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The ultrasonic converter mathematical model of flow rate of flowing environment

Yosyp Y. Bilynsky*[a], Oksana S. Horodetska[a],
Konstantin V. Ogorodnik[a], Andrzej Smolarz[b], Kuanysh Muslimov[c]
[a]Vinnytsia National Technical University, 95 Khmelnitsky Shose Str., 21021 Vinnytsia, Ukraine; [b]Lublin University of Technology, Nadbystrzycka 38A, 20-618 Lublin, Poland; [c]Kazakh National Research Technical Iniversity named after K.I.Satpayev, Almaty, Kazakhstan

ABSTRACT

The ultrasonic method for measuring the flow rate of flowing environment based on the use of the amplitude-frequency modulation scheme is presented. The mathematical model of the ultrasonic converter of the flowing environment flow rate is proposed.

Keywords: ultrasonic method, amplitude-frequency modulation scheme, converter of flow rate of flowing environment

1. INTRODUCTION

The task of measuring the velocity of flowing environment, and therefore flow rate, is an actual task of both modern science and its various applications in the national economy. This issue is particularly urgent in the oil and gas industry, since increasing the accuracy and probability of accounting the flow rate of natural and liquefied petroleum gas, efficient use of these resources, reducing their consumption and reducing losses affects the country's energy security.

Nowadays, the use of ultrasonic measurement technology for commercial and technical needs is widespread[1-2]. The analysis of scientific and technical literature[3-6] shows that by measuring methods the ultrasonic flowmeters are divided into frequency, time-pulse and Doppler. Each of the above methods has certain drawbacks, the main are low precision due to the absence of a stable structure and flow fluctuations, the dependence of the sensitivity, and therefore the pulse signal frequency depending on the size of a pipeline[7]. In pipelines of small diameter, the passage time of the pulse is small enough, which leads to low accuracy of measurement. This drawback is eliminated, using the complexity of the design, which in its turn leads to an increase in the dimensions of the device.

The carried out analysis allows us to conclude that the continuous development of industry and the high requirements for measuring equipment are considered to be of great importance for the developing modern methods and devices of acoustic control of flowing environment, including small diameter of the pipeline.

The purpose of the work is to develop a method for measuring the flowing environment flow rate based on the use of the amplitude-frequency modulation scheme and the mathematical model of the ultrasonic measuring converter.

2. MATERIALS AND RESEARCH RESULTS

The distribution area of the ultrasonic beam of the acoustic converter (acoustic field) is divided into two zones: the near and far. The distant zone is an area of acoustic radiation in which acoustic pressure gradually drops to zero. The near zone is directly in front of the converter and the amplitude of the signal in it changes nonmonotonically, that is corresponds to the last diffraction peak of the sound pressure, after which the field gradually decreases[8].

A study of the ultrasonic waves spreading in a flowing environment was conducted , namely, the spreading of a signal in the near area. The research established the character of the amplitude-frequency characteristic (AFC), according to the distance between the receiver and the transmitter, dependence on the velocity flow.

Figure 1 shows the characteristic of the AFC in several cases of different distance between the receiver and the transmitter in the air environment. As it can be seen from Fig. 1, when changing the distance between the receiver and

*yosyp.bilynsky@gmail.com

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the transmitter, there is a shift of the AFC. As the distance increases, the frequency increases, and with decreasing distance, the frequency decreases. It is also established that when the distance, which exceeds the size of the near area at several times increases, the resonance phenomena of the frequency resonance of AFC are fading.

The distance L of ultrasonic waves passage, which occurs when interference is determined from the condition:

$$L = \begin{cases} 2m\lambda/2 \ - \ \text{maxima}; \\ (2m-1)\lambda/2 \ - \text{minima}; \\ \text{not integer } (\lambda/2) \ - \text{partial} \\ \text{amplification or weakening of a signal} \end{cases}, \tag{1}$$

where λ – the wavelength; $2m=n$ – the number of full fluctuations.

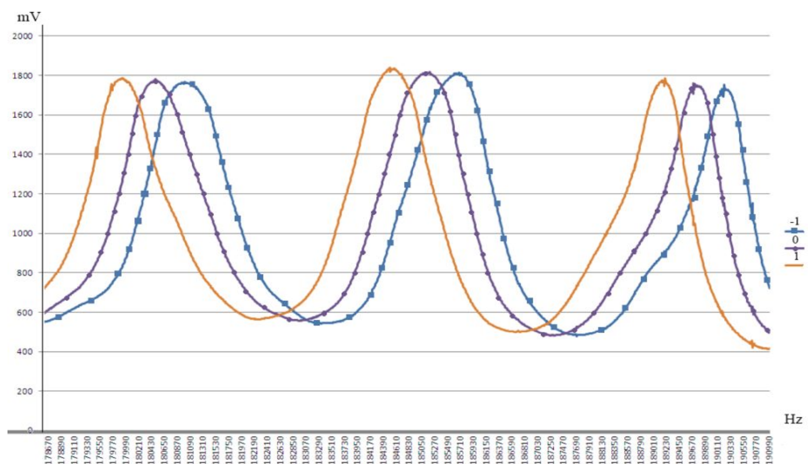

Figure.1. AFC of the receiver - the transmitter when changing the distance between them within the near-range area in the air environment

Thus, it is possible to calculate the number of complete vibrations that correspond to the maxima amplitudes at frequencies that are resonant.

Let us write down a system of equations for our case, in which the number of full vibrations, depending on the frequency in each case, must differ by one.

$$\begin{cases} L = \dfrac{(2m-1)v_{usw}}{f_{-1}}; \\ L = \dfrac{2mv_{usw}}{f_0}: \\ L = \dfrac{(2m+1)v_{usw}}{f_{+1}}, \end{cases} \tag{2}$$

where f_0, f_{-1}, f_{+1} – the main frequency, the previous and the next value respectively; v_{usw} – velocity of ultrasonic wave spreading.

The solution of this system are two equations that determine the number of total vibrations m or wavelengths at a given distance L:

$$m = \frac{f_0}{2(f_0 - f_{-1})}, \tag{3}$$

$$m = \frac{f_0}{2(f_{+1} - f_0)}. \quad (4)$$

According to the results of the research, we will carry out such calculations. So, for AFC with frequency f_{-1}= =180510 Hz, f_0=185150 Hz, f_{+1}=189790 Hz, calculations have shown that the number of complete vibrations according to the first and second formulas is m = 19,96 ≈ 20, that confirms the presence of the phenomenon of interference. The appearance of interference of waves is directly related to the presence of standing waves spreading in mutually opposite directions. Such a statement allows us to speak about resonant phenomena that arise as a result of interference. As it was said above, it can be written $\lambda_1 n_1 = \lambda_2 n_2$. Then the ratio of the resonant frequencies corresponds to the ratio of the corresponding number of vibrations.

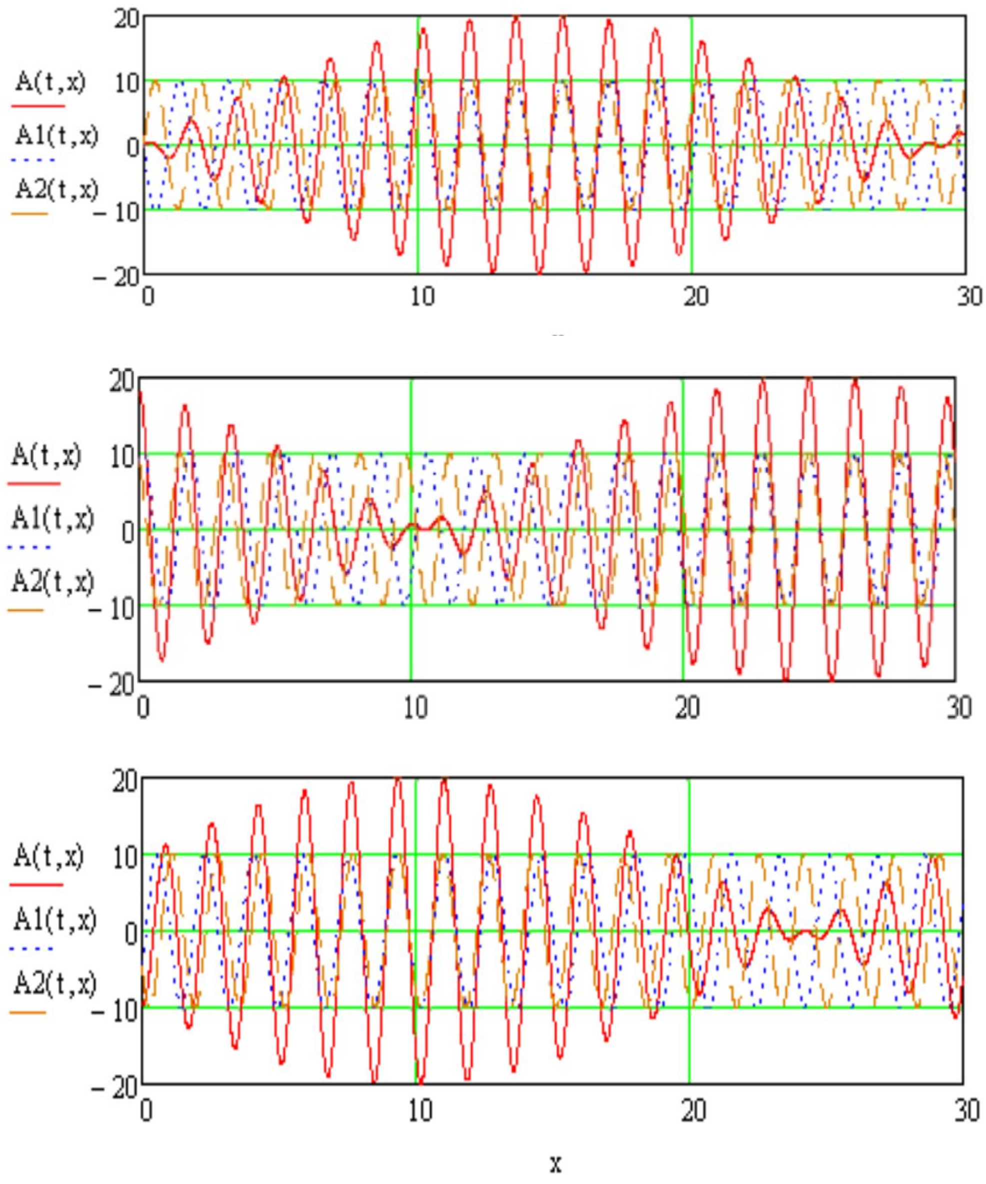

Figure 2. The spreading of two waves for and against the flow and their resulting wave in the space

So we can write the expression where

$$\frac{f_1}{f_2} = \frac{n_1}{n_2}. \tag{5}$$

Let us consider the mathematical model of ultrasonic wave spreading in the presence of a gas flow.

Ultrasonic wave by flow is described by expression

$$A1 = A\cos(\omega t + kx) = A\cos(\omega t + \frac{2\pi fx}{v_{usw} + v}), \tag{6}$$

where A – an amplitude; ω – angular frequency; k – wave number; ν – velocity of flowing environment.

The expression for describing the ultrasonic wave against the flow has the form

$$A2 = A\cos(\omega t - kx) = A\cos(\omega t + \frac{2\pi fx}{v_{usw} - v}). \tag{7}$$

Fig. 2 shows the distribution of the ultrasonic wave for and against the flow, as well as the resulting wave,which is in resonance.

Thus, it was also established experimentally and by simulation that in the presence of a stream, the frequency of the ultrasonic signal for and against the flow is equal. So we can write as follows

$$\frac{\lambda_{for}}{v_{usw} - v} = \frac{1}{f} = \frac{\lambda_{against}}{v_{usw} + v}, \tag{8}$$

where λ_{for}, $\lambda_{against}$ – the wavelength of the ultrasonic signal for and against the flow respectively.

The study of the temperature influence on AFC and the determination of the frequency were carried out at which the maximum amplitude value was observed[9, 10]. The obtained characteristic is shown in Fig. 3.

The dependence of the frequency at which the maximum value of the amplitude from the temperature is linear and with the temperature increase the frequency increases. The obtained temperature dependence coincides with the results of known sources[11, 12].

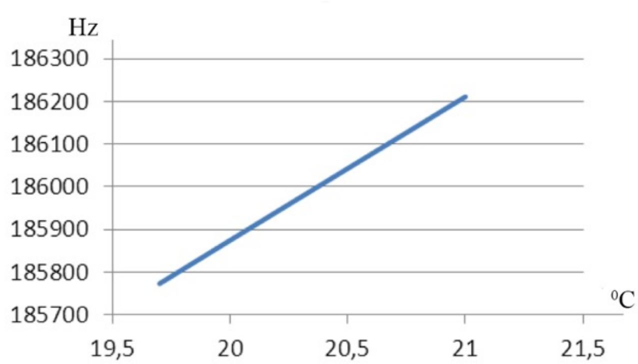

Figure 3. Frequency dependence at which the maximum amplitude value from temperature

The following studies have been carried out to study the frequency dependence of AFC on the velocity and direction of the flowing environment current . In the absence of the flow, the frequency of ultrasonic vibrations was determined by adjusting the signal generator to a certain frequency by achieving the maximum amplitude of the ultrasonic vibrations receiver signal, which was determined with a help of a millivoltmeter. After that the air pump with the known value of the flow rate was switched on. In this case, the amplitude of the signal at the output of the converter sharply decreased, which indicated the inconsistency of the frequency of ultrasonic vibrations, which did not meet the conditions of the near area , that is, the size of the near area pair ultrasonic transmitter-receiver at a given flow rate. Therefore, it was necessary to reconfigure the signal generator to a frequency that corresponds to the conditions of the near area and, accordingly, the flow velocity. The reconfiguration takes place as long as the amplitude of the signal at the output of the converter does not become again maximum. Thus, the frequency of ultrasonic vibrations was determined, which corresponded to the velocity flow.

This process of measuring the frequency of ultrasonic vibrations was repeated at each step of increasing the flow rate up to 20 m/s with a resolution of 0.5 m/s. The results were compared with the device of measuring the velocity Rotameter RE-1ZHUZ with the measurement error (± 2.5%).

Figure 4 shows the dependence of the AFC at a certain velocity flow at the corresponding pressure values.

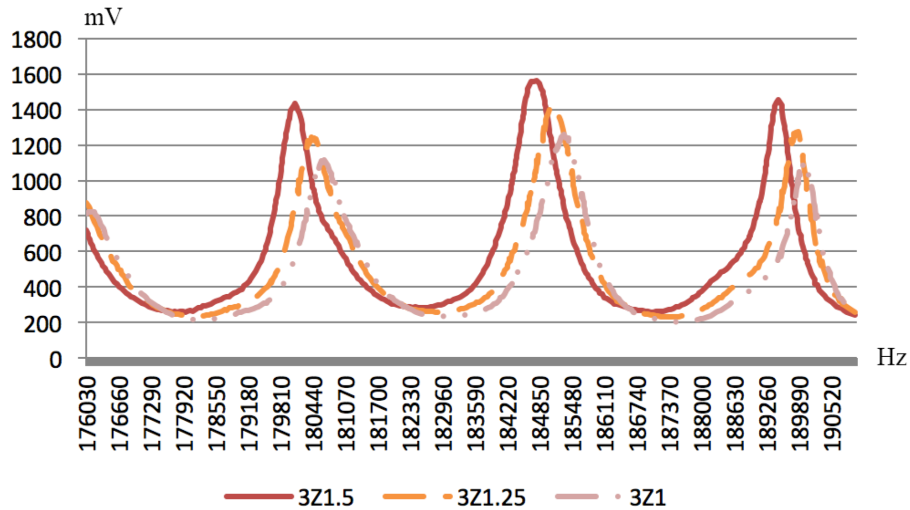

Figure 4. AFC dependence on the velocity flow at the following values of excess pressure: 3Z1 – 1 atm; 3Z1.25 – 1.25 atm; 3Z1.5 – 1.5 atm

As it can be seen from the graphs at an increased pressure, the frequency of the ultrasonic wave decreases, which corresponds to known dependencies[1, 13-17].

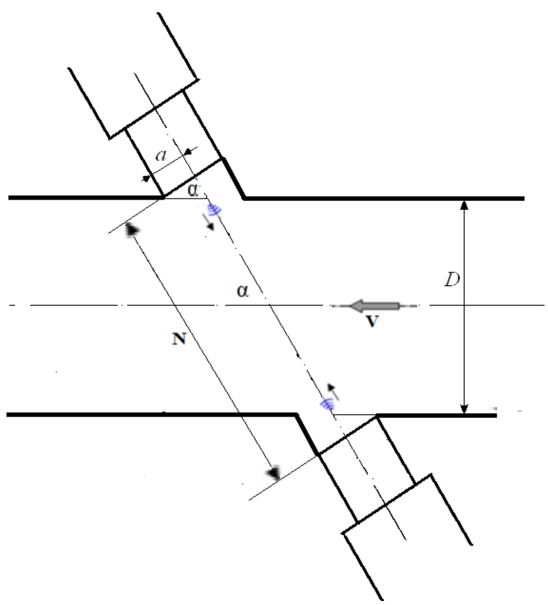

Figure 5. Ultrasonic measuring converter of liquid and/or gaseous environment flow rate

As it can be seen from the results of the simulation at a certain value of the frequency of the ultrasonic signal at a certain distance between the transmitter and the receiver and a certain density of the environment within the near zone a resonance phenomenon occurs. These calculations allow us to propose an ultrasonic method for measuring the velocity of flowing environment , which consists in determining the resonance frequency of the ultrasonic wave spreading which is uniquely associated with the velocity of the flowing environment due to the interference phenomena within the near area[18].

A measuring converter of flowing environment flow rate was developed on the basis of the proposed amplitude-frequency method. To develop a mathematical model let us consider the process of spreading the ultrasonic wave in a flowing environment between ultrasonic converters which are situated at a certain distance from each other on one axis (Fig. 5).

The velocity of ultrasonic wave spreading is defined as:

$$V_{usw} = \lambda f \,, \tag{9}$$

where f - frequency of ultrasonic vibrations.

According to the velocity flow, the wavelength will be determined as:

$$\lambda = \frac{\left(V_{usw} + V\cos\alpha\right)}{f}\,, \tag{10}$$

where α - the angle between the velocity of the ultrasonic wave spreading and the direction of motion of the flowing environment.

The length of the near area for a pair of piezoelements, that is, in the system of the emitter-receiver[1, 19], that corresponds to the last diffractive maximum of the sound pressure is defined as

$$N_{near} = \frac{a^2}{\lambda} + \frac{b^2}{\lambda}\,, \tag{11}$$

where a and b – the radii of the piezoelements respectively.

For a pair of ultrasonic converters of the same size (for $a = b$) the length of the near area will be:

$$N_{near} = \frac{2a^2}{\lambda}\,, \tag{12}$$

Then expression (12) taking into account (10) will look like:

$$N_{near}^{for} = \frac{2a^2 f}{v_{usw} + v\cos\alpha} \tag{13}$$

Thus, the near area of ultrasonic signal against the flow is defined as

$$N_{near}^{ag} = \frac{2a^2 f}{v_{usw} - v\cos\alpha}\,. \tag{14}$$

The ratio of neighboring areas is defined as

$$\frac{N_{near}^{for}}{N_{near}^{ag}} = \frac{v_{usw} - v\cos\alpha}{v_{usw} + v\cos\alpha} \tag{15}$$

Then, by using (13) and (14), (15) taking into account the formulas (5) and (8), as well as the diameter of the pipeline D, where $N_{near} = \dfrac{D + 2a\cos\alpha}{\sin\alpha}$ the frequency of the ultrasonic wave is determined:

$$f = \frac{\left[\left(\frac{D+2a\cos\alpha}{\sin\alpha}\right)(v_{usw}^2 - v^2\cos^2\alpha)\right]\cdot\left(1+\frac{n_0}{k_0}\right)}{4a^2 v_{usw}}, \tag{16}$$

where n_0 - the number of the ultrasonic wave vibrations on the main resonance for the flow, which is defined as $n_0 = \frac{2f\left(\frac{D+2a\cos\alpha}{\sin\alpha}\right)v_{usw}}{v_{usw}^2 - v^2}$; k_0 – the number of the ultrasonic wave vibrations on the main resonance against the flow, which is defined as $\frac{N_{near}^{for}}{N_{near}^{ag}} = \frac{n_0}{k_0}$.

Fig. 6 shows the static characteristics of several neighboring resonance frequencies of the ultrasonic signal. As it can be seen from the graph, the distance between adjacent resonances is about 4.7 kHz, which corresponds to the experimental data.

Graph of frequency dependence of the flow rate at several angles between the direction of the spreading the ultrasonic wave and the flow is shown in Fig. 7

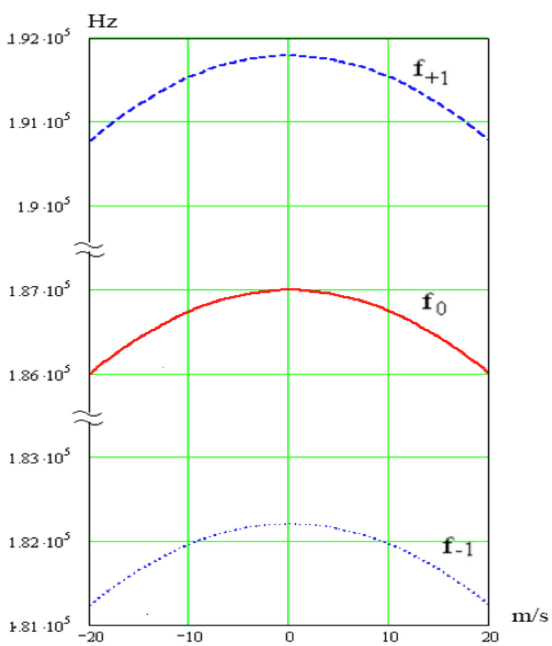

Figure 6. Graph of several neighboring resonant frequencies dependence of the ultrasonic signal from the flow

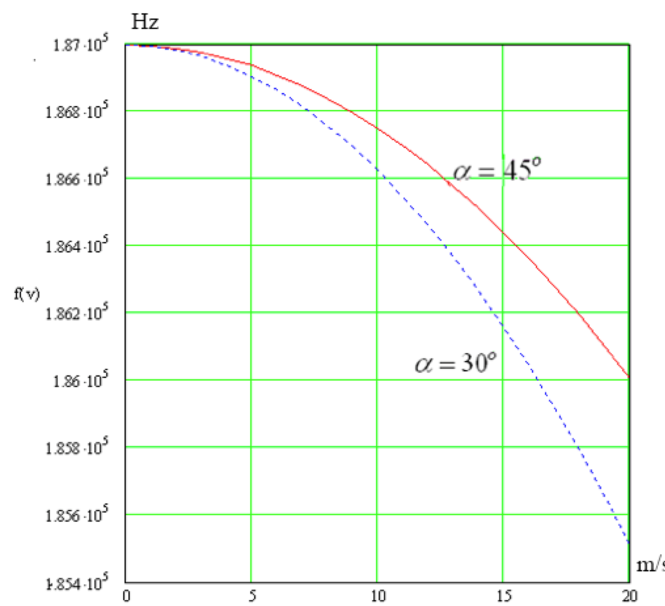

Figure 7. Graph of frequency dependence of the flow rate at several angles of ultrasonic input

The presence of a sharp increase in the signal amplitude, based on the interference of ultrasonic waves in the near area of the transmitter-receiver, makes it possible to develop a flowmeter based on the use of the near area ultrasonic converter.

3. CONCLUSION

Ultrasonic wave spreading studies allow us to offer an ultrasonic method for measuring the velocity of flowing environment, which consists in determining the resonance frequency of the ultrasonic wave spreading, which is uniquely associated with the velocity of the flowing environment due to interference phenomena within the near-range area. The results of the research provide an opportunity to confirm its perspective for the practical application of measurements of the flowing environment.

The measuring converter of flow rate of flowing environment mathematical model has been proposed. A transformation equation which uniquely connects the output value - the value of the resonant frequency of the ultrasonic signal and the input value of the velocity of the flowing environment has been received. It has been stated that static characteristic has a linear character.

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