digitally on the oscilloscope screen. Channel 2 displays the output of the sensing transducer.The RMS value for one cycle and frequency is displayed digitally on the right of the screen. Since only two input channels are available for display, channel 2 is dedicated to show the output of the sensing probe.

Channel 1 is used to display the excitation voltage given to TX1 only. So, during the first period t, TX1 is excited as shown in Fig. 5.8. Here channel 1 displays the excitation voltage given to TX1 and channel 2 displays the output obtained from the sensing transducer. Fig. 5.9 shows the output of sensing transducer when TX2 is excited (channel 1), TX1 is unexcited (channel 2) in this period and hence the record on channel 1 shows zero level. In this manner remaining transducers are excited and the output is recorded. Fig. 5.10 and Fig. 5.11 shows the output for next two periods when TX3 and TX4 are excited. In this mode of operation, it is observed that each transducer is excited for a period of time t over a cycle, whereas the sensing transducer receives pressure waves from each of the transducers TX1 to TX4 excited in sequence over the complete cycle.

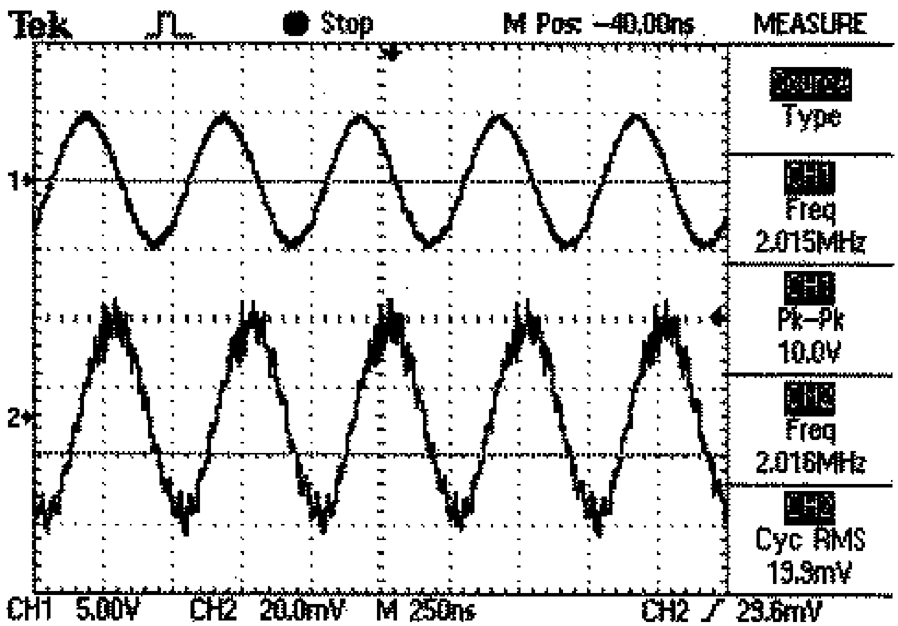


Figure 5.8: Transducer TX1 excited

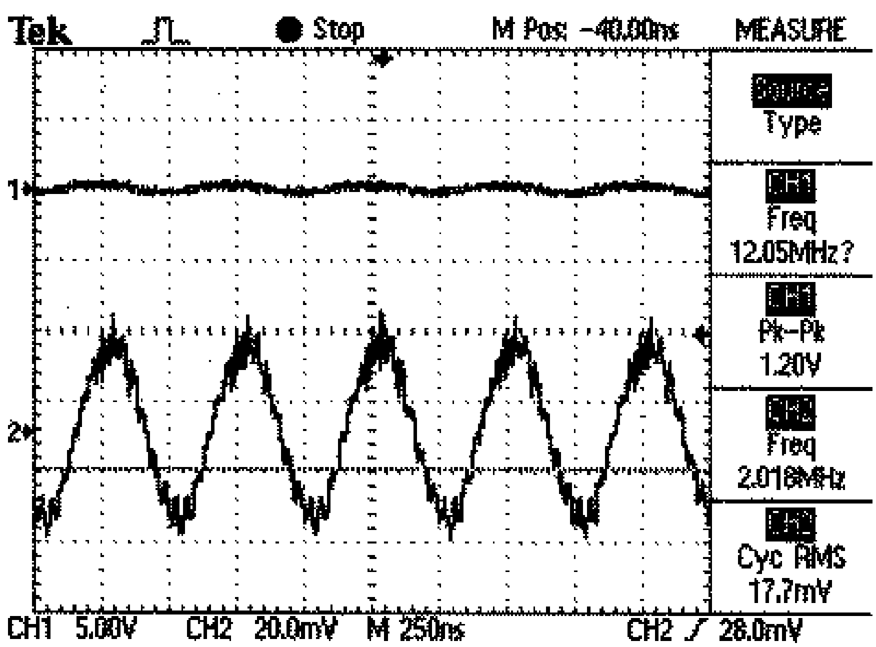


Figure 5.9: Transducer TX2 excited

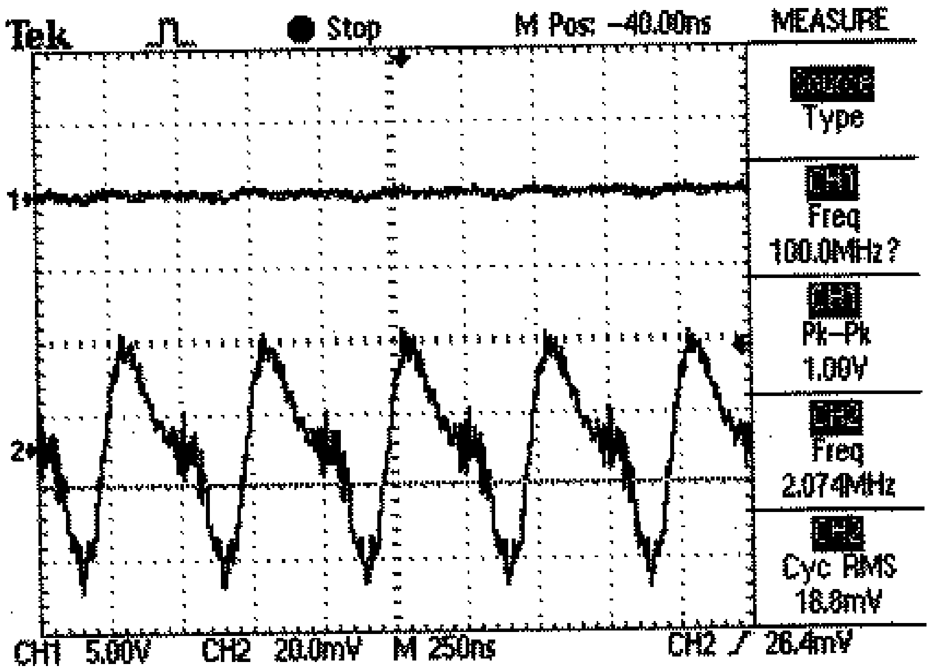


Figure 5.10: Transducer TX3 excited

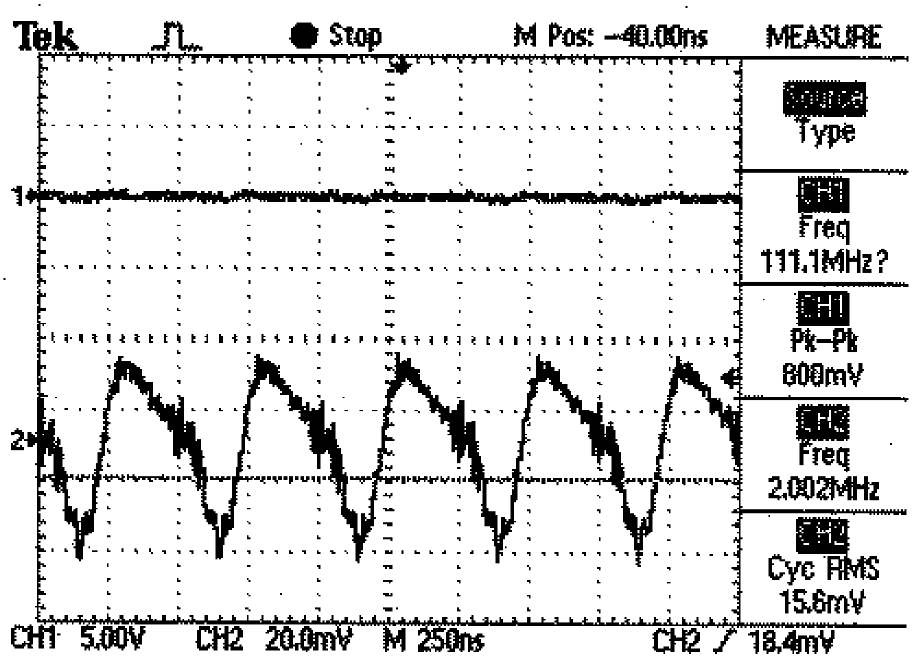


Figure 5.11: Transducer TX4 excited

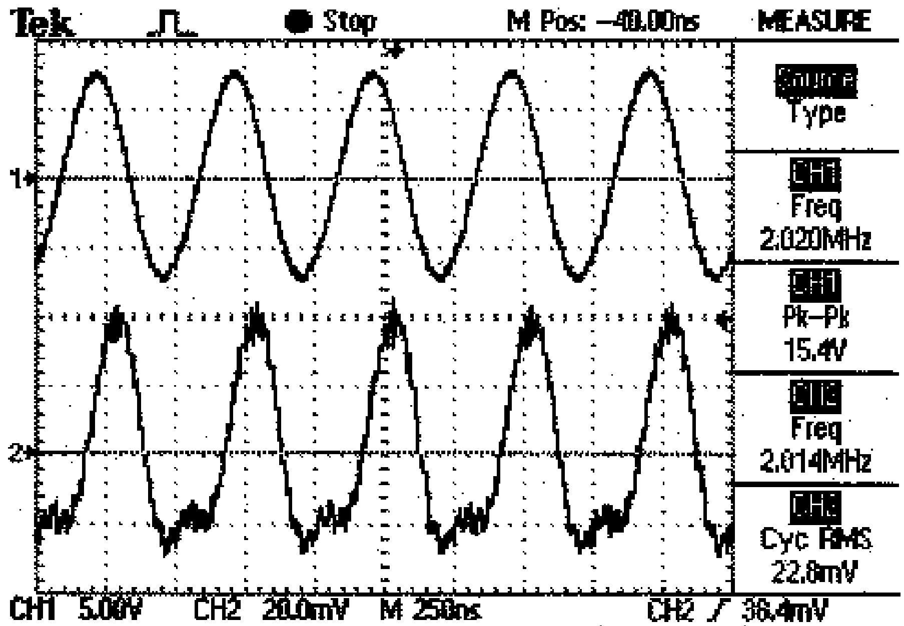


Figure 5.12: Transducer TX1 and TX3 excited simultaneously (mode 1)

Mode 1: In this mode as discussed in Chapter 3, two transducers are excited simultaneously. During the first period t, TX1 and TX3 are excited simultaneously and output is recorded as shown in Fig. 5.12. In this figure channel 1 displays the excitation of TX1, since it is connected to TX1. During the next period, TX2 and TX4 are excited simultaneously and output is recorded as shown in Fig. 5.13. In this period, TX1 is unexcited and hence we cannot see any output in channel 1, but channel 2 displays the output received by the sensing element. It is seen that, the output of the sensing transducer is slightly more than the output in mode 0. This shows that there is slight increase in the ultrasonic output obtained at the sensing element when two transducers are excited simultaneously.

Mode2: In this mode the readings are taken in the same manner as in mode 1, but the combination of excited transducer is change. Here TX1 and TX4 are excited during first period t and waveforms are recorded as shown in the Fig. 5.14. During the next period TX2 and TX3 are excited and readings are taken as shown in Fig 5.15. In this case also, there is increase in the ultrasonic field obtained by the sensing transducer.

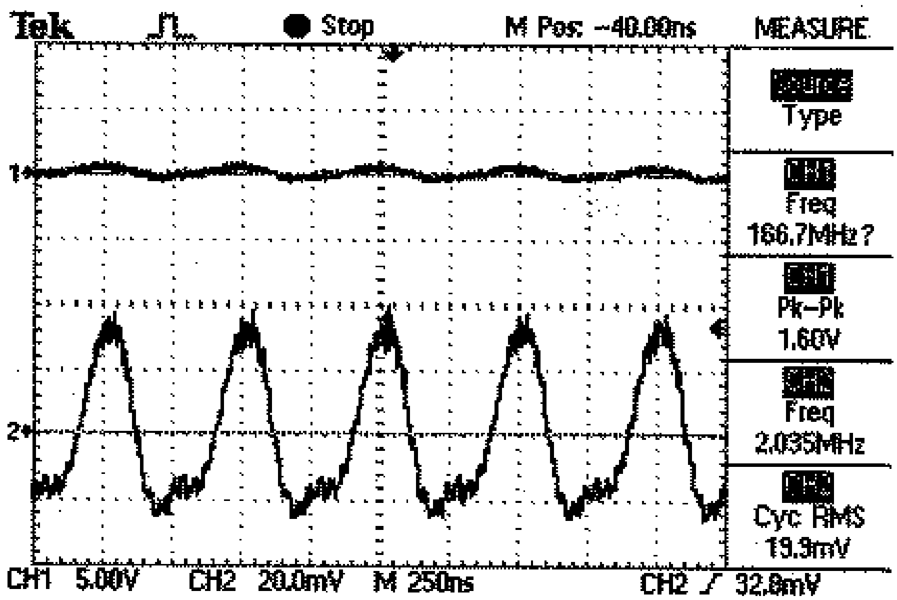


Figure 5.13: Transducer TX2 and TX4 excited simultaneously (mode 1)

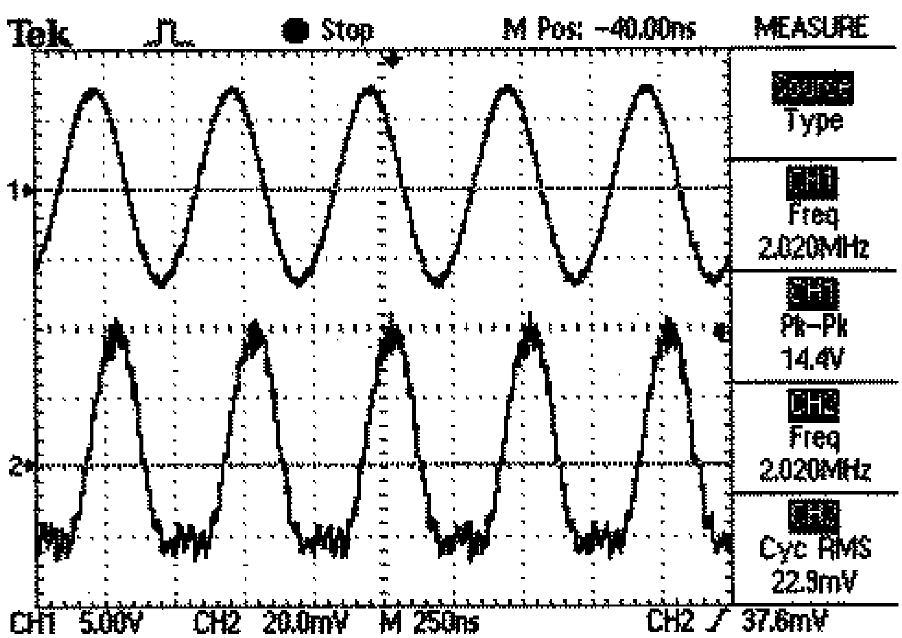


Figure 5.14: Transducer TX1 and TX4 excited simultaneously (mode 2)

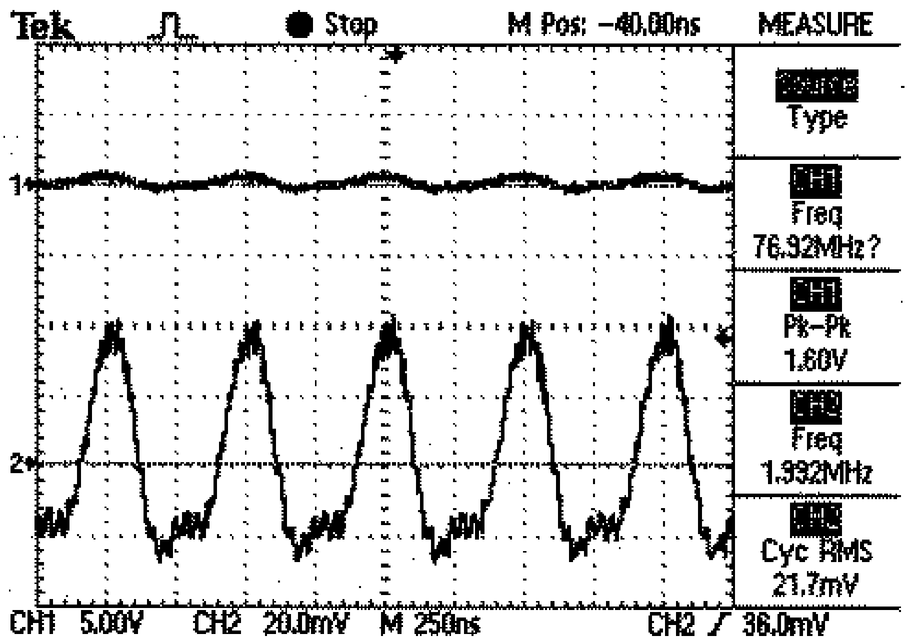


Figure 5.15: Transducer TX2 and TX3 excited simultaneously (mode 2)

5.4 Experiment for temperature rise

Normally, field patterns at the target tissues are not measurable. The only criteria to be employed is to measure the temperature rise at the target. An experiment was performed to measure the rise in temperature. In this experiment a piece of foam soaked in castor oil was packed in a plastic bottle. The temperature of the foam was measured by inserting a thermometer. It was found to be 30^0C. This bottle was made water tight. The bottle was then kept in the water tank and the temperature of water was measure after 30 min. It was found to be 24^0C. Now a transducer was placed above the bottle and transducer was excited with peak-peak voltage of 10 V and frequency 2.0 MHz. The bottle was kept in the field of transducer for $1\frac{1}{2}$ hours. After this, the temperature of the foam was measured to be 25^0C. Thus it has been found that there is one degree rise in the temperature of the oil soaked foam. The volume of water in the tank is much more than the target volume. Due to this there is large amount of heat dissipation from target volume to the water. This makes the rate of cooling very high and very high intensities are needed for longer period of time to get sufficient rise in temperature. Also, there could be reflections at the surface of the bottle, decreasing the intensity of sound at the foam.

Chapter 6

Summary and conclusion

Ultrasound is a promising modality in the treatment of cancerous tissues. Ultrasound heating has many advantages over other techniques. The characteristics of ultrasound and its generation aspect were studied. Heating being the aim in hyperthermia, it has been seen that, continuous wave ultrasound delivers sufficient energy at the target. Circular disc transducers are used as the source of ultrasound. The behavior of field of the transducer in its near and far zone was studied and it was found that though the intensities in the far field are low, the field pattern is more repeatable than in the near field. An amplifier circuit using MOSFET's was implemented for exciting the transducers by a continuous sinewave. Initially experiments for field measurement were carried out using pulsed transducers. The field distribution obtained in the near field and the far field is measured and plotted and it was found to be according to the theory.

Probes were fabricated and tested for continuous excitation using the 2.5 MHz, 20 mm diameter crystals. These probes were then mounted on a circular aluminium disc such that the beams from each probe is directed towards a target. They were then excited excited in different sequence. The waveforms were recorded and it was shown that the receiver receives the sound waves continuously over one cycle of operation, whereas each is transducer is excited only for a fixed period of time which is less than the time for one cycle of operation. From this it can be said that using this method of excitation of transducers the target tissue will receive more energy as compared to the surrounding tissues coming in the path of beams of individual transducers. An experiment for temperature rise using ultrasound was also performed and it was shown that there is a 1 degree rise in temperature of simulated tissue (foam soaked in castor oil).

Switching circuit for connecting the amplifier output to different transducers during various modes of operation was designed, implemented and tested. A microcontroller was used to control the switching of the transducers. Reed relays were used as switches. Following are some aspects which should be looked into in future:

1. Designing power amplifier for higher excitation voltages.

2. Automatic scanning of ultrasonic field using software controlled motion of bridge of the tank.

3. Accurate design of the aluminium disc and brackets for holding the transducers. Also designing a better mechanism for tilting the probes.

4. The probes made are not designed to give the optimum output and hence there is a of scope for improvement in probe design. A transducer using multiple crystals can give more intensities at the target. This is discussed in Appendix B.

Appendix A

Fabrication of probes

The probes already available in the laboratory were damped probes which were meant for pulsed excitation. Since, continuous excitation is be to given undamped probes which can be immersed in water was needed. For this, crystals of central frequency of 2.5 MHz and diameter of 20 mm were ordered. These piezoelectric crystals were used to manufacture the ultrasonic transducer probes for continuous wave excitation. The crystal is coated on positive and negative sides with a silver coating as shown in Fig. 1

Fixing of crystal on copper plate

The crystal was fixed on a thin copper plate of thickness 0.2 mm (approximately $\frac{\lambda}{4}$ thickness). The crystal was fixed on to the plate in two different ways.

1) In the first method, the silver coating of a ring area on negative face of the crystal was removed (hatched area) as shown in Fig. 2. Araldite was applied on the area were silver was removed and stuck to the plate. While pressing the crystal face on the plate it was ensured that the central silver coated part of the face touches the plated. Thus there is a contact between the negative face of the crystal and plate. The positive connection is taken from the top positive face of the crystal and negative connection from bottom plate.

2) In the second method, a thin copper tape, 3 mm wide was inserted between the copper plate and the negative crystal face. Here, araldite was applied on the whole area of the crystal face except the area where the tape touched the crystal. The tape surface is in contact with the crystal face as shown in the Fig. 3. The electrical connections of the positive and negative faces of the crystal were obtained as shown in figure. In this method, there is better mechanical coupling between the plate and the crystal face.

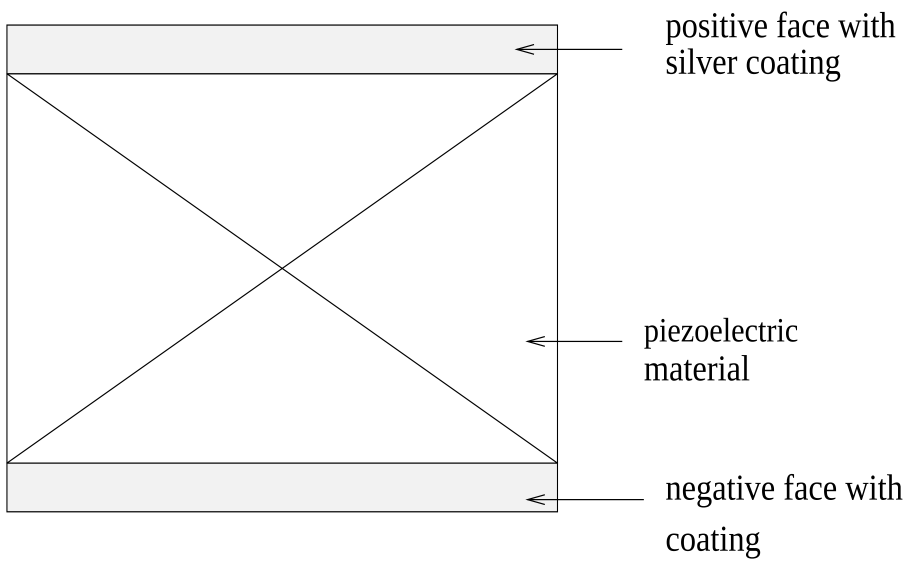


Figure 1: Piezoelectric crystal
Note: Thickness of different layers shown are not proportional.

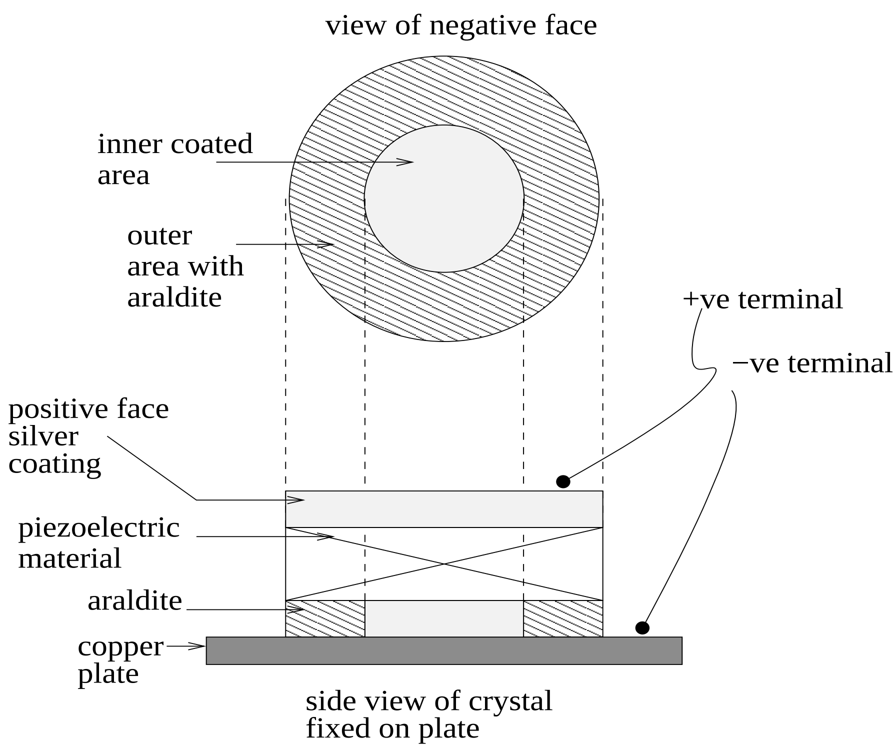


Figure 2: Method 1 of fixing crystal on plate
Note: Thickness of different layers shown are not proportional.

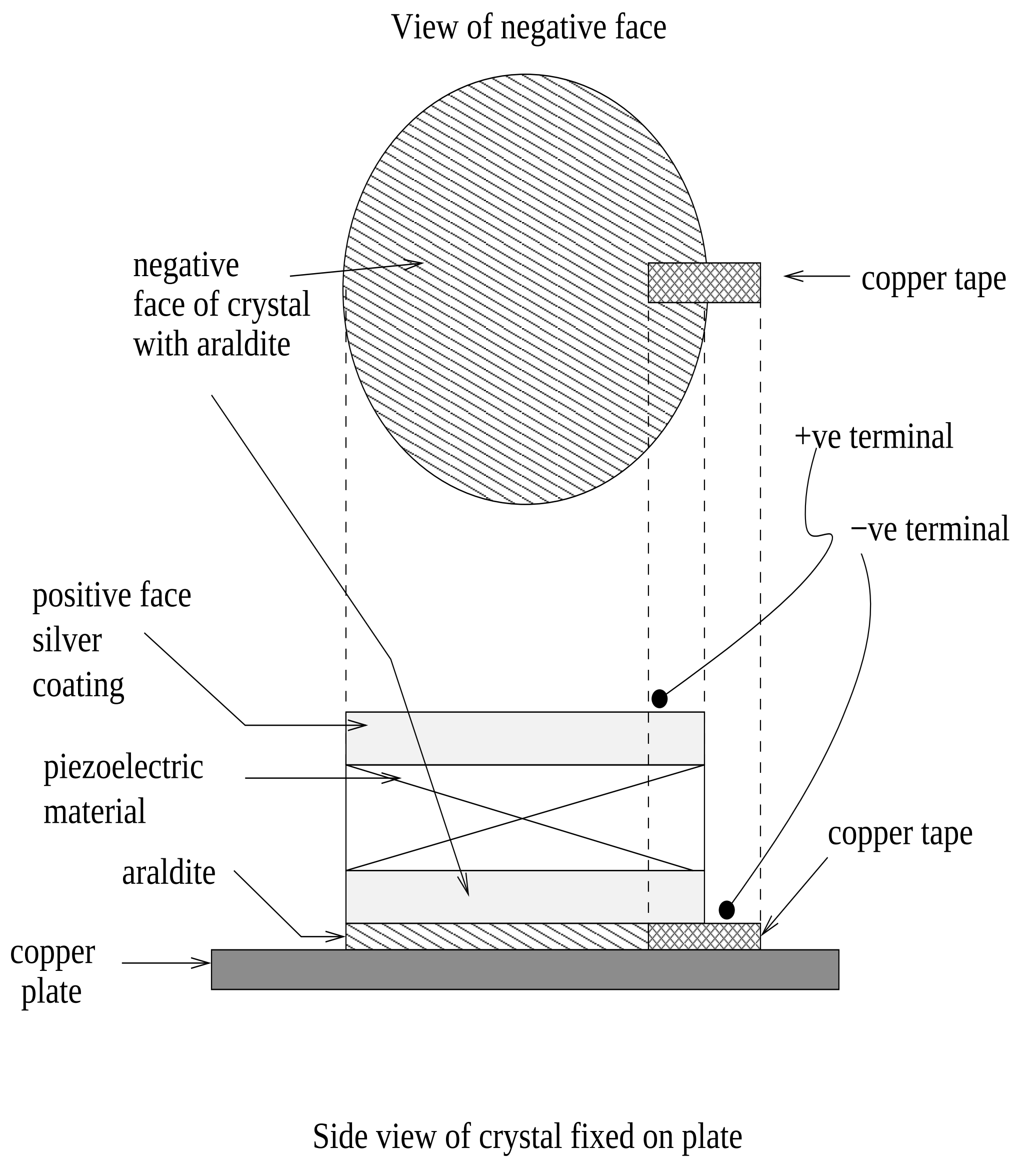


Figure 3: Method 2 of fixing crystal on plate
Note: Thickness different layers shown are not proportional.

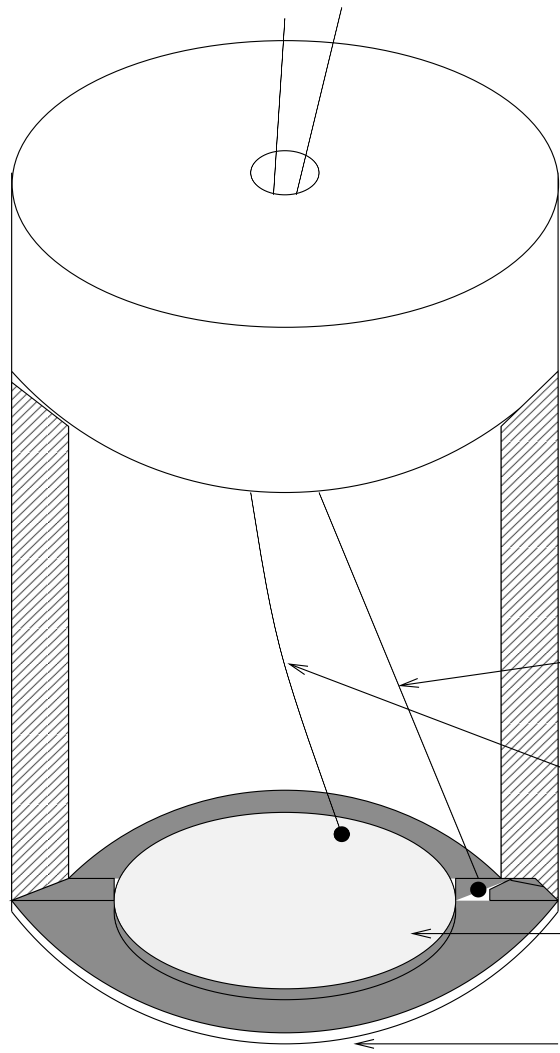


Figure 4: Crystal holder

Crystal holder

A hollow plastic door stopper as shown in Fig. 4 is used as the crystal holder. This door stopper is cylinder of diameter 3.5 cm and height 5.6 cm. Its one side is closed with small hole at the center other side is open. The plate fixed with the crystal was then stuck on the open side of the cylinder in such a way that the crystal was housed inside the holder. The whole assembly was made water tight. The electrical connections were taken out through the hole on other side of the holder using a shielded cable. This hole was then made water tight.

Appendix B

Transducer design for higher power output

A transducer was designed to increase the ultrasonic power output from the probes fabricated in the laboratory. The idea was to connect the two crystals in parallel. In this design one crystal was fixed on other crystal as shown in Fig. 5. The positive faces of the crystal were fixed with each other and the electrical contact was taken out with the help of a thin copper tape as shown in Fig. 5. The two negative faces were shorted and negative terminal was obtained from this shorted connection. This whole block was then fixed on a copper plate as described in appendix A. A probe was made by fixing this plate to the plastic holder as discussed in appendix A.

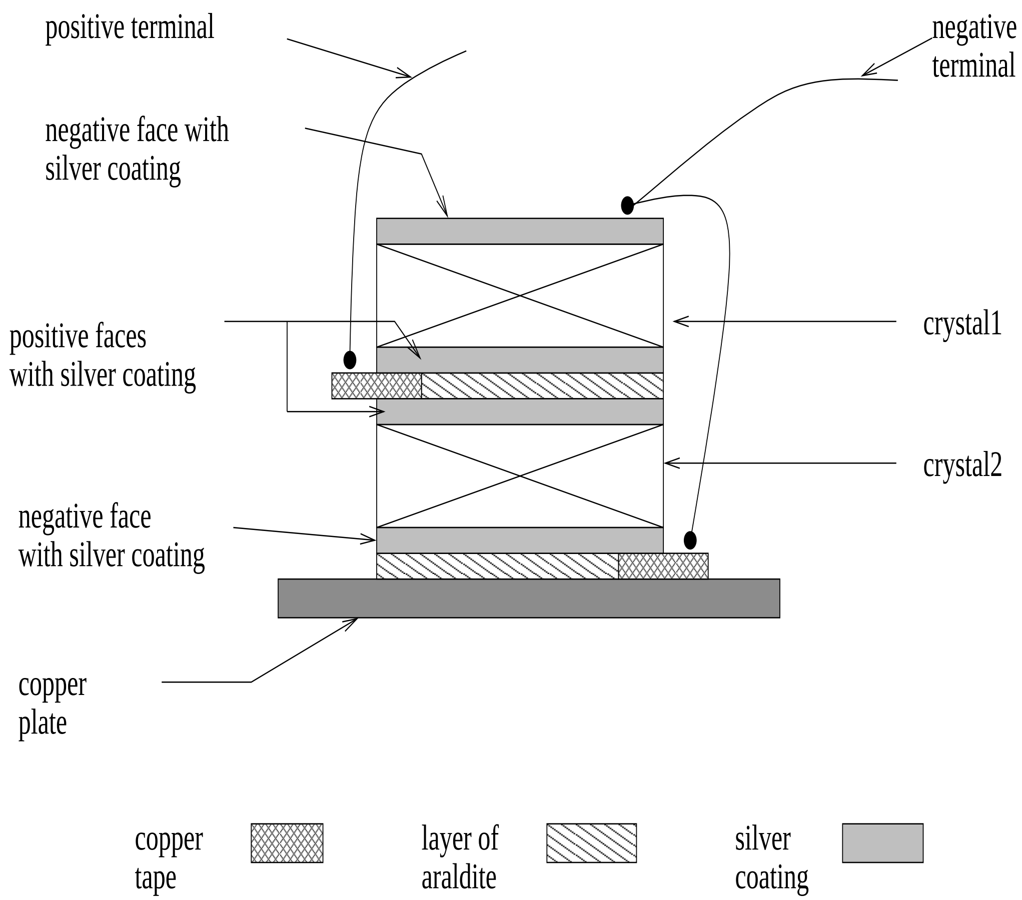


Figure 5: Probe with two crystals connected in parallel.
Note: The thickness of different layers shown are not proportional.

Appendix C

Selection of mode and sequence of operation

As described in chapter 3 the selection of period of excitation and the sequence of excitation in different modes is done using microcontroller (AT 89C52). The microcontroller is programmed to generate delays of 1 sec, 1 min and 5 min. Port 2 of the microcontroller is polled using a 8 switch DIP switch. The port is also polled to select the mode of excitation of transducers. Pin p2.2 is used as a START/STOP switch. A systematic procedure is to be followed to operate the system successfully. The steps are as follows:

1. Ensure that the all the switches of DIP switch are open.
2. Select the period of excitation by changing the status of port 2 pins according to Table 1
3. Select the modes of operation by changing the status of port 2 pins according to Table 2
4. Start the operation by making pin p2.2 = 0.
5. Stop the operation by making pin p2.2 = 1

In this way, the period of excitation and the sequence of excitation can be selected for different modes of excitation.

Table 1: Required polling status of Port 2 pins for selecting period of excitation

Port 2 pins	Status for 1 sec.	Status for 1 min.	Status for 5 min.
p2.0	0	1	0
p2.1	0	0	1
p2.2	1	1	1
p2.3	1	1	1

Table 2: Required polling status of Port 2 pins for selecting the mode of operation

Port 2 pins	mode 0	mode 1	mode 2
p2.4	0	1	0
p2.5	0	0	1
p2.6	1	1	1
p2.7	1	1	1

References

[1] Labthermics Technologies Inc., 701 Devoshire Drive, Champaign IL 61820 USA, "Facts about hyperthermia therapy," `http://www.labthermics.com/hyper.html/`, accessed in December 2001.

[2] First Circle Medica Inc., 530 North Third Street, Suite 400, Minneapolis, MN 55401 USA, "About hyperthermia and EWBH," `http://www.fmedical.com/hyperthermia/history.html/`, accessed in January 2002.

[3] "A history of use of heat to treat disease," `http://www.starfarm.it/hyperthermia/history.htm/`, accessed in January 2002.

[4] Norio Tsuda, Kagayaki Kuroda, and Yukata Suzuki, "An inverse method to optimize heating conditions in RF-capacitive hyperthermia," *IEEE Transactions on Biomedical Engineering.* vol. 43, no. 10, October 1996.

[5] J. Gordan Short, and Paul F. Turner, "Physical hyperthermia and cancer therapy," *Proceedings of the IEEE,* vol. 68, no. 1, January 1980.

[6] James R. Oleson, "A review of magnetic induction methods for hyperthermia treatment of cancer," *IEEE Transactions on Biomedical Engineering,* vol. BME-31, no. 1, pp. 91-97, January 1984.

[7] K. Kirk Shung, "General engineering principles in diagnostic ultrasound," *IEEE Engineering in Medicine and Biology Magazine,* pp. 7-13, December 1987.

[8] U. P. Kulavmode, "Ultrasound focusing system for hyperthermia," Guide: Prof. T. Anjaneyulu. *M. Tech Dissertation,* Dept. of Electrical Engineering, Indian Institute of Technology, Bombay, January 1999.

[9] Douglas A. Christensen: *Ultrasonic Bioinstrumentation,* New York, John Wiley & Sons, 1988.

[10] P.N.T Wells: *Biomedical Ultrasonics,* New York, Academic Press, 1977.

[11] S. O. Harrold, "Ultrasonic focusing techniques," *Research Technique in Nondestructive Testing,* vol. 6, edtd. by R. S. Sharpe, Academic press, London, 1982.

[12] P. P. Lele, "Rationale, technique and clinical results with scanned focused ultrasound (SIMFU) system," *Proceedings of* 8^{th} *Annual Conference of IEEE Engineering in Medicine and Biology Society* (IEEE 86CH 2368-9), pp. 1435-1440, 1986.

[13] P. Fessenden, E. R. Lee, T. L. Anderson, J. W. Strohbehn, J. L. Meyer, T. V. Samulski, and J. B. Marmor, "Experience with a multitransducer ultrasound system for localized hyperthermia of deep tissues," *IEEE Transactions on Biomedical Engineering,* vol. BME-31, no. 1, pp. 126-135, January 1984.

[14] Robert B. Roemer, W. Swindell, Scott T. Clegg, and Reid L. Kress, "Simulation of focused, scanned ultrasonic heating of deep-seated tumors: the effect of blood perfusion," *IEEE Transactions on Sonics and Ultrasonics*, vol. SU-31, no. 5, pp. 456-465, September 1984.

[15] Eduardo G. Moros, Robert B. Roemer, and Kullervo Hynynen, "Simulations of scanned focused ultrasound hyperthermia: the effect of scanning speed and pattern on the temperature fluctuations at the focal depth," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 35, no. 5, pp. 552-559, September 1988.

[16] Shin-ichiro Umemura, and Charles A. Cain, "Acoustic evaluation of a prototype sector-vortex phased-array applicator," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control.* vol.39, no. 1, pp. 33-38, January 1992.

[17] Mathias Fink, "Time reversal of ultrasonic fields-part I: basic principles," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 39, no. 5, pp. 555-565, September 1992.

[18] P. J. Benkesser, L. A. Frizell, S. A. Goss, and C. A. Cain, "Analysis of a multi-element ultrasound hyperthermia applicator," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 36, no. 3. pp. 319-325, May 1989.