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FOCUSING ULTRASOUNDS BEAM

The focused ultrasound beam is very important in diagnostics and medical treatments. The aim of the study is to analyze the basic physical phenomena in the process of focusing the ultrasonic wave. Based on the measured temperature in the focus of the ultrasonic beam. The compatibility of the temperature measurement by the method HIFU optical fiber.

Keywords: ultrasounds, focus ultrasound beam

INTRODUCTION

Sound is a physical phenomenon that transmits acoustic energy from one point to another. It differs from the electromagnetic radiation that the sound can propagate only in the elastic environment. It does not pass through a vacuum, just like electromagnetic radiation. One of the most important physical qualities of sound is the frequency – speed, with which the source of the sound vibrates. The human ear does not react to all frequencies. The range of human audible frequencies is from 20 Hz to 20 000 Hz (20 kHz).

Ultrasound – the spring waves, with frequencies above 20 000 Hz, covering a wide, compared to the audible, frequency range. Low frequency ultrasound (in the range of tens of kHz) produces and recognizes many animals such as dogs, cats, bats, and dolphins [1]. Thanks to its properties, ultrasounds have wide applications. Depending on the intensity, ultrasound is used for: materials testing, structural strength, and tracking of non-observable processes by other methods.

In medicine ultrasound helps in diagnostics and treatments. They help to monitor the progress of treatment. Wide diagnostic has got ultrasonography.

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1. CONSTRUCTION OF THE ULTRASOUND HEAD

Ultrasounds can be used to obtain a lot of information from the inside of the body and to the thermoablation. To obtain an ultrasound image, the transducer must be able to transmit and receive ultrasonic waves, and should be able to focus the beam reaching the tissue. The ultrasound head (Fig. 1) is the basic part of ultrasound. This is an important element because without which it, to watch images of the interior of the organism on the computer screen would be impossible. The correct operation of the head depends on the end of the crystal tip of the head with the tissue. Incorrect coupling results in deterioration image quality. The lack of any coupling can cause damage to the head, because all of the wave energy is converted to heat, in small volumes, near the end of the transmitter element [2].

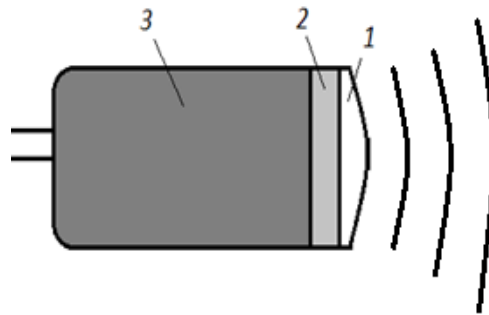


Fig. 1. Ultrasonic head: 1 – impedance transformer, 2 – piezoelectric transducer, 3 – damping material [2]

The main components of the head include:

- **damping material** – which is usually epoxy resin mixed with tungsten powder – provides an acoustic impedance equal to the impedance of the crystal;
- **piezoelectric crystals** – they show piezoelectric effect, consisting of appearing on his surface of electrical charges under the influence of mechanical stresses;
- **impedance transformer** – is responsible for the smooth transition of the wave ultrasonic by tissue.

One of the important parameters determining the quality of imaging ultrasound is the **resolution**, the ability to distinguish closely-spaced structures that differ in properties. The narrower the beam, the easier it will be to distinguish echoes reflected from different tissues. In order to improve image quality, ultrasound beam focusing is used. It can be received by:

- **mechanical (structural)** – using the shape of piezoelectric transducer. The disadvantage of such beam focus is that it is focused only at one point.

This can be a hindrance when there is a need to observe larger objects in the whole field of view;

- **electronic** – it is much better than construction since it allows the beam to be focused throughout the field of vision. This is possible with the delay lines [3].

Ultrasonic delay lines are systems that to slow down an electrical signal (moving at the speed of an electromagnetic wave) they process the signal on ultrasonic (about 10^5 times slower than electrical) and then transform it into an electrical signal. Delay time depends on the length of the ultrasonic path and may range from microsecond fractions to tens of milliseconds [1].

2. PIEZOELECTRIC TRANSDUCER

The piezoelectric transducer is made up of tiny crystals that are several millimeters' length and width corresponding to the thickness of the hair (Fig. 2). He's full alternating two functions: **transmitting** (produces ultrasonic pulses) and **receiving** (detection of returning echoes) [4].

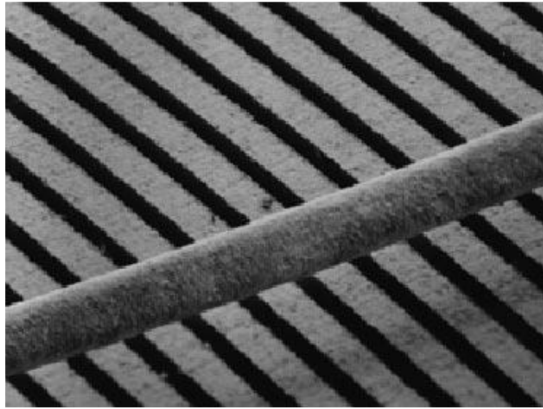


Fig. 2. Piezoelectric transducer. In the foreground, there is a human hair [5]

We can also control each crystal separately, we can emit and receive ultrasounds depending on the element. The transmitter also concentrates the pulse beam to give a specific shape and size at different depths throughout the body and also scans the radius of the anatomical area that is mapped.

The size of the transmitter determines the resonance frequencies of vibration. Assuming that one surface of the tile is firmly bound to the damping material and the other surface is in contact with a material with a much lower acoustic impedance that can be considered free, then by dependence (1):

$$v_{2n-1} = (2n - 1) \frac{c_p}{4l} \quad (1)$$

where: c_p – the velocity of the acoustic wave in a direction perpendicular to the surface; $n = 1, 2, \dots$; l – thickness of the piezoelectric plate

We can calculate the thickness of the piezoelectric plate for the resonance frequency. For example, for a tile made of zirconate-lead titanate – **PZT** and a frequency of 1 MHz the thickness is 0,63 mm [6].

The capacitance of the transmitter results from its design. Each transmitter has a maximum permissible value of alternating supply voltage. This is due to the risk of mechanical damage due to vibration. If the transmitter is energized with too high alternating voltage, the deformation and stress of the element will be so great that the item will be severely damaged.

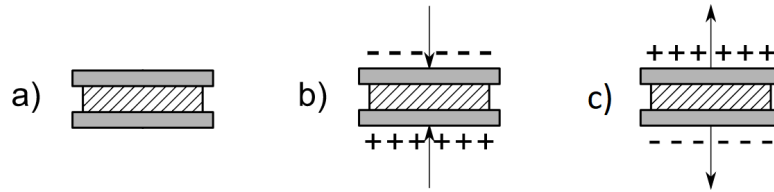


Fig. 3. Piezoelectric effect in quartz crystal SiO_2 : a) crystal in equilibrium, b) compression crystal, c) crystal extended [7]

Ultrasonic transducers are built of crystals that contain electrical dipoles in the crystal lattice. Deformation of the crystal lattice is related to piezoelectric properties. The piezoelectric crystal in equilibrium does not show the presence of electrical charges. After its mechanical deformation, its spatial density of charge is impaired and electrical charge is generated on the surface of this crystal (Fig. 3) [8].

A crystal of thickness x is set to wave length generation: $\lambda = 2x$ and frequency: $f = \frac{c}{\lambda}$. The cycle of this wave is: $T = \frac{1}{f} = \frac{2x}{c}$. If the probe is to produce as short a pulse as possible, the crystal is stimulated with a rectangular pulse of time T_{imp} (2) [8]:

$$T_{imp} = \frac{1}{4}T = \frac{x}{2c} \quad (2)$$

The crystal in the piezoelectric transducer deforms under the electric field and its surface performs a $\frac{1}{4}$ sinusoid motion. Then, when the stimulus pulse ends, the crystal returns to balance (Fig. 4). At the moment of equilibrium, the surface of the crystal has made an appropriate movement of the sinusoidal half. Stored in

the crystal the kinetic energy will cause further crystal oscillations of increasing less amplitude. The quality of the damping material influences how quickly these vibrations expire [8].

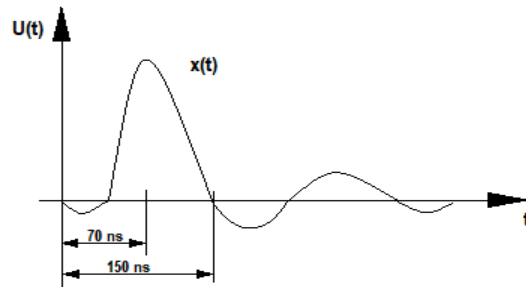


Fig. 4. Impulse stimulation and transducer vibration [8]

Each point of the oscillating crystal is the source of the spherical wave, transmitted at the broadcasting center. For this reason, numerous interferences occur near the transducer. The field in which interference occurs is called a **close field**. On the other hand, the area in which the mechanical wave spreads uniformly, without interference, is called a **far field** [8].

The range of the near field depends on the diameter of the transducer and on the frequency of the ultrasonic wave [8] defined by the formula (3):

$$x_n = \frac{d^2 \cdot f}{4c} = \frac{d^2}{4\lambda} = \frac{r^2}{\lambda} \quad (3)$$

where: x_n – range of near field; d – transducer diameter; r – transducer radius; f – wave frequency; λ – wavelength; c – velocity of wave propagation.

At the boundary of the near and far field there is a small concentration of the wave, called the ultrasonic beam itself (Fig. 5).

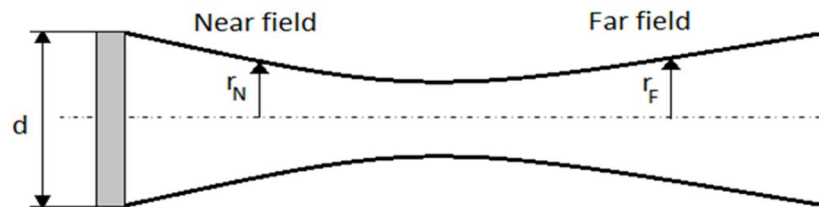


Fig. 5. Near field, far field, and beam self-focusing [8]

The width of a beam can be represented by the relationships (4) and (5) [8]:

- in the near field:

$$2r_N = 2r - \frac{\lambda \cdot x}{r} \quad (4)$$

- in the far field:

$$2r_F = \frac{\lambda \cdot x}{r} \quad (5)$$

where: d – transducer diameter; r – transducer radius; x – distance from transmitter; λ – wavelength.

3. ELECTRONIC FOCUS OF THE ULTRASOUND BEAM

Focusing on the transmitter can be changed electronically when it is in echo reception mode. Knowing the location of the point A and the velocity of the wave (Fig. 6) you can determine the time taken by the wave moving from point A to transmitter elements (crystals). This is accomplished by processing electrical pulses from individual transducer elements for various time delays before they are combined into one electrical pulse. In this way, the effect of focusing echoes is created.

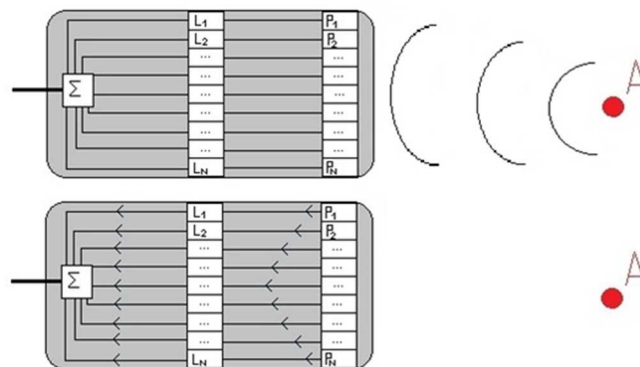


Fig. 6. Scheme of ultrasonic wave reception
(P – transducer, L – delay line) [5]

This phenomenon also works in the opposite direction (Fig. 7). An electric impulse can be applied to the delay line where the pulse is released at different speeds to form a wave. In this way, we will also receive a focused beam, because in the end the ultrasound waves due to interference will be reflected in point A.

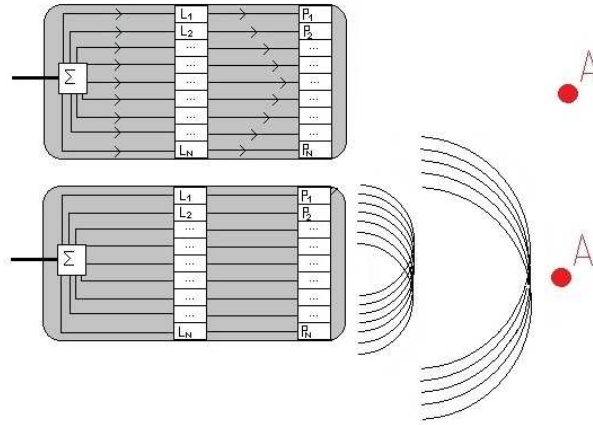


Fig. 7. Scheme of beam focus at point A (P – transducer, L – delay line) [5]

This kind of focus gives flexibility in creating beams of various shapes and sending the beam in any direction. The described dynamic focus is a major achievement that allows the tissue to be examined without moving the probe.

4. MECHANICAL METHODS OF FOCUSING ULTRASONIC BEAM

The focus beam can also be obtained by using, as in optics, focusing lenses. While in optics, convex lenses are used for this, ultrasonography uses concave lenses. This is due to the properties of the material from which the lenses are manufactured, because the ultrasonic velocity in the ultrasonic lenses is greater than in the tissue [9].

The effect of focusing with ultrasonic lenses is related to the law of refraction of waves at the border of two centers (Fig. 8). According to the laws of Snellius (6) we have:

$$\frac{\sin \alpha}{c_1} = \frac{\sin \beta}{c_2} \quad (6)$$

after transformation:

$$\sin \alpha = \frac{c_1}{c_2} \sin \beta = n \sin \beta \quad (7)$$

when $n = \frac{c_1}{c_2}$ – refractive index.

The position of the F point can be calculated using the trigonometric relationships:

$$AB = R \sin \alpha = f \sin(\alpha - \beta) \quad (8)$$

For small angles α and β , and $s \ll R$, sines of angles can be approximated by the values of these angles. Similarly, in optics, and after transforming the equation (8), we obtain the pattern (9) for the location of the focus:

$$f = \frac{R\alpha}{\alpha - \beta} = \frac{Rn\beta}{n\beta - \beta} = \frac{R}{1 - \frac{1}{n}} \quad (9)$$

Depending on the study, the ultrasonic heads are focused at different depths, eg in obstetrics and abdominal studies, ranging from a few to several centimeters, in cardiology for cardiac tests of 5-10 cm, and in angiography 1-2 cm [9].

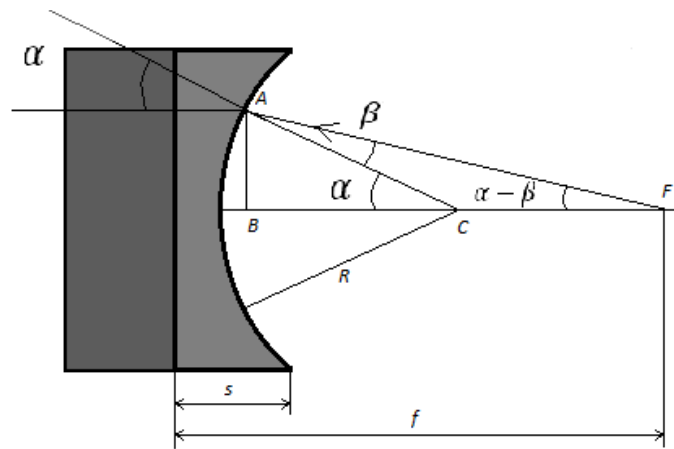


Fig. 8. Principle of focusing ultrasonic beam
(R – lens curvature radius, f – focal length) [9]

5. HIGH INTENSITY FOCUSED ULTRASOUND METHOD IN THERMOABLATION AS ONE OF THE APPLICATIONS OF THE ULTRASONIC BEAM

One example of the use of a spherical ultrasonic beam is thermal ablation. There have been many attempts to develop operations using high-power ultrasonic beams. This non-invasive method of medical treatment was very attractive, but technically out of reach because of the lack of reliable and effective methods of temperature monitoring [10]. Significant technical progress in magnetic resonance imaging enabled temperature monitoring and ultrasound operations (Table 1).

Table 1. Properties of Philips Sonavelle system [10]

Parameters of Philips Sonavelle HIFU System	
Therapy time	1-4 h
Sonication time	10-75 s
Max sonication power	250 W
Ultrasound frequency	1,2-1,4 MHz
Power intensity	500-5000 W/cm ²
Focus size	1.5 x 1.5 x 10 mm
Spot sizes diameter	4/8/12/16 mm

Magnetic resonance magnetic resonance spectroscopy, the stimulation of nuclear spins in the outer magnetic field by rapid changes in the magnetic field causes the recording of electromagnetic radiation by relaxation phenomena. Therefore, the temperature measured by this method achieves an accuracy of $\pm 1^\circ\text{C}$.

There is a linear relationship (10) between the change in the frequency of the proton vibrations and the increase in temperature. The temperature rise is calculated from the phase differences based on the formula:

$$\Delta T = \frac{\Delta\varphi}{\alpha\gamma B_0 t_e 2\pi} \quad (10)$$

where: γ – gyromagnetic ratio – 42,58 MHz/T; α – temperature dependent water resonance chemical shift 0,0094 ppm/ $^\circ\text{C}$.

The PRF of the lipid hydrogen is temperature independent, therefore the temperature

The fat tissue cannot be measured with a MR thermometer.

The HIFU method is used to treat uterine fibroids, palliative bone pain treatment, prostate cancer, and breast cancer [10].

The disintegration of uterine fibroids occurs through sonication, which is the use of ultrasonic energy inside the body. During intervention, the beam of ultrasonic energy penetrates the skin and soft tissues, causing the temperature to rise in a particular area. A thrombotic necrosis area is produced within a few seconds. Therefore, the extent to which the tissues are exposed to temperature increase and the polystyrene plate could be used to protect the affected areas [11].

For this purpose, in the experiment were used:

- biological material – vein tissue;
- fiber optic sensor FOT-M;
- one-channel interface FTI-10 from FISO.

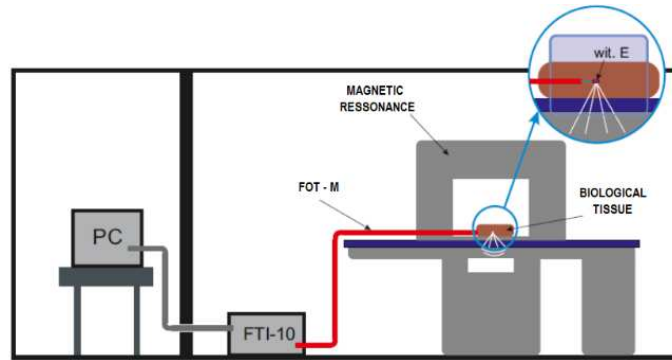


Fig. 9. Diagram of the measuring system [11]

At the beginning, the muscle was heated to 35°C to be close to human body temperature. Below this temperature, the software does not allow for the surgery. Then the tissue is placed inside the magnetic resonance. Inside the room was a sensor with an interface, the sensitivity zone of the sensor was inside the muscle. Also, a vitamin E capsule was placed at the sensitivity of the sensor, which acted as a marker for imaging the sensor by resonance. Also used was the polystyrene plate that was placed behind the focus of the ultrasonic beam. The remaining equipment was located in a separate room (Fig. 9).

Measurements have been made several times. It also succeeded get a denaturation temperature of the protein. There was no cavitation, so we were able to perform the ultrasonic thermoablation treatment properly. The results are presented in Fig. 10.

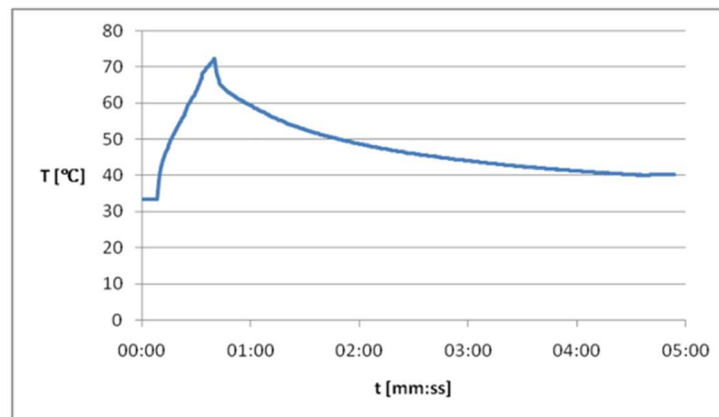


Fig. 10. Dynamics of changes in biological tissue temperature [11]

Plate measurements were also performed inside the muscle tissue. Figure 11 shows the scheme of operation of the system used on the board. It has been verified that it can be used as a manipulator. The measurement results are shown in Fig. 12.

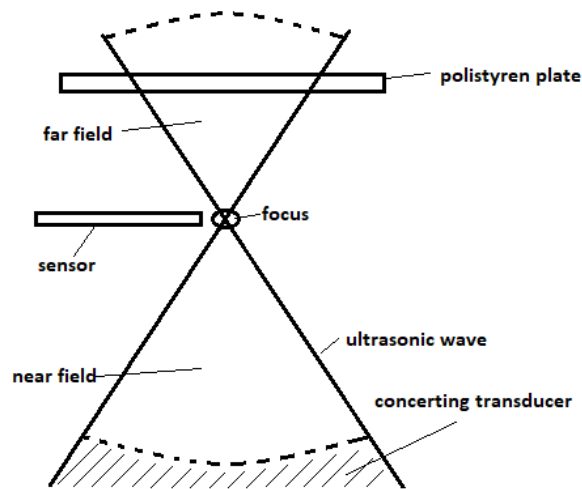


Fig. 11. Philips Sonalleve system diagram for polystyrene board [11]

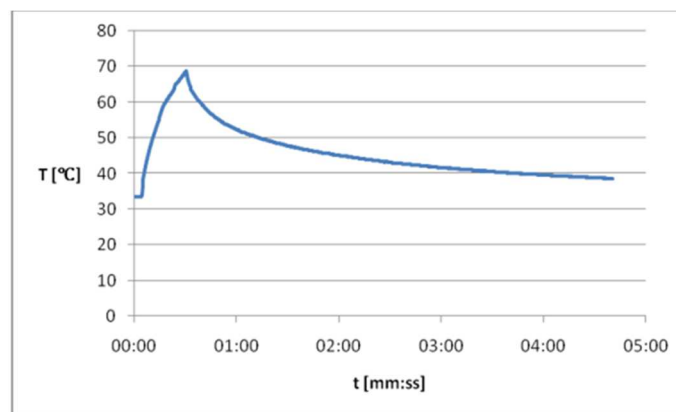


Fig. 12. Dynamics of temperature changes of biological tissue covered by polystyrene plate [11]

As it turned out, the tile was destroyed during the research and therefore could not be used as a manipulator.

6. CONCLUSIONS

Focusing of the ultrasonic beam can be realized by mechanical (structural) and electronic methods. In case of thermoablation, mechanical focusing is used. In the focal point an increase in the power density of the ultrasonic beam is obtained in the absence of cavitation. Achieving a temperature of 70°C set as a parameter in the HIFU was confirmed by the fiber optic sensor used in the measurements. In the case of placement from the polystyrene plate behind the ultrasonic wave, structural damage has been observed.

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OGNISKOWANIE WIĄZKI ULTRADŹWIĘKOWEJ

Ogniskowana wiązka ultradźwiękowa ma bardzo ważne znaczenie w diagnostyce i zabiegach medycznych. Celem pracy jest analiza podstawowych zjawisk fizycznych w procesie ogniskowania fali ultradźwiękowej. Na podstawie przeprowadzonego pomiaru temperatury w ognisku wiązki ultradźwiękowej stwierdzono zgodność pomiaru temperatury metodą HIFU z metodą światłowodową.

Słowa kluczowe: ultradźwięki, ogniskowanie ultradźwięków

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