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USING NONLINEAR ULTRASONIC MEASUREMENTS TO ESTIMATE PARAMETERS OF THE SEDIMENTATION OF SLURRY SOLID PHASE IN THICKENER

Purpose. Improvement of the method for estimating sedimentation process parameters of the slurry solid phase particles in thickener on the basis of measurements of the nonlinear characteristics of ultrasonic waves propagating in a controlled medium.

Methodology. The following methods were used: analysis of scientific results and practical developments; methods of mathematical statistics for evaluating the results of experiments; methods of analytical synthesis; methods of numerical modeling for the synthesis and analysis of a mathematical model.

Findings. It was established that the nonlinearity of the process of propagation of ultrasonic waves in ore slurry, which is determined by the number and size of crushed ore particles in it, can be estimated by determining the amplitudes of several harmonics of the measured acoustic signal. This approach allows maintaining the productivity of the desliming process in accordance with the characteristics of the ore suspension, without allowing the loss of valuable components. Obtaining real-time information about the characteristics of the particle sedimentation process in the ore suspension at the initial stage enables reducing the duration of transitional processes in the control system.

Originality. The method for estimating the parameters of the deposition of the solid phase of the pulp in the thickener has been improved, which is based on the fact that the nonlinearity of the process of propagation of a controlled ultrasonic signal in the thickener; this leads to modulation of the generated ultrasonic packet and, consequently, the appearance of higher harmonics. To obtain a more accurate estimate of the nonlinearity of this process, all the values obtained must be normalized to represent only the relative changes in the acoustic nonlinear response.

Practical value. A system for automatic control of the thickener operation is proposed, which uses nonlinear ultrasonic measurements to estimate the parameters of the sedimentation of the solid phase of the pulp in the thickener. According to the results of industrial tests of the system of automatic control of the thickener based on ultrasonic control devices, it was established that its use as part of the automated control system for the technological processes of beneficiation of iron ore raw materials at the ore beneficiation factory of the Northern mining works will allow reducing water consumption by 3.5 % and iron-magnetite losses by 0.6–0.7 %.

Keywords: *beneficiation of iron ore raw materials, thickener, ultrasonic, automatic control*

Introduction. In most ore beneficiation processes, a significant amount of water is used, and the intermediate product of the beneficiation process is separated from the pulp using special separation devices – thickeners. The thickener has two products: a thicker concentrate, which goes further down the process chain, and water, which can be reused by returning it to the previous stages of the beneficiation process.

Effective control systems are needed to improve the quality of the thickener product. It should be noted that it is quite difficult to see or measure the parameters of the process taking place in the thickener, because the reaction time from the occurrence of a disturbance to a possible change in the process parameters can be quite long. Control of the thickener must take into account fluctuations in the characteristics of the process flow. This is achieved by changing the amount of flocculant and the pumping speed of the precipitated product. The change in the properties of the enriched ore should be considered as an additional problem, the solution of which determines the need to measure and regulate the rate of precipitation and the characteristics of the solid phase of the pulp.

Therefore, it is expedient to develop a method for estimating the parameters of the process of deposition of particles of the solid phase of the pulp in the thickener.

Literature review. Thickeners are used to separate the ore pulp by gravity into two products: a clarified product in the slurry and a concentrated thickened product. In the settling process, a zone of solid particles is created at the bottom of the tank whose concentration is higher than in the incoming flow [1]. The conceptual model proposed by J. B. Christian as-

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sumes five regimes and divides the thickener into five layers according to its concentration profile. The idea proposed in [2] is that in different areas inside the thickener, the material behaves differently, the conditions change, and therefore the light/compaction equations are different for each regime. Fig. 1 shows conditionally separated layers of deposited ore material during its movement in the thickener [2].

As a rule, control of the thickening process is carried out, by adjusting its parameters, which leads to an increase in the transparency of the overflow in order to achieve the minimum content of solid particles and an increase in the density of the precipitated product in order to maximize the extraction of solid particles [3]. The formulated aims could be reached by changing the release rate of the sedimented product and adding a flocculant. The sediment level is a variable parameter that can be changed by adjusting the performance of the thickened product pump. Intermediate beds can be used to control the sedimenting rate of particles by controlling the concentration of flocculant or the rate of sedimented product. Incorrect measurement of the separation limits of the raw ore and the feed rate of the reagent used to change the density of the sedimenting product can cause decreasing of the solids concentration in the thickened underflow, solids will enter the overflow.

The problems described above, in turn, lead to additional costs related to the consumption of flocculant or the need for repeated desliming.

There are some approaches to monitoring of the sediment levels and media interfaces in thickeners [3]. The most favored methods are [4]: manual sampling of ore material, measuring of the hydrostatic pressure, systems using a float, ultrasonic measurements, submersible mechanical systems. Depending on the technological process, the state of the environment and the budget, a technology for sediment levels measuring in thickeners is chosen [5].

Ultrasonic measurement methods are a promising direction for improving the quality of information support for the control of the technological processes at ore beneficiation factories [6].

In [7], it is suggested to use the correlation between the characteristic of nonlinear ultrasound and the properties of the investigated medium. The most common method for processing such kind of signal in time domain is its transformation to the frequency domain. This allows one to obtain the values of amplitude of each harmonic of the used frequency spectrum. At the same time, the main disadvantage of this approach is that the transformation errors increase dramatically when non-linear signals with discontinuities are analyzed. Two algorithms based on wavelet transforms are proposed for waveform analysis in nonlinear ultrasonic control. The experimental results showed that the calculation of the index of ultrasonic nonlinearity on the basis of the mentioned approach, could be improved by using wavelet decomposition.

In the paper [8], a method is proposed for taking into consideration the second harmonic impact of an ultrasonic signal when measuring the index of absolute acoustic nonlinearity on the basis of the calibration approach. To achieve this goal, the *2nd* harmonic measured by the sensor is considered as a sum of two terms: the nonlinearity component which is a property of the investigated medium, and the component which is induced by the controlled ultrasonic signal. The proposed numerical model is based on the distance of ultrasound propagation in controlled medium. The indices related to the nonlinear parameter are obtained by calculating the value that allows achieving the best precision in comparison with the experimental data. The case of the *2nd* harmonic's wave phase opposition to the main wave's phase caused by the nonlinear characteristics of the medium was also considered. The analysis of the experimental investigations allows proving that without the mentioned compensation procedure there is a valuable variation of the nonlinear parameters, which is caused by changing of the distance of ultrasound propagation. At the same time, applying the compensation procedure allows keeping this parameter constant.

As one of the most effective parameters that describes the variation in the investigating material state the acoustic nonlinearity index will be used. At the same time, there are some limitations, caused by using high energy signals and monochromatic waves, which brings difficulty to their practical application.

The paper [9] proposed the approach to the acoustic nonlinearity estimation and monitoring on the basis of the general-purpose ultrasonic pulse receivers. To analyze the results of monitoring of nonlinear ultrasound propagation there was used the method of contact-immersion pulse. To extract *1st* and higher harmonics from measured acoustic signals, there was developed a method of a cross-correlation filtering. There was proved a strong correlation between with the state of the investigating environment and the nonlinearity indices of the *2nd* and *3rd* harmonics. The power of the input signal caused linear variation of the *2nd* harmonic of the acoustic signal.

The work [10] reports on the creation of an ultrasonic measuring channel that forms the induced wave and measured the higher nonlinear harmonics in the received acoustic signal. The proposed acoustic channel consists of two components: for transmission at the resonance frequency a ring piezoelectric

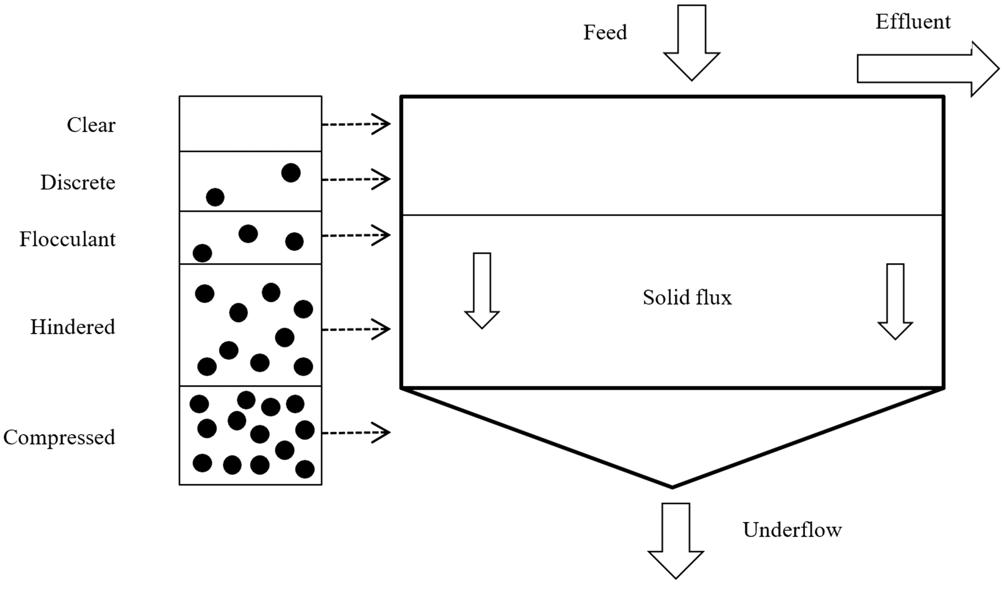

Fig. 1. Layers of thickener's working volume according to the J.B. Christian conceptual model

transducer is used and for reception at the resonance frequency the disk piezoelectric transducer is used. The two components mentioned are placed separately but in the same plane and coaxially to each other. To detect the *2nd* harmonic of acoustic signal and provide high selectivity and sensitivity there was developed a design of the receiving system on the basis of combination of the optimization of the resonance sharpness and the material constants of the piezoelectric transducers.

In [11], a method for measuring the phase velocity and attenuation of ultrasound in suspensions was considered in order to evaluate their characteristics. Research results show that the phase velocity of ultrasonic waves increases with an increase in the number of small particles in the suspension. Dispersion is caused by the presence of a solid phase and correlates with its mass fraction. The results of extinction experiments show that it is possible to back-calculate the pulp properties by fitting the model to the experimental data if the size distribution of the solid phase particles is known.

Thus, the parameters of ultrasonic waves propagating in the pulp during its deposition in the thickener can be used to evaluate the characteristics of this process.

Purpose. Improvement of the method of estimation of the parameters of the deposition process of particles of the solid phase of the pulp in the thickener based on measurements of nonlinear characteristics of ultrasonic waves propagating in a controlled environment.

Methods. Technological processes of ore enrichment are spatially distributed multidimensional objects with a complex multi-connected structure. Technological lines of enrichment consist, as a rule, of several consecutively arranged stages, each of which includes the following main technological operations: grinding, classification, magnetic separation [6].

Fig. 2 presents a technological diagram of the beneficiation process at the ore beneficiation plant (OBP) of the Northern Mining and Beneficiation Plant.

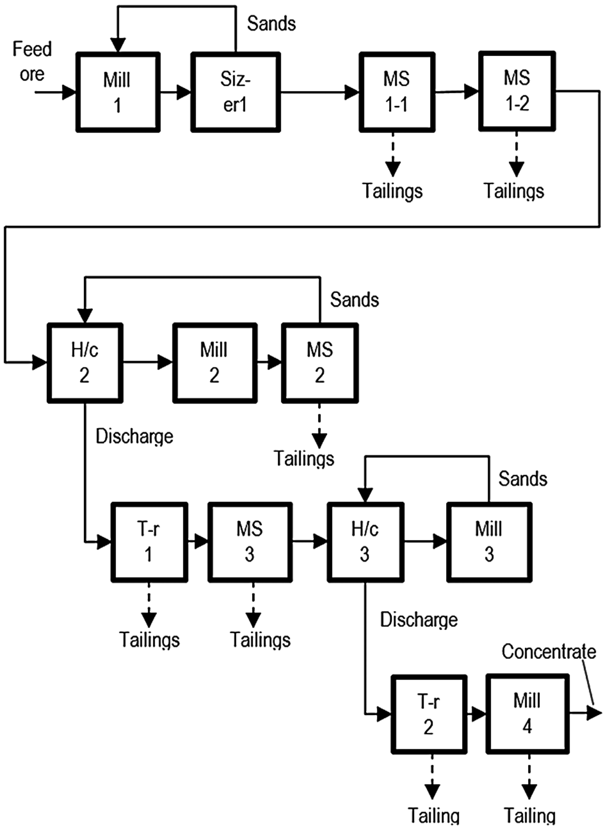

Fig. 2. Technological diagram of the beneficiation process at Ore Dressing Factory No.1 of the Northern Mining and Beneficiation Plant

The main internal governing influences in the enrichment line, which is presented in Fig. 2, are water flows into technological units. In Figs. 3, 4, according to the control points presented in Fig. 1, examples of the obtained qualitative-quantitative dependencies are given, which characterize the influence of this parameter on the course of the technological process [6].

The dependence of the mass fraction of the solid phase in the iron ore pulp on the flow of water to the technological units, distributed along the enrichment line, is shown in Fig. 3; Fig. 4 shows the dependence of iron content in the "–0.044 mm" class on water consumption.

The purpose of thickener control in most cases is to dewater the slurry, return the clarified plume for reuse in the process, and obtain a thickened, denser product that can either be sent to tailings or used as feedstock for further process operations [2].

The process of pulp thickening in the thickener can be accompanied by a significant number of disturbing influences, such as variations in the volume of the initial product, changes in the types of processed ore, the amount, size, density of particles, etc. As noted in [12], that is why it is important to be able to effectively control this process. But at the same time, the task of measuring all possible variables that affect the process of deposition of the solid phase of the pulp in the thickener arises.

As it was shown above, it is advisable to use ultrasonic measurement methods to evaluate the characteristics of the process of deposition of particles of the solid phase of the pulp in the thickener.

In suspensions with high concentrations of the solid phase, there is a noticeable dispersion of the speed of ultrasound, which is associated with vibrational and rotational isomeric

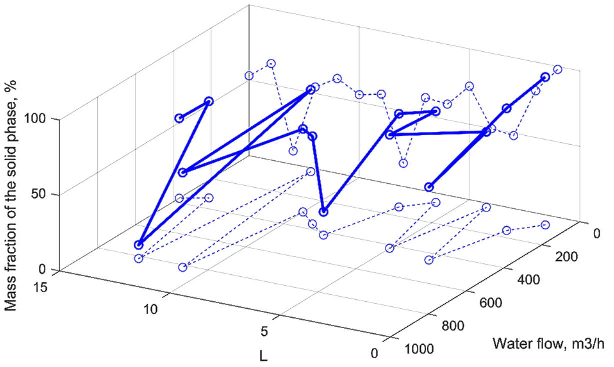

Fig. 3. The mass fraction of the solid phase in the iron ore pulp depending on the flow of water to the technological units:

"———" is a distributed function; "— —" – projections on coordinate planes

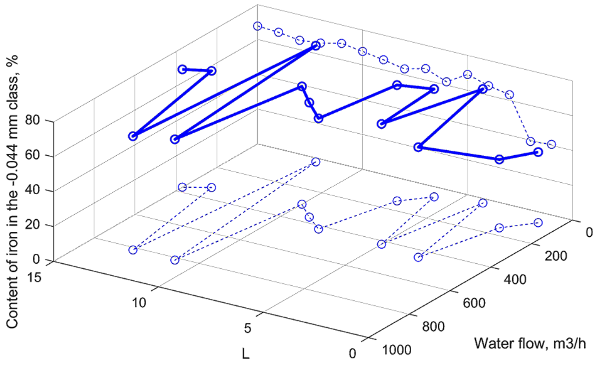

Fig. 4. Content of iron in the "-0.044 mm" class depending on the water flow to technological units:

"———" is a distributed function; "— —" – projections on coordinate planes

relaxations, restructuring of the internal structure of the liquid, dissociation processes, and chemical reactions [13].

In the conditions of variable velocity of ultrasound propagation and variable density of a randomly heterogeneous medium, it is necessary to use k-space methods of the first and second order to model this process. The general principles on which the k-space method is based are presented in the paper [14].

The considered method can be extended to the case of a heterogeneous environment. For a two-dimensional environment without losses, the equations describing this process have the following form [14]

$$\begin{aligned}\rho(r)\frac{\partial u(r,t)}{\partial t} &= -\nabla p(r,t);\\ \frac{1}{\rho(r)c(r)^2}\frac{\partial p(r,t)}{\partial t} &= -\nabla u(r,t),\end{aligned} \qquad (1)$$

where u is the acoustic particle velocity fluctuation vector with u_x and u_y components; p is acoustic pressure fluctuations; $\rho(r)$ is the density of the medium; $c(r)$ is the velocity of ultrasound in the medium, r is the coordinate vector (x,y).

The wave equation of the second order, according to expression (1), has the following form [14]

$$\nabla\left(\frac{1}{\rho(r)}\nabla p(r,t)\right)-\frac{1}{\rho(r)c(r)^2}\frac{\partial^2 p(r,t)}{\partial t^2}=0.$$

The pattern of propagation in a heterogeneous medium of the ultrasonic pulse which has sinusoidal shaped and finite duration can be described by the following expression [13]

$$\psi(t) = \mathrm{sim}\,\omega_0 t \cdot f(t), \qquad (2)$$

where $f(t)=\begin{cases}1, & 0\le t\le \alpha'\\ 0, & t<0,\quad t>\alpha'\end{cases}$; ω_0 is frequency of sinusoidal oscillations; α' is pulse duration.

Despite the fact that the pulse is "filled" with a certain frequency ω_0, its duration is finite and therefore this pulse is possible in the form of a superposition of oscillations with different frequencies. It is advisable to solve the given task with the help of Fourier analysis of the pulse. Mathematically, Fourier analysis is more convenient to perform in a complex form.

Expression (2) in complex form is as follows

$$\psi(t)=e^{i\omega_0 t}f(t). \qquad (3)$$

The reverse transition is carried out by selecting the imaginary part of the expression (3). Let us find the transformation of the Fourier function

$$\phi(\omega)=\int_{-\infty}^{\infty}\psi(t)\,e^{-i\omega t}dt=\int_{0}^{\alpha'}e^{-i(\omega-\omega_0)t}dt=\frac{1-e^{-i(\omega-\omega_0)\alpha'}\alpha'}{i(\omega-\omega_0)}. \qquad (4)$$

Function $j(w)$ determines the frequency spectrum of a rectangular sinusoidal pulse. Suppose that this pulse propagates in a dispersive medium in which the speed of acoustic waves is determined by the function $c_0(w)$. In this case, the wave function of the traveling pulse is represented as a superposition of traveling harmonic waves with a frequency spectrum $j(w)$ [13]

$$\psi(Z,t)=\frac{1}{2\pi}\int\phi(\omega)e^{i[\omega t-k(\omega)Z]}d\omega, \qquad (5)$$

where $k(\omega) = \omega/C_0(\omega)$ – wave number.

We consider the case when the propagation of waves occurs along the Z axis.

Substituting (4) into (5), we get

$$\psi(Z,t)=\frac{1}{2\pi i}\int_{0}^{\infty}\frac{1-e^{i(\omega-\omega_0)\alpha'}}{(\omega-\omega_0)}e^{i[\omega t-k(\omega)Z]}d\omega.$$

Let us make the replacement a variable $u = \omega - \omega_0$ then

$$\psi(Z,t)=\frac{1}{2\pi i}\int_{-\omega_0}^{\infty}\left[\frac{1-e^{-iu\alpha'}}{u}\right]e^{i[(\omega_0+u)t-k(\omega_0+u)z]}dZ=$$

$$=\frac{e^{i[\omega_{o}{}_t-k(\omega_o)Z]}}{2\pi i}\int_{-\omega_0}^{\infty}\left[\frac{1-e^{-iua'}}{u}\right]e^{i\left\{u\left[t-\frac{Z}{C_0(\omega_0+u)}\right]+\beta\right\}}du,$$

where $\beta=\frac{\omega_0 Z}{C_0(\omega_0)}\left[1-\frac{C(\omega_0)}{C_0(\omega_0+u)}\right]$.

Let us enter the notation $t'=t-\frac{Z}{C(\omega_0+u)}$ then

$$\psi(Z,t)=\frac{e^{i[\omega_0 t-k(\omega_0)Z]}}{2\pi i}\int_{-\omega_0}^{\infty}\frac{e^{i(ut'+\beta)}-e^{i[u(t'-\alpha')+\beta]}}{u}du. \qquad (6)$$

Expression (6) defines the wave function of the pulse propagating in the dispersion medium.

Consider the change in the shape of the final pulse of acoustic vibrations during their propagation in the dispersion medium.

Let us mark

$$u_1(t')=\frac{1}{2\pi i}\int_{-\omega_0}^{\infty}\frac{e^{i(ut'+\beta)}-e^{i[u(t'-\alpha')+\beta]}}{u}du. \qquad (7)$$

As can be seen from expression (7)

$$u(t') = u_1(t') - u_1(t' - \alpha'), \qquad (8)$$

where $u_1(t)=\frac{1}{2\pi i}\int_{-\omega_0}^{\infty}\frac{e^{i(ut+\beta)}}{u}du$.

When calculating $u_1(t)$, we select the main value of the Cauchy integral, and present the integrand exponent in the Euler form

$$u_1(t')=\frac{1}{2}+\frac{1}{2\pi}\int_{-\omega_0}^{\infty}\frac{\sin(ut'+\beta)}{u}du-\frac{i}{2\pi}\int_{-\omega_0}^{\infty}\frac{\cos(ut'+\beta)}{u}du.$$

Thus, the wave function (6) will have the form

$$\psi(Z,t)=e^{i[\omega_0 t-k(\omega_0)Z]}\cdot[u_1(t')-u_1(t'-\alpha')]. \qquad (9)$$

Since we are interested only in the imaginary part of the expression (9), then

$$\psi(Z, t) = \mathrm{Im}\,\psi(Z, t) = \psi_1(Z, t) - \psi_2(Z, t),$$

where

$$\begin{aligned}\psi_1(Z, t) &= \sin[\omega_0 t - k(\omega_0)Z]F_1(t') -\\ &- \cos[\omega_0 t - k(\omega_0)Z]F_2(t');\\ \psi_2(Z, t) &= \sin[\omega_0 t - k(\omega_0)Z]\cdot F_1(t' - \alpha') -\\ &- \cos[\omega_0 t - k(\omega_0)Z]F_2(t' - \alpha');\end{aligned}$$

$$F_1(t)=\frac{1}{2}+\frac{1}{2\pi}\int_{-\omega_0}^{\infty}\frac{\sin(\omega t+\beta)}{u}du;$$

$$F_2(t)=\frac{1}{2\pi}\int_{-\omega_0}^{\infty}\frac{\cos(\omega t+\beta)}{u}du.$$

It is not difficult to show that $\psi_1(Z, t)$ describes the leading edge of the pulse, $\psi_2(Z, t)$ – rear front. Let us imagine $\psi_1(Z, t)$ as

$$\psi_1(Z, t) = F(t')\sin[\omega_0 t - k(\omega_0)Z - \gamma], \qquad (10)$$

where $F(t')=\sqrt{F_1^2(t')+F_2^2(t')}$; $\gamma=\arcsin\frac{F_2(t')}{\sqrt{F_1^2(t')+F_2^2(t')}}$.

The function is defined similarly $\psi_2(Z, t)$ [13].

As can be seen from expression (10), the pulse is amplitude modulated, the amplitude modulation is determined by the function $F(t')$. Phase modulation is also observed in these oscillations, which is determined γ. Fig. 5 shows the pulse of acoustic vibrations after it has traveled a distance of 20 cm in an aqueous environment containing solid particles with a radius of 100 μm, the static density of the suspension was 1.4 g/cm^3 [15].

Findings. From the foregoing, it can be concluded that the considered change in the shape of the pulse of acoustic oscillations of finite duration is a consequence of the nonlinear characteristics of the process of ultrasound propagation in the pulp, which, in turn, are determined by its density and granulometric composition.

In the process of movement in the pulp of the wave packet (Fig. 5), there is a decrease in the height of the envelope of the ultrasonic signal along with a simultaneous increase in its width, as well as spreading of the wave packet in space, caused by the dispersion properties of the medium [16].

In a situation where the shape of the incident wave is distorted by the nonlinear elastic response of the medium to this wave, higher harmonics are generated. When sending an ultrasonic waves packet with specific amplitude A_0 and frequency f_0, the detected signal passing through the medium will be distorted. As a result, the measured ultrasonic signal will have an amplitude component A_1 at the main frequency f_0, an amplitude component A_2 at the frequency of the *2nd* harmonic $2f_0$, A_3 at the frequency $3f_0$ [17].

To obtain the expression for the quadratic nonlinearity parameter an approximation of the solution of a nonlinear wave equation was proposed [16]

$$\beta = \frac{8A_2}{A_1^2 k^2 x},$$

where A_1 is the amplitude of the *1st* harmonic of the received signal; A_2 is the amplitude of the *2nd* harmonic of the received signal; k is the wave number; x is the distance of signal propagation.

The coefficient of nonlinear elasticity of the *3rd* order can be written as follows

$$\gamma = \frac{48A_3}{A_1^3 k^3 x},$$

where A_3 is the amplitude of the *3rd* harmonic.

Increasing magnitude of the nonlinear interaction causes energy translation from the main to higher harmonics. Thus, the characteristics of the pulp solid phase particles and its quantitative indices can be obtained by measuring the nonlinearity of the ultrasonic wave propagating through the medium.

The presence of raw ore particles in the pulp leads to modulation of the propagating ultrasonic packet. The result of an irregular waveform in the propagation region after a certain distance is the formation of a harmonic frequency that is twice the frequency of the main signal. Higher harmonics are generated as the ultrasonic wave is distorted by the non-linearity of the medium. Therefore, the received signal consists of several harmonics – the fundamental frequency and higher harmonics. The nonlinear parameter associated with the amplitudes of the fundamental wave and other harmonics [18] is defined as follows

$$S = A_2/A_1,$$

where A_1 and A_2 are the amplitudes of the fundamental wave and its second harmonic, respectively.

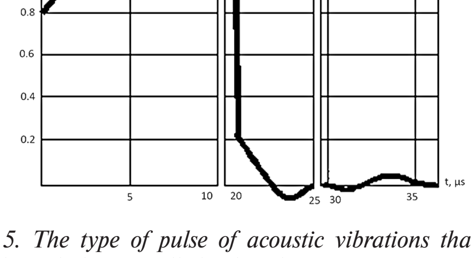

Fig. 5. The type of pulse of acoustic vibrations that passed through the controlled pulp volume:

$\alpha' = 20$ *μs*; $\nu_0 = 106$ *Hz*; $Z = 20$ *cm*

Thus, having determined the amplitudes of the fundamental, second and other harmonics, it is possible to evaluate the nonlinearity of the process of propagation of ultrasonic waves in the ore pulp, which is determined by the number and size of crushed ore particles in it. All the values obtained must be normalized and only a relative change in the acoustic nonlinear response should be presented for a qualitative assessment of the nonlinearity of this process.

Calculation of the adiabatic speed of ultrasonic radiation in liquid media was performed by the following equation [19]

$$C = \sqrt{\left(\frac{dF}{d\rho}\right)_S},$$

where F and ρ are the pressure and the density of the investigated medium respectively; S is the derivative taken for constant entropy.

On the basis of the proposed method, the control algorithm of the sedimentation process can be set as an optimization task [20]

$$\min \int_{t_k}^{t_k+\Delta k} \left(W_x \left(\tilde{x}(t) - x_{ss} \right)^2 + W_u \left(u(t) - x_{ss} \right)^2 \right) dt,$$

where the state equation is

$$\dot{\tilde{x}}(t) = f\left(\tilde{x}(t)\right) + g\left(x(t)\right) u(t),$$

where $\tilde{x}$ is the predicted value of x; k is prediction horizon; W_x and W_u are weights.

The specified approach allows maintaining the performance of the desliming process in accordance with the characteristics of the ore suspension without allowing losses of the useful component. Thanks to obtaining operational information on the characteristics of the process of deposition of particles of the solid phase of the ore suspension already at its initial stage, it is possible to reduce the duration of transient processes in the automatic control system.

The results of industrial tests of the system of automatic control of deposition based on ultrasonic control tools have shown that its use as part of an automated control system for technological processes of beneficiation of iron raw materials is appropriate. In the conditions of the beneficiation plant of the Northern Mining and Processing Plant, the application of the proposed approach will reduce water consumption by 3.5 % and the loss of iron magnetite by 0.6–0.7 %.

The amplitude-frequency characteristic of the signal reflected from the reflector of ultrasonic signal oscillations depends on the distribution of particles of the solid phase of the ore suspension in the process of their free deposition, whose parameters are determined by both the particle size and the pulp density.

Conclusions. The obtained results allow us to conclude that estimates of the nonlinearity of the process of the propagation of ultrasonic waves of the second and third orders in the pulp deposited in the thickener must be used to optimize its operation.

The proposed approach makes it possible to take into account the density of the pulp and the nature of the distribution of particles of the solid phase of the ore material in the thickener by size, to establish the characteristics of the original product of the thickener in accordance with the parameters of the process of sedimentation of ore particles and due to this reduce water consumption by 3.5 % and losses of the useful component by 0.6 –0.7 %.

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Використання нелінійних ультразвукових вимірювань для оцінки параметрів осадження твердої фази пульпи в дешламаторі

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Мета. Удосконалення методу оцінювання параметрів процесу осадження частинок твердої фази пульпи у процесі дешламації залізорудної сировини на основі моніторингу нелінійних характеристик ультразвукових хвиль, що поширюються в робочому об'ємі дешламатора.

Методика. У роботі використані такі методи: аналіз наукових і практичних рішень; статистичні методи для оброблення результатів експериментальних досліджень; методи аналітичного синтезу; методи чисельного комп'ютерного моделювання для синтезу та аналізу математичних моделей.

Результати. Встановлено, що параметри нелінійних процесів поширення ультразвукових хвиль у рудній пульпі обумовлюються кількістю та крупністю часток здрібненої руди в ній і можуть бути оцінені шляхом визначення амплітуд кількох гармонік виміряного акустичного сигналу. Зазначений підхід дозволяє підтримувати продуктивність процесу дешламації у відповідності до характеристик рудної суспензії не допускаючи втрат корисного компоненту. Завдяки отриманню оперативної інформації про характеристики процесу осадження часток твердої фази рудної суспензії вже на його початковій стадії вдається зменшити тривалість перехідних процесів у системі керування.

Наукова новизна. Удосконалено метод оцінки параметрів осадження твердої фази пульпи в дешламаторі на основі ультразвукових технологій. У основі даного методу знаходиться нелінійний характер процесу поширення керованого ультразвукового сигналу в дешламаторі, що призводить до модуляції згенерованого ультразвукового пакету і, як наслідок, до появи вищих гармонік. Для одержання точнішої оцінки нелінійності цього процесу всі отримані значення мають бути нормовані для подання лише відносної зміни акустичного нелінійного відгуку.

Практична значимість. Запропонована система автоматичного управління роботою дешламатора, що для оцінки параметрів осадження твердої фази пульпи використовує нелінійні ультразвукові вимірювання. За результатами промислових випробувань системи автоматичного керування дешламатором на базі засобів ультразвукового контролю встановлено, що її використання у складі автоматизованої системи керування технологічними процесами збагачення залізорудної сировини на РЗФ Північного ГЗК дозволить зменшити витрати води на 3,5 % і втрати заліза-магнетиту на 0,6–0,7 %.

Ключові слова: *збагачення залізорудної сировини, дешламатор, ультразвук, автоматичне керування*

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