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Design and implementation of ultrasonic self-oscillating and optical meters of media parameters

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ABSTRACT

The aim of the research is to improve the technical parameters of ultrasonic meters by using the phenomenon of resonance and standing wave. The basis of the resonance method is the using standing acoustic waves arising in the medium due to the interference of the incident and reflected acoustic waves. The paper proposes a mathematical model of the ultrasonic resonance method for measuring parameters of liquid and gaseous media, which can be used for measuring control of parameters such as density, temperature, thickness, flow velocity, and others. To test the adequacy of the proposed model of ultrasonic wave propagation, its computer simulation and experimental studies were carried out. The air was chosen as the test medium (temperature 20° C, velocity 343m/s, atmospheric pressure 1atm). The time diagrams of the signal at the receiver for a distance of 34.3mm, when the resonance condition was satisfied, and for a distance of 34.73mm, when the ant resonance condition was satisfied, were modeled according to the proposed mathematical model. The dependence of the amplitude of the signal at the receiver is given for signal frequencies of 170–20kHz with a transmitter-to-receiver distance of 35.85mm and a sound speed of 340.8m/s. The simulation results confirm the adequacy of the purposed mathematical model. This allows proposing a new class of self-oscillating ultrasonic methods for measuring and control of medium parameters. The block diagram and the principle of operation of the auto-oscillating ultrasound meters for measuring the thickness, and gas temperature of test objects are described.

Keywords: resonance method, ultrasound, standing wave, thickness meter, gas temperature meter

1. INTRODUCTION

Today, control-measuring equipment based on ultrasound is used in various fields of science and technology. Ultrasonic measurement methods are used to control the parameters of solids and liquids, and more recently, in determining the parameters of gases. The number of scientific publications on this topic is constantly growing, which indicates the relevance of such research. The basis of the construction of ultrasonic measuring instruments is the clear dependence of the parameters and characteristics of the probe ultrasonic signal on the parameters and characteristics of the object of research[1]. There are a large number of ultrasonic methods of measuring control, but in general, they all are divided into two groups: active and passive methods[2,3]. Each of these control methods has certain disadvantages, the main of which is the low accuracy of the traces of the heterogeneity of the structure of the research object, the inaccuracy in the registration of the position of the start of the pulse signal due to the blurring of the signal fronts, the dependence of the sensitivity, and, consequently, the pulse frequency signal from the size of the object, the complexity of the signal processing is related to the use of the multichannel structure of the ultrasound control means. Consequently, the issue of increasing the accuracy of ultrasonic means of control by developing a new class of ultrasonic resonance methods for measuring or controlling quantities based on the use of a standing ultrasonic wave is undoubtedly relevant.

The aim of the work is to improve the technical parameters of ultrasonic meters due to the use of the phenomenon of resonance and standing wave. In order to achieve this goal, the following tasks are solved: theoretical justification of the work of the ultrasonic auto-oscillating meter, development and research of ultrasonic thickness meter, development and research of ultrasonic gas temperature meter.

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2. PRINCIPLE OF OPERATION

The use of optical and acoustic waves is the basis of a number of measurement systems[4-6]. The basis of the resonant control method is the study of the parameters and characteristics of standing acoustic waves that arise in the environment due to the interference of the incident and reflected shockwaves. In the emitter-receiver system there is a resonance provided[7,8]:

$$L = n\lambda/2 \tag{1}$$

where L is the distance between the receiver and the emitter, n is an integer, λ is the length of the acoustic wave in the studied environment.

Since the wavelength depends on the frequency (f) and the ν sound velocity (v) in this medium ($\lambda = v/f$), and the speed v depends on such parameters of the medium as elasticity and density, which, in turn, depend on the composition of the medium, temperature, pressure, etc. Then, by specifying the signals of different frequencies and recording the resonance frequency, it is possible to determine the parameters of the environment[9-11].

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

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

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

$$A_{Bk}(L,t) = R^{2k} A_0 e^{-2\delta kL} \sin\left[2\pi f\left(\left(\frac{-2kL}{v}\right)+t\right)\right] \tag{3}$$

where R is the reflection coefficient, δ is the wave attenuation coefficient in the medium.

To verify the adequacy of the proposed ultrasonic wave propagation model, its computer modeling and experimental research have been carried out. As the studied medium, the air was selected (temperature 20°C, sound speed 343m/s, atmospheric pressure 1atm). Since the ultrasound strongly decays in the air (the attenuation coefficient is about 12dB/m at a frequency of 200 kHz) and the result of incomplete reflection (a reflection coefficient of 0.9 is taken), in the simulation for simplicity only a tenth reflection wave is limited. In this case, the expression of a mathematical model for modeling has the form:

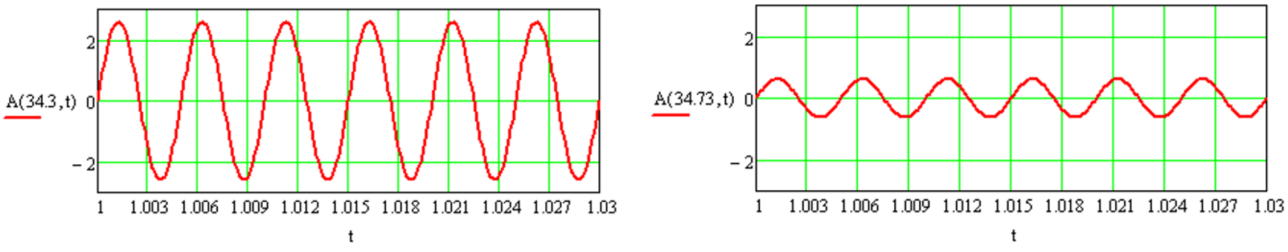
$$A_{Bk}(L,t) = R^{2k} A_0 e^{-2\delta kL} \sin\left[2\pi f\left(\left(\frac{-2kL}{v}\right)+t\right)\right] \tag{4}$$

The graphs in Fig. 1 show time diagrams of the signal on the receiver for a distance of 34.3 mm, modeled according to the proposed mathematical model when the condition of the resonance (a) and for the response of 34.73 mm is fulfilled when the anti-resonance condition (b) is fulfilled. The signal amplitudes differ by about 5 times, which confirms the sensitivity of the model[11,12].

The dependence of the amplitude of the signal on the receiver for the frequencies of the signal 170-205 kHz at a distance transmitter-receiver 35.85 mm and sound speed 340.8 m/s is shown in Fig. 2a. The squares show the results of experimental studies (measurements were performed only for points of maxima and minimum amplitude of the signal). The results of the simulation have a high convergence with the results of experimental studies, which confirms the adequacy of the mathematical model. For higher adequacy, the mathematical model must take into account the amplitude-frequency characteristics of the ultrasonic transmitter and receiver[13,14].

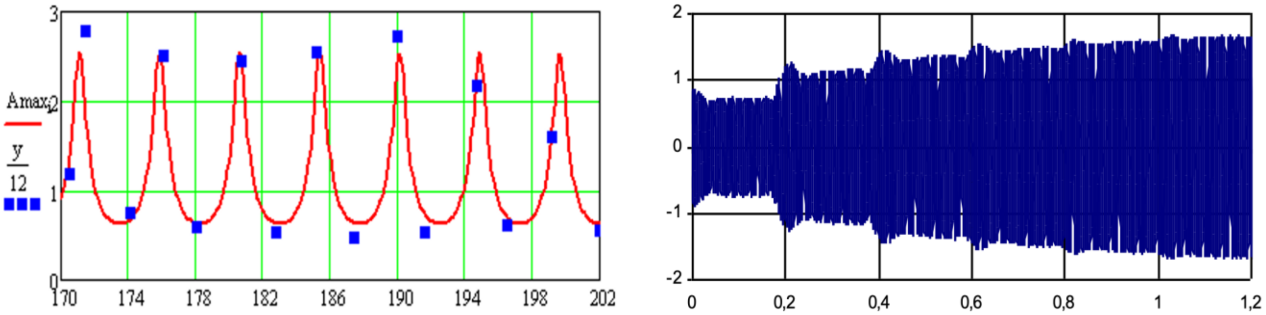
The arrival time of the reflected wave depends on the speed of the ultrasound in the medium, and, consequently, on such parameters of the medium as density, elasticity, humidity, etc. The ultrasonic method of measuring control of environment parameters is proposed, which consists in determining the arrival times on the receiver of another reflected wave. The results of experimental studies of the dependence of the amplitude of the signal on the receiver for a frequency of 171.428 kHz are shown in Fig. 2b. It is evident from the graph that there is a jump-like increase in amplitude at the moment of arrival of a next wave, which confirms the possibility of the practical application of the proposed mathematical model.

The installation used for experimental studies is shown in Fig. 3. It consists of two 200kHz ultrasound emitters and an operational amplifier board. To simplify the scheme and instead of an op.amp the negatrons as active devices can used[9,14-16]. The use of negatrons – devices with negative resistance, capacitance, and inductance can improve the sensitivity and increase the frequency range of work.



a) b)

Figure 1. Timing diagram of the signal on the receiver for the condition of resonance (a) and antiresonance (b).



a) b)

Figure 2. a) The dependence of the amplitude of the signal on the receiver for the frequencies of the signal 170-205 kHz; b) Experimental dependence of the amplitude increase of the signal on the receiver at a frequency of 171.428 kHz

3. DEVELOPMENT OF THE ULTRASOUND AUTO-OSCILLATING THICKNESS METER

At this point, the task of creating an ultrasonic auto generator thickness meter is solved, which, by introducing new elements and connections between them, achieves the ability to measure small changes in thickness, which leads to increased sensitivity, accuracy, and impedance control of this process. Fig. 4 depicts the structure of the thickness meter.

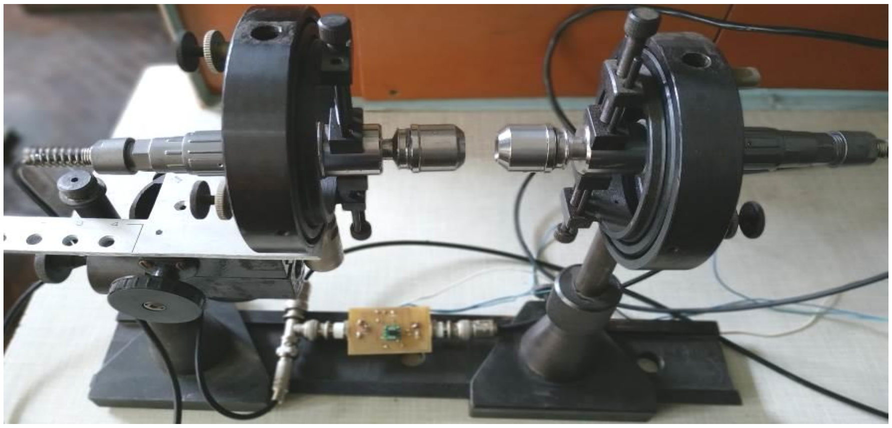


Figure 3. Experimental installation for testing ultrasonic auto-oscillation meter.

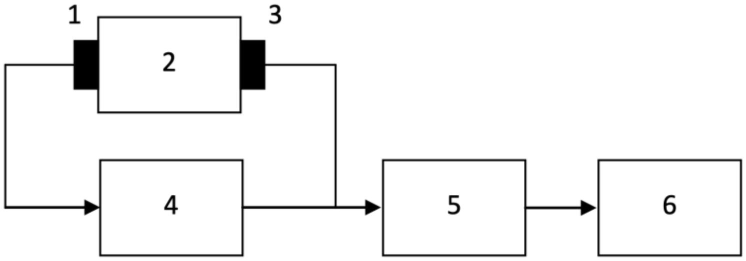


Figure 4. Structural diagram of ultrasonic autogenerator thickness meter.

The device works as follows. When power is on, the first electroacoustic converter 1 and the second electroacoustic converter 3 (emitter-receiver) connected to the positive feedback loop of the amplifier 4 in the circuit will generate autogeneration at the resonance frequency, on which the condition of the phase balance (phase shift at the resonance frequency is 0) and the balance of the amplitudes (the gain must be greater than the loss of the signal in the measuring channel) will be fulfilled. In addition, in the system of the emitter-receiver, the resonance arises under the condition (1).

The thickness of the object is:

$$L = \frac{nV_{us}}{2f_p} \tag{5}$$

where V_{us} – the speed of ultrasound in the object controlled 2, f_p – resonance frequency.

For each value of f_p from formula (5), there exists a set of corresponding values of the thickness (Fig. 5) depending on the value of n, although in practice based on the amplitude-frequency characteristics of the transmitter-receiver system, this set is reduced to one or two values of thickness. But within the thickness of $L_x \ldots L_x + \lambda$ (within the length of one wave) there is a unique dependence of the resonant frequency f_p and thickness L.

By the measured value of the resonance frequency f_p, in the microprocessor signal processing unit 5, a set of L values for the corresponding values $n = 1 \ldots k$, where k is an integer dependent on the range of measurements, is calculated. Next, the value L, which falls into the specified measuring range $L_0 \ldots L_0 + \lambda$, is selected, which will be the true value of the thickness. This value is displayed on indicator screen 6.

The use of the proposed ultrasonic thickness gauge with an auto-generator has significant advantages as it does not use pulsed signals, is less inertial, and is more immune to the effects of the piezo elements' own frequency.

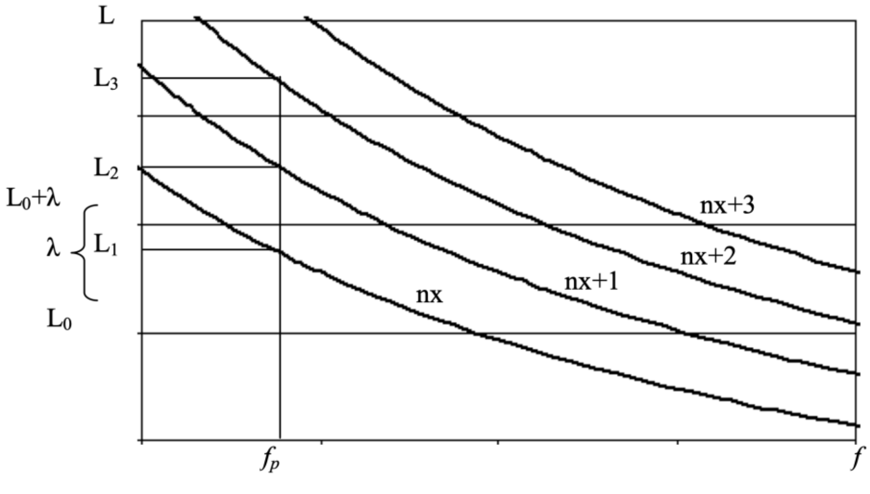


Figure 5. Dependence of thickness on resonance frequency for different values of n.

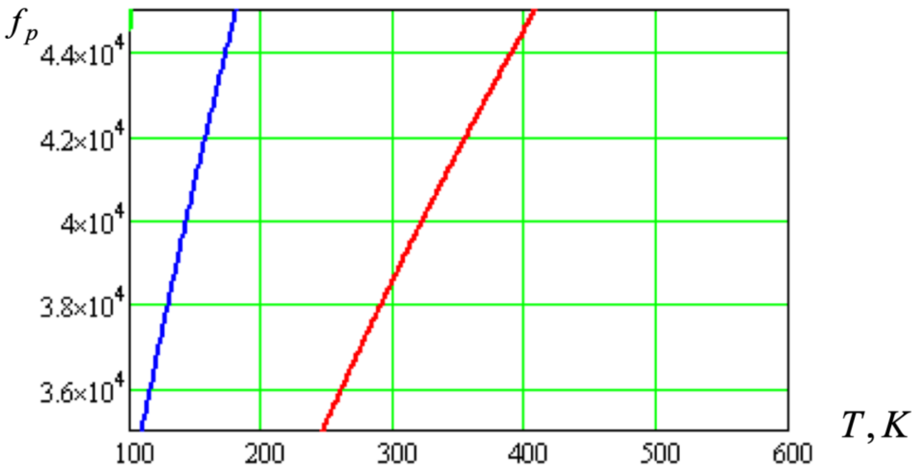


Figure 6. Dependence of the resonant frequency on the temperature for different values of *n*.

4. DEVELOPMENT AND STUDY OF THE ULTRASOUND AUTO-OSCILLATING GAS TEMPERATURE METER

In this section, the task of creating an ultrasonic auto-generator gas temperature meter is solved, which, by introducing new elements and bonds between them, achieves the ability to measure small changes in temperature, which leads to increased sensitivity and precision control of this process.

The block diagram of this meter is similar to the thickness meter, and is depicted in Fig. 4. In the system of the emitter-receiver there is a resonance provided (1). An expression for determining the temperature:

$$T = \frac{4L^2 f_p}{n^2 \chi R} \tag{6}$$

where χ is the gas adiabatic index, R – the gas constant, T – the absolute temperature.

For each value of f_p from the formula (6), there exists a set of corresponding temperature values depending on the value of n (Fig. 6), which in practice, proceeding from the amplitude-frequency characteristics of the transmitter-receiver system, is reduced to one or two values. But within the temperature range Tx…T_xK, where K is the overlap factor $K = (n + 1/n)^2$, there is a unique dependence of the resonant frequency f_p and temperature T. For example, with the use of ultrasonic emitters with a central frequency of 40kHz and a generation range of 35-45kHz at a distance of 9mm, the range the measurement of air temperature ranges from 246K to 408K for n = 2 and from 110K to 181K for $n = 3$.

According to the measured value of the resonance frequency fp, in the microprocessor signal processing unit 5, a plurality of values of T for the corresponding values n = 1..k is calculated, where k is an integer that depends on the range of measurements. Then the value T, which falls into the given measuring range, which will be the true value of the temperature, is selected. Calculating the temperature, the microprocessor unit, according to the tabular value of the adiabatic index, calculates the refined temperature value. This value is displayed on indicator 6.

The use of the proposed ultrasonic auto-generator gas temperature meter has significant advantages, since in the process of measurement, the area of measurement characteristic with higher steepness is used, and it is less inertial and has more noise immunity, thereby increasing the accuracy and sensitivity of the measurements.

5. CONCLUSIONS

A mathematical model of the ultrasonic resonance measurement method for liquid and gaseous media parameters is proposed, which can be used for measuring and control of such parameters as density, temperature, the thickness of objects, etc. To test the adequacy of the proposed model of ultrasonic wave propagation, its computer simulation and experimental studies were carried out. The air was chosen as the test medium (temperature 20 ° C, velocity of sound 343 m/s, atmospheric pressure 1 atm). The simulation results confirm the adequacy of the purposed mathematical model. This allows proposing a new class of self-oscillating ultrasonic methods for measuring and control of medium parameters. The block diagram and the principle of operation of the auto-oscillating ultrasound meters for measuring the thickness and temperature of a gas of test objects were described.

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