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ABSTRACT

New approaches to ultrasonic measurements based on the use of the ultrasonic near-field zone and the resonance method are considered. the approaches can be used to measure such material parameters as density, thickness and humidity. simulation and obtained experimental results are given. a mathematical model of the ultrasonic resonance method for measuring material parameters is presented. shown simulation results and experimental data exhibit the high convergence which indicates the adequacy of the proposed model and allows offering a new class of ultrasonic methods for measuring control. a new approach to ultrasonic measurements based on the creation of ultrasonic wave self-oscillation conditions is proposed.

Keywords: ultrasound, near-field zone of ultrasonic transducer, mathematical model, resonance method, parameter measurement, reflection of waves, auto-oscillation of ultrasonic waves.

1. INTRODUCTION

As is known, ultrasound is a sound oscillation, the frequency of which is higher than the frequency that can be perceived by the human ear, that is, more than 20 kHz. The upper limit of ultrasound is quite conventional. The ultrasound has its own characteristics, which differs from the sounds of the audible range. It is relatively easy to get directional radiation in the ultrasound range. In addition, it is well-focused, and as a result, the intensity of the oscillations is increased. A slight period of oscillation makes it easier to use pulsed ultrasound. When spreading in solids, liquids and gases, ultrasound generates interesting phenomena (cavitation, local heating, disinfection, etc.) that have found practical application in many fields of technology and science[1].

Today, the practical use of ultrasound is primarily the use of low intensity waves for measuring, monitoring and researching the internal structure of various materials and products. High-frequency is used for active influence on different substances, which allows changing their properties and structure. Diagnosis and treatment of many diseases with ultrasound (using different frequencies) is a separate and actively developing direction of modern medicine[2].

Ultrasonic meters are based on the dependence of the characteristics of ultrasonic vibrations on the properties and composition of the medium in which the ultrasound is applied. Depending on the object of control there is a large variety of ultrasonic measurement methods, but in general, they can all be divided into two groups: active and passive. Active ultrasonic measurement methods include radiation in the direction of the acoustic wave control object and their subsequent reception and analysis. Among them the most widely used are the reflection methods (mirror, echo-pulse, delta-method, coherent and others) and the passage through the object of ultrasonic waves methods (shadow, differential, reverbial-through, velosimetric, and others)[3]. Passive control methods are the reception of waves, the source of which is the object of control itself[4].

As a rule, four basic parameters of the waves, which are subjected to analysis in ultrasonic measurements, are used: a phase shift or the difference in phase shifts, a frequency (or measurement of the frequency difference of short pulse repetitions or ultrasonic oscillation packets), a signal amplitude and time (direct measurement of time or time difference of short impulses)[12].

Each of the above methods of analysis has certain disadvantages, the main of which is the low accuracy due to the heterogeneity of a control object structure, as well as the inaccuracy in the registration of the start position of pulse

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signals, due to the blurring of the signal fronts, the dependence of sensitivity, and, consequently, the pulse signal frequency on the size of an object, the complexity of the signal processing in connection with the use of the ultrasonic meter multichannel structures.

Therefore, studies aimed at improving the accuracy of ultrasonic measurements by improving existing or developing new methods for measurement or control are important.

2. CONCEPT OF THE NEAR-FIELD ZONE OF ULTRASONIC CONVERTERS

Consider the acoustic field of an ultrasonic transmitter. The field in the medium is described by essentially different laws at the near and far distances from the transmitter. This difference is particularly pronounced for the round transmitter. In the immediate proximity of it, the ultrasound is distributed in the form of a parallel beam of beams (the searchlight zone), but a bit further, the picture changes dramatically. The energy still remains within the unbranched beam, but there are maxima and minima of amplitude. The entire region is called the near-field zone, the near field or the Fresnel region[5].

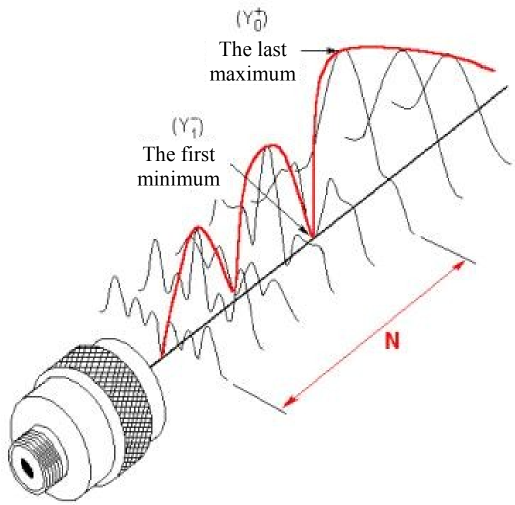


Figure 1. Near area of the acoustic field of a transmitter.

A divergent beam of rays is formed in a distant zone (the far-field zone or the Fraunhofer region), the amplitude decreases smoothly with increasing distance from the transmitter as a result of scattering in space.

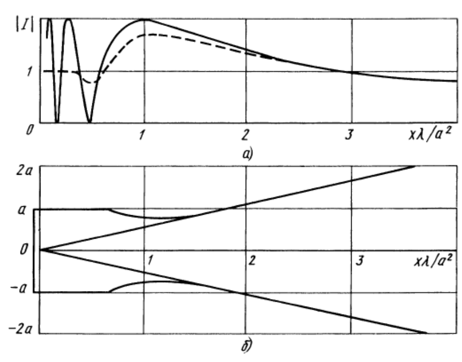


Figure 2. Field on the axis of a transmitter and its schematic representation.

In the near field the amplitude changes in a complicated manner and it depends on position in space. In this case, more than 80% of energy lies within the cylinder, limited to the edges of the piezoelement, but the energy distribution is unevenly distributed across the cylinder.

The near-field boundary corresponds to the last wave's maximum and is approximately determined for a pair of round transducers as[4]:

$$N = \frac{4a^2 - \lambda^2}{2\lambda} \approx \frac{2a^2}{\lambda}, \qquad (1)$$

where N – the distance along the x-axis (coincides with the acoustic axis of the transmitter), λ – the ultrasonic wave length, a – radius of the circular piezoelectric element.

Acoustic pressure on the receiver is determined by the expression:

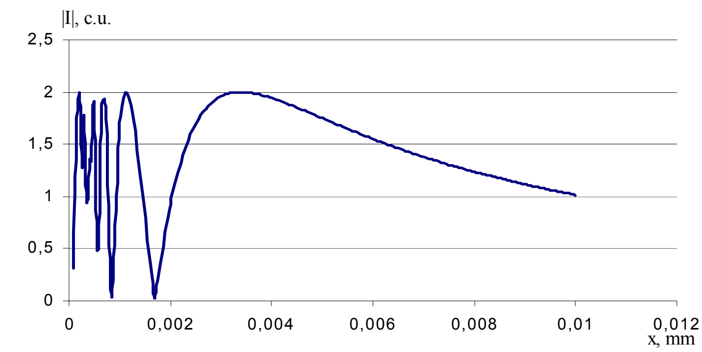
$$P' = \frac{K}{S} P_0 I^2, \qquad (2)$$

where K – a coefficient of proportionality; S – the transducer area; P_0 – the amplitude of pressure on the surface of the transducer; I – a function that takes the form (3) for points on the axis x of transducer radius a:

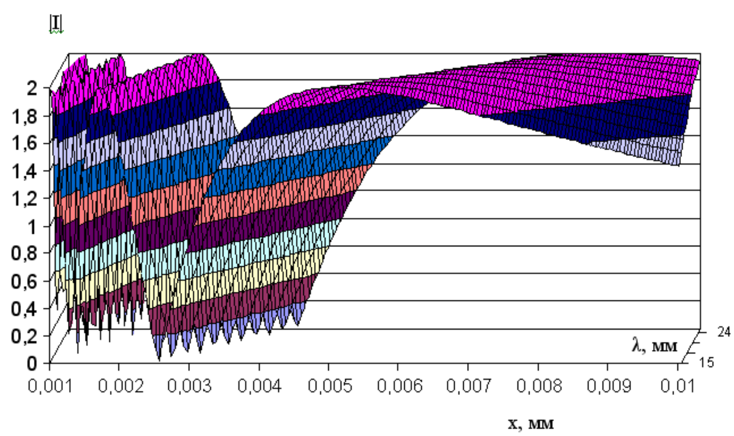
$$I = \left|2\sin\left[ka^2 / 4x\right]\right|, \qquad (3)$$

where k – the wave number.

The simulation of this function I is carried out both for one length of the ultrasonic wave, and for different wavelengths (Fig. 3).



a)



b)

Figure 3. Modeling acoustic pressure on the receiver: a) for one wavelength; b) in the range of wavelengths of 15-24 mm.

The analysis of the results confirms the dependence of the location of the near-field boundary, both on the radii of the piezoelectric converters, and on the length of the ultrasonic wave. But since the length of the sound wave depends on the properties of the medium in which it propagates, it means that by determining the resonant frequency of the last maximum of the near-field, it can also be judged on the parameters of the investigated medium. This statement allows us to propose a new approach to measuring object parameters.

3. JUSTIFICATION OF THE APPROACHES FOR MEASURING PHYSICAL PARAMETERS OF MATERIALS BASED ON THE USE OF THE NEAR-FIELD ZONE

3.1 Justification of the approach to measuring the density

Density is the content of mass of matter in the unit of its occupied volume. Density of matter is one of the main parameters that characterize its composition and structure; in addition, it is a passport quality characteristic in many cases.

The velocity of ultrasonic wave propagation is defined as:

$$V_{us} = \lambda f , \tag{4}$$

where f – the frequency of ultrasonic oscillations.

On the other hand, the velocity of the propagation of ultrasonic waves in a substance depends on its density and is determined by the expression:

$$V_{us} = \frac{Z}{\rho} , \tag{5}$$

where Z – the acoustic resistance of a medium.

Extracting the value λ from expression (1) and substituting it into formula (4), we obtain:

$$V_{us} = \frac{2a^2}{N} f . \tag{6}$$

Taking into account expressions (5) and (6), in the final case we obtain the dependence of the frequency of probing ultrasonic vibrations on the density of a substance:

$$f = \frac{ZN}{2a^2 \rho} . \tag{7}$$

This dependence allows us to propose an approach to measuring the density of a substance, which consists in determining the frequency of the ultrasonic wave propagation uniquely associated with the density of the substance, in which the last diffraction maximum of the near- field zone is detected.

3.2 Justification of the approach to measuring thickness

The thickness of the material is most often measured by the ultrasound indirect method, where the informative parameter is the time of passage of ultrasound through a substance. Knowing the passage time and the speed of ultrasound, calculate the wavelength path, and, consequently, the thickness of the material. The disadvantage of the method is the presence of a dead zone through the use of pulse signals, which makes it impossible to measure the thickness of less than 2.5 mm.

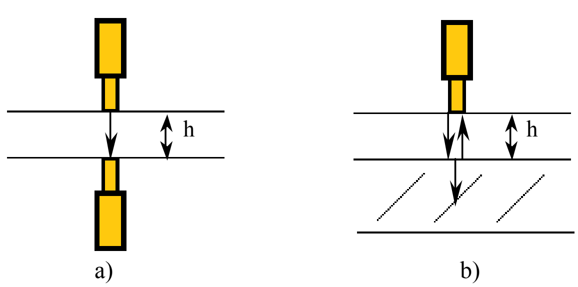


Figure 4. Types of thickness measurement.

Consider two possible cases of thickness measurement:

- determination of the thickness of a homogeneous material (Fig. 4a), when it is possible to locate ultrasonic transducers on both sides (for example, the thickness of sheet steel);
- determination of the thickness of the surface layer (Fig. 4, b) of the multilayer material (for example, the thickness of the film on the metal), when the ultrasonic transducers are located on one side of the material in one housing.

In the first case, by reconfiguring the frequency, it is possible to achieve that the magnitude of the near-field zone corresponds to the thickness of the substance layer. Therefore, taking into account the expression (6), we obtain:

$$h = N = \frac{2a^2}{V_{us}} f \,. \tag{8a}$$

In the second case, the part of the ultrasound energy will go to the depth (in the second layer of the substance), but the part will be reflected from the boundary of the layers and will return to the receiver. In this case, the magnitude of the near-field zone is equal to the double thickness of the layer, i.e.:

$$h = N/2 = \frac{a^2}{V_{us}} f \,. \tag{8b}$$

Consequently, the dependences (6a) and (6b) suggest an approach to measure the thickness of a substance, which consists in determining the frequency of the ultrasonic wave propagation uniquely associated with the thickness at which the last diffraction maximum of the near-field zone is detected.

3.3 Justification of the approach to the measurement of humidity

In a wide range of humidity, there is a single dependence between the magnitude of the ultrasound speed and the moisture content of a substance. But for different substances, this dependence is different in nature. Therefore, for the calculation of ultrasound velocity in complex heterogeneous systems, in particular in moisture-containing materials, there is no single analytical dependence. If we consider these materials as two-component mixtures (dry matter - water) and proceed from the hypothesis of additivity of adiabatic compression, then the dependence will be close to experimental data [6]:

$$V_{us} = \frac{\left[1 + W\left(\frac{\rho_{\text{т}}}{\rho_{\text{в}}} - 1\right)\right] V_{us}^{\text{в}}}{\frac{\rho_{\text{т}}}{\rho_{\text{в}}}\sqrt{W}}, \tag{9}$$

where W – humidity of the system, %; $\rho_{\text{т}}$, $\rho_{\text{в}}$ – solid phase and water density, respectively, kg/m ^{3}; $V_{us}^{\text{в}}$ – ultrasound speed in water.

But in practice, for specific cases, the refined dependencies are usually used, as, for example, in paper[7]. Therefore, we represent the dependence of the velocity of ultrasound on humidity in the general form of function (in practice, this function is specified for the required material):

$$V_{us} = func(W) \tag{10}$$

or the same

$$W = func^*(V_{us}), \tag{10a}$$

where $func^*$ – inverse function.

Equating the expressions (6) and (10), we obtain:

$$func(W) = \frac{2a^2}{N} f \,, \tag{11}$$

or the same

$$W = func * \left(\frac{2a^2}{N} f \right). \tag{11a}$$

Consequently, dependence (11a) allows us to propose an approach to measuring the moisture content of a substance, which consists in determining the frequency of the propagation of the ultrasonic wave associated with each particular case with a certain dependence on the humidity at which the last diffraction maximum of the near-field zone is determined.

The simulation of proposed mathematical models of density and thickness measurement in the MatLab was carried out. The input modeling parameters are as follows: for density simulation – Z = 10^6 kg/m^{2}s, N = 0.025 m, a = 0.01 m, ρ = 710-760 kg/m^3 (gasoline density); for measuring the thickness – V_{us} = 5900 m/s (for steel), a = 0.005 m, h=1-2 mm (Fig. 5).

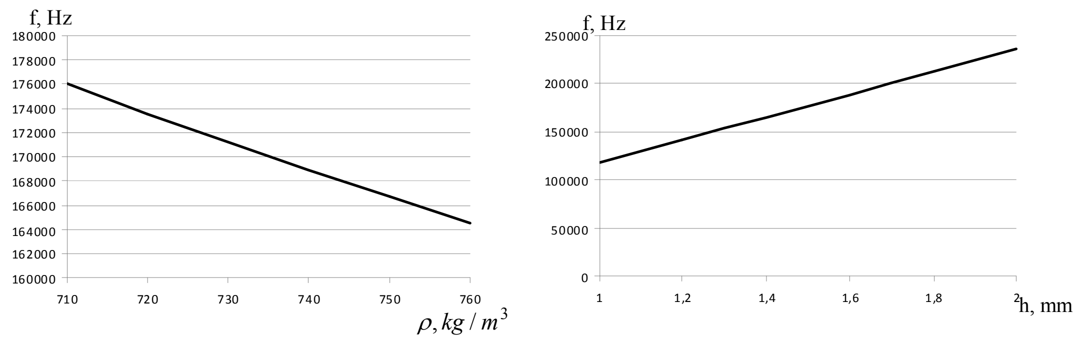


Figure 5. Simulation results of proposed mathematical models.

From the first graph, it can be seen that the dependence of the frequency variation on the material density is almost linear (in the range of studies), with the frequency decreasing as the density of the substance increases, while the sensitivity varies from -248 to -216 Hz / kg / m3, the measurement range depends on parameters of ultrasonic transducers and lies within the stable work of the overwhelming majority of piezoelectric transducers, which suggests the perspective of the approach for practical application.

The modeling results of the material thickness measurement (second graph) are linear, and reflect the unambiguous dependence of the measurement frequency on the substance thickness, the sensitivity of the method in this case is 118 kHz/mm, the measurement range also depends on the parameters of the ultrasonic transducers and lies within the stable work of the vast majority of piezoelectric converters.

4. DEVELOPMENT OF THE STRUCTURAL SCHEME OF THE DEVICE FOR REALIZATION OF THE PROPOSED MEASUREMENT APPROACHES

The similarity of the principle of measuring the density, thickness and humidity on the basis of the proposed models allows us to propose a general structural diagram of the meter, which is shown in Fig. 6.

The principle of this device is as follows. Ultrasonic oscillations are created and adopted by electroacoustic transducers, which are located with the ability to contact the medium under study. Frequency of their excitation is provided by variable frequency generator. These oscillations are analyzed by amplitude using the control unit; the peak values of the amplitude at the given time and in the previous one are recorded. With constant density (thickness, humidity), the variable frequency generator is tuned to a frequency corresponding to the last maximum of the ultrasonic wave. When the informative parameter is changed, the amplitude of the output signal is changed, which leads to the reconfiguration of the frequency. Upon reaching the frequency of ultrasonic waves, which corresponds to the maximum amplitude, the value of the frequency is recorded and the required parameter is calculated.

Thus, it can be argued that the proposed approach to measuring parameters has significant advantages over known ones, since it does not use pulsed signals, it is less inertial and more noise-immune by using its own frequency of piezoelements.

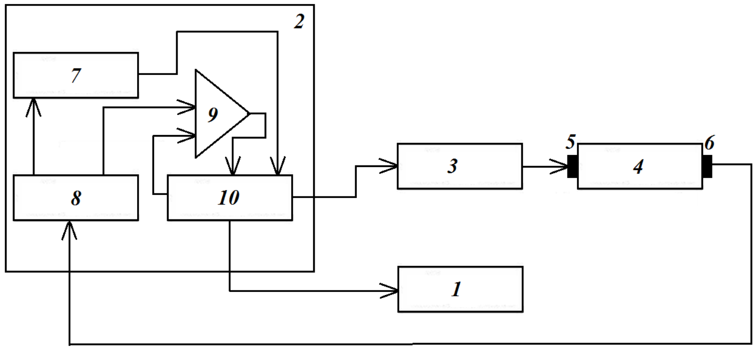


Figure 6. Diagram of ultrasonic density meter (thickness, humidity): 1 - indicator, 2 - block of formation and analysis of electrical impulses, 3 - variable frequency generator, 4 – medium of interest, 5 and 6 - electroacoustic transducers; 7 - ADC, 8 - amplifier; 9 - comparator, 10 – microcontroller.

On the basis of the proposed structural scheme a simplified experimental setup for ultrasonic density measurement was developed. Experimental amplitude-frequency characteristics for different types of petroleum products (motor oil, diesel fuel, gasoline) (Fig. 7) were obtained. Their analysis suggests that when the controlled object density is changed, a clear change in the measured resonance frequency is observed. The experimental frequency values and the calculated frequency are listed in Table 1.

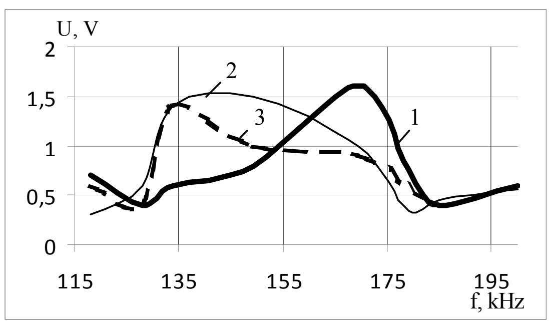


Figure 7. Experimental amplitude-frequency characteristics for different types of petroleum products: 1 - oil, 2 - fuel, 3 – gasoline.

Table 1. Results of experimental research and theoretical calculations with definite errors

Investigated medium	Frequency of the maximum, kHz		Relative error, %	
	measured	calculated	frequency	density
Gasoline	134	133	0,746	0,533
Diesel fuel	149,2	149	0,134	0,118
Motor oil	169,5	168	0,885	1,1

The convergence of theoretical calculations and the results of experimental studies confirm the adequacy of the developed method for measuring the density of petroleum products. Measurement error does not exceed 1.1%.

5. JUSTIFICATION OF THE ULTRASOUND RESONANCE MEASUREMENT METHOD MATHEMATICAL MODEL

The proposed mathematical models can be used in the range of medium and high sub-ranges of ultrasonic waves, when the wavelength is much smaller than the diameter of the converter. In the range of low ultrasonic waves (20-200kHz), when the wavelength is proportional to the diameter of the converter, the boundary of the near-field zone is expressed by the refined formula. And in this case, the element λ^2 can no longer be neglected. Therefore, the notion of near-field zone here is rather conditional - at some wavelengths it may even acquire negative values. Therefore, it is not possible to use the proposed methods in its pure form. It is rather necessary to use the notion of measurements within the first wave period. Experimental studies of the ultrasonic signal (Fig. 8) at frequencies near 40 kHz show the conditional character of the near-field, but rather indicate that the condition of the standing wave in the near-field of the converter is fulfilled. Therefore, the resonance method of ultrasonic measurements is proposed.

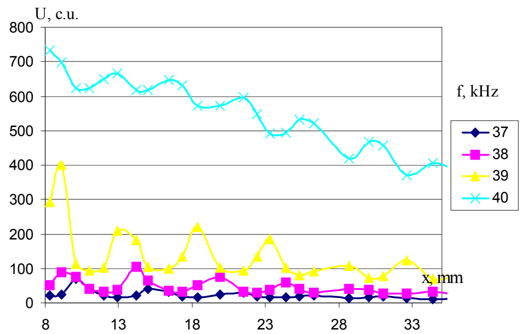


Figure 8. Experimental studies of ultrasonic signal at low frequencies.

The basis of the resonance method is the study of parameters and characteristics of standing acoustic waves that arise in a medium due to the interference of incident and reflected acoustic waves. In a transmitter-receiver system there is the resonance condition [8]:

$$L = {}^{n\lambda}\!/_{2}, \tag{12}$$

where L – the distance between a receiver and a transmitter, n – an integer number, λ – the length of the acoustic wave in the investigated medium.

The amplitude of the signal in the plane of the receiver is determined by the expression [9]:

$$A(L,t) = A_{\Pi}(L,t) + A_{B1}(L,t) + A_{B2}(L,t) + ... + A_{Bk}(L,t), \tag{12}$$

where $A_{\Pi}(L,t)$ – the amplitude of the incident acoustic wave, $A_{B1}(L,t)$, $A_{B2}(L,t)$, $A_{Bk}(L,t)$ – amplitude, respectively, of the first, second and *k*-th reflected waves. The amplitude of the incident wave is determined by the expression:

$$A_{\Pi}(L,t) = A_0 \sin(2\pi f t). \tag{13}$$

The amplitude of the reflected wave is determined by the expression:

$$A_{Bk}(L,t) = R^{2k} A_0 e^{-2\delta kL} \sin\left[2\pi f\left(\left(\frac{-2kL}{v}\right) + t\right)\right], \tag{14}$$

where R – the reflection factor, δ – the coefficient of wave attenuation in the medium.

To verify the adequacy of the proposed ultrasonic wave's propagation model, its computer simulation and experimental research have been carried out. The investigated medium is air with parameters (temperature 20°C, sound speed 343m/s, atmospheric pressure 1 atm). Since the ultrasound is greatly damped in the air (the attenuation coefficient is about 12 dB/m at a frequency of 200 kHz) and due to incomplete reflection (the reflection coefficient of 0.9 is taken), during simulation, only the tenth reflected wave was take into account for simplicity. Dependence of the receiver signal amplitude on the distance between the transmitter-receiver in the range of from 25 to 30 mm is shown in Fig. 9. The squares show the results of experimental studies (measurements were performed only for points of maximum and minimum amplitude of the signal). High convergence of modeling results and experimentally obtained data testify to the adequacy of the proposed mathematical model for the propagation of ultrasonic waves in the medium. For higher convergence it is necessary to take into account the amplitude-frequency characteristics of the ultrasonic transducers.

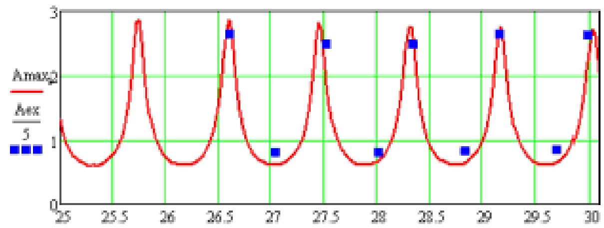


Figure 9. Dependence of the receiver signal amplitude on the distance between the transmitter-receiver in the range of from 25 to 30 mm.

Since the wavelength depends on the frequency f and the sound speed v in this medium ($\lambda = v/f$),and the speed v depends on medium parameters such as elasticity and density, which, in turn, depend on the composition of the medium, temperature, pressure, etc., then, by providing signals of different frequencies and registering the frequency of resonance, it is possible to determine the parameters of the medium.

When the transmitter-receiver system is include in the amplifier's positive feedback loop the circuit will generate auto-oscillation at the resonance frequency, under conditions of the phase balance (phase shift at the resonance frequency is zero) and the balance of amplitudes (the amplifier's gain should be greater than the loss of the signal in the measuring channel).

The developed structural scheme of the ultrasonic autogenerator meter is shown in Fig. 10. When the supply power is on, there is a generation of self-oscillations at the resonance frequency, which, in turn, depends on the parameters of the controlled object.

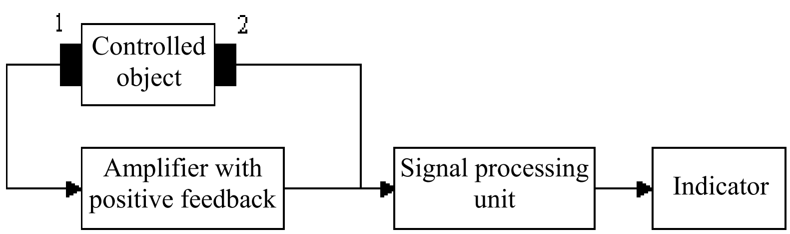


Figure 10. The ultrasonic autogenerator meter structural diagram: 1, 2 - ultrasonic transducers.

On the basis of the proposed structural scheme, an experimental installation was developed and studies of the occurrence of self-oscillations were performed (Fig. 11). Air was used under normal conditions as the object of control.

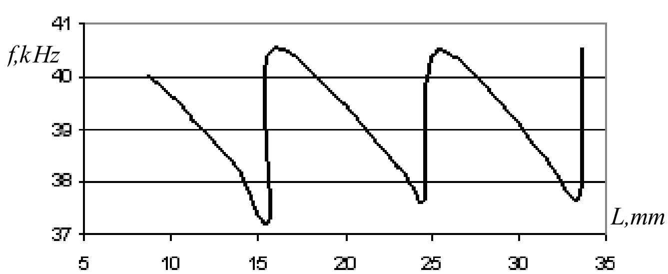


Figure 11. Experimental results of the occurrence of self-oscillations.

The analysis of experimental data (Fig. 11) confirms the dependence of the resonant frequency of self-oscillations on the parameters of the control object (in this case, its thickness). The jump-like frequency change is due to the growth of the number of half-waves of standing wave that is enclosed between the ultrasonic transducers.
Thus, by measuring the frequency of the resonance of self-oscillations, it is possible to study the parameters of the object of control, for example, thickness, density, humidity, temperature, etc.

6. CONCLUSIONS

New approaches to ultrasonic measurements based on the use of near-field zone are substantiated. The simulation of the proposed mathematical models was carried out, their sensitivity was determined.

The proposed structural scheme of ultrasonic density meter (thickness, humidity), on the basis of which a simplified experimental setup is created. The amplitude-frequency experimental characteristics for various types of petroleum products (motor oil, diesel fuel, gasoline) are obtained, the analysis of which allows asserting that when the density of the object of control is changed, a clear change in the measured resonance frequency is observed.

The mathematical model of the ultrasonic resonance method for measuring parameters of materials is proposed, which can be used for measuring control of such parameters as density, humidity, thickness of the object of control, etc.
The results of simulation and experimental data with the high convergence are shown. The adequacy of the proposed model allows us to offer a new class of ultrasonic methods for measuring parameters of controlled objects.

A new approach to ultrasonic measurements is proposed based on the creation of conditions for self-oscillation of an ultrasonic wave. By measuring the resonance frequency of the self-oscillations, it is possible to study the parameters of the object of control, for example, thickness, density, humidity, temperature, etc.

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