Ultrasonic method for measuring of gas bubbles in liquids

I H A Al-Umari¹, N F Kashapov¹, V G Saitkulov² and M Fazlyyyakhmatov¹
¹ Kazan (Volga Region) Federal University, 18 Kremlyovskaya str., Kazan 420008, Russian Federation
² Kazan National Research Technical University named after A.N. Tupolev, 31 K. Markska str., Kazan 420111, Russian Federation
alumari1986@mail.ru

Abstract. The paper proposes to use an ultrasonic method to measure the content of gas bubbles in liquids. The task is relevant in various applications. Industrial ultrasonic analyzer STOK-101 was used to implement the method.

1. Introduction
Currently, a large number of methods and apparatus for the control of various impurities in liquids have been developed [1-4]. Oil products, wastewater and other liquids can act as the object of control. As pollutants and impurities can be solid particles, drops of other liquids. The analyzers are imperfect and have limited parameters.

Existing methods for determining the content of liquid droplets and suspended particles in water can be divided into the following categories:

- Laboratory experiments (colorimetric, gravitational, etc.);
- Methods to analyzing both laboratory and field conditions (UV, fluorescence);
- Acoustic measurement methods.

All of the above methods do not allow automatic real-time monitoring. In addition, the errors of most of these methods are quite large.

Of all these methods, acoustic or more precisely ultrasonic are the most promising.

2. Materials and methods
The method is based on reflection from air bubbles or other ultrasound defects.

The distance between the receiver and the defect, the type of defect (sphere, hole having a spherical bottom, a hole with a flat bottom, a plane, a side hole of a cylindrical shape), the filling of the defect (air or other gas) affect the amplitude of the reflection of the ultrasound signal from the defect. They have a greater impact on the reflection strength of the signal amplitude. The calculation of echo amplitudes for reflection from a sphere or a hole with a spherical bottom of diameter d is carried out as follows:

The attenuation of the signal amplitude when reflected from a sphere or a hole with a spherical bottom with a diameter d can be represented as [5]:

\[
\frac{A}{A_0} = \frac{Sd}{4\lambda r^2} \exp(-2\delta r),
\]

(1)
where $A_0$ is the emitted signal amplitude, $A_1$ is the received signal amplitude, $S$ is the piezoelectric transducer area, $d$ is the diameter of sphere, $r$ is the distance from transducer to defect, $\lambda$ is wavelength, $\delta$ is the attenuation coefficient.

The signal attenuation described by the first part of the formula is called diffraction. The second part of the formula describes the scattering of ultrasound in the medium.

The formula is valid if the diameter of the sphere or cylinder is greater than half the wavelength. If the defect diameter is less than half wavelength, then the reflection amplitude with a decrease in diameter during diffraction rounding of the defect in waves will decrease faster. Therefore, defects that are smaller than the wavelength are difficult to detect. For reflection from holes with a flat or spherical bottom, the formulas remain relevant, even if the diameters of the holes are smaller than the wavelength, since the side walls are an obstacle to bending around.

It is assumed that each point in the sphere is considered a secondary ultrasound emitter. The ultrasonic reflection can be represented as:

$$\frac{|P_1|}{|P_0|} = \frac{\lambda^2}{S} |I|^2 A_c,$$

where $P_0$ is the amplitude of the pressure tensor component emitted by the transducer, $P_1$ is the amplitude of the pressure tensor component received by the transducer, $I = \frac{S}{\lambda x}$ is function characterizing the delay in the far zone, $A_c = \frac{d}{4\lambda}$ dimensionless coefficient characterizing the reflectivity of the sphere.

In fact, there is reflection from a defect even if its diameter is smaller than the wavelength. In the region $d \ll \lambda$, with decreasing $d$, the amplitude decreases much faster ($A_c \approx 4.3d^3/\lambda^3$) than for $d > \lambda$.

In the case of a sphere with a diameter of significantly shorter wavelength:

$$\frac{|P_1|}{|P_0|} = \frac{\lambda^2}{S} \frac{S^2}{\lambda x} \frac{4.3d^3}{\lambda^3} = \frac{4.3Sd^3}{\lambda^3 r^2}.$$

(3)

The dependence of the signal amplitude on the bubble volume is:

$$\frac{|P_1|}{P_0} = \frac{4.3Sd^3}{\lambda^3 r^2} = \frac{25.8S}{\pi \lambda^3 r^2} V,$$

(4)

where $V$ is the bubble volume.

Multiplying the numerator and denominator of expression (4) by the density of the substance we get:

$$\left| \frac{P_1}{P_0} \right| = \frac{25.8S}{\pi \lambda^3 r^2 \rho} m,$$

(5)

where $m$ is the bubble mass.

The amplitude of the ultrasound signal reflected from the bubble in the electrolyte is directly proportional to its mass at $r \ll \lambda$.

The real reflected signal also depends on the ratio of the acoustic resistances of water and gas. The reflection coefficient is determined by the formula:
\[ R = \frac{Z_E - Z_B}{Z_E + Z_B}, \quad (6) \]

where \( Z_E \) is the acoustic impedance of the electrolyte, \( Z_B \) is the acoustic impedance of the gas bubble.

3. Experimental results and discussion

When emitting an ultrasonic signal in the form of continuous wave and receiving reflected signals, it is necessary to eliminate the induced signal to the receiving transducer. Practically, this cannot be done. One solution to this problem is a method of exciting a transmitting transducer with a pulsed signal, and receiving reflected pulses after some time from such a calculation so that at the time of their arrival, the amplitude of the induced signal from the sounding pulse is negligible. It was proposed to implement such a signal as a product of a single function, sinusoid and exponent:

\[ f(t) = \gamma(t) \cdot \exp\left(-\frac{t}{\tau}\right) \cdot \sin(\omega \cdot t). \quad (7) \]

Moreover, the attenuation coefficient of the exponential component \( \tau \) is chosen so that the noise level from the probe signal at the time of arrival of the pulses reflected from oil droplets and solid particles is minimal.

The study of the attenuation of ultrasound in the liquid allowed us to choose the frequency range of ultrasonic vibrations \( \sim 4 \text{ MHz} \), taking into account the fact that 90% of the suspended particles have a size not exceeding 5 \( \mu \text{m} \) in diameter.

The ultrasonic signal coming to the receiving transducer is complex and consists of a set of single pulses having an exponential shape. These pulses are reflected from gas bubbles, suspended liquid and solid particles and carry information about their mass content in wastewater. However, it is impossible to determine their content by simply measuring the amplitude of the signal. To solve this problem, a method based on comparing the reflected signal with the reference voltage and counting the number of pulses exceeding each level is developed.

Figure 1 shows the schematic diagram of the device by which the reflected signals from the air bubbles in the liquid are measured. The main elements of the device are: 1 is generator connected by a high-frequency output with a transmitting piezoelectric transducer, 2 is converter separately-combined type, placed in the body 3. The receiving piezoelectric transducer 4, connected to the input of the amplifier 5, the output of which is directed to the input of the controlled comparator 6. The output of the latter is connected to the logic input of the microcontroller 7, which is connected to the synchronizing output of the generator 1. The logic outputs of the microcontroller 7 are connected to the inputs of the controlled comparator 6. Data analysis is performed from a computer connected to the microcontroller via a USB port.

![Figure 1-Schematic diagram of the STOK-101.](image-url)
The main difficulty of the measurements is that with a large number of air bubbles (more than 100) there is an overlay of reflected signals. To solve the problem, an algorithm is used, which consists in summation of signals depending on the digitized reference voltage levels in the range of 8-120 mV. The number of reflected pulses was given by the formula:

$$Q = a + bM + cM^2 + dM^3,$$  \hspace{1cm} (8)

and the coefficients A, B, C, D were determined by the least squares method based on the number n - by the total number of measurements:

$$Q_i = a + bM_i + cM_i^2 + dM_i^3, i = (1;n)$$  \hspace{1cm} (9)

where $Q_i$ are values of the total content of suspended gas bubbles and solid particles determined from the samples of wastewater by certified method (laboratory analysis) at the time of measurements by ultrasonic method. Taking into account the measured value $M$ and previously defined coefficients $A, B, C, D$ determine the content of suspended impurities in the liquid.

When conducting metrological tests, the device was calibrated for two samples, and then control measurements were carried out. As a result, the relationship between the values measured by ultrasound and the results of laboratory analysis of the samples was obtained. The correlation coefficient is 0.998. The measurement range is from 20 to 300 mg/l. The lower limit of the range is caused by noise from the probing signal.

When choosing the design of the ultrasonic oscillator, various options were considered and a generator with a shock excitation circuit was selected. The sensor is designed in such a way that it can be removed and installed back without stopping the movement of water (water pressure can reach 3 ATM.). The maximum distance of the sensor from the operator up to 700 m. In the receiver of ultrasonic oscillations installed single-stage amplifier with emitter follower input and output. To align the receiving piezoelectric element with the input of the amplifier, a transformer with a transmission coefficient 4 is installed, the amplifier gain is 160. To ensure stable amplification, the signal on the transformer is inverted. The receiver is equipped with a microcontroller that performs primary mathematical processing and transmits information to a computer for further processing, display and storage of measurement results. For microcontroller and computer developed algorithms and written programs. Information on telemetric communication channels can be transmitted to the Central control panel. The main parameters of the analyzer STOK-101: measurement Mode-flow, the frequency of emitted ultrasonic vibrations-3.4 MHz, measurement Error no more than 15 %.

The measuring unit of the analyzer is assembled in a cast sealed case of impact-resistant polystyrene, inside which there are two cast aluminum blocks. There is a generator in one block and a receiver in the other. All the cables are connected through cable glands. Thus, the dust-moisture protection of the analyzer is provided. The electronic components on the circuit Board receiver and generator, encapsulated and organized galvanic isolation based on optical couplers. This achieved the intrinsic safety of the electrical circuit of the device. Analyzer STOK-101 refers to the associated intrinsically safe electrical equipment group II according to GOST R 51330.13.

4. Conclusions
The article was devoted to the development of the ultrasonic method for measuring of the electrolyte condition in the discharge burning process. In this article, the mathematical model for describing gas bubbles in the electrolyte is proposed. The experimental setup of the measuring apparatus is proposed.

References
[1] Fazlyyakhmatov M 2017 J. Phys.: Conf. Series 789 012005
[2] Sagdiev R K, Denisov E S, Evdokimov Yu K, Fazlyyakhmatov M G and Kashapov N F 2014 IOP: Conf. Ser. Mater. Sci. Eng. 69 012012
[3] Denisov E S, Temyanov B K, Sagdiev R K and Fazlyyakhmatov M G 2014 IOP Conf. Series: Mater. Sci. Eng. 69 012014
[4] Evdokimov Yu K, Temyanov B K and Fazlyyyakhmatov M G 2014 *IOP Conf. Series: Mater. Sci. Eng.* **69** 012013

[5] Ermolov I N 1991 *Nerazrushayuschij kontrol’. Akusticheskie metody kontrolya* [Non-destructive control. Acoustical methods of control] (Moscow: High School) p 283