$$Z = \rho\upsilon \qquad x = \frac{t\upsilon}{2}$$

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PRACTICAL WORK
MEDICAL PHYSICS

PART 3. ULTRASOUND

KAZAN FEDERAL UNIVERSITY
INSTITUTE OF PHYSICS
DEPARTMENT OF MEDICAL PHYSICS

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PRACTICAL WORK
MEDICAL PHYSICS

Part 3. Ultrasound

Study aid

**For English-speaking students of medical, biomedical
and pharmaceutical fields of study**

KAZAN
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The textbook "Practical work. Medical physics. Part 3. Ultrasound" is a collection of descriptions of laboratory works on ultrasound. For each work, a brief theory, descriptions of installations, progress of work and a list of questions for self-study are given.

The textbook is addressed primarily to students of medical and biological specialties 31.05.01 "General Medicine" and 31.05.03 "Dentistry" but can also be recommended to students of physics (undergraduate specialties 03.03.02 "Physics" and specialties 12.03.04 "Biotechnical systems and technologies") and students specialized in the master's program 03.04.02 "Medical Physics".

A major list of foreign literature is included. References to only English books are given, including the reference to the "Medical physics" textbook (A.V. Aganov, K.S. Usachev "Medical physics. Part 1. Mechanics. Molecular physics") based on the course of the same name which is read at Kazan Federal University for students of medical specialties.

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Acknowledgments

Introduction

The textbook is addressed primarily to students of medical and biological specialties. The theory of oscillations and wave motion naturally follows from the concepts of mechanics and molecular physics, and for this reason these works are made in the same semester as the tasks from parts 1 and 2 of the present study aid. Basic concepts of the sound waves are described, and the laws of propagation of sound and ultrasound in material are given which are necessary for understanding the physical basics of ultrasonic investigation (USI) in medical practice. Performing the experiments allows students to get acquainted with the operation modes of the equipment for producing and receiving ultrasound, to check the influence of the ultrasound frequency on the obtained image quality, to learn about different scanning modes of USI investigations.

Some works offered here require discussion of flow mechanics, and thus can be regarded as an extension of laboratory tasks dedicated to the phenomenon of viscosity. Diffraction and interference are not included in the studying subjects of this set of tasks, but still they can be discussed in terms of ultrasound to ease the studying of this topic in the following course of optics. The experiment on the ultrasonic computed tomography can serve as the junction between the first and the second semester as well, because X-ray computed tomography is among the laboratory tasks offered in the course of medical physics.

A typical report may be written according to these hints:

1. Write the title of the lab, describe the tasks to solve.

2. Attach the needed tables, graphics and calculations.

3. Make conclusions corresponding to the goals of the work. Explain the shape of each observed dependence (linear, quadratic) based on the theory and formulas. For example: describe how the intensity of ultrasound changes as the sound wave passes through a medium. Find the speed of sound as the function of its frequency.

BASIC THEORY

1. Characteristics of sound

Sound propagates as a mechanical longitudinal or transverse wave. In longitudinal wave back-and-forth particle motion is parallel to the wave travel direction. Such wave can exist in media with tensile-compressive elastic deformations, i.e., in solids, soft solids, liquids, and gas. In transverse wave back-and-forth particle motion is perpendicular to the wave travel direction. Such wave can exist in media with elastic shear deformations, i.e., only in solids. Since most biological tissues are liquids or soft solids (except, maybe, bones), only longitudinal sound waves can exist in them, and only they will be considered further.

Human ears can hear sounds with the frequency in the range approximately from 20 Hz to 20 kHz. The term "ultrasound" refers to high-frequency sound with the frequency above 20 kHz. Bats and dolphins produce sounds in the range of 20 to 100 kHz for precise navigation in space. However, sounds with frequencies above 100 kHz do not occur naturally; only human-developed devices can both generate and detect such ultrasonic waves. Ultrasound frequencies commonly used for medical diagnostic purposes are between 2 and 15 MHz [1].

1.1. Wavelength, frequency, speed

A sound wave, like any other wave, is introduced into a medium by a vibrating object. Motion of the vibrating object is creating the sound wave, and the particles of the medium through which the sound passes are vibrating in a back-and-forth motion (figure 1) at a given frequency f. Frequency can be found from the following formula:

$$f = \frac{1}{T},\qquad(1)$$

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where T is the period, the time it takes for a wave to complete one full cycle (measured in seconds). The unit for frequency is the Hertz (abbreviated Hz); 1 Hz is equivalent to 1 cycle/second.

Transmission of sound requires matter (gas, liquid or solid) as a transmitting medium, unlike light (electromagnetic waves) which can pass through empty space. Sound is the longitudinal wave characterised by the wavelength λ and frequency f; the sound wave is a pattern of varying pressure (or density) zones in the medium which propagate at the speed of sound υ (figure 1). The relation between the speed of sound υ, frequency f and wavelength is given as:

$$\upsilon = \lambda \cdot f . \tag{2}$$

The speed of sound is the material constant (that is, it depends on the molecular structure, temperature, and density of the material); therefore, the product of wavelength and frequency is constant.

Wavelength is the parameter that affects the ***spatial resolution*** in an ultrasonic image, with shorter wavelengths providing better spatial resolution. In a homogeneous medium or tissue, ultrasound frequency and speed of sound are constant; thus, a higher ultrasound frequency results in a shorter wavelength. Examples of the wavelength change as a function of frequency and propagation medium are given below.

Example 1: A typical sound speed in soft tissues is about 1540 m/s. A 2-MHz beam has the following wavelength in a soft tissue, according to Eq. (2):

$$\lambda = \frac{\upsilon}{f} = \frac{1540\,\mathrm{m/s}}{2 \cdot 10^{6}\,1/\mathrm{s}} = 770 \cdot 10^{-6}\,\mathrm{m} = 0.77 \cdot 10^{-3}\,\mathrm{m} = 0.77\,\mathrm{mm}$$

A 10-MHz ultrasound beam in the soft tissue has the wavelength of

$$\lambda = \frac{\upsilon}{f} = \frac{1540\,\mathrm{m/s}}{10 \cdot 10^{6}\,1/\mathrm{s}} = 154 \cdot 10^{-6}\,\mathrm{m} \cong 0.15\,\mathrm{mm}$$

So, higher frequency sound has shorter wavelength.
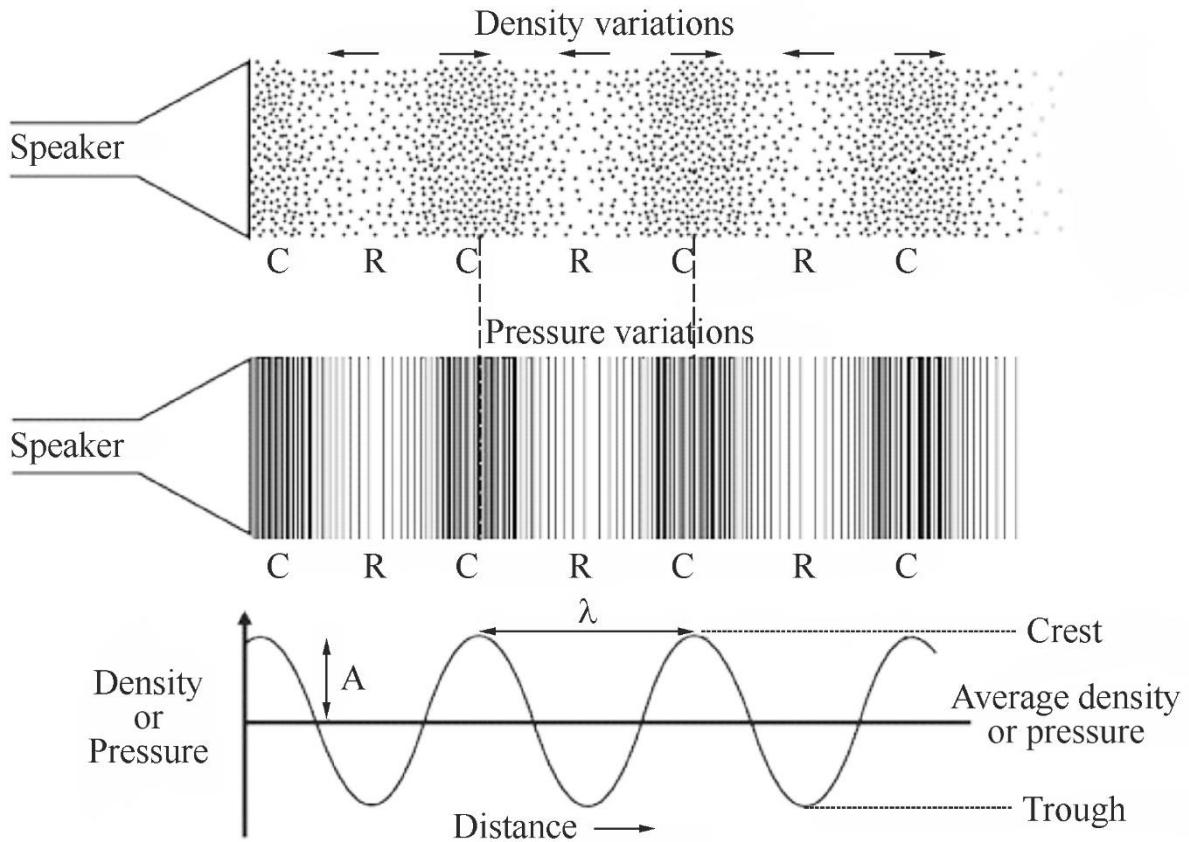
Figure 1. Sound propagates as density or pressure variations around the average value. Sound reaches as a vibration the ear of the listener. C – compressions in the medium, R – rarefactions in the medium, A – amplitude [in appropriate units]: the maximum displacement from the equilibrium; λ –wavelength [m]: repeat distance of the wave

Mathematical representation of waves. Sinusoidal waves are produced by a source experiencing simple harmonic motion. The equation for a sinusoidal wave is a function of position and time:

$$\xi(x,t) = A\sin(\omega_0 t - kx) \tag{3}$$

where $k = 2\pi/\lambda$ is the so-called wave number, and ω_0 is the angular frequency $(\omega_0 = 2\pi f)$.

The speed of sound waves in a medium depends on the compressibility and density ρ of the medium:

$$\upsilon = \sqrt{\frac{elastic\ property\ of\ material}{inertial\ property\ of\ material}}.$$

For sound passing through solids, the elastic property is given by Young's modulus Y, and hence

$$\upsilon = \sqrt{\frac{Y}{\rho}}. \tag{4}$$

If the medium is a liquid or a gas and has a bulk modulus B and density ρ, the speed of sound waves in that medium is

$$\upsilon = \sqrt{\frac{B}{\rho}}. \tag{5}$$

The bulk modulus B of a substance is a measure of how resistant to compression the substance is. It is defined as the ratio of the infinitesimal pressure increase to the resulting relative decrease in the volume. The bulk modulus (which is usually positive) can be formally defined by the equation $B = -V \cdot dP/dV$, where P is pressure, V is the initial volume of the substance, and dP/dV denotes the derivative of pressure with respect to volume.

The speed of sound in an ideal gas is given by the relationship:

$$\upsilon_{sound} = \sqrt{\frac{\gamma RT}{M}}, \tag{6}$$

where M is the molecular weight of the gas in kg/mol, γ is the adiabatic (Poisson's) constant characteristic of the specific gas, R is the universal gas constant 8.314 J/(mol·K), and T is the absolute temperature measured in Kelvin [K]. For dry air, the adiabatic constant $\gamma = 1.4$, and the average molecular mass $M = 28.95$ gm/mol. This leads to

$$\upsilon_{sound} = 20.05\sqrt{T} \tag{7}$$

Values of ρ and υ for various substances are given in Table 1.

Table 1

Values of ρ and υ for various substances

Material	Density of material ρ (kg/m^3)	Speed of sound υ (m/s)	Acoustic impedance Z $(kg/m^2 s \cdot 10^6)$
Air	1.29	331	430
Water (distilled)	1000	1498	1.48
Blood	1060	1570	1.59
Brain	1025	1510	1.58
Adipose tissue (fat)	952	1450	1.38
Muscles (averaged)	1075	1580	1.70
Soft tissue (average)	1060	1540	1.63
Bones (averaged)	1400–1900	4080	5.6–7.8
Acrylic	1200	2700	3.2
Steel	7700–7900	5960	45.9–47.1

1.2. Intensity

The intensity *I* of a sound wave, or the power per unit area is defined as the rate at which the energy E transported by the wave transfers through a unit area S perpendicular to the direction of travel of the wave per time *t*:

$$I = \frac{E}{t \cdot S} = \frac{(Power)_{avg}}{S}. \tag{8}$$

The unit for intensity is the Watt per square metre [W/m²].

The total intensity can be expressed in terms of density ρ:

$$I = \frac{1}{2} \rho \upsilon A^2 (2\pi f)^2, \tag{9}$$

or in terms of the acoustic impedance *Z* (see section 2 for details):

$$I = \frac{1}{2} Z (A\omega_0)^2, \tag{10}$$

where υ is the speed of sound, A is the amplitude, and ω_0 is the angular frequency.

It can be seen from Eq. (9) that the intensity of the ultrasonic wave is proportional to the square of frequency. The intensity can be expressed in terms of change of pressure in transmitting medium:

$$I = \frac{1}{2} \frac{\Delta p_{max}^2}{Z}, \tag{11}$$

where Δp_{max} is the maximum gauge pressure (pressure amplitude) of the medium in bulk.

2. Interactions of ultrasound with tissues

Behaviour of ultrasound in a tissue is mainly based on the acoustic impedance of the tissue and can result in reflection, refraction, scattering, and absorption of the ultrasound energy.

2.1. Acoustic Impedance

Acoustic impedance (the wave resistance of the medium) Z is a measure of tissue stiffness and flexibility, equal to the product of the density ρ and the speed of sound υ:

$$Z = \rho\upsilon. \tag{12}$$

The unit for Z is kg/(m^2·s).

Air, soft tissues, and bone represent the typical low, medium, and high ranges of acoustic impedance values encountered in a patient, as listed in Table 1 (right column). The efficiency of sound energy transfer from one tissue to another is largely based upon the differences in acoustic impedance: if impedances are similar, a large fraction of the incident intensity at the boundary interface will be

transmitted further, and if the impedances are very different, a large fraction will be reflected. In most soft tissues, these differences are typically small, allowing ultrasound to pass to large depths in the patient.

2.2. Reflection

When the incident ultrasound wave is traveling perpendicular to the boundary between two media (at normal incidence or at 90°), a fraction of its energy is reflected back towards the sound source (an echo). The remaining energy is transmitted into the second media and continues to flow in the initial direction (figure 2a).

The fraction of incident intensity reflected back to the transducer is the intensity *reflection coefficient β*, calculated as:

$$\beta = \frac{I_{ref}}{I_{in}} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2, \tag{13}$$

where I_{in} is the incident intensity at the boundary, I_{ref} is the intensity of the reflected sound. The subscripts 1 and 2 represent tissues that are proximal and distal to the ultrasound source, respectively.

The fraction of the ultrasound energy reflected depends on the difference between the Z values of the two media. $β$ increases rapidly as the difference in Z increases (see Table 1). A reflection co-efficient of zero (corresponding to total transmission and no reflection) occurs when the acoustic impedances of the two media are the same. An impedance "match" (no reflection) provides an efficient coupling of sound energy from one medium to another.

The intensity transmission coefficient K_{tr} is defined as the fraction of the incident intensity that is transmitted across an interface, and is equal to $1 - β$.

Normal incident   **Non-normal incident**

a)   b)
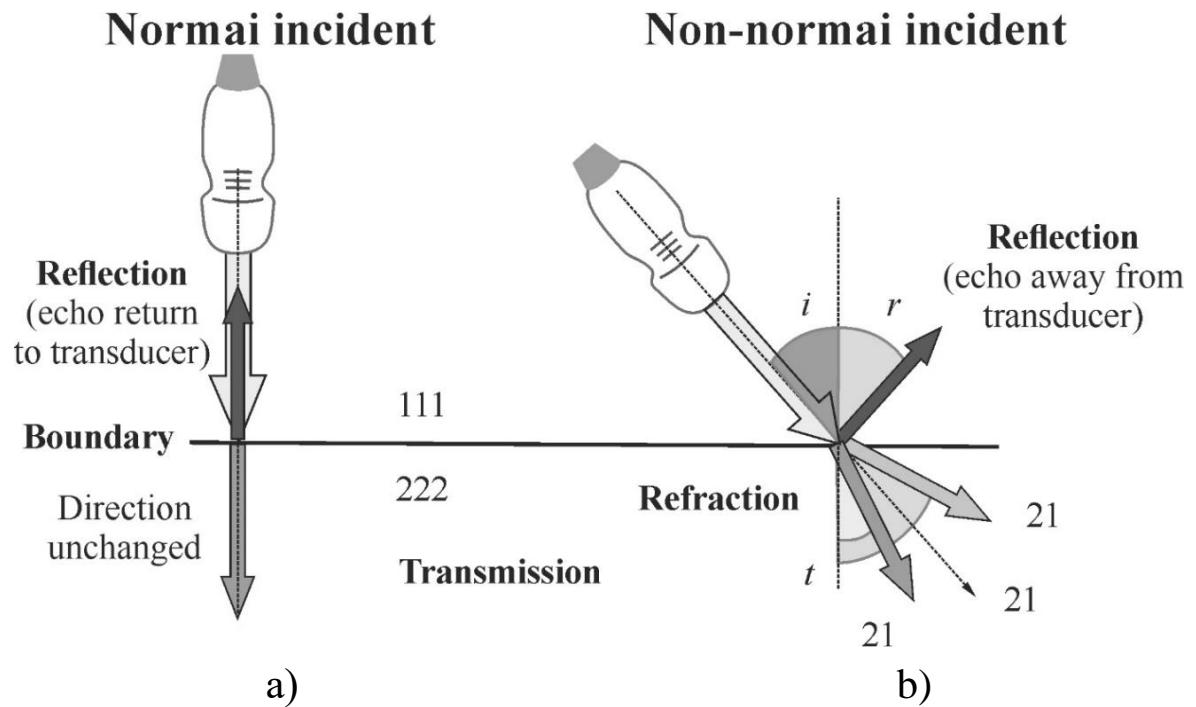
Figure 2. Reflection and refraction of ultrasound occur at tissue boundaries with differences in acoustic impedance *Z*.
a) – Schematic representation of an ultrasonic wave at the interface between two media with different acoustic impedances when the incident ultrasound wave is perpendicular to the boundary. I_{in} is the incident intensity at the boundary, I_{ref} is the intensity of the reflected sound, I_{tr} is the intensity of the transmitted sound.
b) – With non-perpendicular incidence ($\neq 90°$), the reflected fraction of the beam is directed away from the transducer at an angle $\theta_r = \theta_i$. The transmitted fraction of the beam is refracted in the transmission medium at a transmitted refraction angle greater than the incident angle ($\theta_t > \theta_i$) when $\upsilon_2 > \upsilon_1$, and the refraction angle of the transmitted beam is less than that of the incident beam when $\upsilon_2 < \upsilon_1$ [2a]

Example 2: For a fat-muscle interface, the intensity reflection and transmission coefficients are calculated using Eq. (13) as:

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$$\beta_{(fat \rightarrow muscle)} = \frac{I_{ref}}{I_{in}} = \left(\frac{1.38 - 1.70}{1.38 + 1.70}\right)^2 = 0.012;$$

$$K_{tr} = 1 - 0.012 = 0.988$$

For a typical muscle-fat interface, approximately 1% of the ultrasound intensity is reflected, and thus almost 99% of the intensity is transmitted to greater depths in the tissues. This example illustrates that a high fraction of ultrasound is transmitted at tissue boundaries in which the tissues have similar acoustic impedance.

2.3. Impedance matching: ultrasound coupling gel

At a skin-air interface, nearly 100% of incident intensity is reflected, making anatomy unobservable beyond an air-filled cavity. *Acoustic gel* placed between the transducer and the patient's skin is a critical part of the standard ultrasound imaging procedure that ensures good transducer coupling to the skin and eliminates air pockets that would reflect the ultrasound [2].

Perpendicular reflection originates the echo signal. The image formed in an ultrasound investigation is made by tracking reflections (as shown in figure 3a) and mapping the intensity of the reflected sound waves in a two-dimensional plane (see theory for lab 193). Large differences in acoustic impedance between bone and muscle means that these boundaries show up well (figure 3b). Very small differences between soft tissues mean that these boundaries do not show up well on a scan.
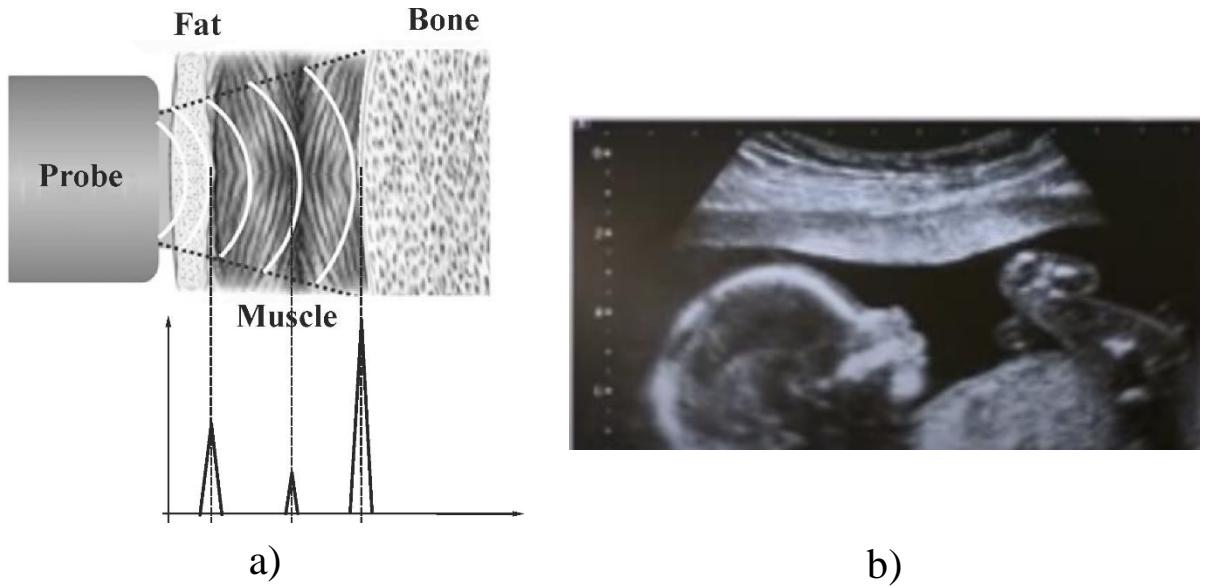
Figure 3. a) Graph of echo intensity versus time.

b) The ultrasound scan of baby

2.4. Refraction

Refraction is a change in direction of the transmitted ultrasound pulse when the incident pulse is not perpendicular to the tissue boundary, and the speeds of sound in the two tissues are different. As frequency remains constant for stationary tissues and reflectors, the speed difference causes the wavelength to change, resulting in a redirection of the transmitted pulse at the boundary as shown in figure 2b. The angle of refraction θ_t and the speed υ_2 in the second tissue depend on the change in the wavelength and are related to the angle of incidence θ_i and the speed υ_1 by the Snell's law:

$$\frac{\sin\theta_t}{\sin\theta_i} = \frac{\upsilon_2}{\upsilon_1} = \frac{Z_2\rho_2}{Z_1\rho_1}. \tag{14}$$

This yields an intensity ratio for nonperpendicular reflection:

$$\beta = \frac{I_{ref}}{I_{in}} = \left(\frac{Z_1 \cdot \cos\theta_i - Z_2\cos\theta_t}{Z_1 \cdot \cos\theta_t + Z_2\cos\theta_t}\right)^2, \tag{15}$$

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Figure 2b illustrates the refraction angle when the speeds of sound in tissue 1 are greater than or less than in tissue 2.

A situation called *total reflection* occurs when $\upsilon_1 \neq \upsilon_2$ and the angle of incidence of the sound beam relative to the boundary between two media exceeds an angle called the *critical angle* θ_c. When $\theta = \theta_c$, the sound beam does not penetrate the second medium but passes along the boundary. The critical angle is calculated by setting $\theta_t = 90°$ in the Snell's law (14), giving the equation $\sin\theta_c = \upsilon_1/\upsilon_2$ [2a].

2.5. Scattering

Scattering arises from objects and interfaces within tissues that are about the size of the ultrasound wavelength or smaller. At low frequencies (1–5 MHz) wavelengths are relatively large, and tissue boundaries appear smooth or specular (mirror-like). A specular reflector represents a smooth boundary between two tissues. At higher frequencies (5–15 MHz), wavelengths are smaller, and on a smaller scale, the same boundaries appear with irregular interfaces causing echo reflection in many directions. This effect is enhanced with increased frequency. A non-specular reflector represents a boundary that presents many different angles to the ultrasound beam and of the returning echoes. Only a fraction of the echo intensity will return to the transducer in this case, resulting in large signal attenuation (figure 4).

Many organs can be identified by a certain "signature" or "echo texture" caused by intrinsic structures that produce variations in the returning scattered intensity. Variations in the scatter amplitude in different tissue regions result in corresponding brightness changes on the ultrasound display. In general, the echo signal amplitude from a tissue or material depends on the number of scattering elements in the unit volume, the acoustic impedance differences at interfaces,

the sizes of the scatterers, and the ultrasound frequency. Tissues generating higher scatter amplitude are called ***hyperechoic*** and tissues generating lower or no scatter amplitude tissues are called ***hypoechoic*** relative to the average background signal. Non-specular echo signals become stronger relative to specular echo signals when using higher ultrasound frequencies, making the images appear more echogenic and granular [2a].

Boundary interaction:

Specular (smooth)
reflection

Nonspecular
(diffuse) reflection
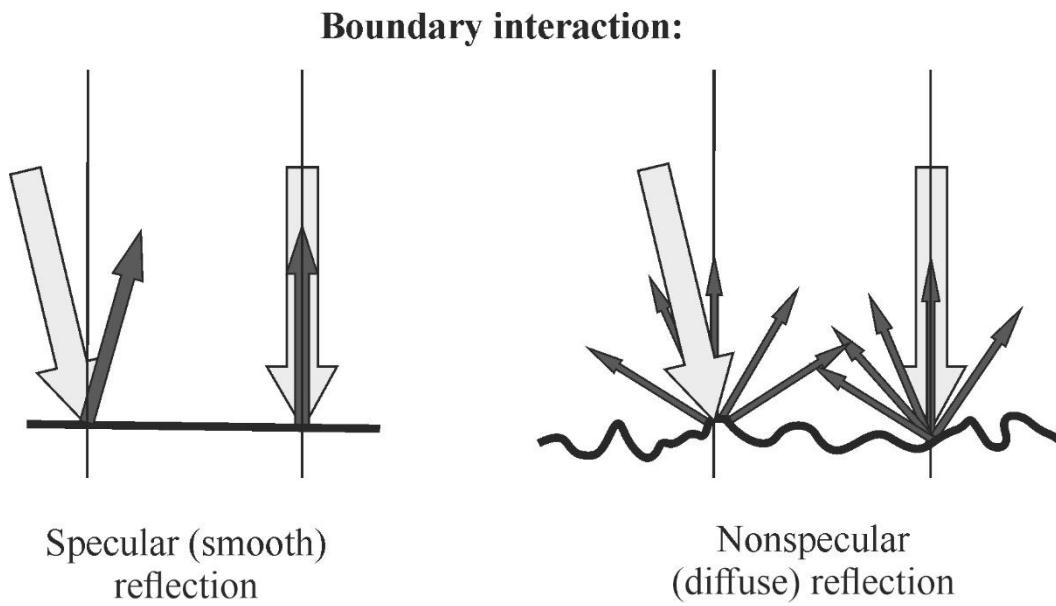
Figure 4. Specular and non-specular boundary characteristics are partially dependent on the wavelength of the incident ultrasound. For long wavelengths, tissue boundary interactions are smooth and mirror-like. As the wavelength reduces with higher frequency ultrasound, the boundary becomes "rough" with non-perpendicular surfaces that result in diffuse scattering from the surface [2a]

2.6. Absorption and attenuation

Attenuation is the loss of intensity with distance passed, caused by scattering and absorption of the incident beam. Scattering has a strong dependence with increasing ultrasound frequency. Absorp-

tion occurs by transferring energy to the tissues, which results in heating or even mechanical disruption of the tissue structure. The combined effects of scattering and absorption result in exponential attenuation of ultrasound intensity with distance passed (see theory for lab 191). Also, energy loss due to these two reasons increases at higher frequencies.

3. Ultrasound transducers

Ultrasound is transmitted and received with a transducer array, comprised of hundreds of small ceramic elements with electromechanical (piezoelectric) properties. These elements are connected to controlling electronics, aligned in a row, and contained in a handheld hardened plastic housing [2a].

3.1. Piezoelectric Materials

Piezoelectric materials are materials which can generate an internal electrical charge from applied mechanical stress. The term *piezo* is a Greek derivation for "press." These materials can also exhibit the *inverse piezoelectric effect* with the internal generation of mechanical strain in response to an applied electrical field. Ultrasound transducers for medical imaging applications employ synthetic piezoelectric ceramics, lead zirconate-titanate (PZT).

PZT is a compound with an asymmetrical crystal lattice structure, possessing an internal molecular dipole (positive and negative charge). When expanded or compressed by a mechanical force, the small displacements create polarisation proportional to the stress that produced it. Re-orientation of the internal dipole structure

generates a positive and negative charge on each of the surfaces of the PZT crystal (figure 5a).
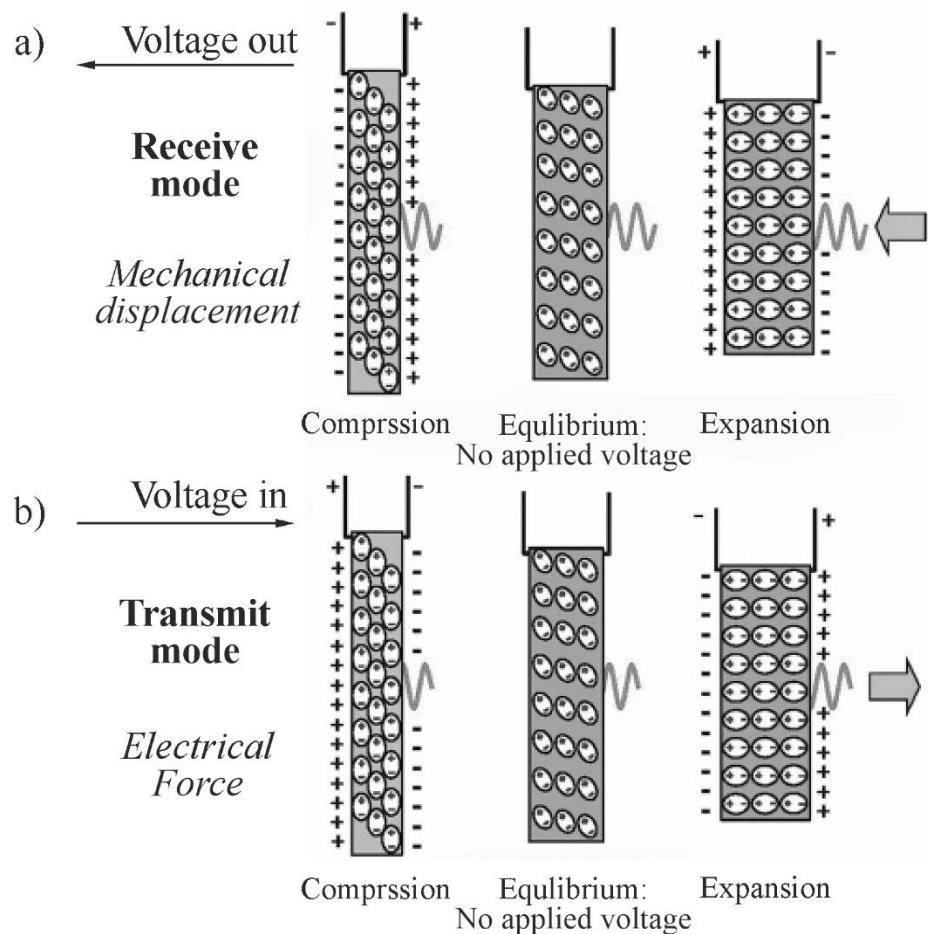
Figure 5. The piezoelectric element is comprised of aligned molecular dipoles. a) – Under the influence of mechanical pressure from an adjacent medium (e.g., an ultrasound echo), the element's thickness decreases (at the peak pressure amplitude), achieves equilibrium (with no pressure), or expands (at the peak rarefactional pressure) causing realignment of the electrical dipoles to produce positive and negative surface charge. Surface electrodes measure the amplitude of the charge in millivolt to microvolt output as a function of time in the reception mode. b) –An external voltage source (~100 V) applied to the element surfaces over several microseconds causes compression or expansion from equilibrium by realignment of the dipoles in response to the electrical attraction or repulsion force in the excitation mode [2a]

To detect ultrasound, electrode wires are attached to each surface to measure the surface charge variations resulting from the compression and rarefaction of returning ultrasound echoes, generating a potential difference on the order of tens or hundreds of μV (μV is one-millionth of a volt). To generate ultrasound, the same electrode wires on the PZT crystal use the inverse piezoelectric effect by applying an alternating voltage to cause contraction or expansion of the transducer crystal thickness as illustrated in figure 5b [2a].

3.2. Transducer

Each transducer element functions in the *excitation mode* to transmit ultrasound energy, and in the *reception mode* to receive ultrasound energy. Different layers in transducer are necessary to control the spatial and transmission characteristics of the ultrasound pulse (figure 6).
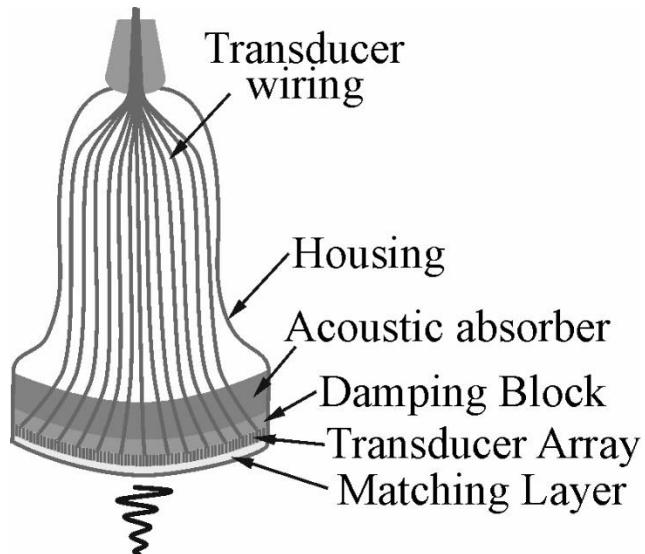

Figure 6. The transducer is comprised of a housing, electrical insulation, and a composite of active element layers, including the PZT crystal, damping block and absorbing material on the backside, and a matching layer on the front side of the multielement array

Layered on the backside of each element is a *damping block* to attenuate the duration of the transducer vibration in order to produce an ultrasound pulse with as short as possible spatial pulse length (SPL). This preserves detail of organ boundaries and echogenic anatomy carried by the returning echoes. Behind the damping block is an *absorbing layer*, which is made to reduce the backside-produced ultrasound energy and to attenuate stray ultrasound signals reflected from the transducer housing. On the front side of the transducer array is the *matching layer*, which provides the interface between the PZT element and the tissue. It consists of one or more layers of materials with acoustic properties intermediate to that of soft tissue and transducer element composition to minimize acoustic impedance differences and maximize the transmission of ultrasound into the tissues.

3.3. Ultrasound beam properties

The ultrasound beam propagates as a longitudinal wave from the transducer surface into the propagation medium and exhibits two distinct beam patterns: a slightly converging beam out to a distance determined by the geometry and frequency of the transducer (*the near field*), and a diverging beam beyond that point (*the far field*), as shown in figure 7.

The near field, also known as the *Fresnel zone*, is adjacent to the transducer face and has a converging beam profile. Beam convergence occurs because of multiple constructive and destructive interference patterns of the ultrasound waves from the transducer surface. "Huygens' principle" describes a large transducer surface as an infinite number of point sources of sound energy where each point

is characterised as a radial emitter (see figure 7, left of the middle diagram). As individual wave patterns interact, the peaks and troughs from adjacent sources constructively and destructively interfere causing the beam profile to be collimated. The ultrasound beam path is thus largely confined to the dimensions of the active part of the transducer surface, with the beam converging to approximately half the transducer size at the end of the near field.
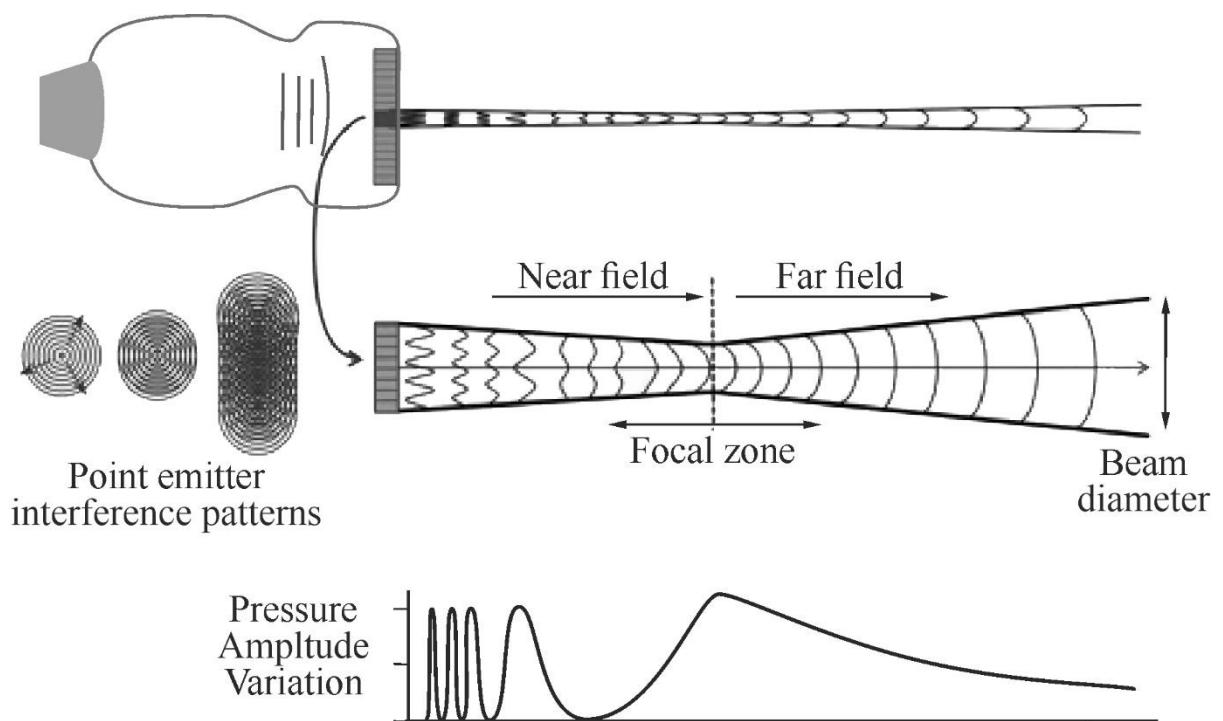
Figure 7. A linear array transducer subgroup excitation (top)
and the expanded beam profile (middle) shows the near-field
and far-field characteristics of the ultrasound beam. The near field
is characterised as a collimated beam, and the far field begins when
the beam diverges. Point emitters (left middle) generate constructive
and destructive interference patterns that cause beam collimation
and large pressure amplitude variations in the near field (lower
diagram). Beam divergence occurs in the far field, where pressure
amplitude monotonously decreases with the propagation distance [2a]

The near field length L depends on the diameter d of the transducer and is inversely proportional to propagation wavelength λ, so higher transducer frequency results in an extended near field:

$$L = \frac{d^2}{4 \cdot \lambda} = \frac{f \cdot r^2}{\upsilon}, \qquad (16)$$

where r is the radius of transducer, υ is the speed of sound. Large radius and frequency result in an extended near zone.

Lateral resolution (the ability of the system to resolve objects in a direction perpendicular to the beam direction) depends on the lateral beam dimension and is the best at the end of the near field for an unfocused transducer element aperture (e.g., a subgroup of linear array transducer elements fired simultaneously).

Example 3: A typical piezoelectric crystal of 2 cm diameter is used to produce an ultrasound frequency of 5 MHz. This allows to calculate the length of the near region:

$$L = \frac{f \cdot r^2}{\upsilon} = \frac{5 \cdot 10^6 [1/s] \cdot 10^{-4} [\mathrm{m}^2]}{1540 [\mathrm{m/s}]} = 0.325 \ [\mathrm{m}]$$

The near range covers nearly the body thickness.

The far-field, also known as the *Fraunhofer zone*, begins at the distance from the transducer where the beam diverges, and lateral resolution degrades. The angle of divergence Θ is directly proportional to the wavelength λ and inversely proportional to the transducer diameter d:

$$\sin \Theta = 1.22 \frac{\lambda}{d} \quad \rightarrow \quad \Theta = \arcsin\left(1.22 \frac{\lambda}{d}\right). \qquad (17)$$

Less beam divergence occurs with higher-frequency and larger sub-element excitations in a linear array. Ultrasound intensity

in the far field decreases monotonously with the distance (figure 7, bottom illustration).

Example 4: The diverging angle of the far field of the ultrasound beam is:

$$\sin \Theta = 1.22 \frac{\upsilon}{f \cdot d} = 0.61 \frac{1540 \ [\text{m/s}]}{5 \cdot 10^6 [1/\text{s}] \cdot 0.1 \ [\text{m}]} = 0.002 \rightarrow \Theta = 0.1^\circ$$

Only small divergence takes place in the far region.

3.4. Basics of pulse echo method

The ultrasonic transducer can be used to transmit a short ultrasound pulse. The same transducer is then can be used as a receiver to record the reflected echoes (figure 8).
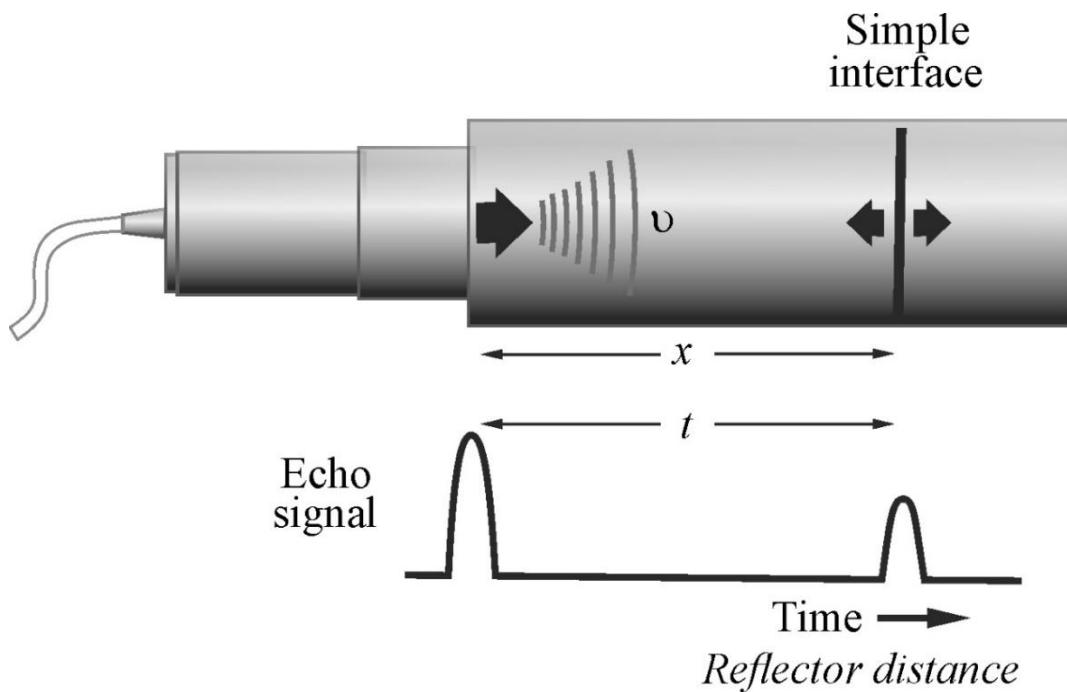

Figure 8. The pulse echo method. t – Pulse Echo travel time; υ – speed of ultasound in the target material; x – distance to the reflectign object

Based on the time interval (t) between sending the signal and receiving the echo (times of flight), the distance to the object (x) can be determined:

$$x = \frac{t\upsilon}{2},$$ (18)

where υ is the speed of ultasound in the target material.

Technique for detecting and determining the distance and direction of objects by acoustic means is known as sonar (Sound Navigation and Ranging). Sonar is used usually underwater, as in submarine navigation, to navigate, measure distances (ranging), communicate with or detect objects on or under the surface of the water.

3.5. Spatial Resolution

In ultrasound, the major factor that limits the spatial resolution and visibility of detail is the volume of the acoustic pulse. The axial, lateral, and elevational (slice-thickness) dimensions determine the minimal volume element (figure 9). Each dimension has an effect on the resolvability of objects in the image. Axial resolution, along the direction of the beam, is independent of the depth; lateral resolution and elevational resolution are strongly depth-dependent. Lateral resolution is determined by transmit and receive focussing electronics; elevational resolution is determined by the height of the transducer elements. At the focal distance, axial is better than lateral, and lateral is better than elevational resolution [2a].

Axial resolution (also known as linear, range, longitudinal, or depth resolution) refers to the ability to discern two closely spaced objects in the direction of the beam. Achieving good axial resolution requires that the returning echoes from adjacent boundary reflectors be distinct without overlap (figure 10) [2a].

a) Rsolution components in 3D space

b) Elevational Prfile of Ultrasound Beam with depth
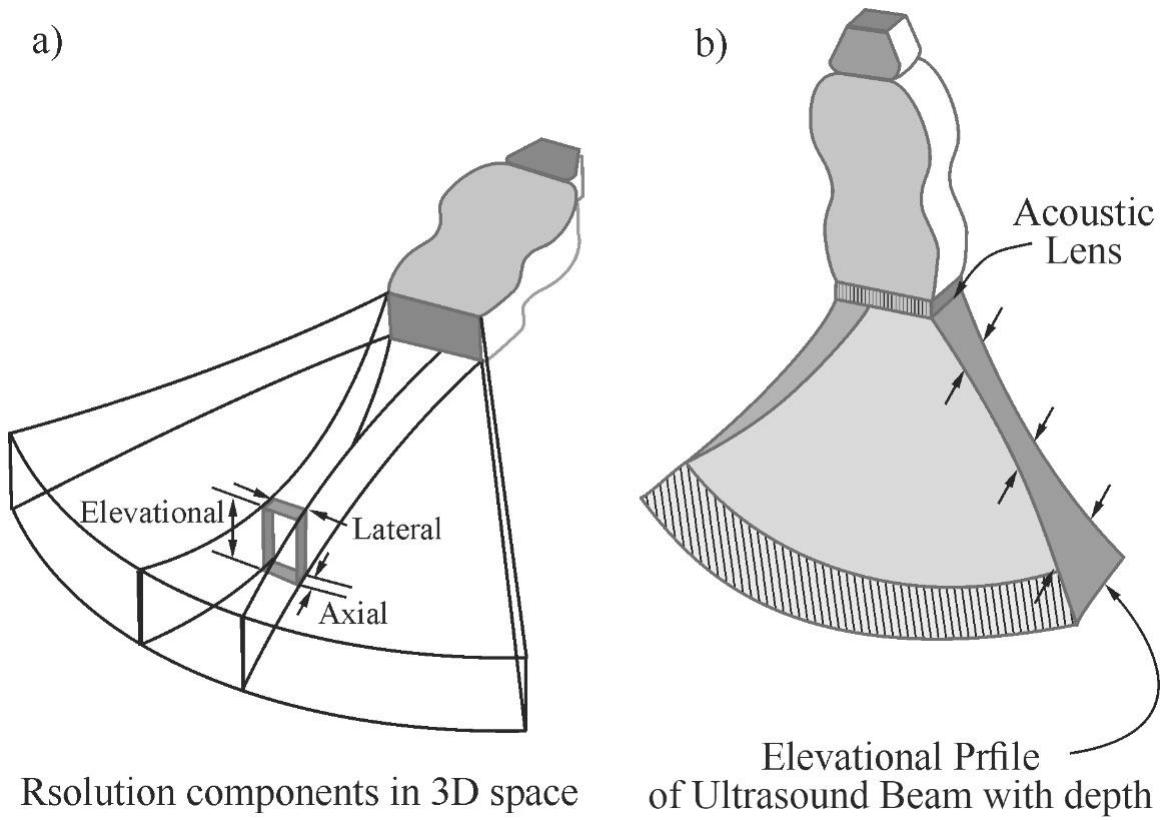
Figure 9. a – The axial, lateral, and elevational (slice-thickness) contributions in three dimensions are shown for a phased-array transducer ultrasound beam. b – Elevational resolution profile with an acoustic lens across the transducer array produces a weak focal zone in the slice-thickness direction

Lateral resolution, also known as azimuthal resolution, refers to the ability to discern two closely spaced objects perpendicular to the beam direction as distinct. The *beam width* determines the lateral resolution (figure 11). Since the beam width varies with distance from the transducer in the near and far-field, the lateral resolution is depth-dependent. The best lateral resolution occurs at the near field / far field interface. At this depth, the effective beam width is approximately equal to ½ the effective transducer width. In the far field, the beam diverges and substantially reduces the lateral resolution [2a].

Ultrasound pulses and real obdects

Echographic represernation
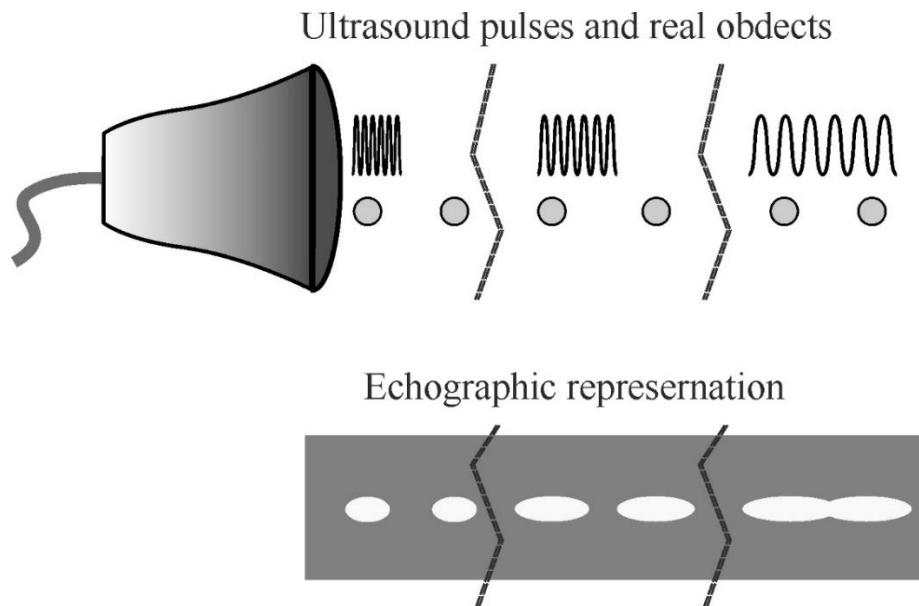
Figure 10. Axial resolution. Higher frequencies reduce the ultrasound spatial *pulse length* and thus improve the axial resolution

Beam profile and real object

Echographic represernation
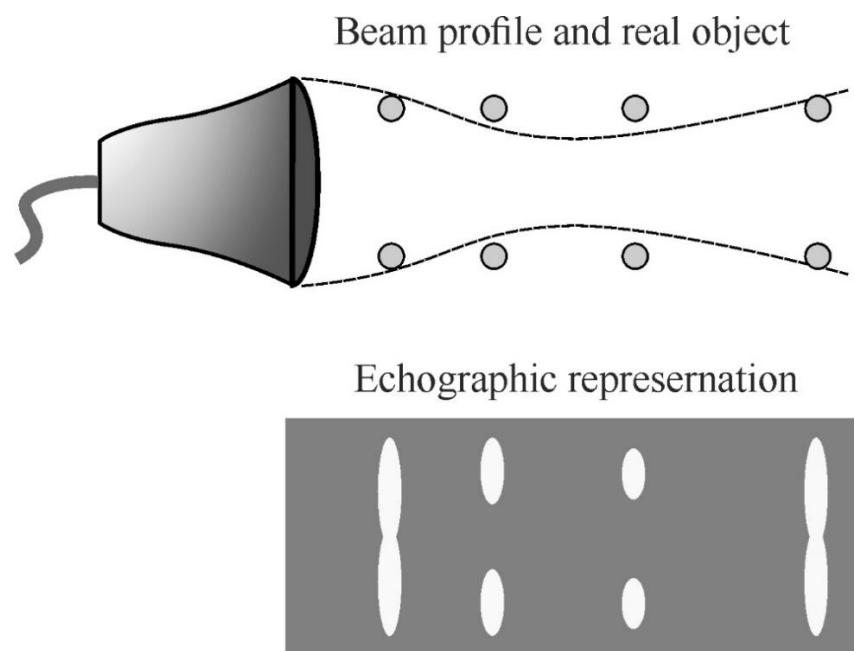
Figure 11. Lateral resolution is a measure of the ability to discern objects perpendicular to the direction of beam travel and is determined by the beam diameter. Point targets in the beam are averaged over the effective beam diameter in the ultrasound image as a function of depth. Best lateral resolution occurs at the focal distance; good resolution occurs over the focal zone [2a]

Elevational resolution. The elevational or slice-thickness dimension of the ultrasound beam is perpendicular to the image plane. Slice thickness plays a significant part in image resolution, particularly with respect to volume averaging of acoustic details in the regions close to the transducer and in the far field beyond the focal zone. Elevational resolution is dependent on the transducer element height in much the same way that the lateral resolution is dependent on the transducer element width. The slice thickness dimension has the poorest resolvability for array transducers. The use of an acoustic lens across the entire array can provide improved elevational resolution at a fixed focal distance. Unfortunately, this compromises resolution before and after the elevational focal zone due to partial volume averaging [2a].

4. Doppler Effect

Doppler effect has many applications in various scientific disciplines, from gas flow measurements in pipes to planetary science. The Doppler effect or the Doppler shift describes the changes in the frequency of any sound or light wave produced by a moving source with respect to an observer.

Doppler effect in physics is defined as the increase (or decrease) in the frequency of sound, light, or other waves as the source and observer move towards (or away from) each other.

Waves emitted by a source traveling towards an observer seem compressed to the observer. In contrast, waves emitted by a source travelling away from an observer get stretched out. Christian Johann Doppler first proposed the Doppler effect (Doppler shift) in 1842 [2b].

Doppler Effect Formula. Doppler effect is the apparent change in the frequency of waves due to the relative motion between the source of the sound and the observer. We can deduce the apparent frequency in the Doppler effect using the following equation:

$$f' = \frac{\left(\upsilon \pm \upsilon_o\right)}{\left(\upsilon \mp \upsilon_s\right)} f_s, \tag{19}$$

where f_s is the actual sound frequency of the source (in the coordinate frame bound to the source), f' is the observed frequency (figure 12, 1), υ is the velocity of the sound wave, υ_o is the velocity of the observer, and υ_s is the velocity of the source.

The above equation changes in different situations depending on the velocities of the observer or the source of the sound.

(a) *Source moving towards the observer at rest* (figure 12, 2).

In this case, the observer's velocity υ_o is equal to zero. Substituting this into the Doppler effect equation above, the equation of the Doppler effect is given as:

$$f' = \frac{\upsilon}{\left(\upsilon - \upsilon_s\right)} f_s. \tag{20}$$

(b) *Source moving away from the observer at rest* (figure 12, 3).

Since the velocity of the observer υ_o is zero, it is eliminated from the equation (19). But this time the source moves away from the observer, so its velocity is negative to indicate the direction. Hence, the equation (19) becomes as follows:

$$f' = \frac{\upsilon}{\left(\upsilon - \left(-\upsilon_s\right)\right)} f_s. \tag{21}$$

(c) *Observer moving towards a stationary source* (figure 12, 4).

In this case, υ_s is equal to zero, hence the equation (19) becomes as follows:

$$f' = \frac{\left(\upsilon + \upsilon_o\right)}{\upsilon} f_s, \tag{22}$$

(d) *Observer moving away from a stationary source* (figure 12, 5).

	Source	Observer	Detected frequency

1) f_s ... $= f'$

2) v_s ... $< f'$

3) v_s ... $> f'$

4) v_o ... $< f'$

5) v_o ... $> f'$
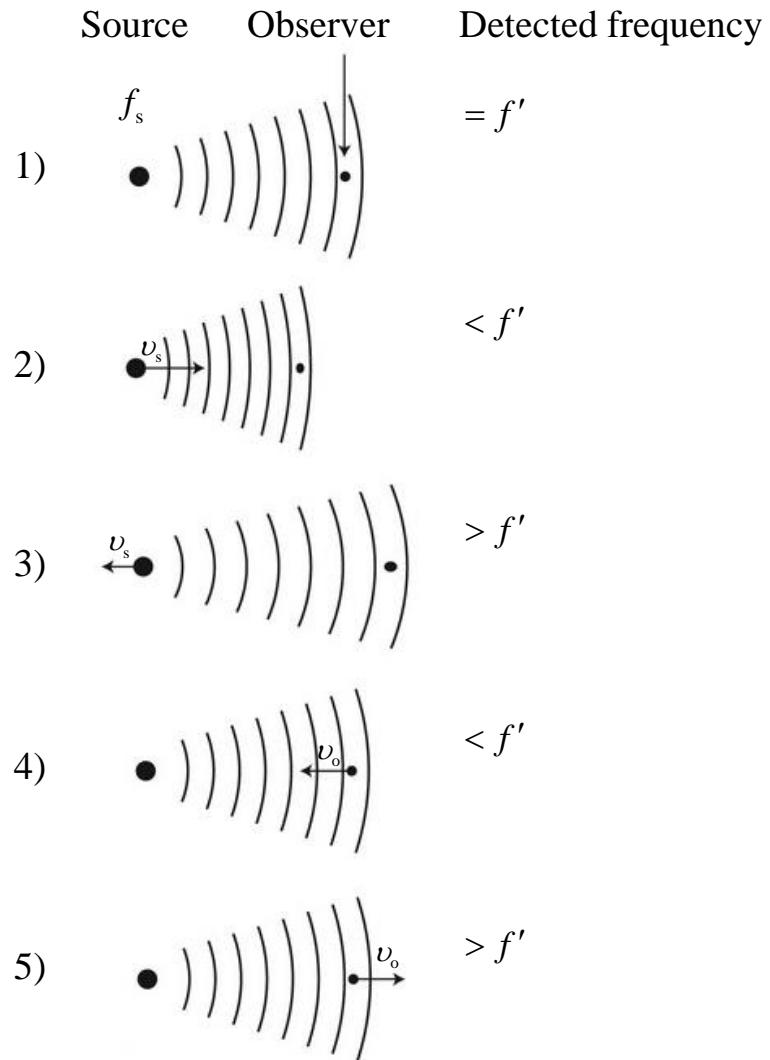
Figure 12. The Doppler effect is the change in the observed frequency due to motion between the source and the observer. (1) The source of the sound and the observer are both stationary, so the observed sound has the same frequency as that transmitted. (2) The source is moving toward a stationary observer, so the detected frequency is increased. (3) The source is moving away from the observer, thus decreasing the frequency observed. (4) The source is stationary and the observer is moving toward the source, so that the observer witnesses a higher frequency than that emitted. (5) The observer is moving away from the source, so the frequency detected is lower than that emitted

Since the observer is moving away, the velocity of the observer becomes negative. So, now υ_o is subtracted, since υ_o is negative:

$$f' = \frac{(\upsilon - \upsilon_o)}{\upsilon} f_s, \tag{23}$$

Applications of Doppler's effect: sirens, radar, astronomy, medical imaging, blood flow measurement, satellite communication, vibration measurement, developmental biology, audio, velocity profile measurement.

ULTRASONIC ECHOSCOPE

5. Safety instructions

Prior to taking the ultrasonic echoscope and the accessories into operation, please carefully read the notes below to ensure your own health and safety and operational safety of the device.

1. The apparatus is connected to the 220 V power mains.
2. The opening slits on the device are for ventilation and must be kept free to prevent the device from overheating.
3. Never try to insert foreign objects into the apparatus, because this can lead to short circuits or electric shocks!
4. Only the ultrasonic transducers supplied by GAMPT GmbH must be connected to the ports named "PROBE 1" and "PROBE 2" (figure 13)!
5. When establishing or when disconnecting the connection between an ultrasonic transducer and the echoscope, the connection plug of the transducer must be specifically held as illustrated in figure 13. Tensile load acting on the connection cable must be avoided to prevent disconnection of the cable from the connector piece.
6. During transmission mode voltage up to 300 V may be applied to the ports. Do not touch the sockets while the apparatus is in work**!**
7. Before using the ultrasonic probe, ascertain its integrity. If the sensor is broken, replace it.
8. Unplug the sensors by holding the socket. Do not pull the wire!
9. The ultrasonic echoscope is a laboratory device not a medical product!

The ultrasonic probes must not be used with people or other living beings.

Figure 13. Connecting/disconnecting a transducer to GS200

6. Control elements on the front side of the echoscope GS200, ultrasonic scanner FlowDop and MultiFlow pump

The major control elements and connection ports for measuring operation using single-element transducers are located on the front side of the GS200 unit. For better illustration of the basic operating principle of the device, the individual components of the echoscope have been grouped according to their functions and are also visually separated accordingly.

Description of the echoscope's front panel:

A – **Power supply block**

(1) On/Off switch of the device

B – **Receiver/transmitter block**

(2) Probe port 2

(3) Rotary switch for transmitter output level

(4) Mode selector switch transmitter / receiver

(5) Rotary switch for receive gain

(6) Probe port 1

C – **Time gain control**

(7) Rotary switch for slope

(8) Rotary switch for start point

(9) Rotary switch for width

(10) Rotary switch for threshold

D – Outputs for oscilloscope

(11) Trigger signal

(12) TGC signal

(13) Ultrasonic signal

(14) A-scan signal

6.1. Receiver/transmitter unit

Two rotary switches are provided on the front side of the device for adjustment of transmitting level and receive gain.

The transmitting level (OUTPUT) is adjusted by means of rotary switch 3 (figure 14). It can be increased in 5-dB increments up to 30 dB, with the maximum transmitting level of 30 dB corresponding to an output voltage of approximately 300 Volt.
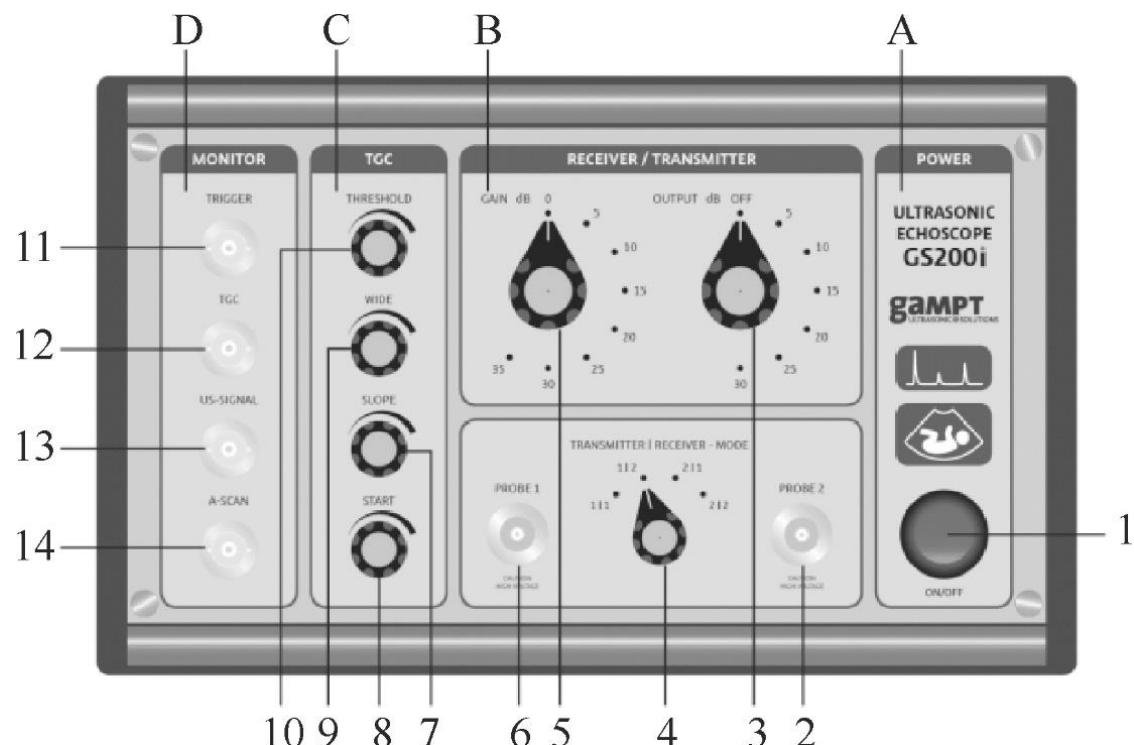

Figure 14. Front view of the GS200

Setting of the receive gain (GAIN) is performed by means of rotary switch 5 (figure 14). It can be adjusted within a range from 0 to 35 dB.

Selection of the mode of operation (reflection or transmission), i.e., switching of the probe ports 6 and 2 as transmitting output, receiving input, or both (Table 2), is carried out with the help of rotary switch 4 (figure 14).

Table 2

Receiver/transmitter setting

Switch position	Transmitter	Receiver	Mode of operation
1 | 1	Probe 1	Probe 1	Reflection
1 | 2	Probe 1	Probe 2	Transmission
2 | 1	Probe 2	Probe 1	Transmission
2 | 2	Probe 2	Probe 2	Reflection

6.2. TGC unit (Time Gain Control)

Sound undergoes attenuation during propagation within a medium. Sound attenuation results in a decrease of the sound signal intensity with increasing run time or depth. By means of TGC (Time Gain Control, referring to a time-dependent or depth-dependent gain) it is possible to partly compensate for attenuation of the intensity of the ultrasound signal. In this way it is possible to amplify and visualise echoes of deep discontinuities. The following TGC parameters may be modified by means of the rotary switches 7 to 10 (figure 14):

• THRESHOLD (rotary switch 10): Threshold value for the starting point of TGC.

• WIDE (rotary switch 9): Width, i.e., the time or depth range to which the TGC is applied.

• SLOPE (rotary switch 7): Gradient of the gain [dB/µs or dB/mm].

• START (rotary switch 8): Starting point of the TGC.

The TGC is infinitely variable between 0 and maximum of approximately 30 dB. The maximum adjustable time range to which the TGC can be applied is approximately 150 μs. By changing the start value, the TGC curve can be shifted along the time axis.

The GS-EchoView measuring and control software provides a separate diagram window that displays the TGC in the form of a curve (figure 15). The TGC diagram is always available parallel with the A-scan diagram in all program modes.
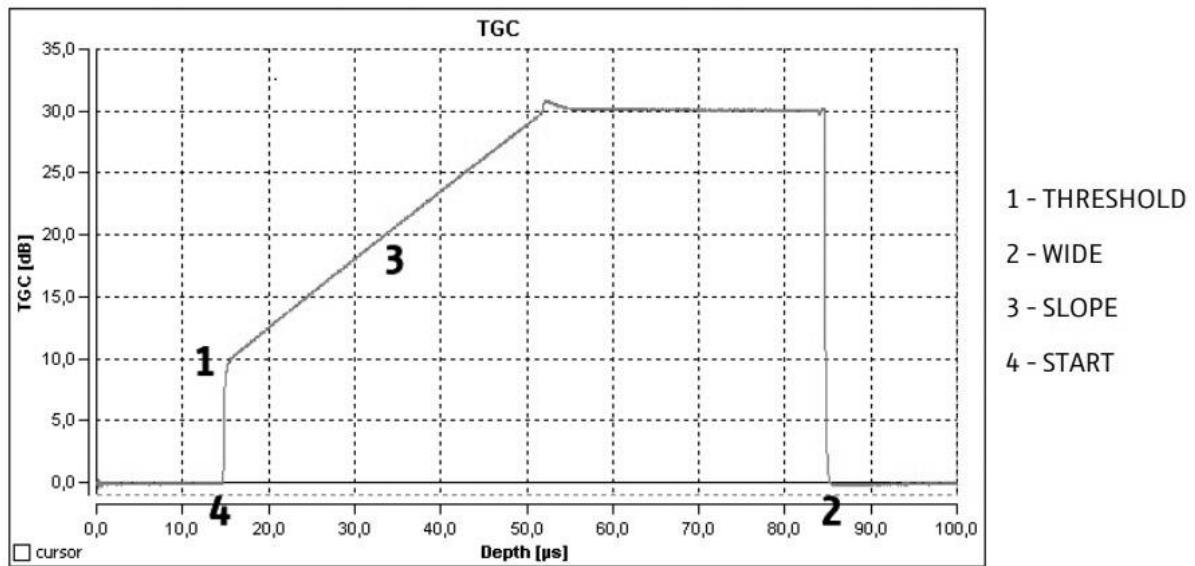
Figure 15. Diagram with TGC curve (GS-EchoView)

Two figures below illustrate the principle of functioning of the TGC. Figure 16 shows the amplitude scan of a reflection measurement without TGC using a homogeneous test sample. The scan shows a number of echo pulses resulting from repeated reflections at the bottom of the specimen (material-air boundary). Based on the attenuation of sound inside the material and the mere partial reflection at the border between the test specimen and the transducer head, the amplitude of the echo impulses decreases with increasing run time and number of reflections.

Two figures below illustrate the principle of functioning of the TGC. Figure 16 shows the amplitude scan of a reflection measurement without TGC using a homogeneous test sample. The scan shows a number of echo pulses resulting from repeated reflections at the bottom of the specimen (material-air boundary). Based on the attenuation of sound inside the material and the mere partial reflection at the border between the test specimen and the transducer head, the amplitude of the echo impulses decreases with increasing run time and number of reflections.
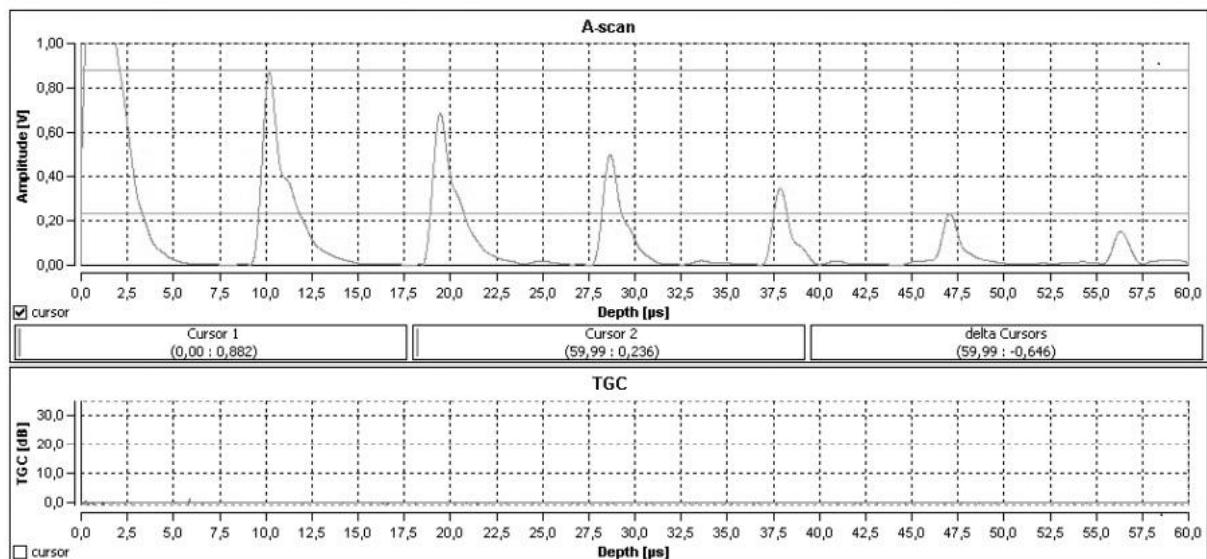
Figure 16. Amplitude scan without TGC

Figure 17 shows an amplitude scan performed in the same test sample as figure 16 applying the same measurement conditions but also implementing time gain control.
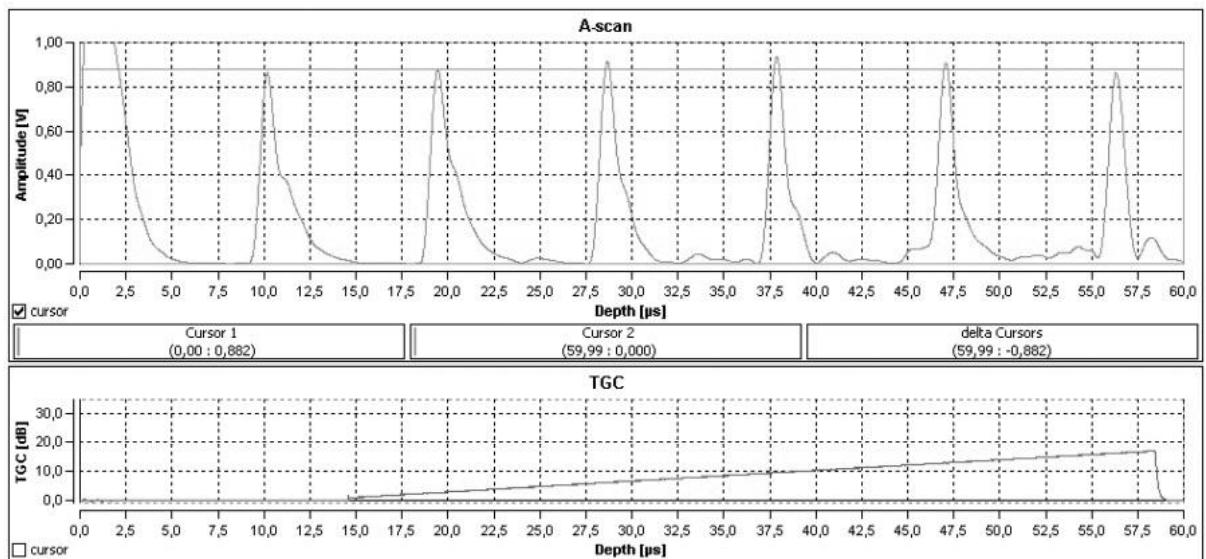
Figure 17. Amplitude scan with TGC

6.3. Control elements on the front side of the Doppler FlowDop

Ultrasonic device for carrying out experiments on the subject of Doppler effect, fluid mechanics and Doppler sonography in vascular diagnostics is shown in figure 18.
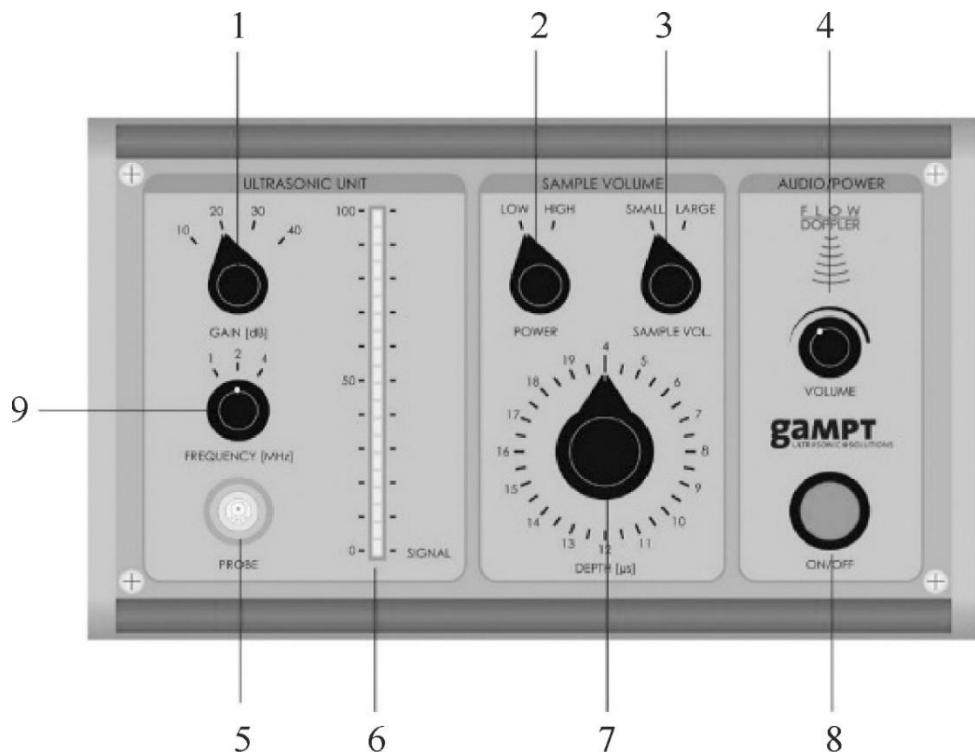
Figure 18. Front view of the ultrasonic scanner FlowDop

Description of the scanner's front panel:

1. Signal gain switcher.
2. Switcher of the packet time or of the transmitter power.
3. Switcher of the receiver time window or of the sample volume.
4. Audio signal level (volume).
5. Probe port.
6. Indicator of the input signal level.
7. Time window of the receiver (when switcher "3" is in position "Low").
8. On/Off switch of the device.

6.4. Centrifugal pump MultiFlow

The MultiFlow centrifugal pump creates a laminar and constant flow with different flow rates as a precondition for the investigation of flow phenomena. The flow rate is adjusted via the speed control of the pump in the range from 0 to 10 L/min (figure 19).

a   b
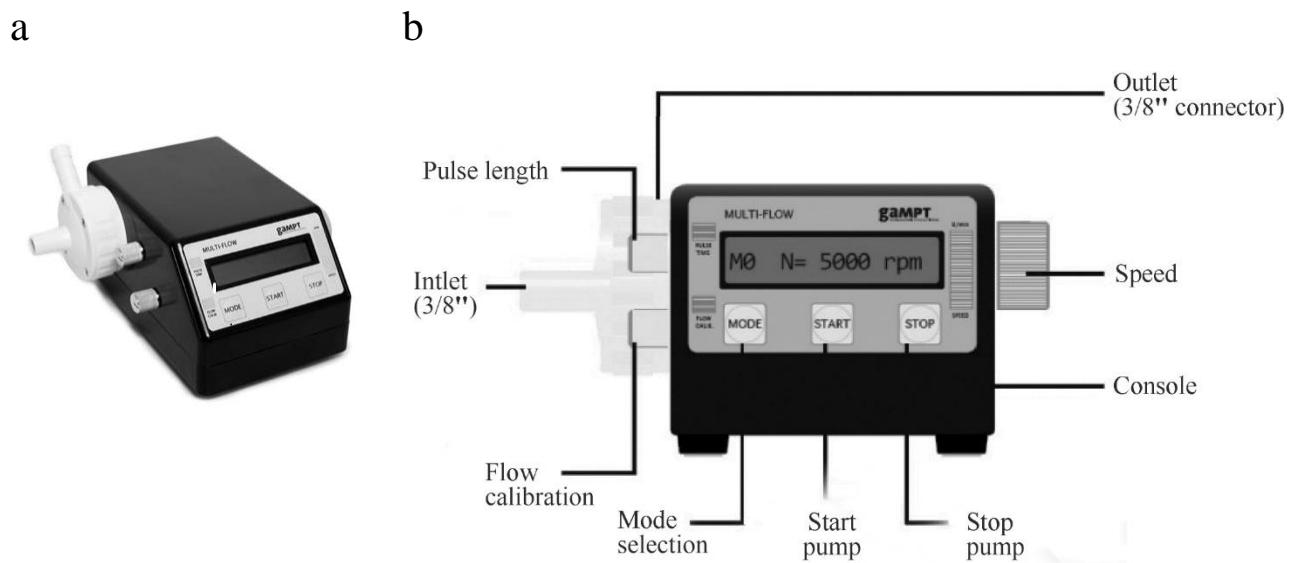
Figure 19. a – The MultiFlow pump. b – Front view of the GS200 MultiFlow pump. On/Off switch is on the rear side (not shown here)

EXPERIMENTS

191. Attenuation of ultrasound waves in solids

Aim

Determination of the attenuation of an ultrasonic wave on its way through a medium. Study of the frequency dependence of acoustic attenuation.

Subject matter of the experiment

Amplitude measurement by the ultrasound transmission method in samples of various lengths to determine the attenuation of ultrasonic wave along its path through the medium. Determination of the acoustic attenuation coefficient at different ultrasonic frequencies.

Brief theory

Sound waves lose energy on their way through a medium due to different processes such as absorption, scattering or reflection. This loss of energy causes a change in the sound intensity, which decreases as the distance increases. The strength of this attenuation depends on the material. It can be determined by the measurement of the amplitudes of transmission pulses or reflection pulses in an amplitude scan for different path lengths and can be described by the material-specific attenuation coefficient. In the experiment, these measurements are carried out with acrylic cylinders of different lengths. In order to be able to make statements about the frequency dependence of sound attenuation in acrylic, these measurements are carried out for different sound frequencies [3].

The amplitude of the plane ultrasonic wave on its way through a medium decreases according to the equation:

$$A = A_0 \cdot e^{-\alpha x}, \qquad (191.1)$$

where A_0 is the initial sound amplitude, x is the distance from the source, α is the *amplitude attenuation coefficient* of ultrasound in the medium. The attenuation coefficient represents the sum of the absorption coefficient α_a and the scattering coefficient α_s. The attenuation coefficient is expressed either in *decibels per meter* (*dB/m*) or in *Nepers per meter* (*Np/m*). Attenuation of 1 Np/m means that at a distance of 1 m the wave amplitude decreases by a factor of e ($e = 2.718$).

For a plane wave, the attenuation coefficient *by amplitude* with distance is determined by the formula:

$$\alpha = \frac{1}{x}\ln\frac{A_0}{A} \ \left[1/\text{m}\right], \tag{191.2}$$

where α is the attenuation coefficient with distance, 1/m or Np/m.

The attenuation coefficient in the unit dB/m is determined by the formula:

$$\alpha = \frac{1}{x}\cdot 10\lg\left(\frac{A_0}{A}\right) \ \left[\text{dB/m}\right]. \tag{191.3}$$

Using the properties of logarithms $\lg b = \ln b \cdot \lg e$, expression (191.3) can be converted into:

$$\alpha\left[\text{dB/m}\right] = \frac{1}{x}\cdot\ln\left(\frac{A_0}{A}\right)\cdot 10\lg e. \tag{191.4}$$

Then the units of measurement (dB/m) and (1/m) are related as follow:

$$\alpha\left[\text{dB/m}\right] = 4.343\cdot\alpha\left[1/\text{m}\right]. \tag{191.5}$$

Since the intensity of a plane wave is proportional to the square of its amplitude ($I \sim A^2$), the intensity is given by:

$$I_x = I_0 \cdot e^{-2\alpha x} = I_0 \cdot e^{-\mu x}, \tag{191.6}$$

where I_0, I are the sound intensities at the initial point and at the distance x, μ is the attenuation coefficient *by intensity* measured in 1/m

($\mu=2\alpha$). The units of measurement (dB/m) and (1/m) are related as follow: $\mu[\text{dB/m}] = 4.343 \cdot \mu[1/\text{m}]$.

Attenuation coefficient *by intensity* measured in dB/m and attenuation coefficient *by amplitude* measured in 1/m are related as follow:

$$\mu[\text{dB/m}] = 8.686 \cdot \alpha[1/\text{m}], \tag{191.7}$$

or considering the formula (191.2):

$$\mu[\text{dB/m}] = \frac{8.686 \cdot \ln(A_0/A)}{x} \tag{191.8}$$

Equipment (figure 20)

1. Ultrasonic echoscope GS200
2. Ultrasonic transducers (1 MHz, blue; 2 MHz, red; 4 MHz, green)
3. Objects to study (a set of acrylic cylinders)
4. Ultrasound transmission gel
5. Laptop
6. Ruler or callipers

► Prior to taking the ultrasonic echoscope and the accessories into operation, please carefully read and follow the **safety instructions** on page 31.

► Read about control elements on the front side of the ultrasonic echoscope GS200 (see Section 6).

Depending on the operating mode of the probe ports, either two ultrasonic transducers operate as transmitter and receiver (transmission mode) or a single probe works as transmitter/receiver (reflection mode).
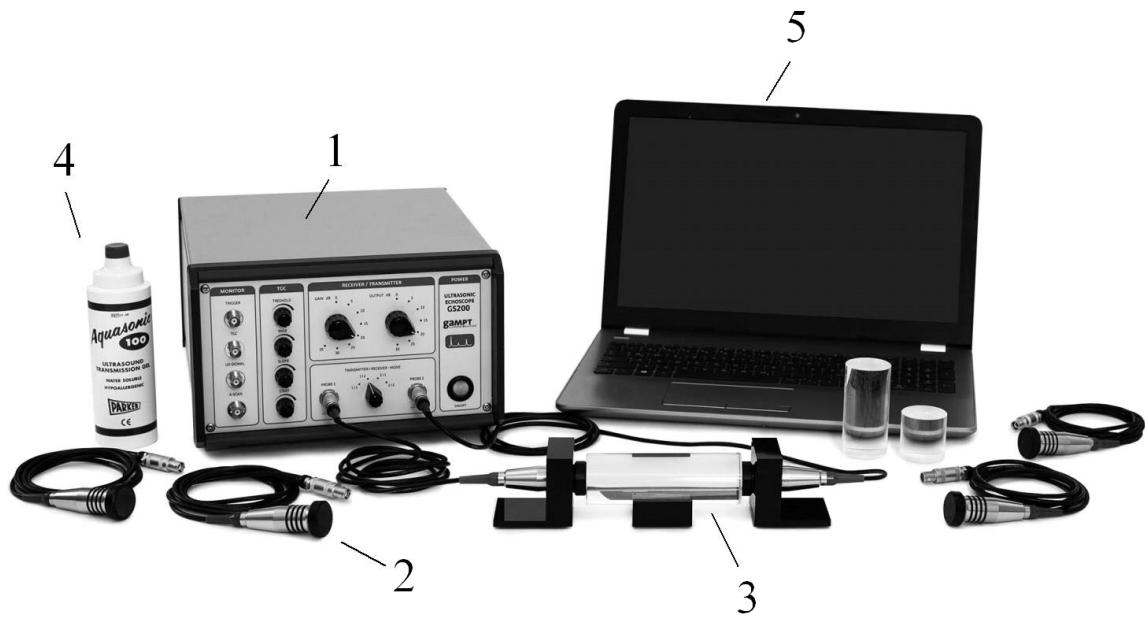
Figure 20. Laboratory setup for studying ultrasound decay in solid objects. (1) Ultrasonic echoscope GS200; (2) ultrasonic transducers (blue, 1 MHz; red, 2 MHz; green, 4 MHz); (3) acrylic test cylinders; (4) ultrasonic gel; (5) laptop

Algorithm of measurements

Preparations (connecting and tuning)

1. Connect the echoscope GS200 to the computer.
2. Take acrylic cylinder with **the length of 4 cm.**
3. Apply a small amount of ultrasonic gel on the end sides of the cylinder and attach two ultrasonic transducers with the same operating frequencies (as shown in figure 20). Press them firmly to the end sides of the cylinder.
4. Connect **1-MHz ultrasonic transducers** (blue) to the probe connection ports named "PROBE 1" and "PROBE 2" at the echoscope (figure 13).
5. Launch the program **GS-EchoView** on the desktop of the laptop;
6. In the window "**A-mode**" find the **"params"** tab and set the parameters "**begin [µs]**" and "**end [µs]**" to 0 and 100, respectively.

43

7. At the scaling **unit in diagrams** of the **"params"** tab select "**μs**" (microseconds) for the run time measurement.

8. Press the button "**Start A-scan**."

9. By means of TGC (Time Gain Control), attenuation of the intensity of the ultrasound signal can be compensated. Get the TGC profile as shown in figures 21 (tune the time gain) using the rotary switches 7–10 of the block C (figure 14). Initial settings of the switchers 3 and 5 (figure 14) of the block B should be "Gain" = 10 dB, "Output" = 10 dB. *If it will be necessary*, you can change these settings (depending on the studied model).

Measurement range
Begin [μs]   0
End [μs]   100
Sound Velocity [m/s]   2710
unit in diagrams
● μs   ○ mm
Begin [mm]   0,0
End [mm]   67,8
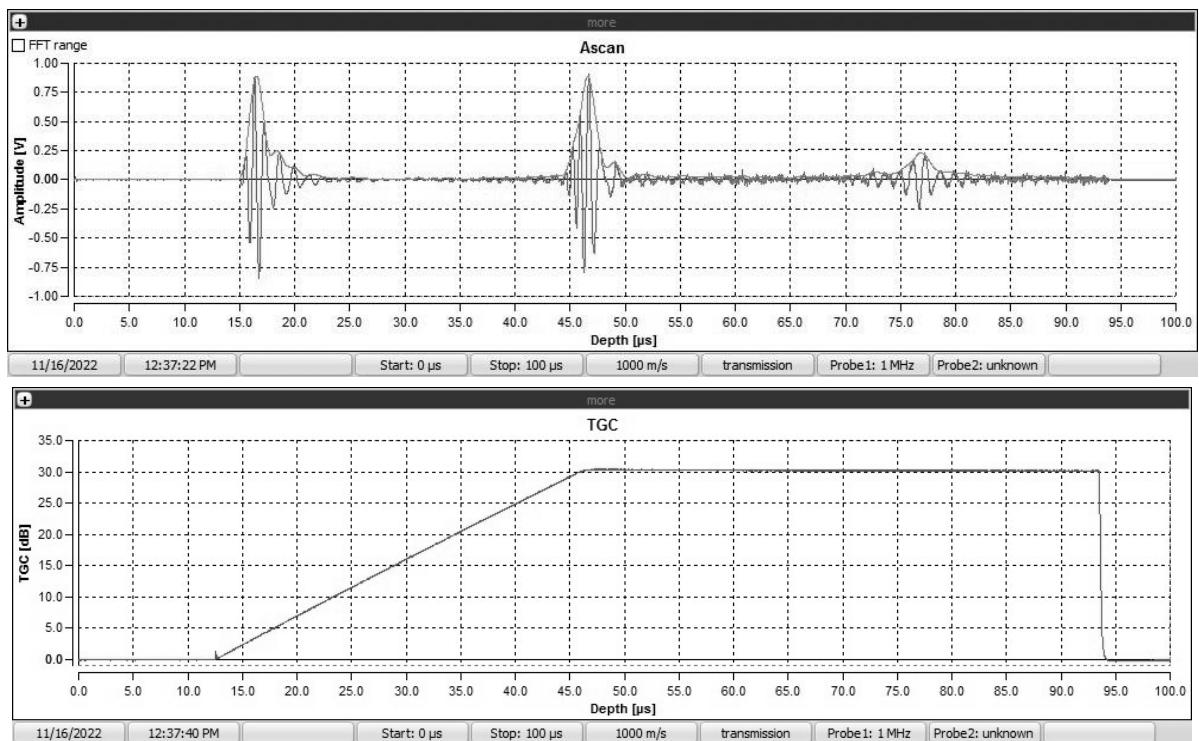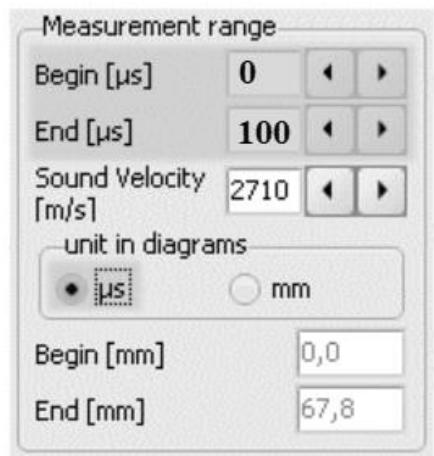
Figure 21. Main window of the GS-EchoView program
in the transmitter/receiver mode "1|2" for 4-cm acrylic cylinder
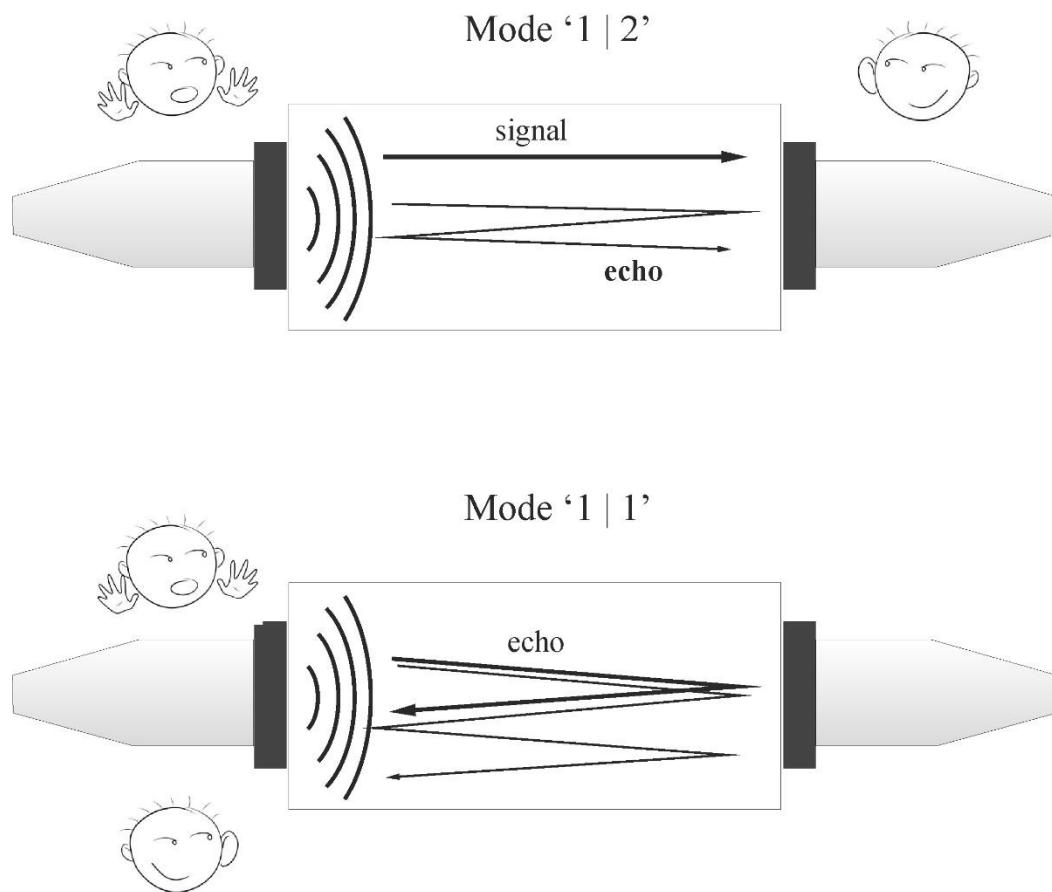
Figure 22. Two measuring modes: transmission and reflection

Task 1

Amplitude measurement in the ultrasound transmission mode in samples of various lengths.

1. **Set the transmitter/receiver mode to "1|2"** (transmission mode; figure 22) at the front side of the echoscope GS200 (figure 14).

2. By clicking the "**Start A-scan**" button, the program changes to measuring mode.

3. Using the mouse cursor, find the time when the signal is acquired by the second probe. Put the cursor near the maximum point of the signal and read the data from the pop-up window: **amplitude A^{sc}** (V, vertical axis) and **time t** (μs, horizontal axis).

   Note: In addition to the first signal there may be other signals coming to the second probe at later times. These are echoes: the wave goes the distance *s*, reflects partially from the wall of the cylinder,

goes back, reflects again and finally goes to the receiving probe after passing the distance of $3s$ (see figure 22). Echoes of higher orders are also possible.

4. Since sound undergoes attenuation during propagation within a medium, the amplitude of echoes is decreasing exponentially (see function (191.1)). By means of TGC it is possible to partially compensate for the attenuation of the ultrasound intensity (read about TGC unit on page 34).

5. Using mouse pointer, read the TGC(t) value (dB) for all echoes acquired at time moments t, determined at step 3 (see figure 15).

6. Check out **important information** on page 46.

7. The **true amplitude A** of the echo acquired at time t can be calculated from the value A^{sc} shown on the screen by the programme in the A-scan window as:

$$A(t) = A^{sc} \cdot 10^{-TGC(t)/20}. \qquad (191.9)$$

8. Write down the results (A^{sc}, t, TGC, A) for acquired signals into the **table**.

Task 2

Amplitude measurement in the ultrasound pulse-echo mode (reflection) in samples of various lengths.

9. **Set the transmitter/receiver mode to "1|1"** (reflection mode; figure 22) at the front side of the echoscope GS200 (figure 14).

10. In the A-mode, start the measurements with the "**Start A-scan**" button.

11. Using the mouse cursor, find the time when the signal is acquired.

Note: the first echo corresponds to the ultrasonic signal which has gone the way $x = 2s$

12. Write down the results (A^{sc}, t, TGC, A) for acquired signals into the table.

Task3

Determination of the acoustic attenuation coefficient at various ultrasonic frequencies.

13. Calculate natural logarithms of the sound wave amplitudes ln$A(x)$.

14. Draw the dependencies of the **lnA versus distance x** passed by the wave in the medium.

15. Approximate the plot ln$A(x)$ by a **straight line** and find the slope **tanα** of this line.

16. Find the attenuation coefficient as

$$\mu = 8.686 \cdot \tan \alpha. \qquad (1.10)$$

17. Repeat these measurements (tasks 1 and 2) with ultrasonic transducers with sound frequencies 2 MHz and 4 MHz.

18. Draw the dependencies of the attenuation coefficient versus frequencies.

19. Make conclusion about the frequency dependence of sound attenuation in acrylic.

20. After completing the experiments, clean the probe and the test cylinders.

Important information

► To be able to compare the measured amplitude values, the measurements must be performed under equal conditions (transmitting power, gain, set-up, …). Try not to remove and reattach the probes to the cylinder until you finish to measure every series of ultrasound echoes.

► For digitization in the echoscope, the analogue ultrasonic measuring signal is limited to a voltage range between –1 and +1 V. All voltage values that are higher and lower are cut out (figure 23). This kind of overdriving of the measurement signal by exceeding

transmitting power or exceeding gain is indicated as HF data overrun in the status display.

Since the envelope (Amp signal) of the ultrasonic measurement signal is also calculated in cases where the measurement signal is overdriven, the HF data overrun status message must always be taken into account. Particularly for amplitude measurements, the transmission level and gain level must be selected such that the voltage amplitude of all signals does not exceed ±1 volt.
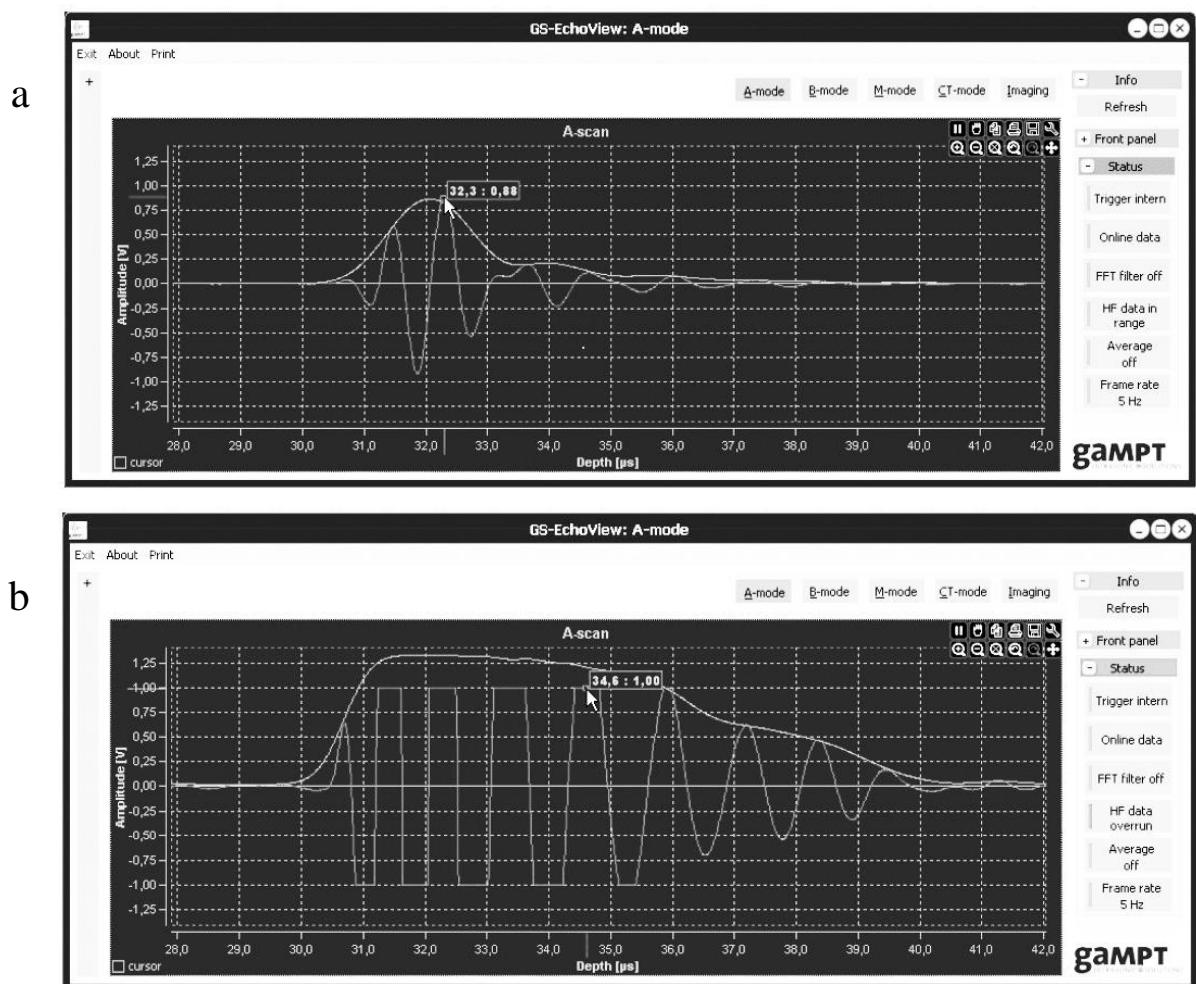

Figure 23. a) Amplitude signal within the valid value range between –1 V and +1 V; b) Overdriven measurement signal cut out at ±1 V

Frequency of sound, *** MHz						
Mode	x, cm	t, µs	A^{sc}, V	TGC, dB	A, V (*Eq .(191.9)*)	ln$A$
"1|2"	…					
"1|1"	…					
"1|2"	…					
…	…					
$\mu = \dots$ dB/cm						

General questions for works with ultrasound:

What are harmonic oscillations? What is amplitude, frequency, cyclic frequency, period of harmonic oscillations? What is a wave? What is wavelength? What is the difference between longitudinal and transverse waves? Why are there no transverse waves in gases and liquids? What wave is called plane, spherical? Write the equation of a traveling plane wave.

What are acoustic oscillations? Which frequency range does the human ear perceive? What determines the speed of sound in air? Compare the speed of sound propagation in different media.

How the ultrasonic sensor works? Forward and reverse piezoelectric effect. Why do we need to apply the gel when conducting ultrasound studies? What determines the intensity of the reflected ultrasound wave?

Acoustic impedance. The use of ultrasound in medicine.

Special questions for work 191:
1. Interaction of ultrasound with matter.
2. The reasons for the attenuation of the sound wave.
3. The law of attenuation of sound wave intensity.

192. Ultrasonic A-scan (echography)

Aim

Examination of a sample with built-in discontinuities by means of the pulse echo method (A-Scan). Measurement of times of flight at an eye phantom as a typical biometric ultrasonic application.

Subject matter of the experiment

Examination a sample with built-in discontinuities by means of the pulse echo method. Carrying out of amplitude scans from different sides of the sample. Examination and analysis the echo signals imaged in the recorded A-scan images.

The measurement of times of flight of ultrasonic signals at an eye phantom and calculating the sound paths from the measured times of flight.

Brief theory

The pulse echo method forms the basis of many imaging methods in non-invasive medical diagnostics and non-destructive testing. In this method, electrical pulses are transformed into mechanical vibrations by an ultrasonic probe. These are coupled into the sample under examination and pass through it as sound waves. Waves that are reflected on discontinuities return to the probe and are converted back into an electrical signal. The chronological recording of the amplitude of this signal (amplitude scan) is graphically imaged as a so-called ultrasonic A-scan image. Based on the reflection echoes in the A-scan image, times of flight can be determined, the sound velocity in the material calculated and discontinuities in the sample detected [4].

Equipment (figure 24)

1. Ultrasonic echoscope GS200
2. Ultrasonic probes (1 MHz, blue and 2 MHz, red)
3. Objects to study: test block (transparent), the eye phantom
4. Ultrasonic gel
5. Laptop
6. Ruler or callipers

► Prior to taking the ultrasonic echoscope and the accessories into operation, please carefully read and follow the **safety instructions** on page 31.

► Read about control elements on the front side of the ultrasonic echoscope GS200 (see Section 6).
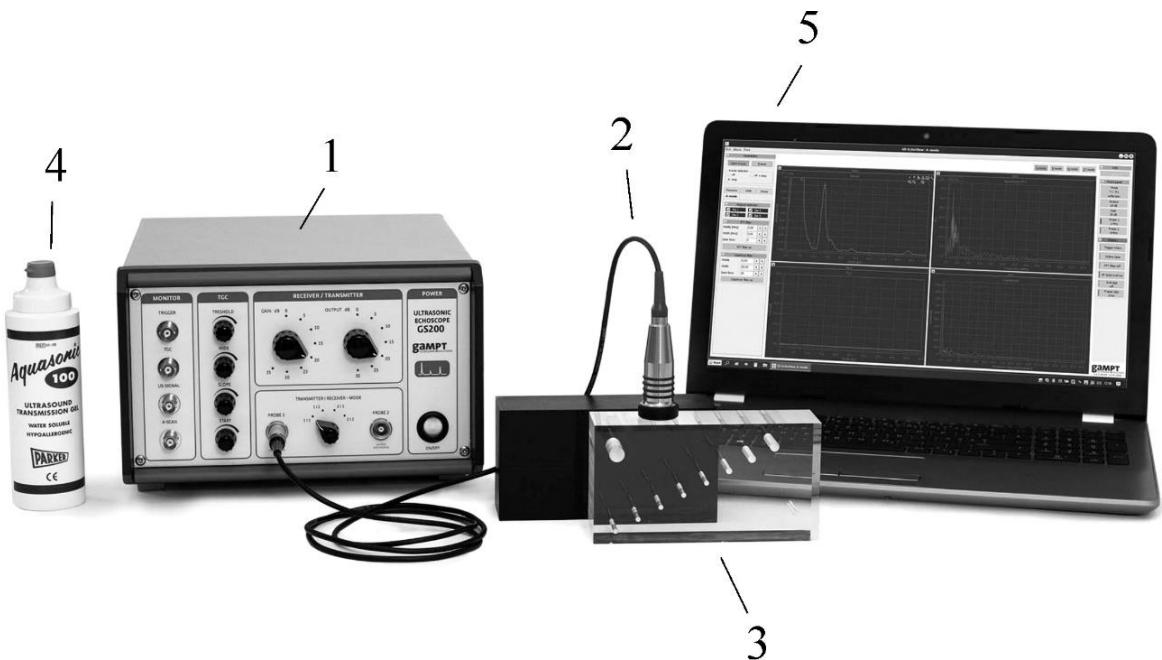

Figure 24. Laboratory setup for studying ultrasonic echography. (1) Ultrasonic echoscope GS200; (2) probe (1 MHz, blue); (3) test block; (4) ultrasonic gel; (5) laptop

I. Echoscopy investigations with the transparent test block

Test block made of homogeneous, transparent acrylic (figure 25) has a group of differently sized defects at different depths, a large defect (acoustic shadow) and a double defect (for determining the resolution power).
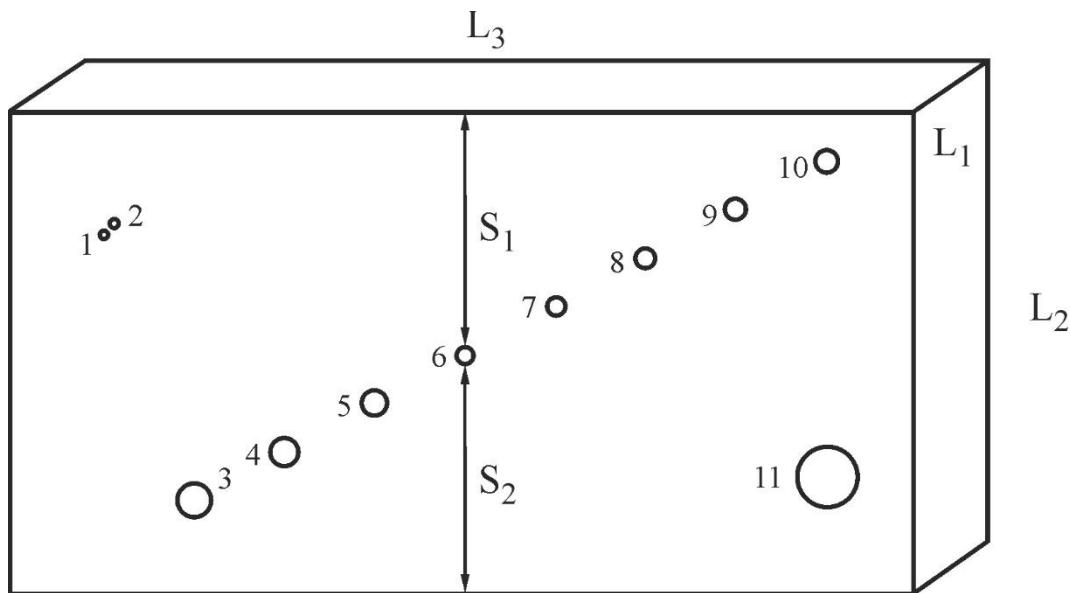
Figure 25. Test block

Algorithm of measurements

Measuring distances in the test block with a ruler

1. Using a ruler define the **height L2** (see figure 25) of the test block.
2. Using a ruler define the **holes sizes** (from 1 to 11)
3. Write down the results in **table A (line "Hole sizes measured directly")**.

Preparations (connecting and tuning)

4. Connect the **echoscope** GS200 to the computer.
5. Connect **1-MHz ultrasonic transducers** (blue) to the probe connection ports named "PROBE 1" at the echoscope (figure 13).

6. **Set the transmitter/receiver mode to "1|1"** (reflection mode; figure 22) at the front side of the echoscope GS200 (figure 14).

7. Launch the program **GS-EchoView** on the desktop of the laptop.

8. In the window **"A-mode"** find the **"params"** tab and set the parameters **"begin [μs]"** and **"end [μs]"** to 0 and 100, respectively.

9. At the scaling **unit in diagrams** of the **"params"** tab select **"μs"** (microseconds).

10. Apply a small amount of ultrasonic gel on the one of the long sides (plane L1–L3 in figure 25) of the test block and attach ultrasonic transducers with the operating frequency of 1 MHz.
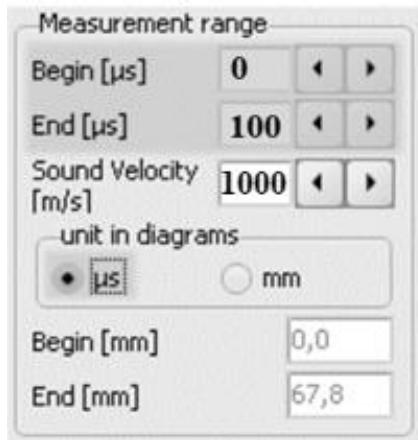
Task 1

Determination of the sound velocity in the acrylic test block.

11. Press the button **"Start A-scan."**

12. By means of TGC (Time Gain Control), attenuation of the intensity of the ultrasound signal can be compensated. Get the TGC profile as shown in Figures 26 (tune the time gain) using the rotary switches 7–10 of the block C (Figure 14). Initial settings of the switchers 3 and 5 (Figure 14) of the block B should be "Gain" = 10 dB, "Output" = 10 dB. *If necessary*, change these numbers (depending on the studied model).

13. Using the mouse cursor find ***echo arrival time*** from rear side of the test block (size L_2 in figure 25). Note that this echo signal does not disappear when you move the probe (see figure 26) and appears always in the same position. The vertical measuring line of one of the measuring cursors must be moved to the starting point of the rising edge of the echo pulse to be measured (as shown in figure 26).
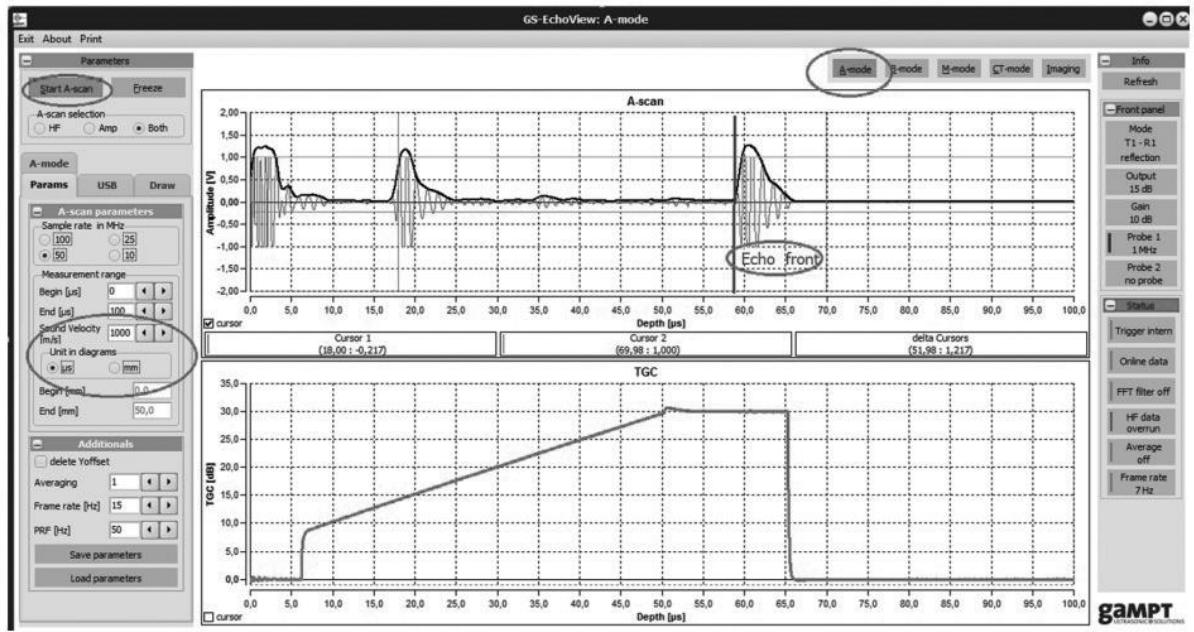
Figure 26. Main window of the GS-EchoView program

14. Using the time found on the previous stage, determine the sound velocity in acrylic test block using equation:

$$\upsilon = \frac{2 \cdot L_2}{t}, \tag{192.1}$$

where υ is the speed of sound, L_2 is the brick's height (figure 25), and t is the time of arrival of the echo from the rear side.

Note 1: Transform the units of measurement to the SI units: meters and seconds.

Note 2: With the sound velocity known, scaling of the x axis can be switched over from time of flight to depth.

15. In the **"params"** tab set obtained value υ into the **"Sound velocity"** input field (in m/s)**.**

16. At the scaling **unit in diagrams** of the **"params"** tab select **"mm"** (millimetres) for the depth measurement.

Task 2

Determination of differently sized defects at different depths in the acrylic test block by means of the pulse echo method.

17. Determine the depth of discontinuities in acrylic test block from two sides, in other words, measure distances S_1 and S_2 (see figure 25) for different holes.

18. Calculate the size of the holes based on the found values S_1 and S_2 and the vertical size L_2 of the test block:

$$d_i = L_2 - (S_1 + S_2). \qquad (192.2)$$

19. To verify the results, measure the hole diameters by the callipers or the ruler. Write down the results in Table A.

20. After finishing the experiments, wipe the probe and test block with tissue paper.

Table A

Hole	1	2	3	4	5	6	7	8	9	10	11
S_1											
S_2											
Hole sizes from the A-scan											
Hole sizes measured directly											

II. Biometry at the eye phantom

Ophthalmology is one of the area of medicine in which ultrasound is used. Here, ultrasound is especially important for the biometric surveying of the eye, i.e., the measurement of distances in the eye. For example, the distance between cornea and iris is very important for the calculation of the characteristics of an artificial lens, such as is implanted for patients with cataracts. Because the cornea or lens is too cloudy for optical methods, it is here necessary to use ultrasonic methods. Although new methods with laser light and the ultrasonic B-scan method are now used, time of flight measurements of the ultrasonic echoes of an A-scan at the eye offer a simple way to measure the eye. When calculating the sound paths from the measured times of flight it is to be noted that different sound velocities occur in the cornea, the lens, the vitreous humour and in the other areas of the eye. In the eye phantom provided, the sound velocity in the lens is around 2500 m/s, and in the vitreous humour it is around 1410 m/s [5].

The measurement of times of flight of ultrasonic signals in the eye phantom at an enlarged scale demonstrates a typical biometric ultrasonic application based on the A-scan method in medical diagnostics in ophthalmology.

Figure 27. Measurement of times of flight in an eye phantom as an example of the biometric ultrasonic application

Task 3

Measurement of the distances to anatomical structures in the eye phantom.

21. Apply a small amount of ultrasonic gel on the eye model approximately on its pupil (figure 27) and attach ultrasonic transducers with the operating frequency of 2 MHz.

22. At the scaling **unit in diagrams** of the **"params"** tab select **"μs"** (microseconds) for making the time measurement.

23. Record the A-scan of the structures comprising the eye model.

24. Measure the time of flight of echo signals of distances in the eye (figure 28): t_1 (vertical line 4), t_2 (vertical line 5), t_3 (vertical line 6).

    Note: The vertical measuring line of the measuring cursors must be moved to the starting point of the rising edge (left) of the echo pulse to be measured.

25. Assuming that the sound velocity in the lens is $v_2 = 2500$ m/s and in other regions of the eye model it is $v_1 = 1410$ m/s (for example, in the vitreous humour), determine the mean sound velocity in the eye model using the expression:

$$ v = \frac{v_1(t_1 + (t_3 - t_2)) + v_2(t_2 - t_1)}{t_3}. \qquad (192.3) $$

26. Determine the depths in the eye phantom (see figure 28):

    1) the depths till the front side of the lens (vertical line 4);

    2) the depths till the back side of the lens (vertical line 5);

    3) the depths till the retina (vertical line 6).

27. Write down the results in the Table B.

28. Make conclusion and discuss the obtained results.
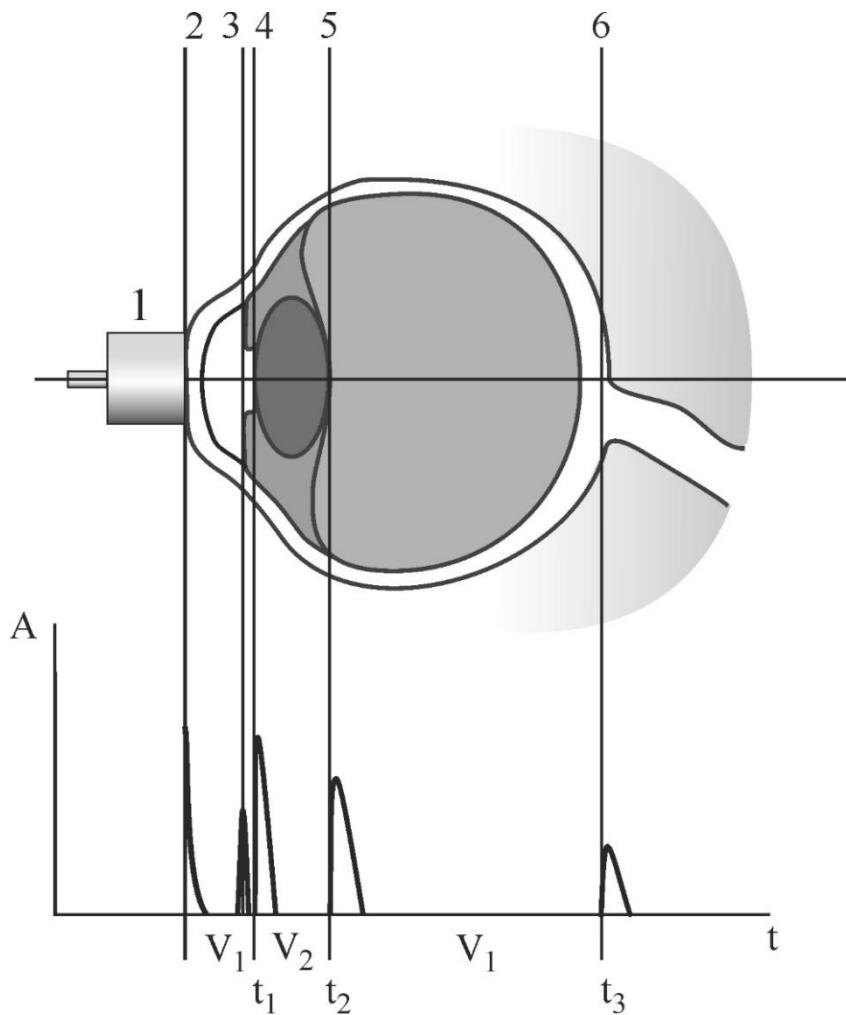
Figure 28. Schematic presentation of the eye phantom and recording an A-scan image. The individual ultrasonic echoes are here assigned to the sites of their origin in the eye phantom.
Labels: (1) ultrasonic probe, (2) cornea, (3) iris, (4) front side of the lens, (5) back side of the lens, (6) retina

Table B

Structure	Front side of the lens	Back side of the lens	Retina
Echo arrival time, µs			
Mean sound velocity, m/s			
Measured depth, mm			
Real depth, mm	9.66	18.91	56.77
Thickness, mm	9.66	9.25	37.96

General questions for works with ultrasound:

What are harmonic oscillations? What is amplitude, frequency, cyclic frequency, period of harmonic oscillations? What is a wave? What is wavelength? What is the difference between longitudinal and transverse waves? Why are there no transverse waves in gases and liquids? What wave is called plane, spherical? Write the equation of a traveling plane wave.

What are the acoustic oscillations? What frequency range does the human ear perceive? What determines the speed of sound in air? Compare the speed of sound propagation in different media.

How the ultrasonic sensor works? Forward and reverse piezoelectric effect.

Why do we need to apply the gel when conducting ultrasound studies? What determines the intensity of the reflected ultrasound wave? Acoustic impedance. The use of ultrasound in medicine.

Special questions for work 192:
1. Ultrasonic echography, reflection, pulse echo method.
2. Basics of pulse echo method based on the reflection echoes in the A-scan image.
3. Ultrasound beam properties: The near field, the far field, focal zone.
4. Effects of dimensions on the resolvability of objects in the image: The axial, lateral, and elevational (slice-thickness) dimensions of the spatial resolution.
5. The structure of the eye.

193. Ultrasonic B-scan (brightness)

Aim

Demonstration of the basics of the B-scan method by recording the ultrasonic cross-sectional image of a simple test object using an ultrasonic echoscope. Examination of a realistic breast phantom with tumours and their localization and estimation of their size in the B-scan method.

Subjects matter of the experiment

Demonstration the basics of the B-Scan method by recording the ultrasonic cross-sectional image of a simple test object using an ultrasonic echoscope. Investigation and analysis of special features regarding scan quality such as sound focus, spatial resolution or imaging errors.

Examination of a realistic breast phantom with tumours and their localization and estimation of their size in the B-scan method as a typical application of ultrasound in medical diagnostics.

Brief theory

The conversion of the amplitude values of an amplitude scan into grey scale or colour values and the presentation of the time of flight as penetration depth yield a line of points with different brightness and/or colour values. The stringing together of such adjoining depth scans of an ultrasonic probe, which is guided along a line over the test area produces a sectional image, the so-called B-scan image. Localisation along this line is based on the position of the probe and its movement speed. A simple way to obtain a B-Scan image is to guide the ultrasonic probe slowly by hand (figure 29). Scan quality is here dependent on the coordinate-accurate transferral of scan points, the axial and lateral resolution of the ultrasonic probe, the grey scale and/or colour value resolution, the number of lines and imaging errors.

In order to achieve, e.g., fine lateral resolution, an additional coordinate-recording system is necessary such as a linear scanner [6a].

For more detailed information about brightness mode read [6b, 6c].
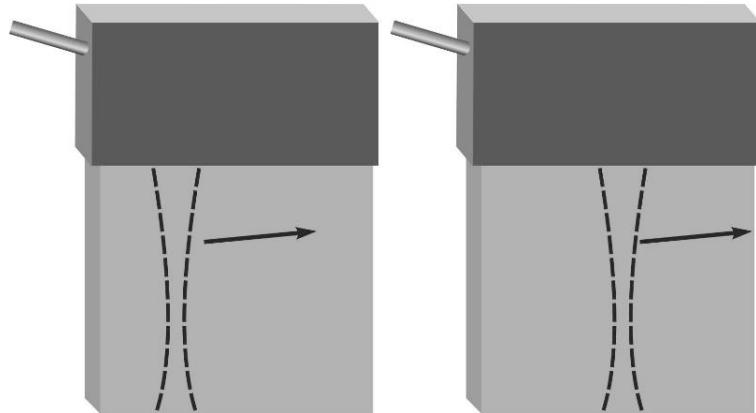
Figure 29. Ultrasound B-mode scanning using a linear array. Each sketch shows the position of an ultrasound beam line interrogating the scanned field. The resultant B-mode echo display trace changes with the position of the beam line

Equipment (figure 30)
1. Ultrasonic echoscope GS200
2. Ultrasonic probes (1 MHz, blue and 2 MHz, red)
3. Objects to study: test block (transparent), breast phantom
4. Ultrasonic gel
5. Laptop
6. Ruler or callipers

► Prior to taking the ultrasonic echoscope and the accessories into operation, please carefully read and follow the **safety instructions** on page 31.
► Read about control elements on the front side of the ultrasonic echoscope GS200 (see Section 6).
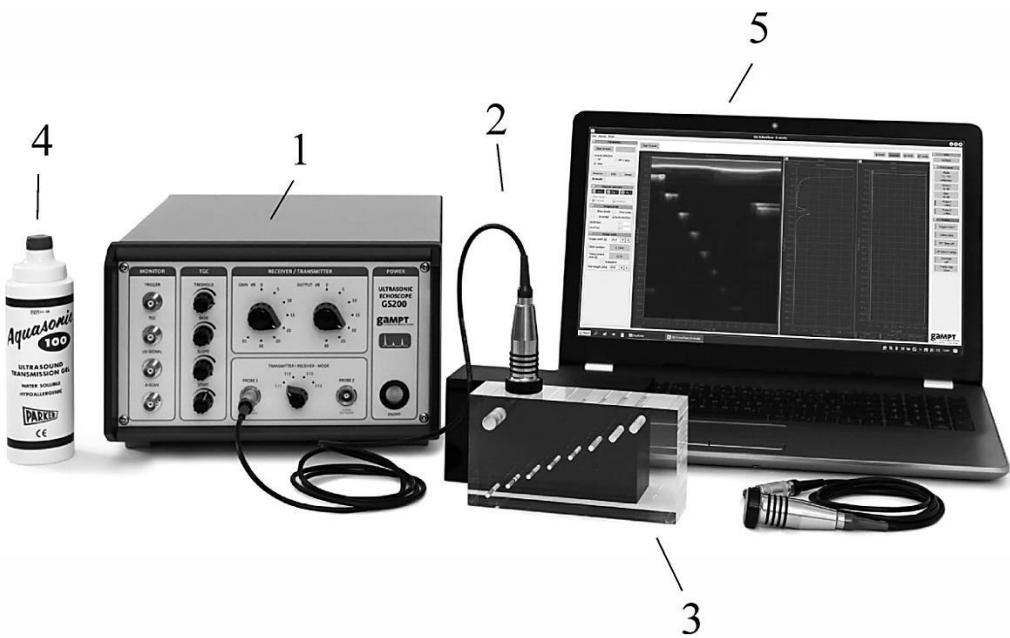
Figure 30. Laboratory setup for studying ultrasonic B-scan.
(1) Ultrasonic echoscope GS200; (2) probe (1 MHz, blue); (3) test
block; (4) ultrasonic gel; (5) laptop

I. Echoscopy investigations with the transparent test block

Test block made of homogeneous, transparent acrylic (figure 25, below) has a group of differently sized defects at different depths, a large defect (acoustic shadow) and a double defect (for determination of the resolution power).
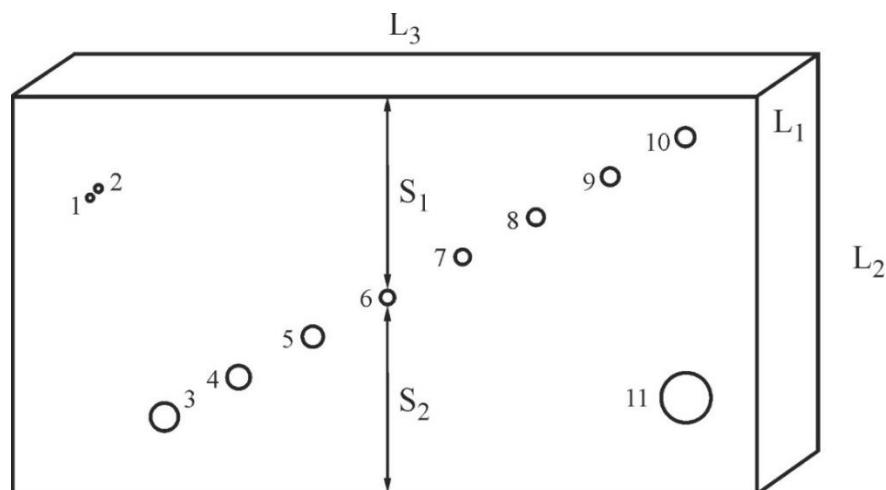
Figure 25 (copy). Test block

Algorithm of measurements

Measuring distances in the test block with a ruler

1. Using a ruler define the height L_2 of the test block (figure 25).
2. Using a ruler determine the depth of discontinuities (channels) S_1 (from 1 to 11).
3. Write down the results in the Table (line "Depth of discontinuities S1 measured by a ruler").

Preparations (connecting and tuning)

4. Connect the echoscope GS200 to the computer;
5. Connect **1-MHz ultrasonic transducers** (blue) to the probe connection ports named "PROBE 1" at the echoscope (figure 13).
6. Set the transmitter/receiver mode to "1|1" (reflection mode; Figure 22) at the front side of the echoscope GS200 (figure 14).
7. Launch the program GS-EchoView on the desktop of the laptop.
8. In the window "**A-mode**" find the **"params"** tab and set the parameters "**begin [μs]**" and "**end [μs]**" to 0 and 100, respectively.
9. At the scaling **unit in diagrams** of the **"params"** tab select "**μs**" (microseconds) for the time measurement.
10. Apply a small amount of ultrasonic gel on the one of the long sides (plane L_1–L_3) of the test block (figure 25).
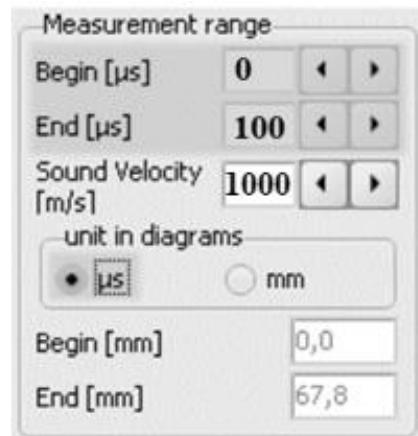
Task 1

Determination of the sound velocity in the acrylic test block.

11. Press the button "**Start A-scan**."
12. By means of **TGC** (Time Gain Control), attenuation of the intensity of the ultrasound signal can be compensated. Get the TGC profile as shown in figures 35 (tune the time gain) using the rotary switches 7–10 of the block C (figure 14). Initial settings

of the switchers 3 and 5 of the block B (figure 14) should be "Gain" = 10 dB, "Output" = 10 dB. *If necessary*, change these numbers (depending on the studied model).

13. Using the mouse cursor find the echo arrival time from the rear side of the test block (height L_2). Note that this echo signal does not disappear when you move the probe (see figure 26, below). The vertical measuring line of one of the measuring cursors must be moved to the starting point of the rising edge of the echo pulse to get the time value.
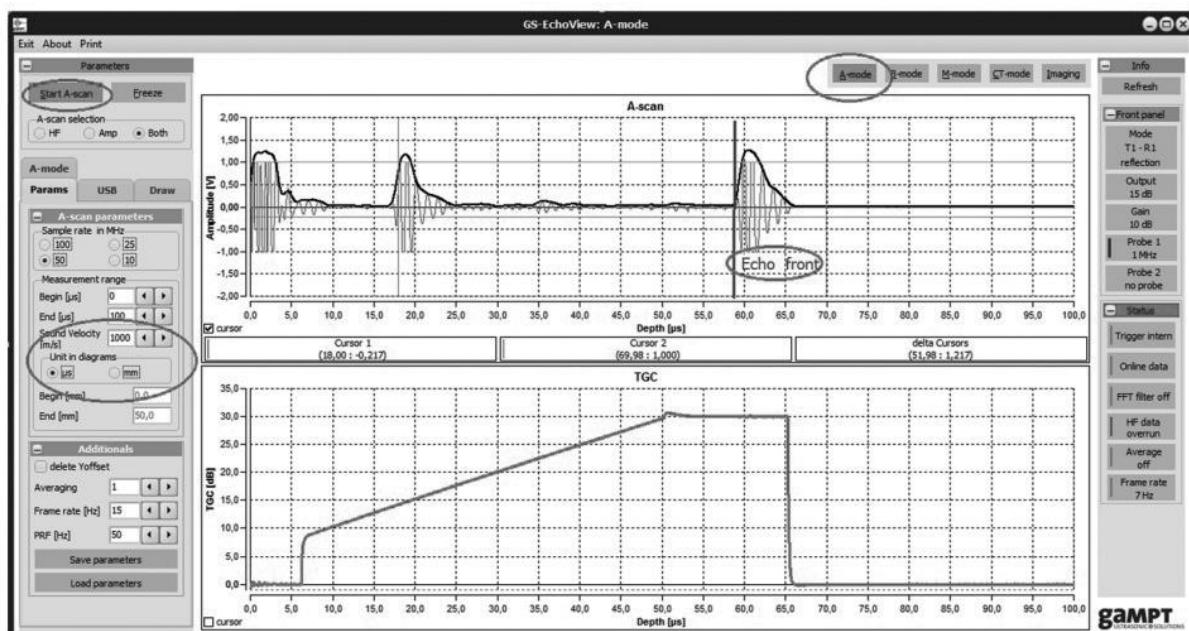
Figure 26 (copy). Main window of the GS-EchoView program

14. Using the time found on the previous stage, determine the sound velocity in the acrylic test block using equation:

$$\upsilon = \frac{2 \cdot L_2}{t}, \qquad (193.1)$$

where υ is the speed of sound, L_2 is the brick's height (figure 26), and t is the time of arrival of the echo from the rear side.

Note 1: Transform the units of measurement to the SI units: meters and seconds.

Note 2: With the sound velocity known, scaling of the *x* axis can be switched over from time of flight to depth.

15. In the **"params"** tab set the obtained value υ to the **"Sound velocity"** input field (in m/s)**.**

16. At the scaling **unit in diagrams** of the **"params"** tab select "**mm**" (millimetres) for the depth measurement.

Task 2

Determination of differently sized defects at different depths in acrylic test block by means of the B-scan method using ultrasonic transducers operating at 1 MHz (blue) and 2 MHz (red).

17. Apply a small amount of ultrasonic gel on the long side (plane L_1–L_3) of the test block.

18. Distribute gel uniformly over the whole plane L_1–L_3.

19. Use 1-MHz ultrasonic transducer (blue)

20. In the "**B-mode**" tab press the button "Start B-scan".

21. Run the probe over the side with a smooth uniform movement to obtain the image of the holes in the test block (figure 31). Repeat it a few times to get a satisfactory picture.

22. Press "Stop." Save the image by clicking on the button.

23. Use the *y* axis of the B-scan diagram for mapping the depth.

24. Determine the depth S_1 of the hole in the acrylic test block for different holes by means of the B-scan image obtained with the 1-MHz ultrasonic transducer.

25. Write down the results into the Table.

26. Set the transmitter/receiver mode to "2|2" at the front side of the echoscope GS200 (figure 14) and repeat the above described procedure with the 2-MHz ultrasonic transducer (figure 32).

27. Determine the depth S_1 of the discontinuities in the acrylic test block for different holes by means of the B-scan images with the 2-MHz ultrasonic transducer.

28. Write down the results into the Table.

29. After finishing the experiments, wipe the probe and test block with tissue paper.
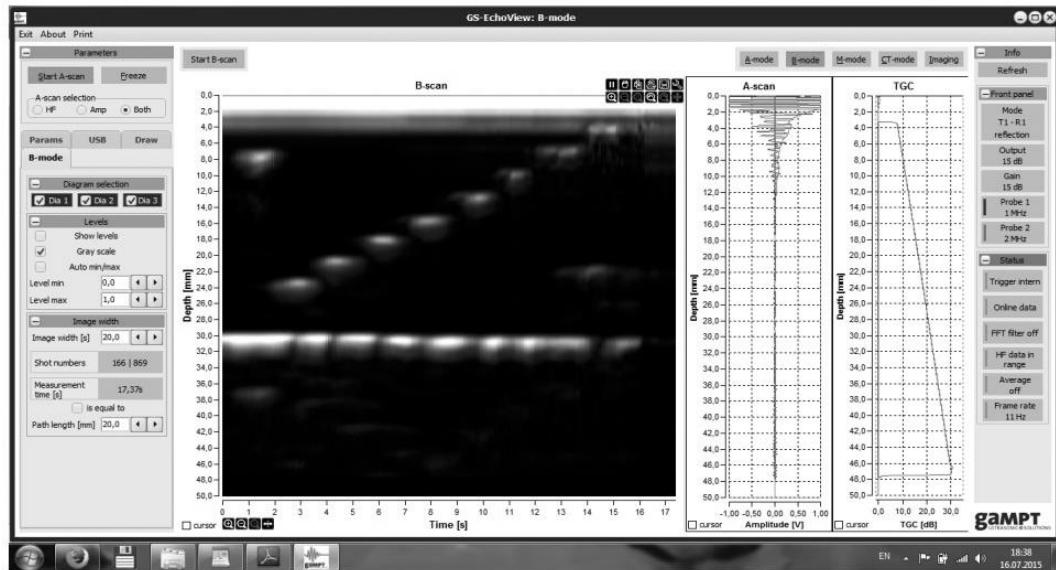
Figure 31. Three diagrams are available for evaluation: B-scan (Dia 1), A-scan (Dia 2) and TGC (Dia 3) obtained with the 1-MHz probe. A-scan and TGC diagram are adapted to the B-scan diagram in terms of alignment
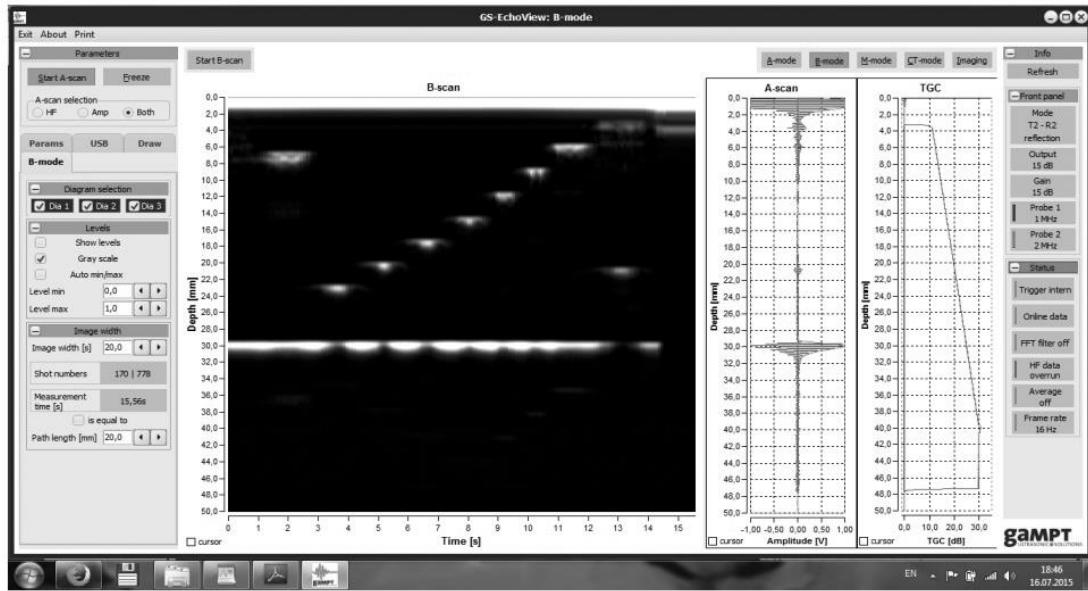

Figure 32. Three diagrams are available for evaluation: B-scan (Dia 1), A-scan (Dia 2) and TGC (Dia 3) obtained with the 2-MHz probe. A-scan and TGC diagram are adapted to the B-scan diagram in terms of alignment

Distances found from analysis of the B-scan images and by a ruler.

The hole 1 is not observed by the 1-MHz probe

(grey-coloured table cell)

Hole	1	2	3	4	5	6	7	8	9	10	11
Depth, mm (1 MHz)											
Depth, mm (2 MHz)											
Depth S1, mm, measured by a ruler											

Task 3

Investigation and analysis of special features regarding scan quality such as sound focus, spatial resolution.

30. Calculate the wavelength of the ultrasound beam for the probes operating at 1 and 2 MHz:

$$\lambda = \frac{\upsilon}{f}, \tag{193.2}$$

where υ is the sound velocity in acrylic test block (found in task 2), f is the ultrasound frequency (1 or 2 MHz).

31. Calculate the focal lengths x for the two transducers using the formulas:

$$x = \frac{d^2}{4 \cdot \lambda}, \tag{193.3}$$

where d is the diameter of the transducer.

32. How does the wavelength affect *spatial resolution* in an ultrasound image?

33. Estimate the resolution of the probe using the obtained images.

II. Ultrasonic imaging at breast phantom (mammasonography)

Mammasonography – the ultrasonic examination of the breast – is, together with mammography (X-ray examination), the most important imaging method for the diagnosis of benign and malignant changes in the breast tissue. It is used in the early detection of breast cancer. The strength of sonography lies in particular in the distinguishing of changes consisting of solid tissue and cavities filled with liquids (cysts). This method can be used, for example, to guide a biopsy from the breast. Immediately before an operation, the ultrasonic examination can show the exact location of the findings and thus make it possible for the physician to make a targeted intervention. In the experiment, a realistic breast model is first of all examined for any pathological changes by palpating with the fingers. The two tumours included are found during this and their approximate location is determined. The found areas are then examined with the ultrasonic probe in the A-scan mode, suitable device parameters and a suitable orientation of the ultrasonic probe are set. Using the settings found, a B-scan image of the breast model is recorded and analysed along a selected line (figure 33) [7].

Figure 33. Laboratory setup for studying ultrasonic mammasonography

The examination of a realistic breast phantom with tumours and their localisation and the estimation of their size in the B-scan method demonstrate a typical application of ultrasound in medical diagnostics.
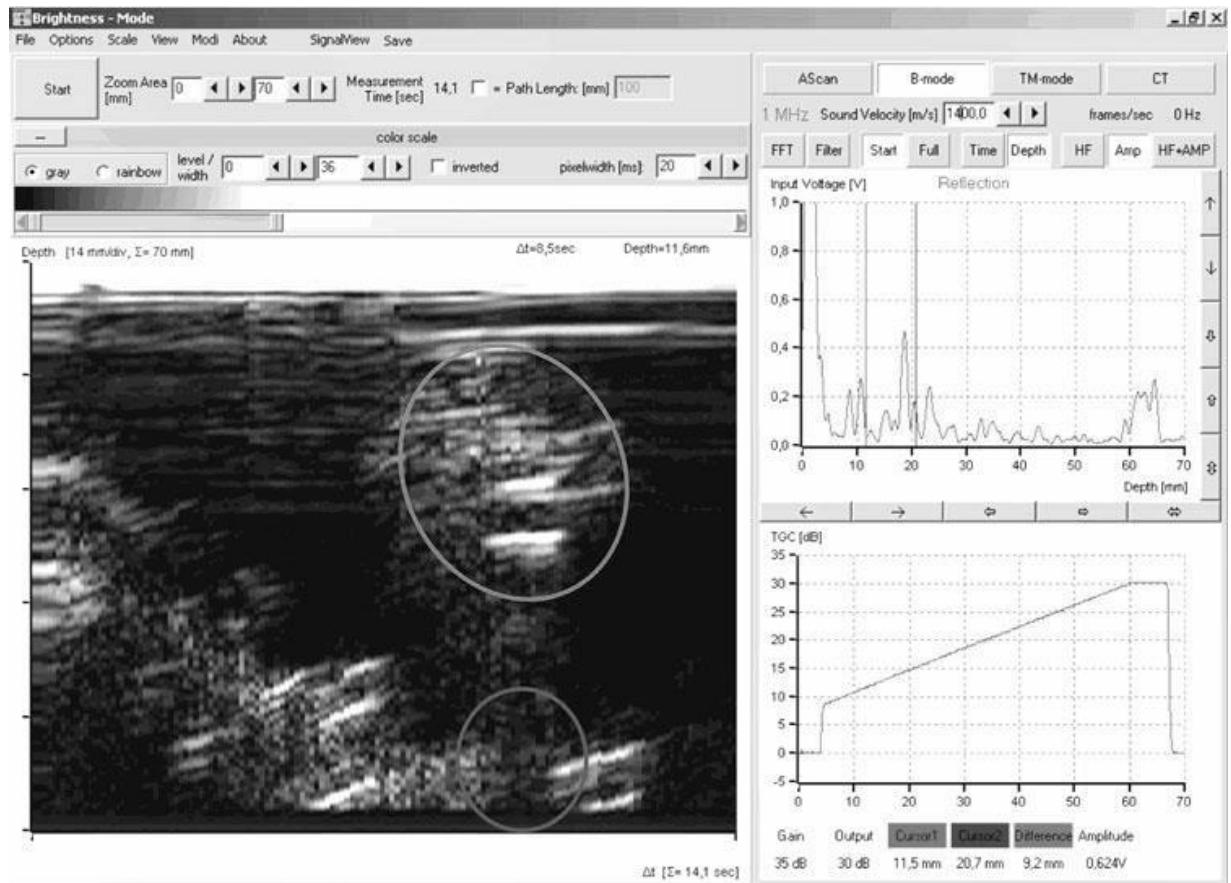
Figure 34. The ultrasonic B-Scan image recorded with the measurement software shows the tumours with an oval shape and slightly inclined axis (yellow marks). The attenuation in the tumour tissue is increased, causing a sound shadow on the back wall of the breast phantom (blue circle) [7]

Task 4

Examination of a human breast phantom with anatomical structures and their localization and estimation of their size in the B-scan method.

34. Find the location of indurations in the breast model by palpation.

35. Apply the ultrasonic gel to the region where you have found the induration.

36. Similarly to task 2, acquire the B-scan of the region with the induration (figure 34) using the probes with the working frequency of 1 and 2 MHz. If necessary, adjust the TGC tuning.

37. Discuss the influence on the probe frequency on the obtained image.

General questions for works with ultrasound:

What are harmonic oscillations? What is amplitude, frequency, cyclic frequency, period of harmonic oscillations? What is a wave? What is wavelength? What is the difference between longitudinal and transverse waves? Why are there no transverse waves in gases and liquids? What wave is called plane, spherical? Write the equation of a traveling plane wave.

What are the acoustic oscillations? What frequency range does the human ear perceive? What determines the speed of sound in air? Compare the speed of sound propagation in different media.

How the ultrasonic sensor works? Forward and reverse piezoelectric effect.

Why do we need to apply the gel when conducting ultrasound studies? What determines the intensity of the reflected ultrasound wave? Acoustic impedance. The use of ultrasound in medicine.

Special questions for work 193:

1. B-mode: the brightness image method.
2. Ultrasound beam properties: The near field, the far field, focal zone.
3. How does the wavelength affect *spatial resolution* in an ultrasound image?
4. Effects of dimensions on the resolvability of objects in the image: The axial, lateral, and elevational (slice-thickness) dimensions of spatial resolution.
5. Grey scale representation.

194. Ultrasonic time-motion (TM) scan

Aim

Simulation of the movement of the cardiac wall with a simple heart model, examination by means of the time-motion method (TM-mode, echocardiography), determination of heart rate and cardiac output.

Subjects matter of the experiment

Examination the movement of the cardiac wall simulated with a simple heart model by means of the time-motion method (TM-mode).

Determination the heart rate and the cardiac output using the TM-mode recording.

Brief theory

In echocardiography, the time-motion mode (TM-mode), also known as motion mode (M-mode) for short, is used to investigate movement sequences of the heart and its structures. As with a B-scan representation, the amplitudes of the ultrasonic signal echo of a TM-scan are imaged on the vertical axis in grey or false colour values. The time-staggered echoes that are produced with a high pulse repetition rate are shown next to each other on a horizontal time axis. In this way a graph is produced that reproduces the movement of the examined structure over time. In the experiment described here, movement is produced by hand using a membrane. This simulates the periodically repeating movement of a cardiac wall or heart valve. A TM-mode image of the simulated cardiac wall movement is recorded using the measurement software. This can be analysed and evaluated in terms of the characteristic quantities for the description of heart activity [8].

Equipment (figure 35)

1. Ultrasonic echoscope GS200
2. Ultrasonic probe 4 MHz
3. Objects to study: heart model
4. Laptop
5. Ruler or callipers

► Prior to taking the ultrasonic echoscope and the accessories into operation, please carefully read and follow the **safety instructions** on page 31.

► Read about control elements on the front side of the ultrasonic echoscope GS200 (see Section 6).
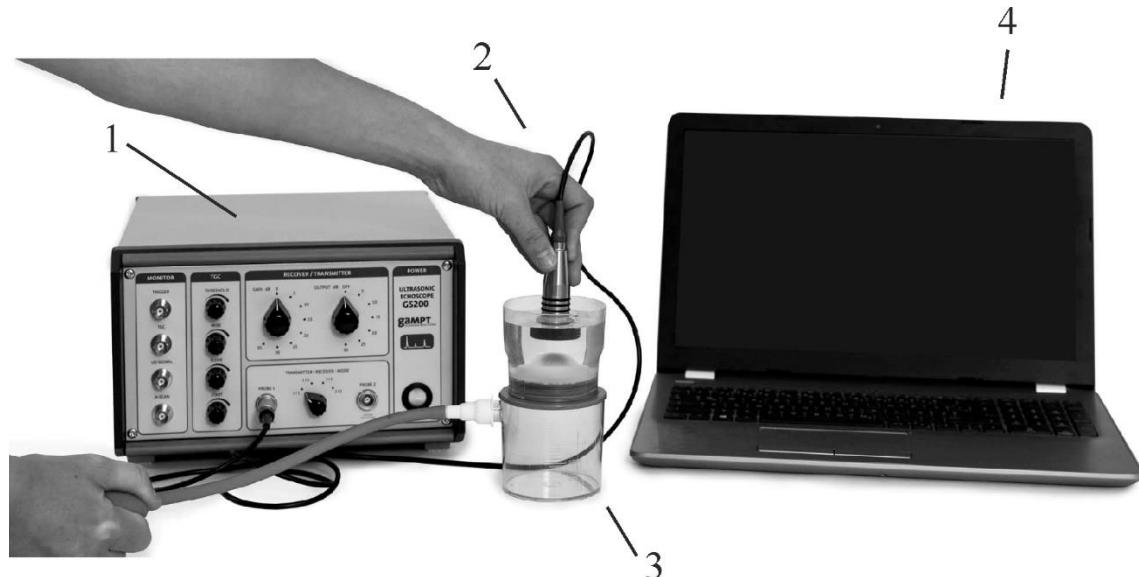
Figure 35. Laboratory setup for studying ultrasonic echocardiography.
(1) Ultrasonic echoscope GS200; (2) probe (4 MHz, green);
(3) heart model; (4) laptop

Heart Model

The heart model includes a movable membrane, the echo of which produces a TM-mode image similar to a movement of the heart valve and/or cardiac wall (figure 36). The membrane is periodically arched upward with the rubber ball. Due to a slow return

flow of air one receives a characteristic curve progression. The wall speed and the stroke volume can be calculated from the recorded curve.

Figure 36. Heart model. Double container with rubber membrane for simulation of cardiac wall and heart valves movements: (1) lower container with tubing adapter, (2) upper container with lid, (3) rubber pressure ball with tubing, (4) membrane, (5) locking ring.

Algorithm of measurements

Preparations (connecting and tuning)

1. Connect the echoscope GS200 to the computer.
2. Connect **4-MHz ultrasonic transducer** (green) to the probe connection ports named "PROBE 1" at the echoscope (figure 13).
3. Set the **transmitter/receiver mode** to "1|1" (reflection mode; figure 22) at the front side of the echoscope GS200 (figure 14).
4. Launch the program GS-EchoView on the desktop of the laptop.
5. In the window "**A-mode**" find the **"params"** tab and set the parameters "**begin [μs]**" and "**end [μs]**" to 0 and 100, respectively.
6. In the **"params"** tab set the parameter **"Sound velocity"** to 1480 m/s (the speed of sound in water).

7. At the scaling unit in diagrams of the **"params"** tab select "**mm**" (millimetres) for the depth measurement.

8. Set all regulators of the TGC amplification (figure 14, block C) to zero by rotating the rotary switches anti-clockwise up to the stop position (see figure 37).

9. Set the switchers 3 and 5 on the Receiver/Transmitter block (figure 14, block B) to positions "Gain" = 20, "Output" = 20.
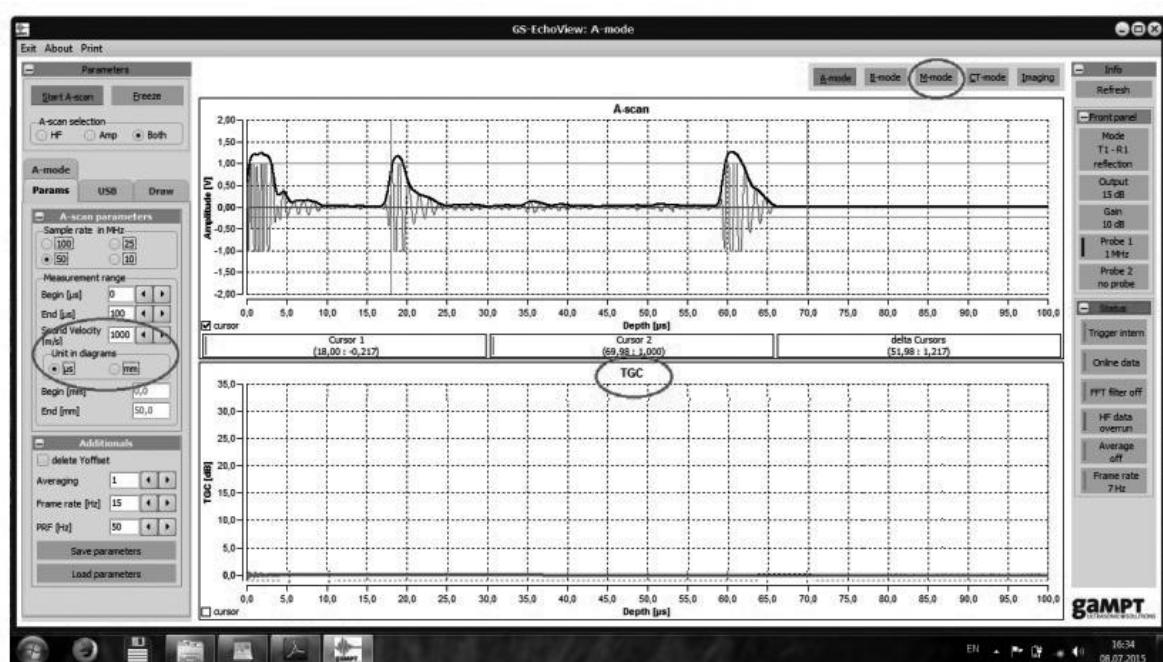
Figure 37. Main window of the GS-EchoView programme

Task 1

Examination of the movement of the cardiac wall simulated with a simple heart model by means of the time-motion method.

10. Fill the upper container of the heart model with distilled water so that 2-3 cm from the rim remain empty (figure 35).

11. Switch to the M-regime by the "**M-mode**" button (figure 37).

12. Insert the probe into water so that **water does not cover the black tip of the probe**. The centre of the probe should coincide with

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the centre of the heart model. Hold it so that it does not move up or down.

13. Start the measurements by pressing the "**Start M-scan**" button.

14. Squeeze the rubber bulb periodically and record several contractions. Try different contraction frequencies, quick and slow (figure 38).

15. Save the obtained image by pressing the label 💾.

16. Determine the period of heart contractions from the beginning (T_{start}) and final (T_{end}) points of the pulses; take five (in the slow contractions case) or ten pulses (in the large frequency case):

$$T_{start} = t_{s_2} - t_{s_1},$$ (194.1)

$$T_{end} = t_{e_2} - t_{e_1}.$$ (194.2)

17. Write down the results into Table A (slow) and Table B (fast contractions); calculate mean periods $<T_{start}>$ and $<T_{end}>$.

18. Find the average heart contractions period T using the formula:

$$T = \frac{\langle T_{start} \rangle + \langle T_{end} \rangle}{2}.$$ (194.3)

19. For each pulse, determine the end systolic diameter (ESD), which is the distance between the highest (X_{max}, mm) and the lowest (X_{min}, mm) positions of the membrane (figure 38; X_{min} is the zero level):

$$ESD = h = X_{max} - X_{min}.$$ (194.4)

20. Calculate the mean value $<h>$.

21. Write down the results into Tables 1–3.
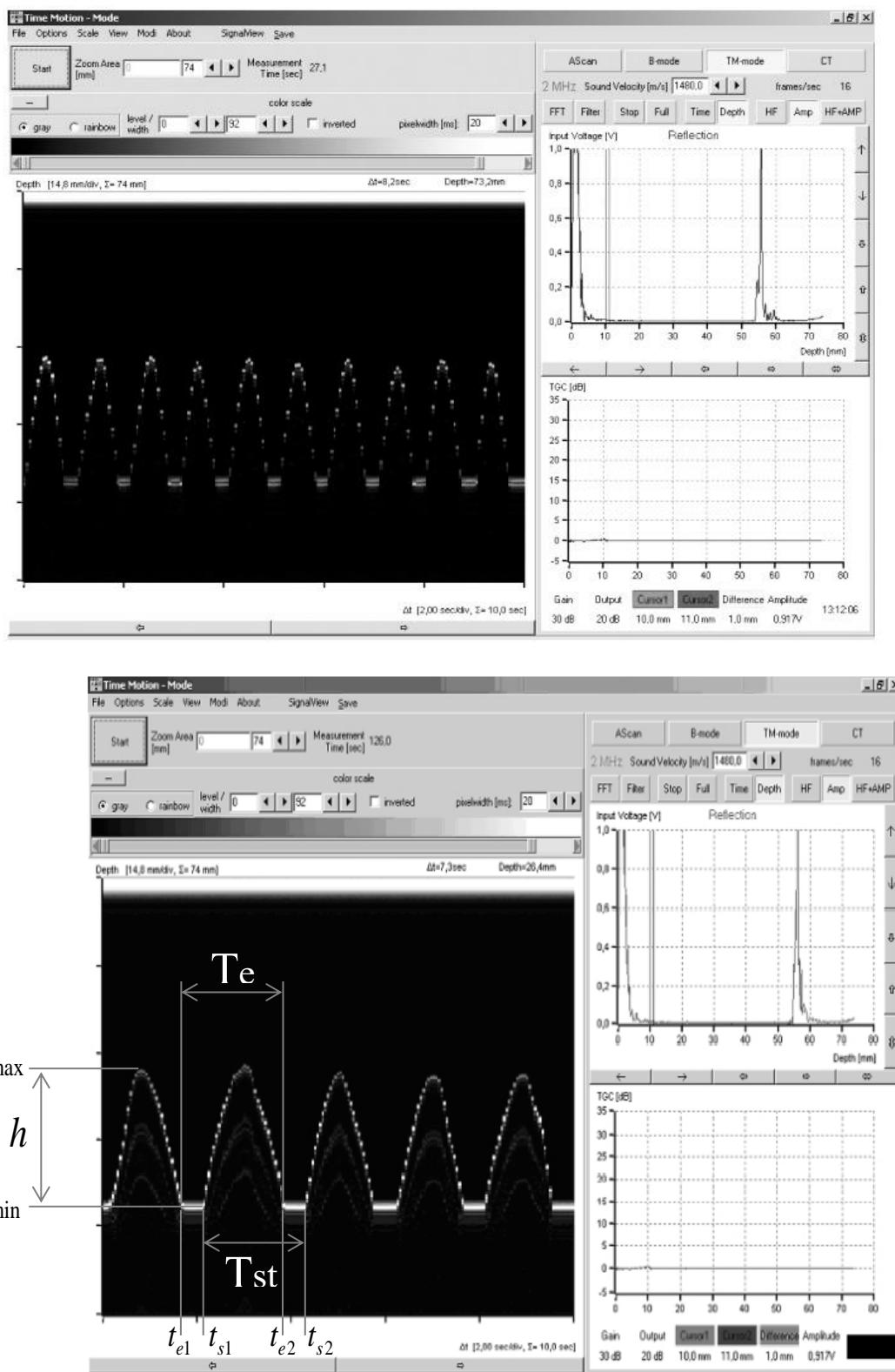
Figure 38. Working window in the M-scan regime. Typical images for quick (upper picture) and slow (bottom picture) tempos of heart contraction

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Task 2

Determination of the heart rate and the cardiac output using the TM-mode recording.

22. Calculate the heart contraction frequency (HCF) f:

$$HCF = f = \frac{1}{T}. \qquad (194.5)$$

23. Assuming that the deformed membrane has a conical shape, the **displaced volume** is

$$V = \frac{1}{12}\pi D^2 \langle h \rangle , \qquad (194.6)$$

where the diameter of the membrane is $D = 45$ mm.

24. Since the membrane is flat, the end diastolic volume (EDV) can be assumed to be zero; then the **cardiac output** is found using the expression:

$$Q = Vf , \qquad (194.7)$$

where V is the end systolic volume and f is the heart contractions frequency.

25. Write down the results into Tables A–C.

Table A

Parameters of the TM image for slow contractions

Pulse no.	1	2	3	4	5	Mean
Measurements						
t_s, s						
t_e, s						
X_{max}, mm						
X_{min}, mm						
Calculations						
T_{start}, s						
T_{end}, s						
h (ESD), mm						

Parameters of the TM image for fast contractions

Pulse no.	1	2	3	4	5	Mean
Measurements						
t_s, s						
t_e, s						
X_{max}, mm						
X_{min}, mm						
Calculations						
T_{start}, s						
T_{end}, s						
h (ESD), mm						

Table C

Summary parameters of the TM images

	Slow contractions	Fast contractions
Heart contraction period T, s		
Hear contraction frequency (HCF) f, Hz		
End systolic diameter \<h\> (ESD), mm		
End systolic volume (ESV), ml*		
Cardiac output Q, ml/s		

* In your calculations, pay attention to measurement units for h and D!

26. Transform the units of measurement to the SI units: metres and seconds. (1 L $= 10^{-3}$ m^3 $= 1000$ mL.)

General questions for works with ultrasound:

What are harmonic oscillations? What is amplitude, frequency, cyclic frequency, period of harmonic oscillations? What is a wave? What is wavelength? What is the difference between longitudinal and transverse waves? Why are there no transverse waves in gases and liquids? What wave is called plane, spherical? Write the equation of a traveling plane wave.

What are the acoustic oscillations? What frequency range does the human ear perceive? What determines the speed of sound in air? Compare the speed of sound propagation in different media.

How the ultrasonic sensor works? Forward and reverse piezoelectric effect.

Why do we need to apply the gel when conducting ultrasound studies? What determines the intensity of the reflected ultrasound wave? Acoustic impedance. The use of ultrasound in medicine.

Special questions for work 194:
1. Ultrasonic echography, reflection, pulse echo method
2. Time-of-flight measurements based on the reflection echoes in the A-Scan image
3. M-mode: the TM (Time-Motion) method
4. Presentation of movement sequences, cardiac wall movement
5. Echocardiography

195. Ultrasonic Doppler effect

Aim

Examination the basics of flow measurements on the basis of the ultrasonic Doppler effect.

Subjects matter of the experiment

Demonstration the basics of flow measurement on the basis of the acoustic or ultrasonic Doppler effect and examination its dependence on flow velocity and Doppler angle [9a].

Brief theory

The term "Doppler effect" refers to the change in the perceived frequency of waves while the transmitter and receiver are in motion in relation to each other. This effect is used to image moving structures. For example, ultrasound can be used to determine the velocity and/or the flow rate of a flow of liquid. Here the frequency shift of an ultrasonic wave, which is coupled into the flow of liquid at a particular Doppler angle, is measured when the wave is scattered on small particles (inclusions).

The **Doppler frequency shift**, Δf is the difference between the transmitted frequency, f_s and received frequency f':

$$\Delta f = f_s - f'. \qquad (195.1)$$

In the experiment, the dependence of the Doppler frequency shift Δf on the flow velocity υ_o (movement speed of the scattered particles) and the Doppler angle α (incidence angle) is investigated for different fundamental frequencies f_s by varying the pump power and the angle α [9a].

When the speed of the object υ_o is small compared to the speed of sound υ, the Doppler frequency shift can be determined as

$$\Delta f = f_s \frac{\upsilon_o}{\upsilon}\left(\cos\alpha + \cos\beta\right), \qquad (195.2)$$

where α is the angle between the flow direction and the emitted ultrasonic beam, β is the angle between the flow and the direction to the receiving probe, and f_s is the fundamental ultrasound frequency transmitted by the transducer (source of the sound).

For a pulse-echo system with one ultrasonic probe, which serves as the transmitted and as the receiver, $\alpha = \beta$ and the following relationship applies:

$$\Delta f = 2f_s \frac{\upsilon_o}{\upsilon}\cos\alpha. \qquad (195.3)$$

Here the factor of 2 can be explained by the fact that the Doppler shift occurs twice – when the original wave is incident on the moving particles in the liquid and when the moving particle reflects it back.
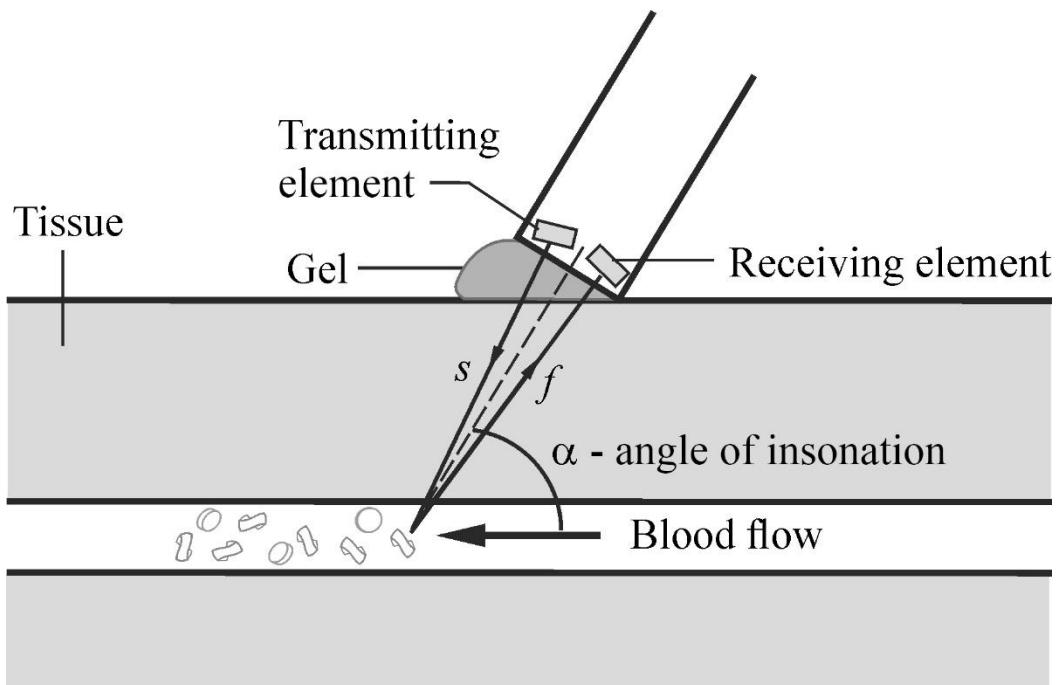

Figure 39. Simple Doppler ultrasound instruments use transducers consisting of two piezoelectric elements, one to transmit ultrasound and the other to receive the returning echoes back-scattered from the moving blood cells [9b]. Here $\alpha \approx \beta$.

Equipment (figure 40)

1. Ultrasonic scanner FlowDop
2. Ultrasonic probe 2 MHz
3. Doppler prism (3/8")
4. Flow measuring set

5. Pump MultiFlow
6. Ultrasonic gel
7. Doppler fluid
8. Laptop

► Prior to taking the accessories into operation, please carefully read and follow the **safety instructions** on page 31.

Additional safety notes:

➢ Do not unplug the tubes with liquid from each other.
➢ Do not drink the Doppler liquid.
➢ **Important!** When starting the pump program (with the "Start" knob), assure that the flow rate control handwheel is in the leftmost position (**rotate it anti-clockwise**), corresponding to the minimal flow speed.

► Read about control elements on the front side of the ultrasonic scanner FlowDop in the Section 6.3 (figure 18) and about MultiFlow pump FlowDop in the Section 6.4 (figure 19).
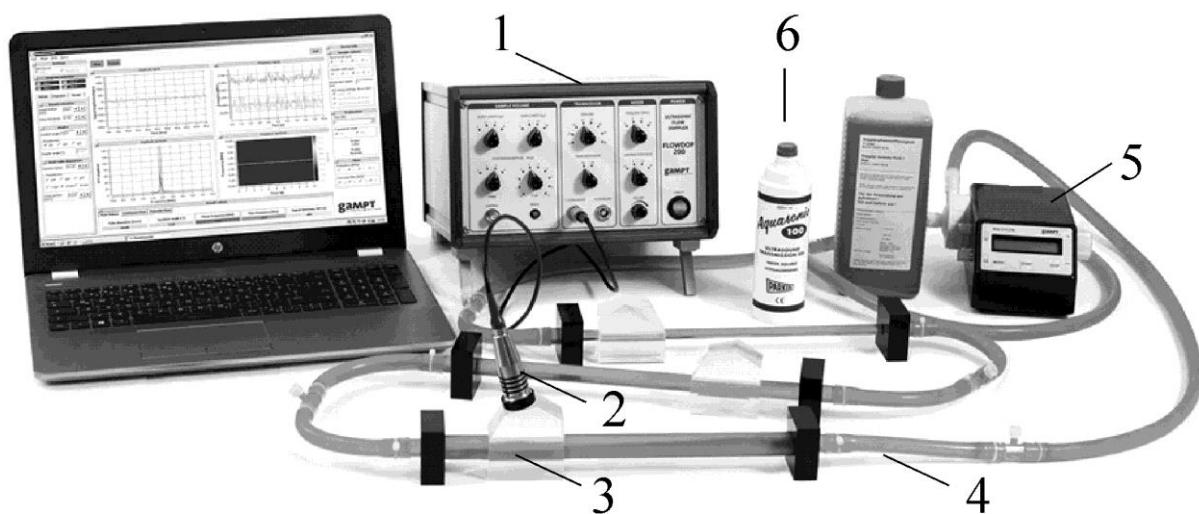

Figure 40. General view of the experimental setup for investigation of the Doppler effect in flow: (1) ultrasonic scanner FlowDop; (2) ultrasonic probe (2 MHz); (3) prism 3/8"; (4) set of tubes; (5) Multiflow pump; (6) ultrasound gel

Doppler Prism 3/8"

Acrylic attachment for 3/8" flow pipe for investigations of frequency shift using three different incidence angles of the prism α_P (figure 41).

The Doppler prism serves as a connection between ultrasonic probe and the flow pipe and/or tube. Due to its design it can be simply and securely coupled to the flow pipe or the tube. The planar surfaces allow simple coupling of the ultrasonic probe. The strength of the frequency shift depends largely on the angle between the irradiated ultrasonic wave and the direction of flow. The Doppler prism makes it possible to irradiate with three different angles and thus to investigate the influence of the Doppler angle on the observed frequency shift.
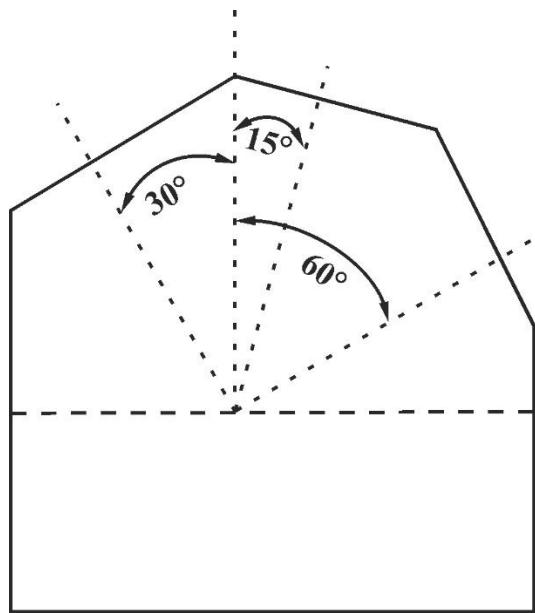

Figure 41. Prism for studying the Doppler effect

Doppler Fluid

Doppler Fluid is a phantom fluid with outstanding scatter characteristics for the measurement of ultrasonic Doppler signals. This fluid contains *scattering particles* with acoustic impedance and size which are suitable for the ultrasonic frequency measurements.

Algorithm of measurements

Preparations (connecting and tuning)

1. Connect the ultrasonic **scanner FlowDop** to the computer.
2. Connect 2-MHz ultrasonic transducer to the probe connection ports named "PROBE" at the scanner FlowDop (figure 18).
3. Check that there are no air bubbles in the tubes.
4. Turn the switchers "Power" and "Sample vol." to positions "High" and "Large," respectively.

Task

Examination of the dependence of the Doppler frequency shift Δ*f* on the flow velocity (movement speed of the scattered particles) and the Doppler angle

5. Knowing the speed of sound in the Doppler Liquid ($\upsilon_L = 1800 \ m/s$) and in the prism ($\upsilon_P = 2670 \ m/s$), we can write down the law of refraction:

$$\alpha = 90° - \arcsin\left(\frac{\upsilon_L}{\upsilon_P} \sin\alpha_P \right). \tag{5.4}$$

6. Calculate the angles α (angle between the beam and the flow) and the values of $\cos\alpha$ for three different angles of the prism α_P (shown in figure 40) and write down the results into **Table A**.

Table A

Prism angle α_p, °	Incidence angle α, °	$\cos\alpha$
15°		
30°		
60°		

7. Turn on the ultrasound scanner FlowDop and launch the programme FlowView on the laptop.

8. Turn on the Multiflow pump ("Start" knob). In the second regime (controlled by the "Mode" knob, **regime M1**), set the flow rate to 1 L/min using the handwheel on the side of the pump.

9. Apply a small amount of gel onto the glass tube and put the prism above it. Check that there are no air bubbles between the tube and the prism.

10. Apply a small amount of gel onto a prism side corresponding to a chosen angle and put the ultrasonic probe (2 MHz, red) above.

11. In the FlowView program choose the proper tube diameter and the angle α_p in the "**Parameter**" tab (figure 42).
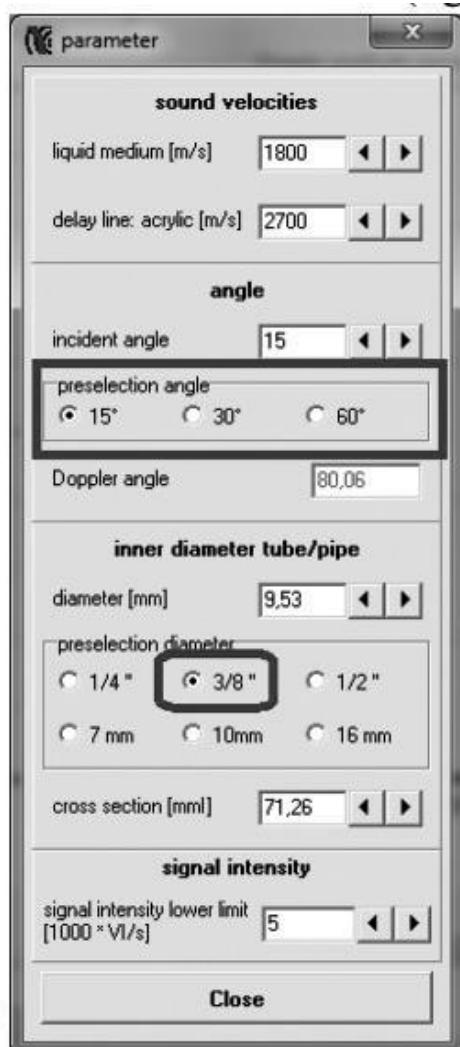

Figure 42. "Parameter" tab

12. Close the "Parameter" tab and start the experiment with the "Start" button.
13. Look at the spectrum and measure the average frequency shift Δf (parameter "f-mean" in the FlowView program window, figure 43).
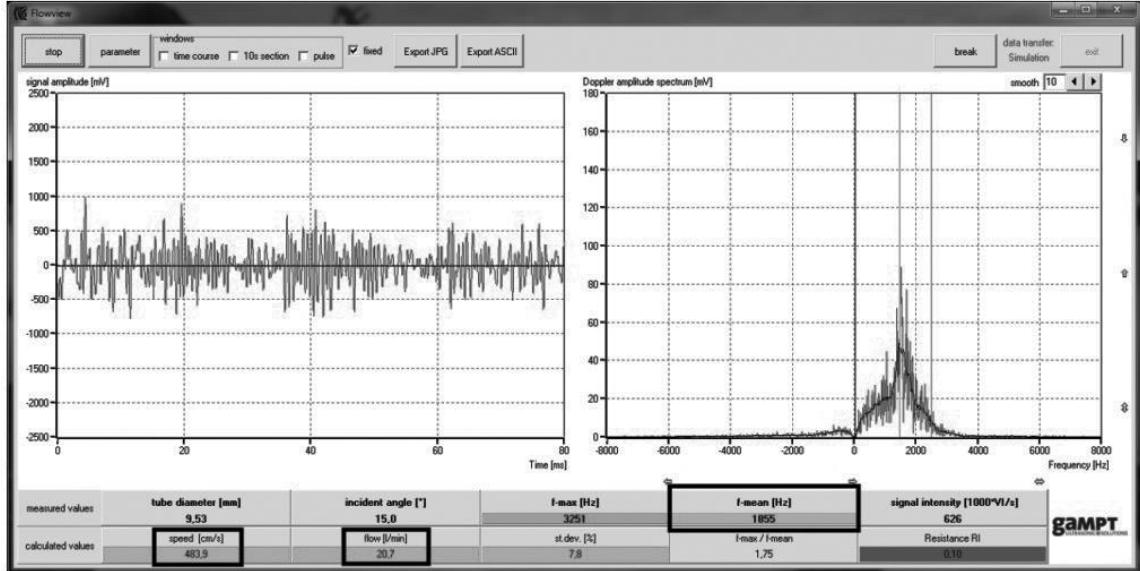

Figure 43. Main window of the FlowView program

14. Taking into account the frequency shift Δf, calculate the flow speed υ_o using Eq. (195.3), and compare it with the values obtained in the experiment (parameter "Speed", figure 42).
15. Write down the results into **Table B**.

Table B

Flow, L/min	15°			30°			60°		
	Δf, Hz	υ_o, cm/s		Δf, Hz	υ_o, cm/s		Δf, Hz	υ_o, cm/s	
		Calcul.	Exper.		Calcul.	Exper.		Calcul.	Exper.
1									
1.5									
2									

16. Repeat steps 2–10 for other flow rates (1.5, 2 L/min).
17. Build the plots for the dependency of the frequency shift on the flow rate $\Delta f(\upsilon)$ and on cosα: $\Delta f(\cos\alpha)$.
18. Make conclusions.

General questions for works with ultrasound:

What are harmonic oscillations? What is amplitude, frequency, cyclic frequency, period of harmonic oscillations? What is a wave? What is wavelength? What is the difference between longitudinal and transverse waves? Why are there no transverse waves in gases and liquids? What wave is called plane, spherical? Write the equation of a traveling plane wave.

What are the acoustic oscillations? What frequency range does the human ear perceive? What determines the speed of sound in air? Compare the speed of sound propagation in different media.

How the ultrasonic sensor works? Forward and reverse piezoelectric effect.

Why do we need to apply the gel when conducting ultrasound studies? What determines the intensity of the reflected ultrasound wave? Acoustic impedance. The use of ultrasound in medicine.

Special questions:

1. Doppler effect, Doppler shift frequency Δf.
2. Dependence of the Doppler frequency shift Δf on the flow velocity.
3. Doppler sonography, flow measurement.
4. Viscosity of liquids. Laminar and turbulent flow. Reynolds number.
5. Hagen-Poiseuille equation, flow velocity, flow resistance.

197. Mechanics of a flow

Aim

Study of fundamental fluid laws during flow measurements using the ultrasonic Doppler effect.

Subjects matter of the experiment

Demonstration of the fundamental laws governing the flow of liquids in pipes and their dependence on the flow velocity and the pipe geometry by flow measurements according to the ultrasonic Doppler method [10].

Brief theory

In this experiment the Doppler frequency shift can be measured for different pump speeds in measurement sections with different pipe diameters. At the same time, the corresponding pressure drops can be measured by means of standpipes. In this way, it is possible to obtain clear evidence of the laws that apply to a liquid with laminar flow. From the flow velocities determined according to the Doppler method, the pipe geometries and the measured pressure drops, it is possible to determine flow rates, flow resistances and the dynamic viscosity of the Doppler liquid by formulaic application of the continuity equation, Bernoulli's equation and the Hagen-Poiseuille equation. By calculating the Reynolds numbers for the different flow velocities and pipe diameters, it is possible to check whether stationary laminar flow states were prevalent during the measurements [10].

Continuity equation for a flow in tubes of various diameters is written as:

$$S_1 \upsilon_1 = S_2 \upsilon_2 = const = Q, \tag{197.1}$$

where v_1 and v_2 are the mean speeds of the flow in two tubes, S_1 and S_2 are the tubes' cross-areas, and Q is the flow rate (volume passing per time unit).

Static pressure in moving liquid is smaller than in motionless liquid, and the faster is the flow speed the smaller is the pressure (the Bernoulli equation). If we consider a horizontal tube (so that the pressure of the liquid column shouldn't be considered), the net pressure p_0 is defined by the formula

$$p_0 = p + \frac{1}{2}\rho v_L^2, \qquad (197.2)$$

where ρ is the density of the liquid, v_L is the speed of the liquid, and p is the hydrostatic pressure. The net pressure p_0 is a constant only if there is no internal friction in liquid. In the presence of the internal friction, the net pressure is reduced depending on the coefficient of viscosity η, tube length l, tube cross-area S, and the flow speed v_L. When the speed is relatively low (and the flow is laminar), the Hagen–Poiseuille law is fulfilled in thin tubes, which states that the pressure drop is proportional to the flow rate:

$$\Delta p = RQ. \qquad (197.3)$$

Here R is the hydraulic impedance which equals to

$$R = \frac{8\eta l}{\pi r^4}, \qquad (197.4)$$

where r is the tube radius. Thus, decreasing the vessel diameter two times results in 16-fold increase of its hydraulic impedance.

*Equipment (*figure 44)
1. Ultrasonic scanner FlowDop
2. Ultrasonic probe 2 MHz
3. Doppler prisms (1/2", 3/8", and 1/4") (figure 40)
4. Set of tubes of different diameters (1/2", 3/8", and 1/4")
5. Multiflow pump

6. Stand pipes for measuring the pressure
7. Doppler Fluid
8. Ultrasound gel
9. Laptop

► Prior to taking the accessories into operation, please carefully read and follow the **safety instructions** on page 31.

Additional safety notes:

➢ Do not unplug the tubes with liquid from each other.

➢ Do not drink the Doppler liquid.

➢ **Important!** When starting the pump program (with the "Start" knob), assure that the flow rate control handwheel is in the leftmost position (**rotate it anti-clockwise**), corresponding to the minimal flow speed.

► Read about control elements on the front side of the ultrasonic scanner in the Section 6.3 (figure 18) and about MultiFlow pump FlowDop in the Section 6.4 (figure 19).
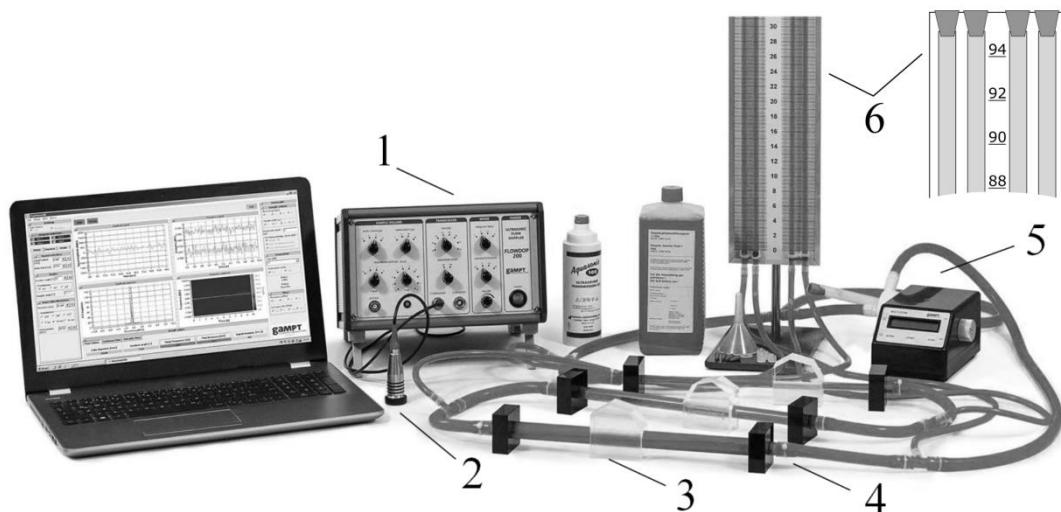

Figure 44. General view of the experimental setup for investigation of the flow mechanics: (1) ultrasonic scanner FlowDop; (2) ultrasonic probe (2 MHz); (3) prism; (4) set of tubes; (5) Multiflow pump; (6) standpipes (manometer)

Algorithm of measurements

Preparations (connecting and tuning)

1. Connect the ultrasonic **scanner FlowDop** to the computer.
2. Connect 2-MHz ultrasonic transducer to the probe connection ports named "PROBE" at the scanner FlowDop (figure 18).
3. Check that there are no air bubbles in the tubes.
4. Turn the switchers "Power" and "Sample vol." to positions "High" and "Large," respectively.
5. Before you begin the measurements, put off red caps from upper ends of the standpipes (see insert in figure 43).

Task 1

Measuring basic characteristics of a laminar flow of a liquid. Determination of the dependences of the flow rate on the tube cross-area and of the hydraulic impedance on the tube diameter. Verifying the Hagen–Poiseuille law. Calculation the mean values of viscosity.

6. Turn on the ultrasonic scanner FlowDop and launch the programme FlowView on the laptop.
7. Turn on the Multiflow pump ("Start" knob). In the second regime (controlled by the "Mode" knob, **regime M1**), set the flow rate to 1 L/min using the handwheel on the side of the pump.
8. Apply a small amount of gel onto the 1/2" glass tube (the biggest diameter) and put above it a prism of a suitable size. Check that there are no air bubbles between the tube and the prism.
9. Apply a small amount of gel onto a prism side corresponding to a chosen angle and put the ultrasonic probe on it.
10. In the FlowView programme, choose the proper tube diameter and the angle in the "**Parameter**" tab (figure 45).
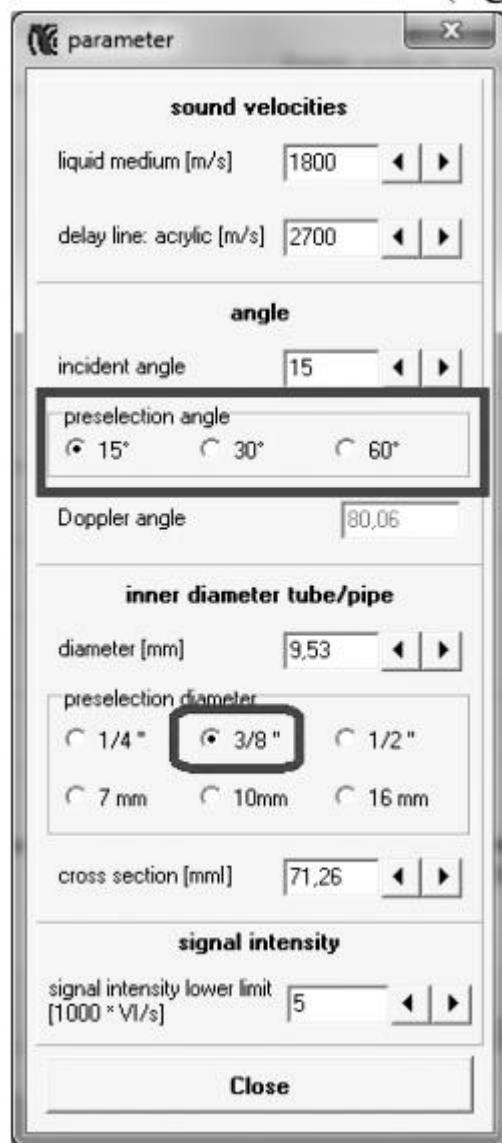
Figure 45. "Parameter" tab

11. Close the "Parameter" tab and start the experiment with the "Start" button.
12. Look at the FlowView program window (figure 46) and measure the speed of the liquid υ_L and the flow rate Q.
13. Write down the results into **Table A**.
14. Measure the difference of the liquid levels between the pipe attached to the investigated tube and the right pipe. Calculate the pressure drop as:

$$\Delta p = \rho g \Delta h, \qquad (197.5)$$

where ρ is the density of the Doppler liquid (1150 kg/m^3; check it for the liquid used in the laboratory), g is the gravitational acceleration (9.8 m/s^2), and Δh is the difference between the liquid levels in the water columns.
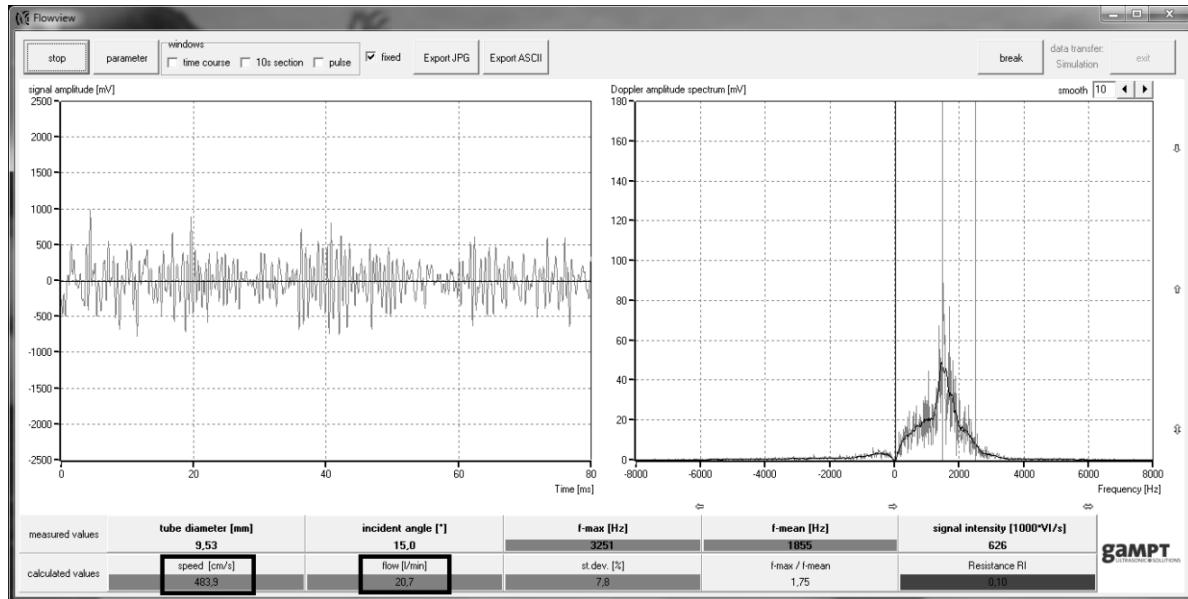

Figure 46. Main window of the FlowView programme

15.   Calculate the hydraulic impedance of each tube using the formula

$$R = \Delta p / Q, \tag{197.6}$$

where Q is the flow rate (measured in m^3/s!).

16.   Write down the results into **Table B**.

17.   Find the coefficient of viscosity for each flow as

$$\eta = \frac{R \pi r^4}{8l}, \tag{197.7}$$

where the tube length is $l = 0.3$ m.

18.   Calculate the mean values of the coefficient of viscosity η and hydraulic impedance and write down the results into **Table C**.

19.   Repeat the experiment for the flow rates of 1.5 and 2 L/min.

20. Repeat all steps for the tubes with the diameters of 3/8" and 1/4".

21. Build the graphs showing the dependencies of the flow speed υ_L and the hydraulic impedance R on the inner diameter of the tube d. The inner diameter is displayed in the operating window.

22. Make necessary conclusions.

Table A

Tube	1/2"		3/8"		1/4"	
Present flow, L/min	υ_L, cm/s	Q, L/min	υ_L, cm/s	Q, L/min	υ_L, cm/s	Q, L/min
1						
1.5						
2						

Table B

Tube	1/2"		3/8"		1/4"	
Present flow, L/min	Δp, Pa	R, Pa·s/m³	Δp, Pa	R, Pa·s/m³	Δp, Pa	R, Pa·s/m³
1						
1.5						
2						

Table C

d, mm	R, Pa·s/m³	η, Pa·s

General questions for works with ultrasound:

What are harmonic oscillations? What is amplitude, frequency, cyclic frequency, period of harmonic oscillations? What is a wave? What is wavelength? What is the difference between longitudinal and transverse waves? Why are there no transverse waves in gases and liquids? What wave is called plane, spherical? Write the equation of a traveling plane wave.

What are the acoustic oscillations? What frequency range does the human ear perceive? What determines the speed of sound in air? Compare the speed of sound propagation in different media.

How the ultrasonic sensor works? Forward and reverse piezoelectric effect.

Why do we need to apply the gel when conducting ultrasound studies? What determines the intensity of the reflected ultrasound wave? Acoustic impedance. The use of ultrasound in medicine.

Special questions:
1. Doppler effect for sound waves, Doppler frequency shift Δf.
2. Dependence of the Doppler frequency shift Δf on the flow velocity.
3. Viscosity of liquids. Laminar and turbulent flow. Reynolds number.
4. Continuity equation, Bernoulli's equation.
5. Pressure scales, static and dynamic pressure.
6. Hagen-Poiseuille equation, flow velocity, flow resistance.

198. Measuring arterial pressure using ultrasound

Aim

Acquiring the physical and signal-theoretical basics for blood flow examinations by means of the ultrasonic Doppler effect (Doppler sonography).

Subjects matter of the experiment

Investigation the dependence of the colour-coded Doppler spectra on signal amplitude, flow velocity, direction of blood flow and choice of the measuring window with the pulse Doppler method using a realistic arm phantom [11].

Brief theory

The notion of blood pressure usually implies the pressure experienced by the wall of blood vessels. In different parts of the blood circulatory system there are different conditions and pressure gradients. The blood pressure depends on the cardiac output, total blood volume, and resistance of the vessels to the blood flow.

Blood pressure (in particular, arterial pressure) is an important parameter in medical diagnostics. Blood tension changes between the maximal and minimal values during a cardiac cycle. On the ventricular systole, the blood is pushed into aorta at the pressure of about 120 millimetres of mercury (mmHg, sometimes denoted as Torr). On the diastole, the tension decreases to about 80 mmHg.

Measuring the blood tension

The blood tension can be measured directly (invasively) or indirectly (non-invasively). Usually the pressure is measured with the aid of an arm cuff.

1) *Riva-Rocci method (using a sphygmomanometer)*

In this method, the inflatable arm cuff is fastened around the arm at the level of the heart and is inflated until the pulse on the brachial artery disappears. Strong compression of vessels under the cuff makes the blood flow stop. After that the pressure in the cuff is smoothly decreased until the pulse tones appear. The pressure in the cuff observed immediately after the reappearance of the pulse corresponds to the systolic blood pressure.

2) *Korotkoff tones*

Detonation noise synchronized with the pulse, which was discovered by Nikolai Korotkoff in 1905, enhanced indirect measurement methods by allowing measuring diastolic pressure. Korotkoff tones arise due to turbulent blood flow appearing in a pinched vessel. The tones can be heard using a stethoscope under the sphygmomanometer's cuff (on the bend of the elbow). The first tone appears when the pressure in the cuff decreases to the systolic pressure. Blood runs through the arm only near the peak value of the tension. As the pressure in the cuff decreases further, periods when the blood flow is not occluded become longer and longer. Finally, normal pulse in the artery will recover. At this moment, when the artery in not pinched any more, the blood flow loses turbulence and becomes laminar, smooth; as a result, no audible sound is produced. The pressure in the arm cuff after disappearing of the Korotkoff tones is regarded as the diastolic pressure.

3) *Using ultrasound: Doppler blood pressure measurement*

One of possible non-invasive methods of measuring the blood pressure is a combination of ultrasonic investigation based on the Doppler effect (Doppler sonography) and a sphygmomanometer's arm cuff. Doppler measurement is used instead of a stethoscope; it allows not only hearing, but also watching the blood flow in a vessel.

In Doppler sonography, the ultrasonic scattering signal of moving particles (actually, blood cells) is detected and evaluated. Due

to the movement of the blood cells relative to the ultrasonic probe, the signal has a frequency shift Δf and can thus be well separated from the signals of the more or less stationary vascular walls and organ boundary surfaces. The frequency shift is here dependent on, among other things, the direction of the blood flow and its velocity:

$$\Delta f = 2 f_s \frac{\upsilon_o}{\upsilon} \cos \alpha, \qquad (8.1)$$

where Δf (the **Doppler frequency shift)** is the difference between the transmitted frequency of ultrasound f_s and received frequency f': $\Delta f = f_s - f'$; υ is the speed of ultrasound in blood; υ_o is the flow speed (movement speed of the scattered particles); α is the angle of incidence with respect to the blood flow direction (the Doppler angle) (figure 39).

Similarly to direct measurement of the blood pressure by the Riva-Rocci or Korotkoff methods, the studied blood vessel is squeezed by the arm cuff, and the blood flow stops ($\Delta f = 0$). The measurements are performed distally using an elongated ultrasonic probe. The pressure inside the cuff at which the blood flow starts again ($\Delta f > 0$) is the systolic pressure. Since the pressure in the cuff gives the maximal value of the oscillations of the pulse pressure, the diastolic pressure cannot be measured.

Frequency variations Δf which are typical of the blood flow fall within the audible region. Thus, they can be monitored additionally as acoustical signals (via loudspeakers); the pitch level of the signals would depend on the blood flow speed.

If, in the chronological progression of the measurement (time, x-axis), the scattering intensity (signal amplitude, colour) is presented in dependence on the size of the frequency shift (velocity, y-axis), one receives the so-called Doppler spectra. They show characteristic changes in dependence on the scattering amplitude (number, size, type of blood particles), flow direction (to the probe, away from the probe), and velocity of the scatterers [11].

*Equipment (*figure 47)

1. Ultrasonic scanner FlowDop
2. MultiFlow pump
3. Ultrasonic probe working at 2 MHz with a fixed Doppler angle (30°)
4. Arm phantom
5. Ultrasound gel

► Prior to taking the accessories into operation, please carefully read and follow the **safety instructions** on page 31.

Additional safety notes:

➢ Do not unplug the tubes with liquid from each other.

➢ Do not drink the Doppler liquid.

➢ **Important!** When starting the pump program (with the "Start" knob), assure that the flow rate control handwheel is in the leftmost position (**rotate it anti-clockwise**), corresponding to the minimal flow speed.

► Read about control elements on the front side of the ultrasonic scanner in the Section 6.3 (figure 18) and about MultiFlow pump FlowDop in the Section 6.4 (figure 19).

➢ Pumping can be ceased with the "Stop" button. Working regimes from M0 to M4 are set using the "Mode" button. Other regimes are described in detail in the manual of the pump.

➢ **Important!** For measuring the pressure, the pump should operate at 3000 to 5000 revolutions per minute.

➢ **Important!** The pump must not operate for a long time at the maximal rate (no longer than 30 minutes!).

Figure 47. Laboratory setup for studying ultrasonic sonography

Software

The Doppler instrument works in combination with FlowView software which allows receiving and analysing the data. Functions and parameters of the programme are described in detail in the manual to the FlowDop device.

Working area of the FlowView window (figure 48):

1. Amplitude of the ultrasonic Doppler signal.
2. Spectrum of the Doppler signal (obtained by Fourier transform) indicating the mean Doppler frequency shift *f-mean* and the maximal frequency shift *f-max*. Scaling is adjusted by arrows on the bottom part of the window.

Switching between the processing windows (ticks in the upper part of the window, below the title bar):

3. "Time course": temporal behaviour of the Doppler spectrum, colour-coded.
4. "10 s section": changes in *f-mean* and *f-max* in last 10 s of measurements.
5. "Pulse": frequency spectrum of pulsation averaged over 10 s.
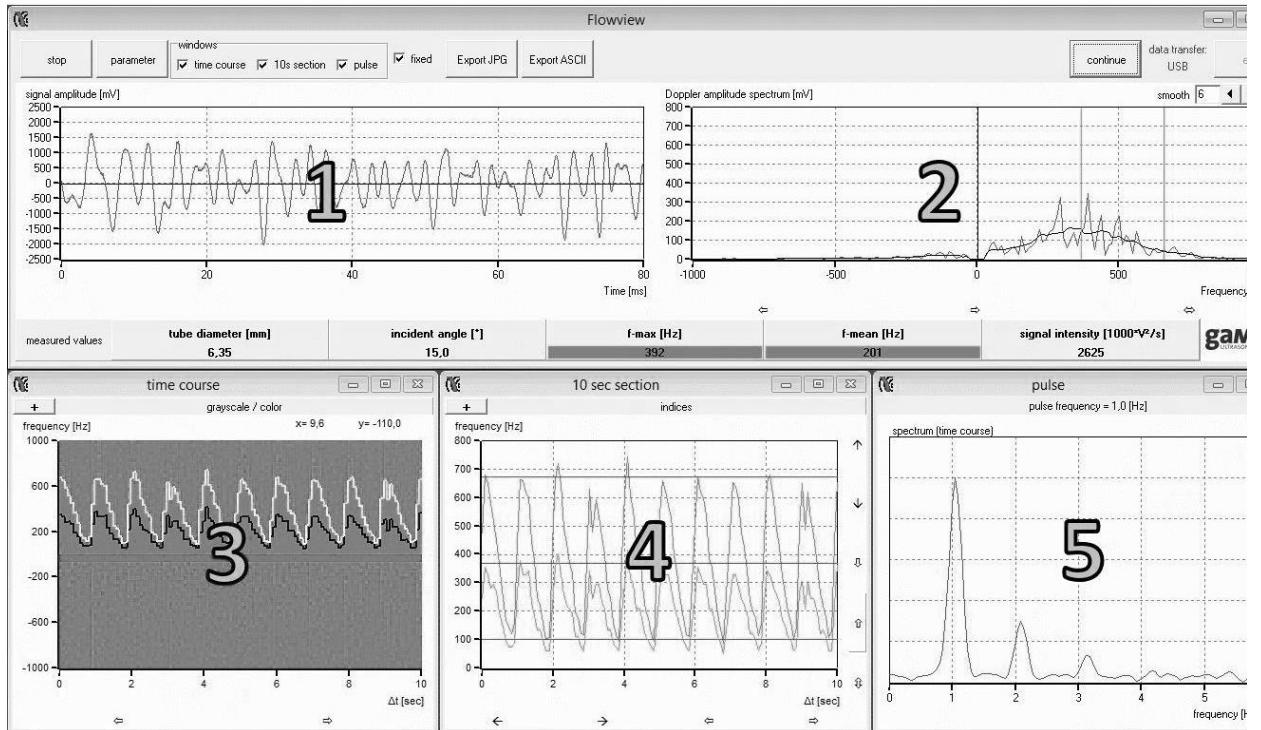
Figure 48. Interface of the FlowView programme

Algorithm of measurements

Preparations (connecting and tuning)

1. Connect and tune the experimental setup.

2. Check that there are no air bubbles in the tubes.

3. Put the cuff on the arm in the region of the brachial artery (figure 49).

To carry out ultrasonic pressure measurement (indirect method), put the cuff firmly on the part of the silicon tube imitating the brachial artery which is about 8–10 cm from the model arm's end. The measurement itself is performed in an area between the cuff and the bend of elbow. The measurement procedure depends strongly on the position of the cuff and on the power of the pump (number of revolutions per minute, rpm).

Figure 49. The place for putting on the cuff on the arm model

Task 1

Measurement of the blood pressure with continuous flow.

Studying continuous blood flow using colour coding of the Doppler spectrum as a function of the pressure in the arm cuff.

Determination of the dependence of the mean and maximal frequency shift and of the pressure parameters for two different blood flow speeds (cardiac output dependence)

4. Set the "Gain" switcher on the front panel of the scanner to 40 dB.

5. Set the switchers "Power" and "Sample volume" to "high" and "large," respectively (figure 18 on page 34).

6. Set the pump regime to "M0" using the "Mode" button; the pump rate should be within 3000–5000 revolutions per minute (rpm).

7. In the "Parameter" tab of the FlowView programme window choose the appropriate tube diameter (1/4") and angle (30°) (figure 50).
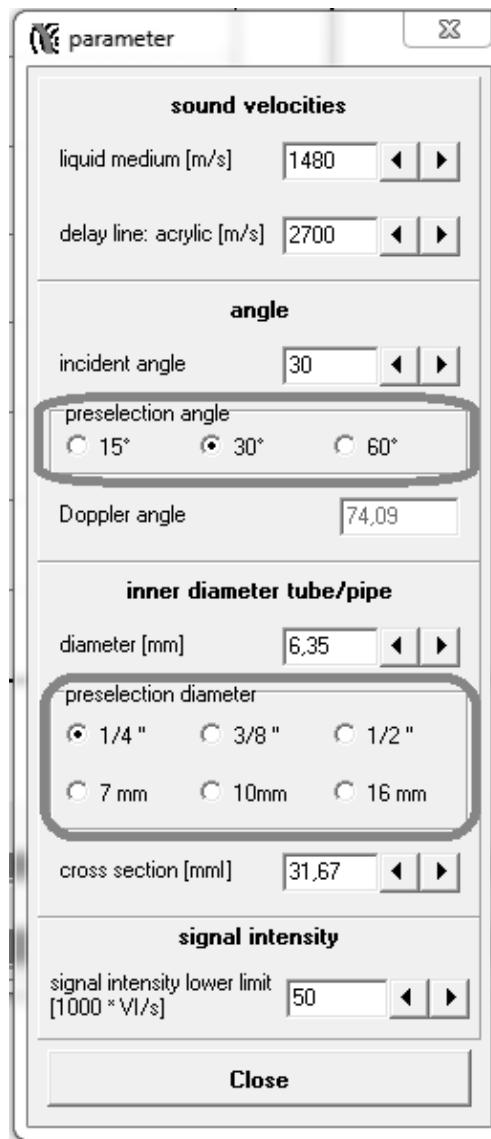
Figure 50. "Parameter" tab

8. Apply ultrasonic gel and put the probe onto the vessel, visible through the skin of the model arm, like in figure 48. Find the position of the probe at which the signal intensity is maximal (by observing the spectrum and the sound).

9. Demonstrate the influence of the pressure in the cuff by changing it with a rubber bulb. The frequency shift and the sound should disappear as the cuff occludes the liquid flow. When air is released smoothly from the cuff, the image in the "time course" window should change (figure 51, upper panel) according to reappearance of liquid flow and sound signals. The frequency shift also appears

as the pressure in the cuff decreases (white line corresponds to f_{max} and black line reflects f_{mean}).

10. Set the pump rate to 3000 rpm.
11. Pump the cuff until the frequency shift and the sound signal disappear.
12. Release gradually air from the cuff and write down the values of f_{max} and f_{mean} in steps of 10 mmHg (down to 0 mmHg).
13. Repeat the measurements at the MultiFlow pump rate of 4000 rpm.
14. Decrease the pump rate to 0 rpm.
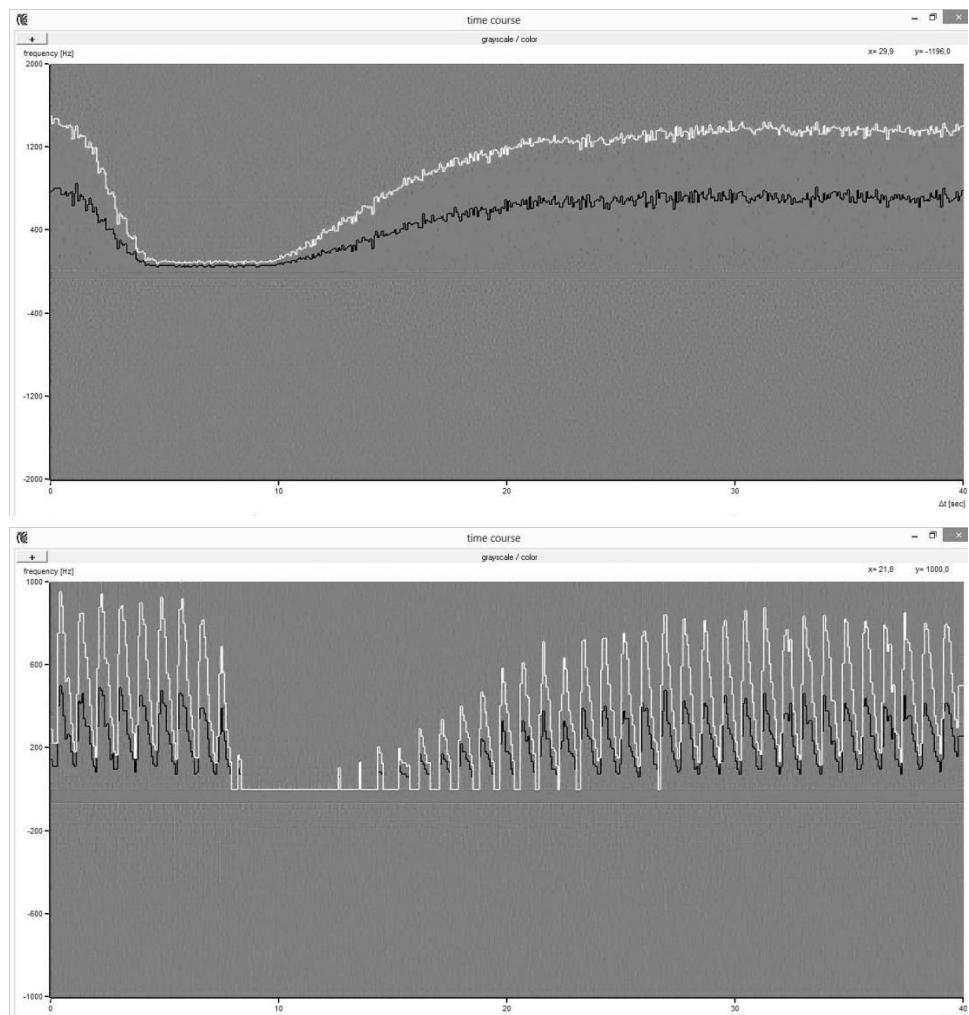
Figure 51. Behaviour of the signal in the colour-coded spectrum with changing pressure: pumping of the cuff – smooth releasing of air – onset of the flow – total release of air

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15. Build the plot of the dependency of f_{max} and f_{mean} on the pressure in the arm cuff at the two pump rates (draw four curves on a single diagram).

16. Make conclusions about the influence of the pump rate (which is analogous to the cardiac output) on the pressure in the system (in the blood-vascular system).

Task 2

Measurement of the blood pressure with pulsed flow.

Studying the pulsed flow using colour coding of the Doppler spectrum as a function of the pressure in the cuff and pump rate.

Determination of the pressure of the pulsed flow at various pump rates and pressures in the cuff

17. Change the pump regime to "**M2**" (**pulsed flow regime**).

18. Set the pulse length to a value in the range from 0.7 to 1 s using a small handwheel on the side.

19. Set the pump rate to 3000 rpm.

20. Pump the arm cuff until the sound, the signal in the spectrum and in the pulse window (figure 47, window 5) disappear.

21. Release air gradually from the cuff and find the pressure values at which the changes will occur in the spectrum, in the sound indication, and in the pulse window. In other words, use three criteria of reappearing of the pulse: spectrum (figure 47, window 3), sound from the apparatus, and pulse recording (figure 47, window 5).

22. Repeat previews steps 20, 21 at higher pump rates (increase it in steps of 500 rpm up to 5000 rpm, so that finally you have five different pump rates).

23. Build a plot showing the dependency of the pressure in the cuff, at which the changes appear according to the chosen criteria (spectrum, sound, pulse), on the pump rate. Draw three curves on a diagram.

24. Make a conclusion about the effect that the choice of criterion for measuring the pressure has on the measurement accuracy.

General questions for works with ultrasound:

What are harmonic oscillations? What is amplitude, frequency, cyclic frequency, period of harmonic oscillations? What is a wave? What is wavelength? What is the difference between longitudinal and transverse waves? Why are there no transverse waves in gases and liquids? What wave is called plane, spherical? Write the equation of a traveling plane wave.

What are the acoustic oscillations? What frequency range does the human ear perceive? What determines the speed of sound in air? Compare the speed of sound propagation in different media.

How the ultrasonic sensor works? Forward and reverse piezoelectric effect.

Why do we need to apply the gel when conducting ultrasound studies? What determines the intensity of the reflected ultrasound wave? Acoustic impedance. The use of ultrasound in medicine.

Special questions:

1. Doppler effect for sound waves, Doppler frequency shift Δf.
2. Dependence of the Doppler frequency shift Δf on the flow velocity.
4. Principles of hemodynamics (continuity equation, Bernoulli's equation, Hagen-Poiseuille equation, flow velocity, flow resistance).
3. Arterial pressure. Methods of measuring.
4. Blood flow examinations by means of the ultrasonic Doppler effect (Doppler sonography).
5. Pulsed wave Doppler, continuous wave (CW) Doppler.

199. Ultrasonic computed tomography

Aim

Demonstration of the formation of an ultrasonic computer tomography (CT)

Subjects matter of the experiment

Demonstration the formation of an ultrasonic CT scan image. Investigation and analysis of the relevance and differences of individual measurement parameters such as attenuation and sound velocity and the influence of filters and image processing [12].

Brief theory

X-ray computed tomography (CT) is one of the most important diagnostics methods in modern medicine. Furthermore, it is widely used in industry and scientific research to obtain information on inner structure of an object without the need of destroying the object. A well-known application of this method, which has attracted much attention of mass-media, is study of mummies in archaeology.

A single image obtained in a CT procedure is a two-dimensional projection of a three-dimensional object, through which the irradiation has passed (figure 52). In this projection different layers of the object are superimposed on each other, so this image is also called a superposition of images.

The principle of obtaining scans is the same for different CT methods; the only difference is in the radiation type used. An ultrasonic wave may be used instead of X-rays. In the X-ray CT, absorption of X-ray irradiation is registered, while in ultrasonic computed tomography (UCT), the decay of ultrasound is measured. The image processing algorithms are similar in both methods.

Ultrasonic CT method gives also additional information about the propagation time of the sound wave in the object, which allows

determining regions with different speeds of sound inside the object. However, to avoid loss of ultrasound energy on the way from the sensor to the object, the object (patient) should be immersed into water, and for this reason UCT is rarely used as a medical diagnostics method compared to X-ray CT.
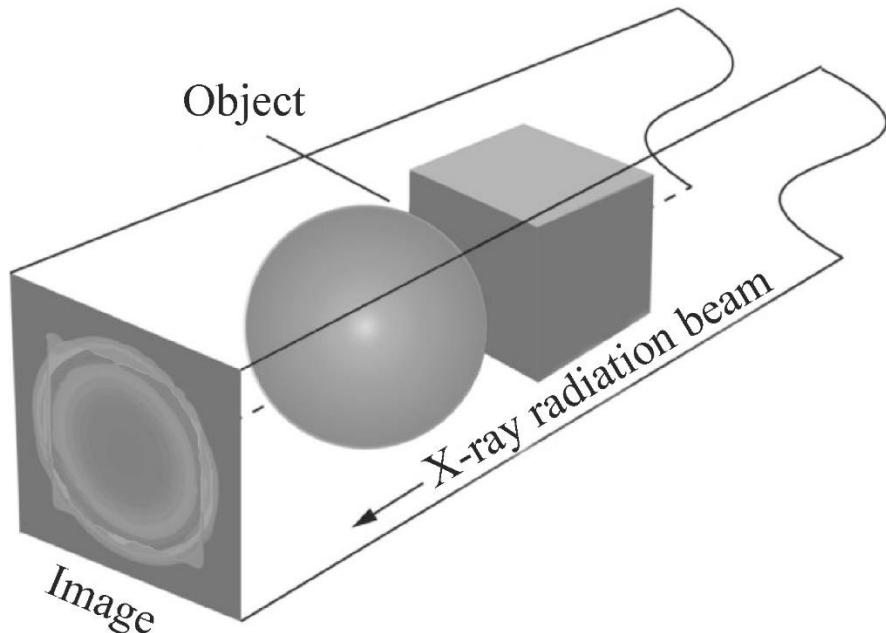

Figure 52. Image obtained as a projection in a single relative position of the object, radiation source, and detector

In an X-ray CT investigation, X-rays from a source are passing through an object, and then the irradiation absorption level is registered in an array of points at the same time. The "source – sensor" system is then rotated around the object (patient) by a certain angle, and a new scan is acquired (figure 53a). This action is repeated several times until the whole required angle range is swept.

In an UCT study, there is only one sensor, which can measure the signal intensity only at a single point at a time. Therefore, signal intensity should be measured in several positions one by one. The smaller is the distance between neighbour points, the better is the resulting image. The sum of the distances between all points gives

the scanning width. After the scan is acquired, the object should be moved back to the initial position in the "transmitter – sensor" system to start the next scan (figure 53b).
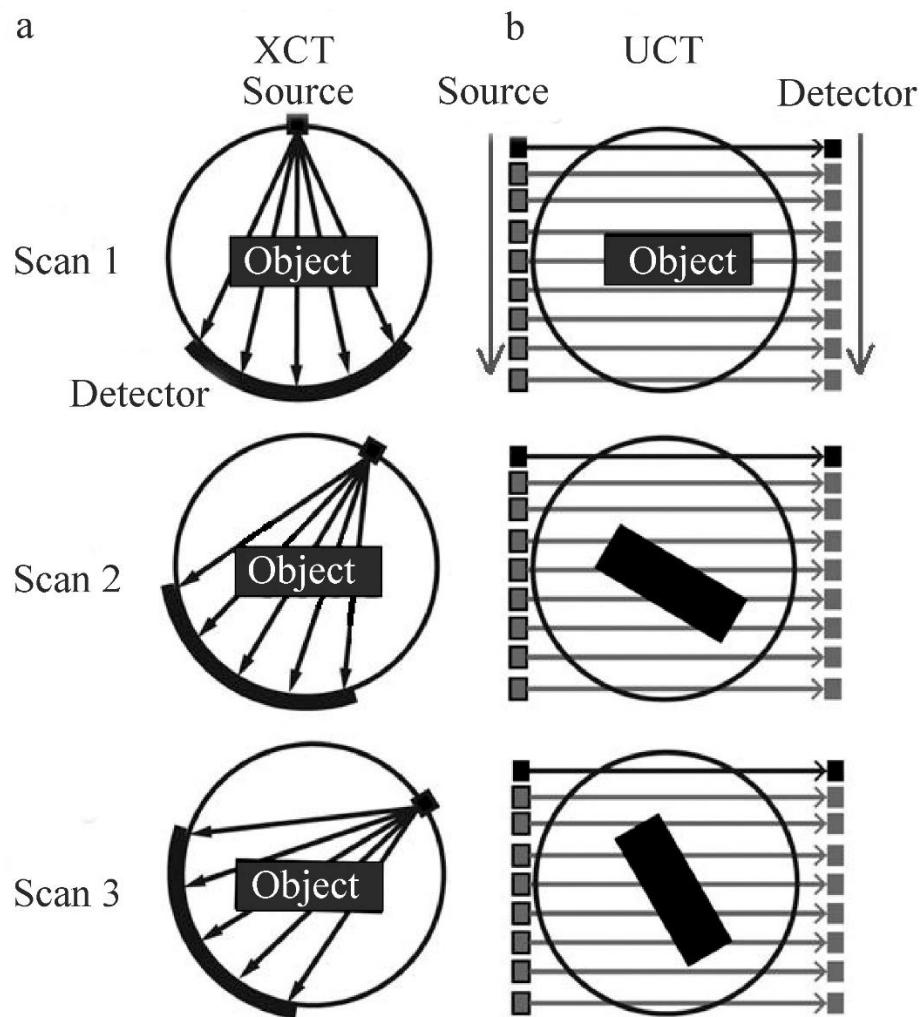

Figure 53. General principle of obtaining images in (a) X-ray and (b) ultrasonic computed tomography.

After obtaining a series of scans, the reconstruction step begins. Usually, several scans are obtained, and then the patient is moved along the axis of the tomography apparatus, and the process is repeated until the whole region to investigate is covered.

Decay of a wave passing through a homogeneous medium fulfils the exponential law:

$$I = I_0 e^{-\mu x}, \qquad (199.1)$$

where I is the radiation (wave) intensity which leaves the object, I_0 is its initial intensity, μ is the attenuation factor, and x is the thickness of the material layer.

If the medium is inhomogeneous and can be divided into volume elements (voxels) with the size of Δx each, then

$$I = I_0 e^{-\sum_k \mu_k \Delta x}, \qquad (199.2)$$

where μ_k is the attenuation factor in the kth element. If we move I_0 to the left part of this equation and calculate logarithm, we derive

$$\sum_k \mu_k = \frac{1}{\Delta x} \ln \frac{I_0}{I}. \qquad (199.3)$$

This expression allows us to divide the whole profile of the image into regions characterised by different attenuation factors taken in different scans. If then the results obtained for all scanning angles are considered, the two-dimensional image with the pattern of distribution of the attenuation factors can be reconstructed.

Special envelope filters are used to allow for logarithmic decay profiles before the superposition procedure to obtain good images (without severely blurred details).

Which should be the angle increment? Superpositions of the directions in the 1 and 3 quadrants and in the 2 and 3 quadrants (figure 54) should not overlap. The rotation angles for different directions also should be constant. If these criteria are fulfilled in 1 and 3, and also in 2 and 4 quadrants, then we have:

$$nx = 180° + x/2, \qquad (199.4)$$

$$x = \frac{180°}{n - 1/2}, \qquad (199.5)$$

here x is the angle increment, and n is an integer number. Rational solutions of this equation are listed in the table (below).

Table. Angle increments x corresponding to n scanning directions

n	x	n	x
1	360°	23	8°
2	120°	38	4.8°
3	72°	63	2.88°
5	40°	113	1.6°
8	24°	188	0.96°
13	14.4°		
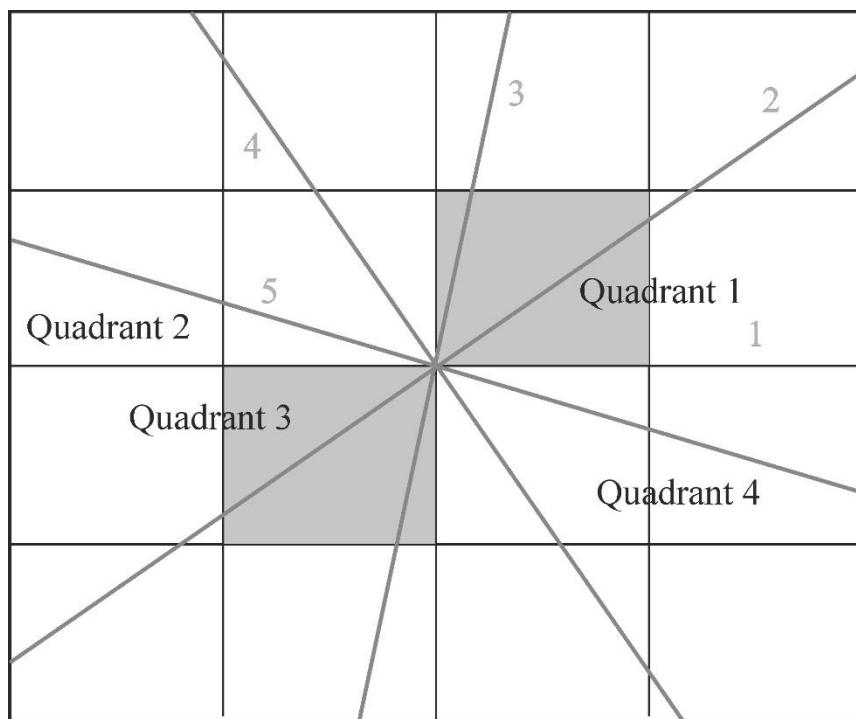
Figure 54. Quadrants and an example set of scanning ray orientations for $n = 5$.

Equipment (figure 55)

1. Ultrasonic echoscope GS200
2. Ultrasound probes (1 MHz, blue; 2 MHz, red)
3. CT scanner
4. CT control unit

5. CT sample
6. CT reservoir
7. Ultrasonic gel
8. Laptop

Figure 55. Experimental setup for performing ultrasonic computed tomography

Algorithm of measurements

Preparations (connecting and tuning)

1. Fill the bath with water so that the water level is 5 cm above the holder of ultrasound (US) probes.
2. Lower the scanning system using the screws until the magnetic holder of the sample is below the water surface (as in figure 54).
3. If necessary, clean the glass surface within the US probe holders to remove impurity and remaining gel.
4. Apply gel onto two 2-MHz sensors (red) and attach them to the holders in the opposite positions. Make sure that the amount
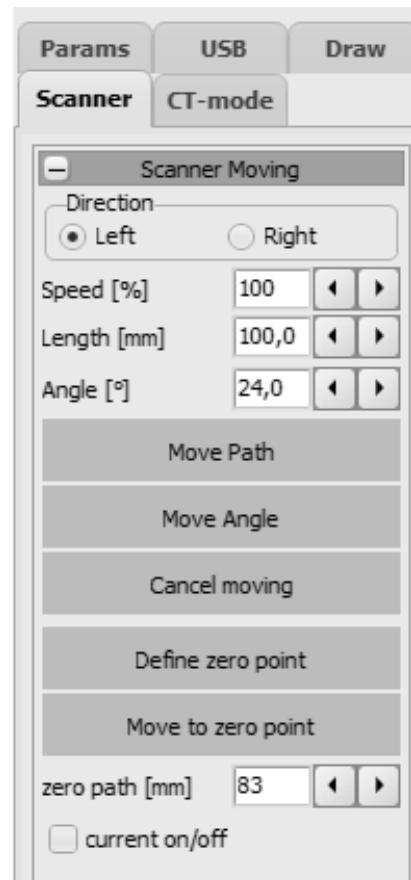
of gel is sufficient and there are no air bubbles between the sensor and glass, since they would distort the image.

5. Connect the sensors to the echoscope's input jacks "Probe 1" and "Probe 2."

6. Check that the CT scanner is connected to the CT-Controller unit, and that the echoscope, Flow Doppler CT scanner, and the CT-Controller are connected to the computer (laptop).

7. Launch the GS-EchoView programme, choose the "CT-mode" tab, and press the "Start A-scan" button.

8. Set the "Gain" and "Output" selectors of the echoscope to 10 dB. Make sure that the signal observed by the computer does not exceed the sizes of the window. **The TGC controls should be set to zero.**

9. Signal amplitude can be regulated by accurate moving and turning the US probes in their holders if you slightly loose the holder screws. After you finish regulating, fasten the screws back again.

10. Attach the object to study (a black cylinder) to the scanner's magnetic holder (the magnet on the sample top has a lug which should be inserted into the scanner's holder).

11. Turn the "Gain" and "Output" selectors of the echoscope to 25 dB. (Do not move the TGC selector.)

12. Using the "Linear" control on the UCT200 sensor control unit, move the sample so that the centre of the cylinder is exactly between the probes. This position will be the initial position in all further experiments.
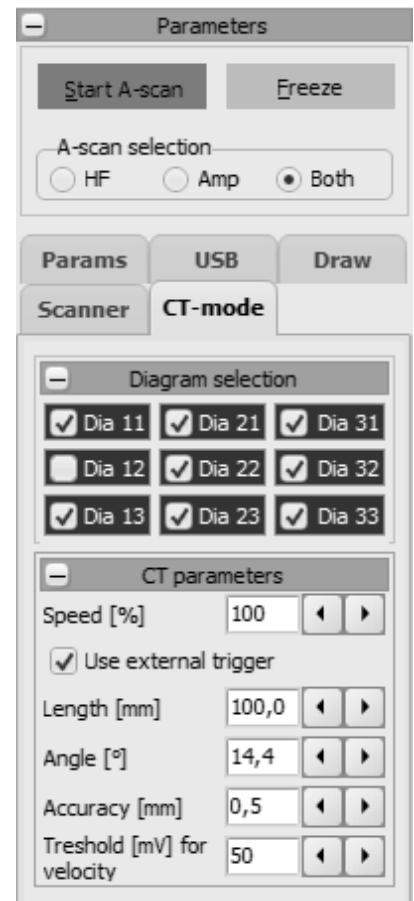
13. Go to the "Scanner" window in the GS-EchoView programme and choose the "Define zero point" option. After you make it, the control unit will move the sample to the limit position of the rail and return it back.

14. Then you should define the scanning length so that the measurements start before the sample goes between the probes and complete after it leaves the region between the probes. In the leftmost and rightmost positions, ultrasound should pass through water but not through the sample. To do this, set the value of 100 mm in the "Length" input line in the "CT parameters" tab of the GS-EchoView programme.

15. Set the resolution of the image as 0.5 mm in the corresponding input line "Accuracy." The smaller is this value, the more detailed image you will obtain, and the longer will be the experiment duration.

16. Set the angle to 14.4° in the same tab. The measurements will be done until the sample makes one full revolution with this angle step.

Task

Study the principles of image formation in ultrasonic computed tomography

17. Switch to the "CT scan" mode and press the "Smart CT scan" button.

18. Six pictures will appear on the screen (figure 56). Two upper images correspond to the absorption spectrum of ultrasound waves by the sample and the sound propagation time in the sample obtained in the last scan (without image filtering). Two panels in the middle show the absorption spectrum and propagation time averaged over all scans (without filtering). Two bottom pictures are the same images processed using the filtration algorithm.

19. Save the obtained images (menu Save → Save Images).

20. Repeat the experiment with other transmitter and amplifier settings: output 20 dB, gain 25 dB;
    output 30 dB, gain 30 dB;
    output 30 dB, gain 35 dB.
21. Compare the obtained images and determine which parameter set was the best. Repeat the measurements with these settings.
22. Analyse obtained tomograms; make conclusions on the inner structure of the investigated object.
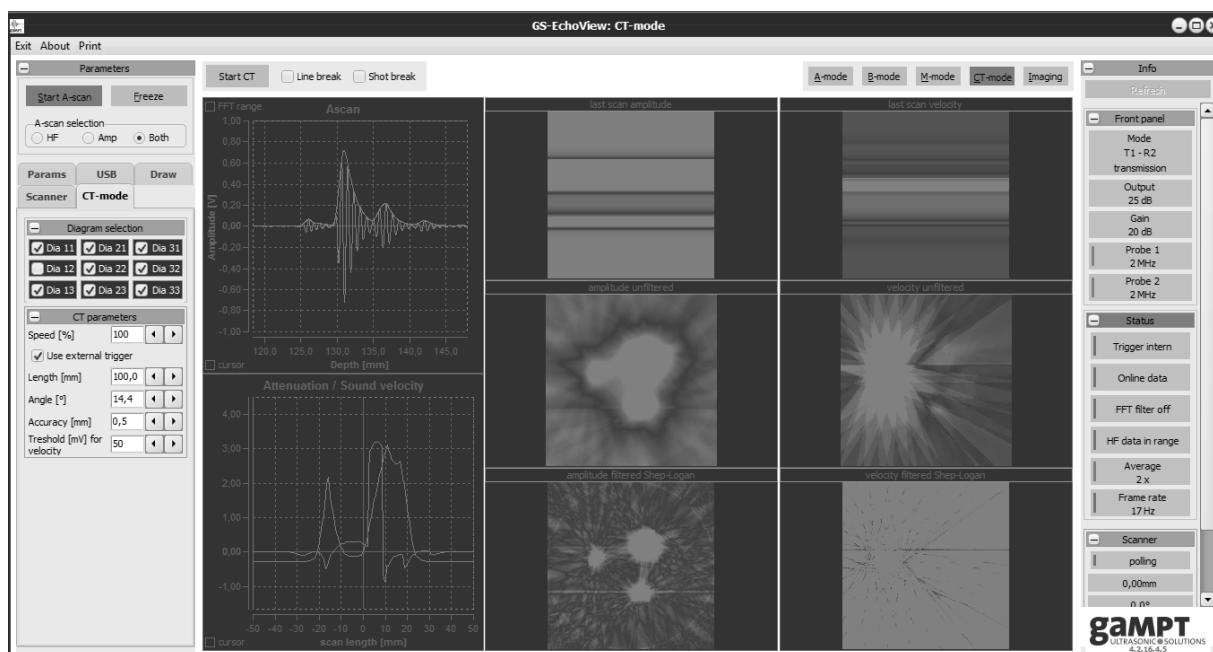

Figure 56. A typical screenshot of the GS-EchoView programme

General questions for works with ultrasound:

What are harmonic oscillations? What is amplitude, frequency, cyclic frequency, period of harmonic oscillations? What is a wave? What is wavelength? What is the difference between longitudinal and transverse waves? Why are there no transverse waves in gases and liquids? What wave is called plane, spherical? Write the equation of a traveling plane wave.

What are the acoustic oscillations? What frequency range does the human ear perceive? What determines the speed of sound in air? Compare the speed of sound propagation in different media.

How the ultrasonic sensor works? Forward and reverse piezoelectric effect.

Why do we need to apply the gel when conducting ultrasound studies? What determines the intensity of the reflected ultrasound wave? Acoustic impedance. The use of ultrasound in medicine.

Special questions:
1. Interactions of ultrasound with media. Acoustic impedance. Reflection, scattering, transmission, absorption, acoustic attenuation.
2. Speed of sound.
3. Spatial resolution in an ultrasound image (axial resolution, lateral resolution and elevational resolution)
4. Ultrasonic echography (A-scan, B-scan).
5. Ultrasonic computer tomography (CT).
6. CT scan image, image processing, filters.

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Further reading:

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For notes