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METHOD AND DEVICE OF AUTOMATIC NON-DESTRUCTIVE CONTROL OF MAGNETIC IRON CONTENT IN SLURRY FLOW

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Abstract *The object* is to investigate the automatic non-destructive control of iron ore slurry characteristics in ore concentration and to propose the method and the device of automatic non-destructive control of magnetic iron content in slurry flow.

The methods of systematization and analysis of specifics of ultrasonic waves propagation, mathematical and computer modelling, computer technologies and experimental investigations provide the results.

The scientific novelty consists in method of controlling the magnetic iron content in the slurry flow improving based on the Lamb waves propagation parameters assessment. The expression for determining the fraction of the ferromagnetic component in the slurry solid phase which contains the ratio of the measured Lamb waves amplitudes both in the magnetic field and without it and also contains the ratio of the Lamb waves amplitudes in the presence of the slurry and pure water in the measuring module (with no magnetic field was considered.

The practical significance of the studies is a flow chart of the device based on the Lamb waves propagation for controlling the magnetic iron content in the slurry proposing.

The results of the research investigate the regularities of the Lamb waves propagation in a metallic plate in contact with the iron ore slurry under various characteristics of the magnetic field was proposed. On the basis of the regularities of ultrasonic waves propagation in a metallic plate in the presence of the magnetic field, the authors analyze basic factors determining the magnetic susceptibility value, in particular, the size, form and initial magnetization of solid phase particles in the iron ore slurry. The method of controlling the magnetic iron content in the slurry flow is suggested based on the Lamb waves propagation parameters assessment. **Key words**: automatic control, magnetic iron, ore slurry, ultrasound, magnetic field

Introduction. Currently, real time measurements of the useful component content in the slurry flow are essential for optimizing iron ore magnetic concentration. The methods of nondestructive on-line control based on ultrasonic, magnetic, microwave and radiometric means are considered the most promising. In particular, research work [1] considers application of ultrasonic volume waves to controlling milled material characteristics. It should also be noted that ultrasonic (elastic) waves have been widely used lately. The reason for this is their specific features like relatively large energy concentration in a wave because of its small localization layer and the possibility of receiving an ultrasonic signal from any point of the surface (including the curvilinear one) along which it propagates.

Materials and methods

1. Systematization and analysis of specifics of ultrasonic waves propagation

Let us consider basic types of ultrasonic surface waves and features of their propagation, primarily, with regard to the problems of controlling industrial slurry characteristics.

As is known, the equation of the isotropic homogenous elastic medium movement can be presented as follows [2-6]

$$\rho\frac{\partial^2\overline{U}}{\partial t^2}=\mu\Delta\overline{U}+(\lambda+\mu)qrad\overline{U} \tag{1}$$

where $\overline{U}$ is a displacement vector of the medium particles; ρ is the medium density; λ and μ are elastic constants (the Lame parameters) of the medium; Δ is the Laplace operator.

The displacement vector is presented as

$$\overline{U}=\overline{U}_l+\overline{U}_t \tag{2}$$

where $\overline{U}_l=grad$; $\overline{U}_t=rot\psi$; φ and ψ are scalar and vector potentials. Thus, we obtain the equations describing longitudinal and transversal waves correspondingly

$$\rho\frac{\partial^2\overline{U}_l}{\partial t^2}-(\lambda+2\mu)\Delta\overline{U}_t=0 \tag{3}$$

$$\rho\frac{\partial^2\overline{U}_l}{\partial t^2}-\mu\Delta\overline{U}_t=0 \tag{4}$$

The ultrasonic Rayleigh waves are the most investigated and widely used among the known surface waves at present [4]. These waves propagate along the boundary of the solid space Z>0 (Fig. 1*a*).

For this case, the equations (3) and (4) can be transformed into a system of linear homogenous equations with relation to arbitrary constants *A* and *B*

$$\left[k^2\frac{\lambda}{2\mu}-q^2\left(1+\frac{\lambda}{2\mu}\right)\right]A+iksB=0 \quad (5)$$

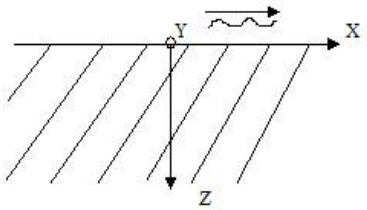
$$2iqA+(k^2+s^2)^2B=0 \quad (6)$$

where $q^2=k^2-k_t^2$; $s^2=k_2-k_t^2$; k_2 and k_t are wave numbers of longitudinal and transversal waves. The characteristic equation for finding the wave number *k* is determined on the basis of the equal-zero determinant of the system (5), (6). The equation which allows calculating the basic parameters of the Rayleigh wave looks like

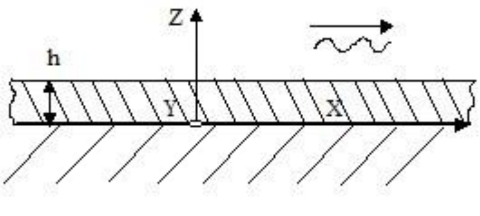
$$F(k)=4k^2qs-(k^2+s^2)^2=0. \quad (7)$$

As follows from (3) and (4), the Rayleigh wave consists of two plane heterogeneous waves – longitudinal and transversal. These waves and the Rayleigh waves composed of them are vertically polarized ones.

a



b



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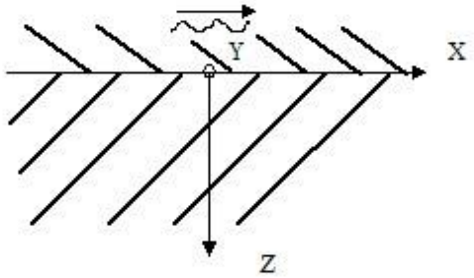

d

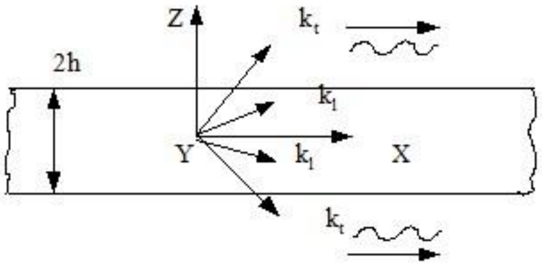

Figure 1. Ultrasonic surface waves: a - Rayleigh waves; b - Love waves; c - Stoneley waves; d - Lamb waves

The next type of ultrasonic waves is the waves inherently similar to the Rayleigh waves, yet, they are horizontally polarized. These are Love waves and they also satisfy the equation (1) being its linearly independent solution. It corresponds to the case when the wave vector is in the plane *XZ* and the displacements are parallel to the axis *Y*, i.e. $U_y \neq U, U_x=U_z=0 \ \ \partial/\partial_y=0$.

Then, the equation (1) will look like

$$\rho\frac{\partial^2\overline{U}}{\partial t^2}=\mu\Delta\overline{U} \quad (8)$$

where $\overline{U}=U_y\bar{y}_0$. The Love waves being the surface ones come into existence due to the addition of a solid layer to the semi-space and it becomes a load for the latter (Fig. 1*b*). As weak heterogeneousness of the surface layer of the solid body often occurs in practice and can be easily created deliberately, the Love waves enjoy a wide practical application.

The third basic type of ultrasonic waves at the boundary of two semi-spaces is Stoneley waves [2]. Let the plane harmonic surface wave propagate in the direction of the positive axis *X* along the plane boundary *Z* = 0 of two semispaces (1), (2) (Fig. 1, c). As before, we will suppose that a wave in each semi-space consists of a sum of longitudinal and transversal plane waves, each of them is a solution of the equations (3) and (4) with corresponding values ρ,λ,μ. The real root K_o

corresponds to the surface Stoneley wave and satisfies the condition

$$K_0 > K_t1, K_t2 \qquad (9)$$

If one of the semi-spaces is a solid body and the other one is fluid, the equation describing the wave movement looks like

$$4k^2 q_1 s_1 = (k^2 + s_1^2)^2 = \frac{\rho_ж}{\rho_1} = \frac{q_1 k_1^2}{q_ж} \qquad (10)$$

where ρ_f is the fluid density; $q_ж{}^2 = k^2 k_ж{}^2$. This equation differs from the Rayleigh equation (7) as it contains the right part that considers the influence of fluid on the solid semi-space. The thickness of layers of the Stoneley waves localization in the fluid makes

$$Z_f >> \lambda_f \qquad (11)$$

in the solid body

$$Z_s >> \lambda_f / 2\pi \qquad (12)$$

We also refer the waves in planes including normal horizontally polarized waves (transversal normal waves) and normal vertically polarized waves or Lamb waves (Fig. 1, d) to surface ones. In transversal normal waves, there is only one displacement component U_y parallel to the plane surface and perpendicular to the direction of the wave propagation, i.e. the deformation in the traversal wave is a pure shear. The basic property of transversal normal waves including the Lamb ones is the fact that with the designed values ☐ and *h* only a certain number of waves can propagate in the plate. The larger this ratio is

$$2h/\lambda_t = \omega h/\pi C_t \qquad (13)$$

the larger the number of waves is.

Specificity of the Lamb waves propagation along the surface in contact with industrial slurries is presented in detail in [5].

Besides the mentioned basic types of surface ultrasonic waves, there are also several varieties [4]: waves in a fluid layer on the solid semi-space; waves in a solid layer on the solid semi-space; quasi-volume waves in crystals; Bleustein-Gulyaev waves (surface waves in crystals with piezo-properties), etc. These varieties are applied in the sphere of ultrasonic control over characteristics of industrial slurries because of their specific features.

Analyzing basic types of ultrasonic surface waves we can draw the following conclusions. The Rayleigh waves have the largest energy concentration on the solid body surface, yet, the characteristics of their propagation depend much on the condition of the surface along which they propagate. The Love waves are characterized by their strong dependency on the heterogeneous surface layer due to which they exist, this fact making the measuring surfaces, along which they propagate, vulnerable and, thus, "unstable". The Stoneley waves (considered here) propagate in both fluid and solid semi-spaces and their component propagating in the fluid semi-space is under the influence of the same perturbing factors as the usual volume ultrasonic oscillations. For example, one should expect a strong dependency of their attenuation value on the content of gaseous bubbles in industrial slurries.

Taking into account the fact that the walls of technological tanks and trunks at concentration plants are made of sheet metal, it is convenient to apply the Lamb waves for ultrasonic control of the media parameters in contact with them. These waves are characterized by high energy concentration and less subjected to perturbing factors as the Rayleigh and Love waves are.

2. Basic regularities of ultrasonic surface waves propagation in the metallic plate with the magnetic field

Application of ultrasonic surface waves to developing and realizing methods and technical means of milled material characteristics control allows considerable expansion of their potential [7-9]. The basic expressions describing the Lamb surface waves propagation in a metallic plate in contact with the slurry flow are in [5]. From research [6] it follows that the presence of the magnetic filed causes additional rate attenuation and dispersion of volume ultrasonic waves propagating in the investigated medium.

Let us consider the influence of the magnetic field on surface waves propagation. Let this wave propagate in the solid perfectly conducting semi-space with the constant magnetic filed H_o. In this case, the elastic wave is accompanied by variable electric and magnetic fields and currents.

The elasticity equations and the systems of Maxwell equations considering the elements movement and the volumes of the conducting semi-space in the magnetic field should be satisfied [10]

$$(\lambda+G)\operatorname{grad}\operatorname{div}\overline{U}+G\Delta\overline{U}-\rho\frac{\partial^2\overline{U}}{\partial t^2}+ \frac{\mu}{4\pi}\times\left[\operatorname{rot}\operatorname{rot}(\overline{U}\times\overline{H}_0)\right]\times\overline{H}_0=0 \qquad (14)$$

where λ, G are Lame parameters; ρ is the medium density; μ is the medium magnetic susceptibility; $\overline{U}$ is the displacement vector in the wave. As in [5], we present the displacement vector in the following way

$$\overline{U}=qrad\varphi+rot\overline{\psi}\,, \qquad (15)$$

where $div\overline{\psi}=0$. The scalar φ and the vector $\overline{\psi}$ potentials of the vector $\overline{U}$ are connected with the volume expansion

$$div\overline{U}=\Delta\varphi \qquad (16)$$

and revolution

$$rot\overline{U}=-\Delta\overline{\psi} \qquad (17)$$

The equation (14) solutions in the form corresponding to the plane harmonic waves propagating in the direction of the axis x are the expressions

$$U_{x,y,z}=\frac{A,B,C}{k}e^{\beta kz+i(kx-\omega t)} \qquad (18)$$

where k is a wave number; $\beta(k)$ is a function of k; A,B,C are arbitrary constants. In case of the weak magnetic field the following solutions are valid [6]

$$k=k_R(1-\alpha) \qquad (19)$$

$$U_x=\frac{A}{k}\left[e^{\beta_{10}kz}-\frac{2\beta_{10}\beta_{20}}{2-\eta^2}\right]\times e^{i(kx-\omega t)}+\Delta\left(\left[h_xh_y\right]^{\frac{1}{2}}\right) \qquad (20)$$

$$U_y=\frac{A(h_xh_y)^{\frac{1}{2}}}{k}\left[-e^{\beta_{10}kz}+\frac{0{,}25\eta^2h_x-(\beta_{10}/\beta_{20})h_y}{(\beta_{20}/\eta^2)h_x)h_y-h_y}\right]\times e^{i(kx-\omega t)}+\Delta\left(\left[h_xh_y\right]^{\frac{1}{2}}\right), \qquad (21)$$

$$U_z=\frac{i\beta_{10}A}{k}\left[-e^{\beta_{10}kz}+\frac{2}{2-\eta^2}e^{\beta_{20}kz}\right]\times e^{i(kx-\omega t)}+\Delta\left(\left[h_xh_y\right]^{\frac{1}{2}}\right), \qquad (22)$$

where k_R is the wave number of the Rayleigh wave with $H_0=0$; □ is a correction to k_R because of the magnetic field; $\eta=k_t/k_R$. For the metallic plate made of steel 12X18 H10T

$$\alpha=\frac{2{,}09-0{,}3(h_xh_y)-0{,}16h_y}{4-0{,}57h_x-h_y^{-1}} \qquad (23)$$

Thus, the one-component magnetic field changes the phase velocity of the wave and the two-component field changes the wave structure. The magnetic field causes the third displacement U_y proportional to $\sqrt{h_x\ h_y}$ (Fig. 2, 3).

In strong magnetic fields, the displacements are determined by the following expressions [10]

$$U_y=\frac{A}{k}e^{\beta kz+i(kx+\omega t)}+\Delta\left(h_y^{1/2}\right) \qquad (24)$$

$$U_{x,t}=\Delta\left(h_y^{1/2}\right) \qquad (25)$$

Expressions (24) and (25) indicate the presence of the surface wave connected with the magnetic field only. The possibility to use this wave depends on the magnetic field intensity. The wave only exists with those values h_x, which satisfy the condition $\beta>0$.

The above mentioned also indicates that in the two-component magnetic field ($h_x\neq0$ и $h_y\neq0$) the volume (transversal) wave is transformed into the surface one.

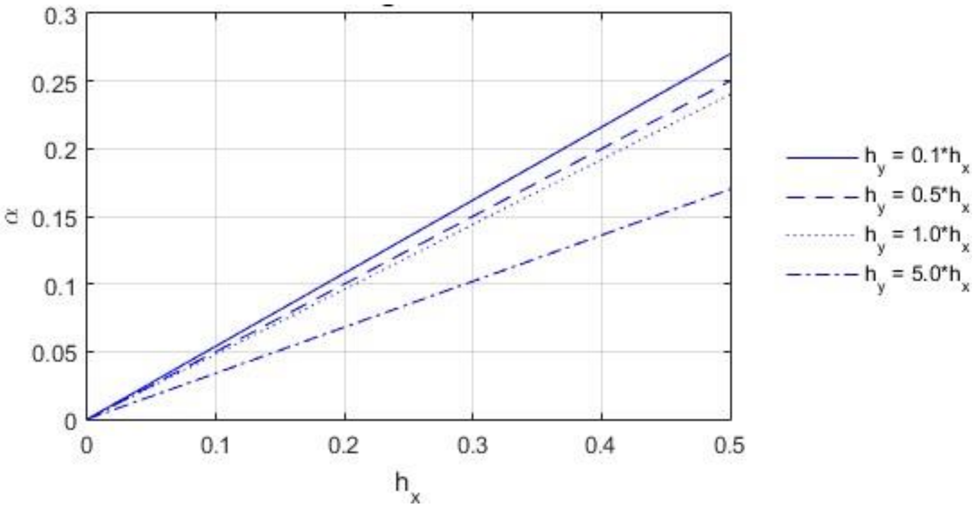

Figure 2. Dependency of α on h_x with various values of h_y

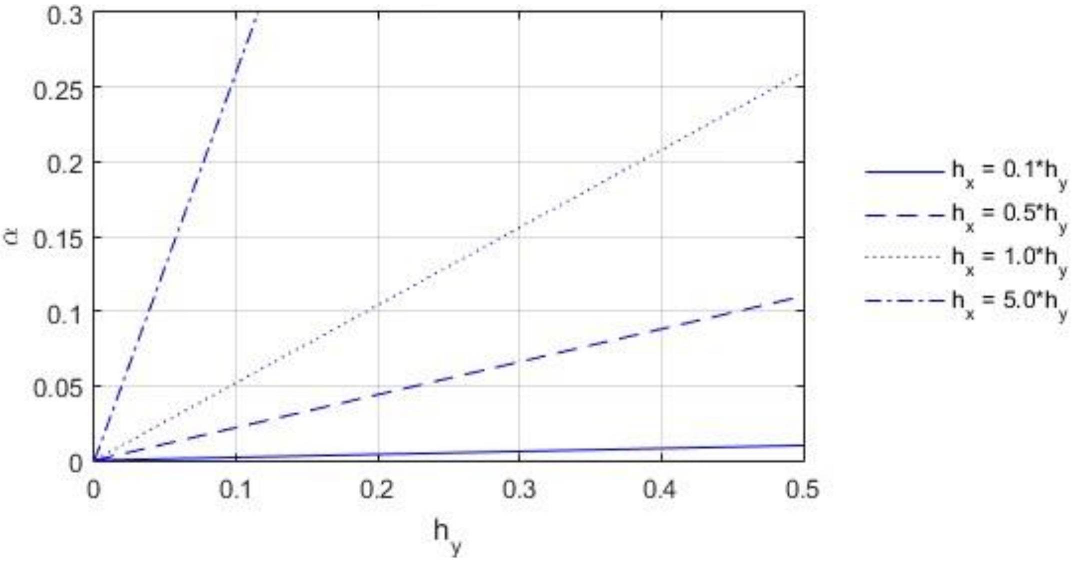

Figure 3. Dependency of α on h_y with various values of h_x

3. Method of controlling magnetic iron content in the slurry flow based on measuring parameters of the Lamb waves propagation

The considered regularities of the Lamb waves propagation along the metallic plate in contact with the slurry flow in the presence of the magnetic field allow forming the method of controlling the magnetite-iron content in its solid phase.

In the presence of the magnetic field (the transversal one, $H_z \neq 0$, $H_x = 0$; $H_y = 0$) the Lamb wave will attenuate according to the law

$$I_v = I_\infty exp\{-k(1\alpha(1\alpha(\}\times \\ \times exp\left\{-\frac{[(1-W_\tau)\rho_в W_\tau \rho_{тв}]}{\rho_{пл}} C_v l\right\} \qquad (26)$$

Here, $I_{ov}(H) \equiv I_\infty exp\{-k(1-\alpha(H))l\}$ is the wave attenuation function in the absence of the contacting fluid medium (water, slurry, etc.), □(H) is the parameter considering the magnetic field impact (if $H=0$, then □(0)□0). $□_{пл}$ is the density of the plate material.

According to the above mentioned the parameter considering the magnetic field impact is determined by

$$\alpha(H_2)=\mu_2 H_2 const, \qquad (27)$$

where μ_2 and H_2 are magnetic permeability and intensity of the magnetic field in the plate along which the Lamb wave propagates. If the field is homogenous, the magnetic permeability of the controlled medium can be determined by the expression

$$H_2 \approx \frac{(nJ_0)}{\mu_2} \qquad (28)$$

where H_2 is magnetic permeability of the controlled medium, n is the number of turns in a coil, J_0 is the current in a coil. It is presumed that $(l_1 >> l_2)$ and $(\mu_1 < \mu_2)$. Substituting (28) in (27), we obtain

$$\alpha(H_2)= \mu_1(nJ_o)const. \qquad (29)$$

Then, the method of measuring implies the measurements of the wave amplitude in the presence of the magnetic field ($I_v(H)$) and without it ($I_v(H)$ and the value is calculated

$$Ln\frac{I_v(H)}{I_v(0)} = \alpha(H)kl = \mu_1[kl(nJ_0)const] \qquad (30)$$

whence it follows that

$$\mu_1 = \frac{1}{[kl(nJ_0)const]} ln\left(\frac{I_v(H)}{I_v(0)}\right) = C_3 ln\left(\frac{I_v(H)}{I_v(0)}\right) \qquad (31)$$

where we find from the expression

$$C_3 = \frac{1}{[kl(nJ_0)const]}$$

According to the method of controlling the concentration of the slurry solid phase on the basis of changed parameters of the Lamb waves propagating along the metallic plate in contact with the slurry and the dependencies of iron ore slurry magnetization in the magnetic field mentioned above we can present the following expression for determining the fraction of the ferromagnetic component in the slurry solid phase

$$\eta = \left[\frac{(\rho_{тв} - \rho_{в})}{\rho_{пл} I_{м}}\right] = A\frac{(\mu_2 - 1)}{ln\left(I_{ov}/I_{v}\right)} \qquad (32)$$

Substituting (31) into (32) we acquire

$$\eta = A\frac{(\mu_2 - 1)}{\ln\left(I_{ov}/I_{v}\right)} =$$

$$= (AnJ_0)\frac{\left(C_3 \ln\left(\frac{I_v(H)}{I_v(0)}\right) - 1\right)}{\ln\left(I_{ov}/I_{v}\right)} = \qquad (33)$$

$$= A_3\frac{\left(C_3 \ln\left(\frac{I_v(H)}{I_v(0)}\right) - 1\right)}{\ln\left(I_{ov}/I_{v}\right)}$$

The expression (33) numerator contains the ratio of the measured Lamb waves amplitudes both in the magnetic field and without it and the denominator contains the ratio of the Lamb waves amplitudes in the presence of the slurry and pure water in the measuring module (with no magnetic field).

The conducted research indicates that the value calculated according to (33) does not depend on the solid phase concentration and at the same time it explicitly determines the magnetic iron content in the controlled volume of the slurry.

4. Device for controlling the magnetic iron content in the slurry flow

The device for controlling the magnetic iron content in the slurry flow (Fig. 4) consists of a multivibrator *1*, starting univibrators *2, 16, 18, 36*, generators *3, 17, 19, 37*, forming prisms *5, 7, 23, 24*, radiating transducers *4*, *25*, receiving transducers *8*, *26*, amplifiers *9*, *27*, temporary selection blocks *11*, *29*, forming univibrators *12*, *28*, pulse transducers *13*, *30*, analog-digital transducers *14*, *31*, a microcomputer *15*, a data panel *42*, coils *20*, *38*, a magnetic circuit *21*, a measuring vessel *6*, *22*, an accumulating vessel *32*, pipelines *33*, *34*, *35*, valves *40*, *41*.

The device controlling the magnetic iron content in the slurry flow functions as follows. The iron ore slurry from the accumulating vessel *32* (the technological tank) along the pipelines *33, 34* enters the measuring vessels *6*, *22*. In the measuring vessel *22,* it is affected by the magnetic field generated in the coil *22* and the magnetic circuit *21* by means of the generator *17* and the starting univibrator *16*.

In the walls of the measuring vessels *6, 22* the Lamb waves are formed by means of the starting univibrators *2*, *16*, generators *3*, *17*, piezoelectric transducers *4, 25* and forming prisms *5*, *23*. Passing the fixed distance along the measuring vessels walls, the Lamb waves are transformed into electric signals by forming prisms *7, 24* and piezoelectric transducers *8, 26* and are amplified by amplifiers *9*, *27*. In the temporary selection blocks *11*, *29,* an information component of the received signals is distinguished by means of univibrators *12, 28* and it is transformed into a signal of direct current of the same amplitude by transducers *13*, *30*. By means of analog-digital transducers *14, 31* these signals are input into the microcomputer *15*. The microcomputer *15* starts the system by means of multivibrator *1* and the data is output by the D-A converter *42*.

Preliminary de-magnetization of the iron ore slurry is performed by the impulse magnetic field of decreasing amplitude formed by the univibrator *36*, the generator *37* and the coil *38*. The valves *40, 41* are applied for controlling slurry and water flows to ensure the system operation and calibration.

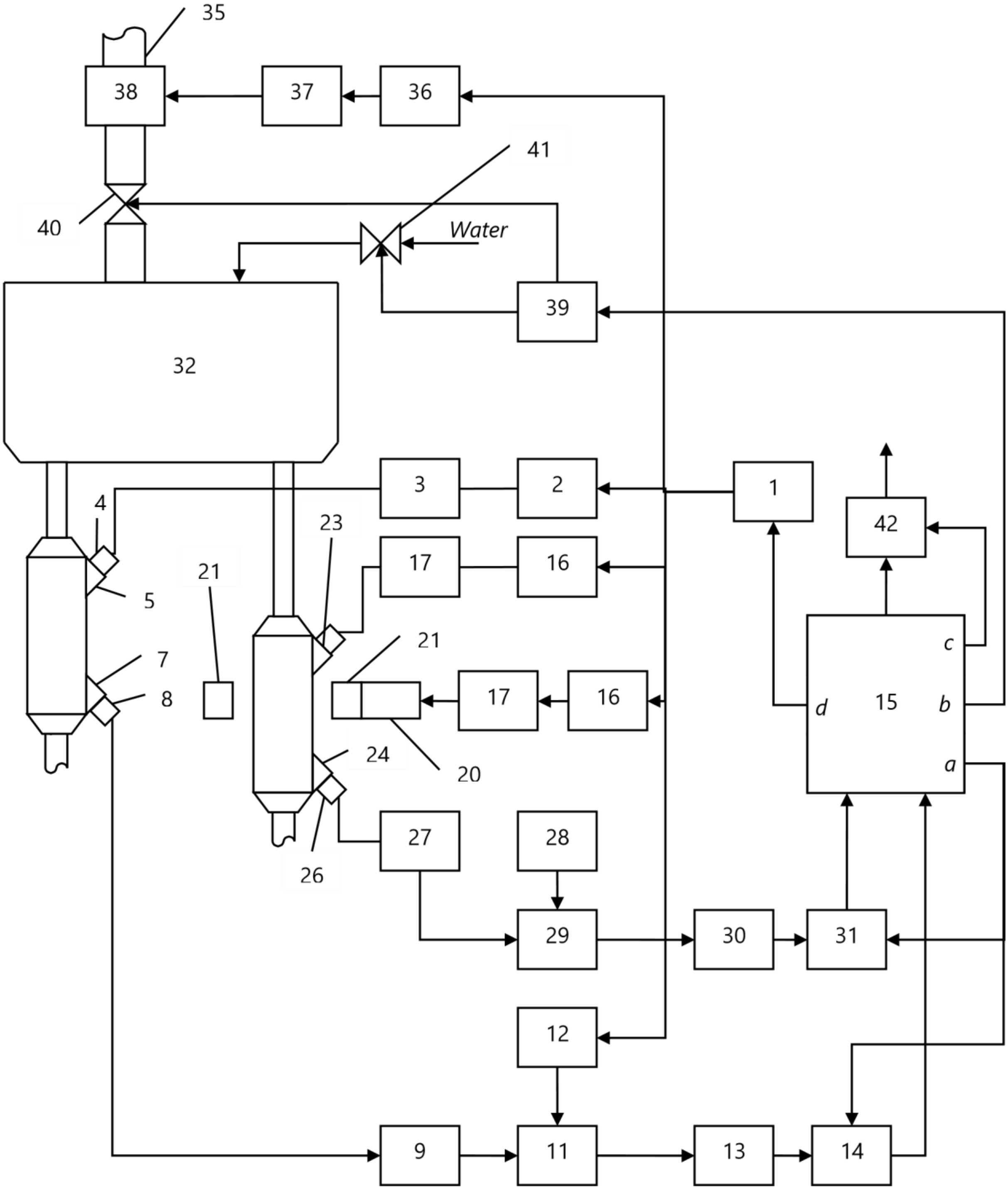

Figure 4. Flow chart of the device for controlling the magnetic iron content in the slurry

Results. The ultrasonic control system was tested as part of the automated system of controlling iron ore concentration [11-17]. The calibration (preliminary adjustment) of the ultrasonic control system of the magnetic iron content in the slurry flow was performed as follows. In the absence of the controlled medium in the measuring vessel, the amplitude of the Lamb wave with the magnetic field ($I_v(H)$) and without it ($I_v(0)$) is determined and the value is calculated

$$\ln\frac{I_v(H)}{I_v(0)} = \mu_1[kl(nJ_0)const] = \frac{\mu_1}{c_3} \qquad (34)$$

The magnetic permeability for air is almost 1 and, then, the expression (34) will look as

$$ln\frac{I_v(H)}{I_v(0)} = \frac{1}{C_3} \qquad (35)$$

$I_v(0)$ c_3 whence it follows that

$$C_3 = \frac{1}{ln\left(I_v(H)/I_v(0)\right)} \qquad (36)$$

To determine the constant A_3, the real slurry

$$\frac{(C_3 \ln\frac{I_v(H)}{I_v(0)} - 1)}{\ln(\frac{I_{ov}}{I_v})}$$ is

is measured and the value $\frac{\left(C_3\, ln\left(I_v(H)/I_v(0)\right)\right)}{ln\left(I_{ov}/I_v\right)}$ is determined. The content of the magnetic component in the sample is measured by standard laboratory methods. The proportionality coefficient value A_3 is found according to

$$\eta = \frac{\left(C_3 \ln\left(\frac{I_v(H)}{I_v(0)}\right) - 1\right)}{\ln\left(I_{ov}/I_v\right)},$$

$$= A_3 \frac{\eta}{\frac{\left(C_3 \ln\left(\frac{I_v(H)}{I_v(0)}\right) - 1\right)}{\ln\left(I_{ov}/I_v\right)}}$$

The conducted testing indicates that the given device ensures stable measurements of the solid and magnetic iron content in the ore slurry. The measuring error of the solid percentage in the slurry makes □ 0,25 % abs.; The measuring error of the magnetic iron percentage in the slurry solid phase makes □ 0,25 % abs.

Conclusion. As in processing lines of concentration plants, the walls of technological tanks and trunks are usually made of sheet metal, it is convenient to apply the Lamb waves to implementing ultrasonic control of the parameters of the media in contact with them. These waves are characterized by high energy concentration and are less subjected to perturbing factors than the Rayleigh and Love waves.

The parameters of the Lamb waves propagation in the metallic plate in contact with the iron ore slurry depend on the characteristics of the applied magnetic field and the magnetic susceptibility of the slurry. To measure the magnetic iron content in the slurry flow, one should measure the attenuation values of the Lamb waves propagating along the metallic plate in contact with the controlled medium in the presence of the magnetic field and without it.

We suggest the system of ultrasonic control of the magnetic iron content enabling us to maintain the optimal useful component content in the concentrated ore with changing qualities of the initial ore and the technological equipment conditions.

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