ARCHIVES OF ACOUSTICS
26, 2, 133–141 (2001)

VERIFICATION OF MEASUREMENT POSSIBILITIES OF QUASI-CONTINUOUS ACOUSTIC WAVE PACKETS FOR TECHNICAL AND MEDICAL APPLICATIONS

M. SZUSTAKOWSKI*, L. JODŁOWSKI* and M. PISZCZEK**

Military University of Technology
*Institute of Optoelectronics
**Institute of Fundamental of Electronics
(00-908 Warszawa, 2 Kaliskiego Str., Poland)

Quasi-continuous acoustic wave packets are used for investigations of real objects due to determination of their material parameters such as, for example, propagation velocity of an acoustic wave, or localisation of their inner structures. Application of low sampling frequencies (500 kHz) in comparison with the strict harmonic probing signals ~ 1.5 MHz offers very promising measuring possibilities (detection of the transit time changes of acoustic signal ≈ 5 ns). This paper shows the test measurement results for a glass vessel (300 mm probing path in distilled water) and patients with pathological changes (ischemia and internal haemorrhage in the brain tissue) using the phase and time methods. High sensitivity of measurements ensures detection of differences in density of the order of $\sim 3 \cdot 10^{-3}$ kg/m^3, propagation velocity of acoustic wave $\sim 4 \cdot 10^{-2}$ m/s, temperature $\sim 1.5 \cdot 10^{-2}$ K and change of the acoustic path $\sim 4\,\mu$m. Sensibility and simplicity of the measuring system makes the proposed solution a very attractive tool for investigations. It can be applied for measurement of different changes of the material properties in the automatic systems and medicine.

1. Basic information on measuring method and details of a measuring system

The measuring process consists in determination of temporal relations between the transmitted and received acoustic signals as a result of the phase analysis of these signals.

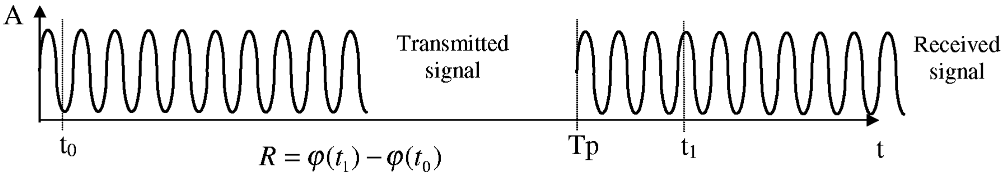


Fig. 1. Idea of the measuring method of phase relations of acoustic wave packets.

Phase method [2] is based on the analysis of the phase relations R between the transmitted and received signals for one probing frequency f. Time method [4] is a developed phase method that employs two suitably selected frequencies and determines the transit time of a probing signal Tp

$$\begin{aligned} Tp &= (t_1 - t_0) + \frac{1}{4\pi}\left(\frac{R_1 + 2\pi P_1}{f_1} + \frac{R_2 + 2\pi P_2}{f_2}\right), \qquad (1.1)\\ P_1 &= \text{integer}\left(\frac{R_{12} f_1}{2\pi(f_1 - f_2)} - \frac{R_1}{2\pi}\right),\\ P_2 &= \text{integer}\left(\frac{R_{12} f_2}{2\pi(f_1 - f_2)} - \frac{R_2}{2\pi}\right),\\ R_1 &= \varphi(t_1) - \varphi(t_0) \quad \text{for } f_1, \qquad R_2 = \varphi(t_1) - \varphi(t_0) \quad \text{for } f_2, \qquad R_{12} = R_1 - R_2\,. \end{aligned}$$

Both methods are aimed at determination of the elementary phases [1]. It is possible to find the signal parameters, including the phase value φ, using solutions of the problem approximation of n samples satisfying the equation of a harmonic wave.

The measuring system consists of a transmitting–receiving module and a computer with the A/D converter card.

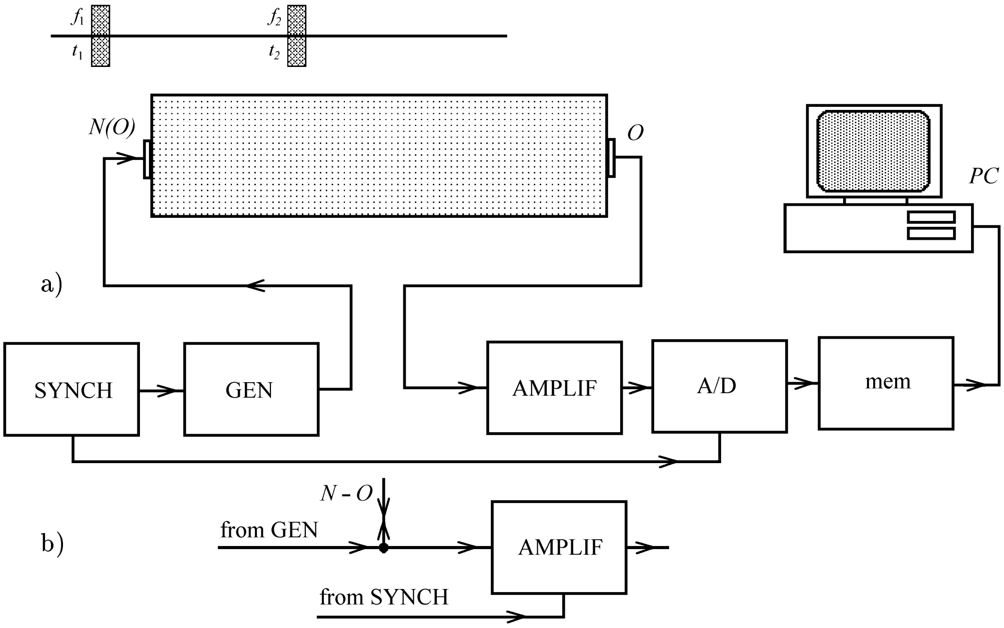
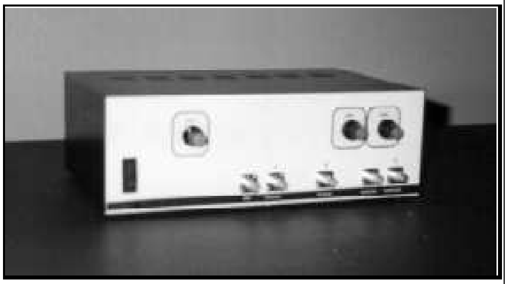
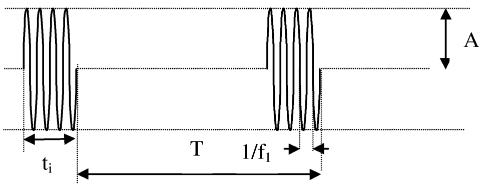
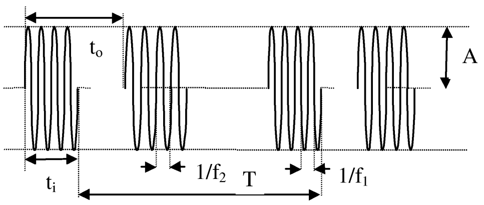


Fig. 2. Block scheme of a system for measurement of the phase relations between acoustic wave packets: a) transmitting version, b) reflecting version.

The measuring system is connected to the test stand by an ultrasound transducer. For the measurement of an oscillation phase, the steady oscillations of an ultrasound transmitter are used. It is sufficient to get several samples to determine the phase of a signal, so the generated signal is called a quasi-continuous wave. An acoustic transducer with the following parameters was used: the diameter $D = 20\,\mathrm{mm}$, the resonance frequency

Table 1. Characteristics of transmitting–receiving modules.

System for phase method	System for time method
	
Type of system work: — transmitting, reflecting Transmitting path: — amplitude of signal coming to converter (40, 50, 60, 70) [$V_{p\text{–}p}$] — acoustic wave frequency $f_1 = 1.4(6)$ MHz, — period of pulse repetition $T = 1.5$ [s], — pulse duration $t_i = 34$ [μs]	Type of system work: — reflecting Transmitting path: — amplitude of signal at the converter input (4 – 60) [$V_{p\text{–}p}$] — acoustic wave frequency $f_1 = 1.4(6)$ MHz, — period of pulse repetition $T_1 = 0.1$ [s] and $T_2 = 2$ [s], — pulse duration $t_i = 45$ [μs], — delay between pulses $t_0 = 640$ [μs]
	
Receiving path: — time intervals 0 – 60 μs —- attenuation 100 dB, 60 – 80 μs — gain to 20 dB, 80 – 500 μs — gain to 90 dB, — receiving band 3 dB 1.385 – 1.530 MHz dimensions: 300 × 100 × 190 mm weight: 2 kg supply voltage: 220 V/50 Hz	Receiving path: — time intervals 0 – 90 μs — attenuation 100 dB, 90 – 640 μs — gain to 90 dB, 640 – 730 μs — attenuation 100 dB 730 – 1200 μs — gain to 90 dB, — receiving band 3 dB 1.385 – 1.530 MHz dimensions: 260 × 150 × 250 mm weight: 2.5 kg supply voltage: 220 V/50 Hz

$f_0 = 1.43$ MHz and the quality factor $Q \sim 5$. Testing of the measuring method employs the low-frequency signal sampling, so that relatively long-duration probing pulses of ~ 45 μs were used.

According to the relationship defining the minimum error of determination of the phase φ as a function of the sample number n, the period of the signal sampling being

t_{pr} the frequency sampling signal f is

$$f = \frac{m}{t_{\mathrm{pr}} \cdot n} \qquad \text{for} \quad f > f_{\mathrm{pr}}, \tag{1.2}$$

where m is a natural number.

The relationship defining correctness of an algorithm of the measuring method of the transit time of the probing signal is

$$|Tp - Tp_Z| < \frac{1}{2|f_1 - f_2|}, \qquad \Delta\varphi < \frac{\pi(f_1 - f_2)}{4f_1} \quad \text{for} \quad f_1 > f_2, \tag{1.3}$$

where Tp_Z is the permissible error of rough estimation of the transit Tp, and $\Delta\varphi$ is the error of phase signal determination.

The parameters for each measuring method were determined:

— for the phase method

$$n = 15, \qquad t_{\mathrm{pr}} = 2\,\mu\mathrm{s}, \qquad f = 1.4(6)\,\mathrm{MHz},$$

— for the time method

$$n = 15, \qquad t_{\mathrm{pr}} = 2\,\mu\mathrm{s}, \qquad f_1 = 1.4(6)\,\mathrm{MHz}, \qquad f_2 = 1.4\,\mathrm{MHz}.$$

The data acquisition was made with the A/D converting card (AMBEX LC-30-1612) and for data processing, the Pentium 166 computer was used [1].

2. Results of test measurements

Analysis of the presented measuring method in the proposed application was based on:

— Computer simulations showing that 12-bits A/D conversion card sampling with 500 kHz frequency limits the theoretical measuring resolution (concerning indeterminancy of the sampling time) to $R_r = 0.2°$ and $Tp_r = 0.4\,\mathrm{ns}$;

— Signal generator (Hewlett Packard 33120A): operation in a harmonic signal mode determining $R_r = 0.4°$ and operation in a switching mode (frequency f_1 and f_2) limiting the measuring resolution to $Tp_r = 1\,\mathrm{ns}$;

— Laboratory system, including a glass cell with a movable barrier. Precise shift of the barrier was done by means of a micrometer screw (with a 10-μm scale). Distilled water was the measuring medium in the cell. During the measurement, the temperature of liquid was controlled by the "Fat-mini" system ensuring water circulation and interacting with a heating element and a thermostat (RT-2).

During the tests with a transmission method (reflection), the measuring space L (acoustic path) was 150 mm in length (300 mm), depending on the character of investigations. The tests were aimed at verification of the measuring possibilities of the devices used for investigation of the physical and structural properties of the media. This laboratory set limits the real measuring resolution to $R_r = 2.5°$ and $Tp_r = 5\,\mathrm{ns}$.

A model device employing the phase method [2] is used for monitoring the medium properties when the changes of the phase relations R (between the transmitted and received waves), determined in the consecutive measurements, do not exceed the value $\pm\pi$,

$$\Delta R(i) = R(i) - R(1). \tag{2.1}$$

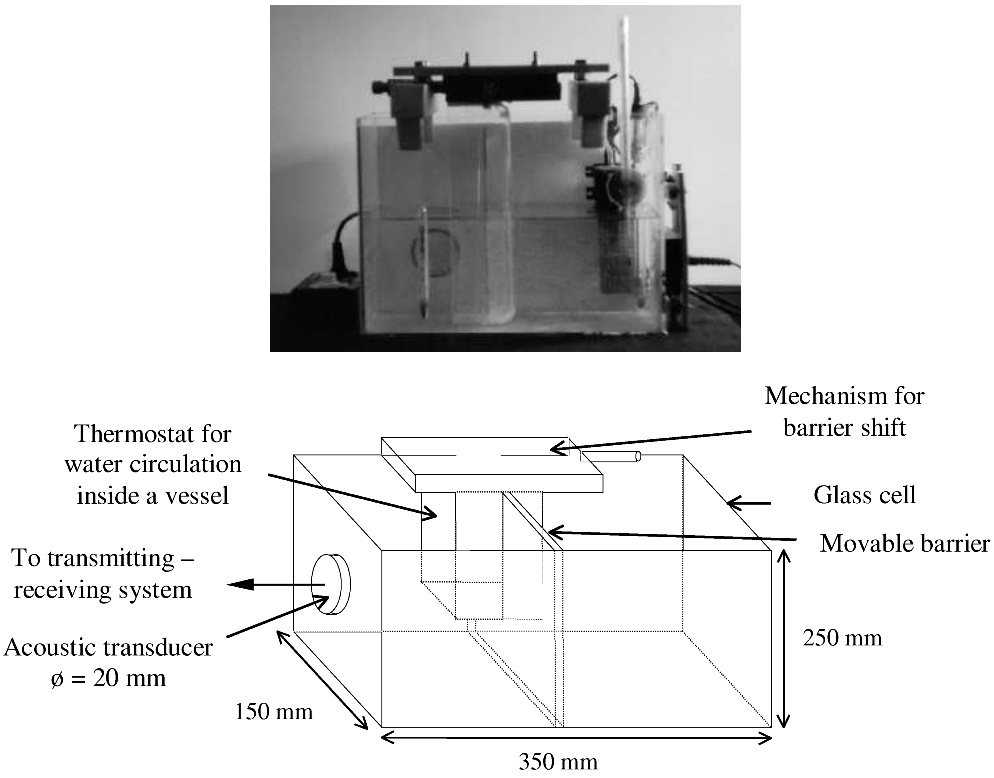


Fig. 3. Laboratory set-up.

The test performed, using the reflection method, traced the changes of the liquid temperature for 3 hours.

Theoretical considerations show that such a modification of physical parameters results in a change of the velocity of wave propagation c,

$$c = 1402.385 + 5.038813T - 5.799136 \cdot 10^{-2}T^2 + 3.287156 \cdot 10^{-4}T^3 - 1.398845 \cdot 10^{-6}T^4 + 2.787860 \cdot 10^{-9}T^5 \tag{2.2}$$

(where T is the temperature in Celsius degrees), what causes a change of the echo return time and also a change of phase signal relations

$$c = \text{var}, \qquad L = \text{const} \qquad \Delta R = 2\pi f(Tp_2 - Tp_1) = 2\pi f\left(\frac{L}{c_2} - \frac{L}{c_1}\right). \tag{2.3}$$

The obtained results confirm high consistence of theoretical results ($\Delta R \approx -585^\circ$) with the experimental ones ($\Delta R \approx -580^\circ$).

The model device employing the time method [4] is free from limitations of the phase method (range of phase changes $\pm\pi$) and gives information on the system state — the transit time of acoustic wave Tp

$$Tp = (t_1 - t_0) + \frac{2\pi P + R}{2\pi f}. \tag{2.4}$$

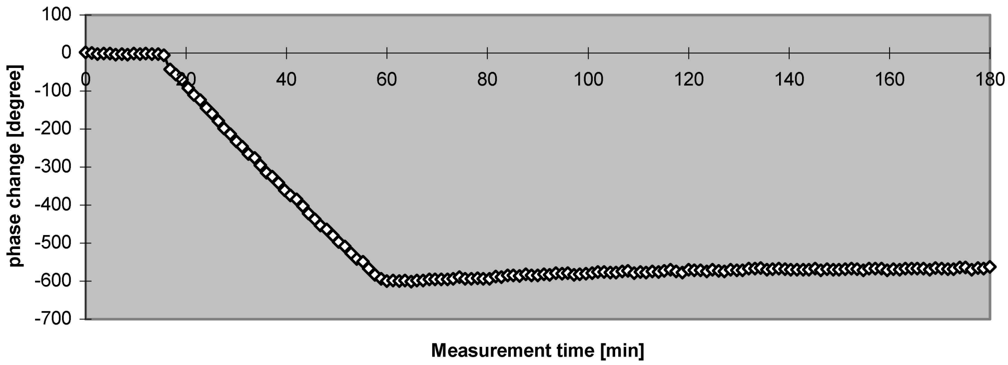


Fig. 4. Test results of temperature changes within an investigated object.

Determination of the transit time is based on the phase φ analysis and concerns the solution of the, so-called, full multiplicity of the wavelength P on the acoustic path. In order to verify correctness of the method, measurements of the path length change have been made ($\Delta L_{\max} = 4 \times 0.5\,\mathrm{mm}$) in the investigated object using a movable barrier. It follows from theoretical investigations that such a modification of a structure should induce a change of the transit time

$$c = \text{const}, \qquad L = \text{var}, \qquad \Delta Tp = (Tp_2 - Tp_1) = \left(\frac{L_2}{c} - \frac{L_1}{c}\right). \tag{2.5}$$

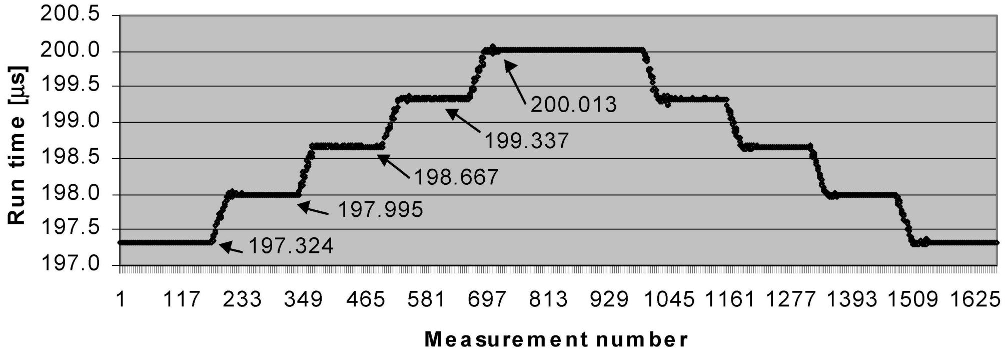


Fig. 5. Test results of discreet length changes of an acoustic probing path.

The obtained experimental results are consistent with the theoretical ones what is confirmed by the time leap t_{leap} corresponding to an elementary barrier shift:

$$t_{\text{leap}} = \frac{2z}{c} = \frac{2 \cdot 0.0005\ [\mathrm{m}]}{1487\,[\mathrm{m/s}]\ (T = 21.5^\circ\mathrm{C})} = 6.725 \cdot 10^{-7}\ [\mathrm{s}]. \tag{2.6}$$

The test results are presented in Table 2.

Table 2. Measuring resolution.

Phase relations R	$2.5°$
Transit time Tp	5 ns
Shift	3.75 µm
Acoustic wave velocity	1.12 (m/s)/cm
Temperature	0.45°C/cm
Density	0.09 (kg/m^3)/cm

3. Results of medical tests

New approach in acoustic research of brain blood supply has been made. Vascular diseases in a nerve tissue cause edema or haemorrhage of the brain. Thus, physical parameters of the brain are changed. The density ρ and the elasticity modulus K are the main acoustic properties of the tissues. The velocity of acoustic wave c is dependent on density and elastic properties $c = \sqrt{K/\rho}$. The distance L of an acoustic beam inside the brain is constant, what guarantees rigidity of the skull. The transit time of acoustic wave Tp depends on the ratio of the acoustic path and velocity of the acoustic wave, $Tp = L/c$. Changing the velocity Δc causes the change of the transit time ΔTp. The best region for acoustic probing is located between temporal bones, because most of the brain structures are parallel to each other and perpendicular to the acoustic beam. Human brain is 15-cm long (between the temporal bones) and it consists of soft tissues (density of about 1000 kg/m^3, sound velocity of about 1530 m/s). The transit time of an acoustic wave (between temporal bones) is about 100 µs. In a diseased brain, this time can change by about 100 ns.

The measuring device called *Encephalodensometer* and used for monitoring the pathological changes of blood circulation in blood vessels was prepared in cooperation with Prof. Roman Mazur from the Neurology Clinic of Medical Academy in Bydgoszcz. The obtained results show the possibilities of investigation of this kind of brain blood vessels pathology [3] what is confirmed in Figs. 6 and 7.

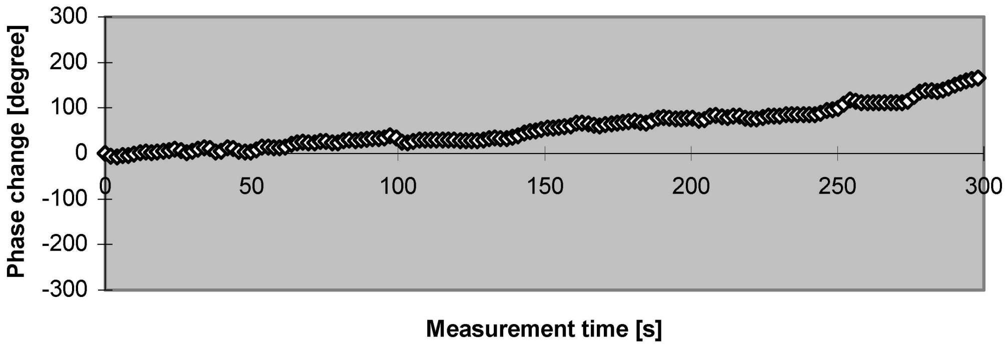


Fig. 6. Typical results for patients with diagnosed ischemia or retreating haemorrhage.

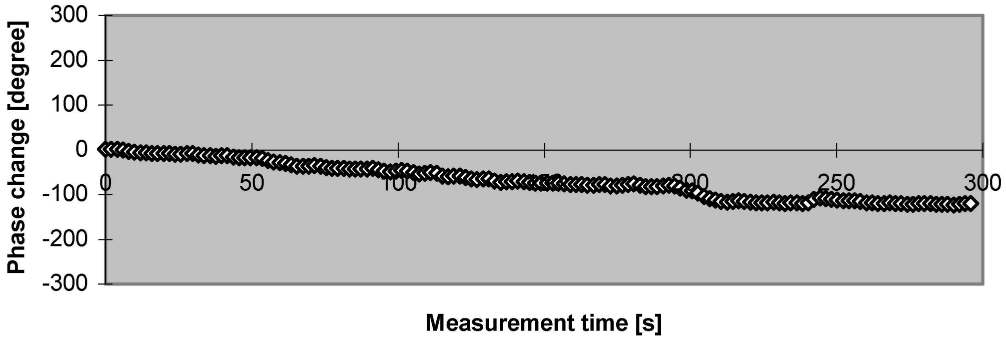


Fig. 7. Typical results for patients with diagnosed haemorrhage or retreating edema.

However, the obtained results are not sufficient for drawing a distinction between ischemia and haemorrhage processes for pathological changes. It is caused by the restitution mechanism in a brain. Restitution can appear alternately with pathological changes, the dynamics of which are opposite to the self-control ones.

4. Conclusions

The proposed measuring method is an innovative one:

1. It leads to a solution including the elements applied in the methods based on a continuous wave and elements used for the pulse technique.

2. Steady oscillations of piezoelectric receiver are used for the measuring process, both for transmission and receiving the signals, what ensures a very good quality of the harmonic signal and finally, reduces the error of phase determination.

3. Wavelength and number of the examined samples are optimised for minimum error of the phase detection. It is in close relation to the frequency of the tested signal and its sampling rate. Lower sampling rates of a signal can be used than the frequency of wave propagating in a medium with a similar measuring precision. Satisfactory phase determination can be obtained using at least 10-bits A/D converters (recommended 12-bits). It has been shown in the error analysis and confirmed by the experiments.

4. The phase relation analysis, for a single frequency of an acoustic probing signal (phase method), is suitable for the measurements of relative signals (phenomena monitoring). Application of two different and appropriately optimised probing frequencies makes it possible to determine the transit time.

5. The measuring method, based on the phase relations analysis, ensures resolution in the range of a few hundredths of the period of the probing wave used.

The features presented above make this method attractive for applications. It does not employ any sophisticated equipment. The obtained results show that the method can be applied in fundamental research on materials, sensors, and for medical diagnosis.

References

[1] L. Jodłowski, *Measurement of harmonic signal phase using low sampling frequency*, 27th Winter School on Molecular and Quantum Acoustics, Ustroń 23-27.02.1998.

[2] M. Szustakowski, L. Jodłowski and M. Piszczek, *Measurements of changes of phase velocity in a fluid using digital signal processing*, 27th Winter School on Molecular and Quantum Acoustics, Ustroń, Feb. 1998.

[3] M. Szustakowski, L. Jodłowski and M. Piszczek, *First experience by using ultrasound in measurement of change brain density*, 1st INTERDISCIPLINARY FORUM OF STROKE — conference materials, Wrocław, September 1998.

[4] M. Szustakowski, L. Jodłowski and M. Piszczek, *Passage time measurement of medium probe signal with the use of phase method with quasi-continuous wave*, 28th Winter School on Molecular and Quantum Acoustics. Ustroń, Feb. 1999.