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METHOD OF INDUCTION CONTROL OF IRON WEIGHT FRACTION IN MAGNETITE ORE

Ivan N. BAZHENOV, Oleg O. BASOV
Russian Federation Security Guard Service Federal Academy, Orel, Russia

This paper analyzes the peculiarities of existing methods and means of induction control of magnetic susceptibility of the medium are analyzed. It is concluded that these means have a common drawback due to the low measurement accuracy caused by the wave-like dependence of the instrument sensitivity on the gap between the probe and the medium surface. The ways of increasing the instrument sensitivity and measurement accuracy of controlled parameters by means of inductive measuring transducers are revealed. A method for induction resonance control of iron weight fraction in magnetite ore has been developed, and its effectiveness has been estimated using simulation modeling. Practical recommendations for the development of quality control instruments for magnetite ores have been developed. A variant of the quality control unit layout for working with magnetite ores is proposed.

Keywords: method of resonance control of ore magnetic susceptibility, mutual inductance, measuring probe

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Introduction. The main indicator for quality of raw materials for ferrous metallurgy enterprises is the content of the iron weight fraction in iron ore concentrate, the stability of which substantially affects the technical and economic performance of blast furnaces and the cost of cast iron. According to the mineral processing technology used at the end of each technological stage, it is necessary to maintain a certain iron weight fraction [1, 6]. The existing technical tools, such as X-ray and ultraviolet analyzers, are quite complex and expensive and do not allow solving the tasks of complex monitoring of the current iron percentage in the ore mass or after each technological stage at a processing plant [13, 14].

For non-destructive control and assessment of magnetite ore quality it is advisable to use the principle of measuring mutual magnetic induction between two inductance coils located at a fixed distance in a measuring probe. In this case, the sensitivity to the controlled parameter of the ore quality depends not only on the distance between the probe and the surface of the ore-bearing rock, but also on the relative positioning of these coils [2-4, 9].

The general method of induction control of the iron percentage in the ore composition is practically reduced to measuring the amplitude and phase of the signal transmitted to the receiving (measuring) coil from the source inductor, which forms an electromagnetic field in the kilohertz frequency range. In the probe design, these inductors are placed either parallel or perpendicular to the surface of the studied ore, and the percentage of iron in the ore is judged by the amplitude and phase of the signal at the output of the measuring coil [16, 17, 22]. With this indirect method of measuring the ore quality, the calibration of the control devices is carried out directly on specific samples of the ore mass, which differ in their mineralogical composition.

To control the ore processing, they also use magnetic induction signals in the working area of the magnetic separator [16, 17] or perform assessment of iron weight fraction in the concentrate using the signal of the normal component of the magnetic induction vector [14]. As part of the magnetic field sensors, magneto-sensitive resistors are sometimes used instead of the measuring inductors, but their use does not give significant advantages for the sensitivity of instruments controlling the iron weight fraction in the concentrate. The accuracy of measuring the ore magnetic properties is affected by the methodological error caused by the wave-like dependence of the instrument sensitivity on the distance between the probe and the medium surface.

One of the options for increasing the measurement accuracy and the instrument sensitivity for monitoring the magnetic susceptibility of the ore is to increase the increment of the EMF ΔE on the receiving coil. To implement such an option, it is proposed to use the resonance mode of the probe. To obtain a resonance the capacitors are connected in parallel to the compensation and measuring coils. In this case, oscillatory circuits are formed, the resonance frequency of which must be set equal to the generator frequency: $f_r = 1/2\pi\sqrt{L_n C_n}$, where L_n is the inductance of the compensation or measuring coil; C_n is the condenser capacitance [10]. The resistance of the oscillating circuits at the resonance frequency is tens of times higher than the inductive resistance of the compensation and receiving coils, which makes it possible to significantly increase the amplitude of the signals on these contours when measuring the magnetic susceptibility of the medium.

The sensitivity of any device is determined by the ratio of output value U increment to the measured parameter χ, i.e. $S_\chi = \Delta U/\Delta\chi$. In our case, with a constant amplitude of the signal on the generator winding, the output parameter is the voltage on the measuring coil. When the metal sheet is brought to a fixed distance (for example, h = 10 cm), the increment is $\Delta\chi$ = const, so the sensitivity of the inductive converters can be unambiguously compared to the voltage on the measuring coil with and without resonance mode.

Theoretical studies of the induction sensors sensitivity with different mutual arrangement of the source and receiving induction coils. During the research, inductors with square cross-sectional area of windings were used. They were chosen due to the ease of manufacturing under conditions of industrial production. According to the recommendations of [11], the coil with the square cross-section area of the windings has the highest inductance L, if the ratio of the average diameter d of the winding to the length a of the inductor is $d \approx 3a$. When coaxial placement in the probe of the source and receiving coils of the same diameter with the same number of turns of windings w at a distance y from each other (Fig. 1, *a*), their mutual inductance is determined by the formula [11]

$$M = kL = \frac{\mu_0}{4\pi} 8{,}497 w^2 k d\ , \tag{1}$$

where k – coefficient of magnetic coupling of coils, it depends on the relation $y/a = (3y)/d$; L – coil inductance, H; μ_0 – magnetic constant, H/m; w – number of turns of a winding; d – average diameter of a coil, m.

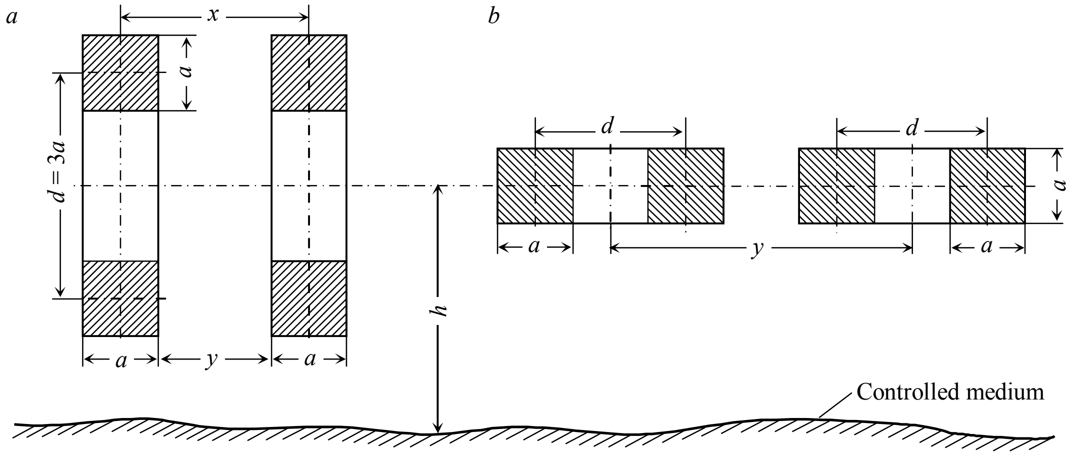

Fig.1. Arrangement of induction coils of square cross-section: *a* – coaxial to each other; *b* – parallel to each other

The mutual inductance of coils moved far away from each other ($y > 2a$) is determined by the method of equivalent circular contours. In this case, each inductor is replaced by a single circuit having a diameter

$$d_l = d(1 + a^2/6d^2) = d(1 + 1/54) = 1.01852d\,. \tag{2}$$

The mutual inductance M_l of two of these contours located coaxially at a distance of $x = y + a$ from each other is calculated by the formula

$$M_1 = w^2 M_l\,. \tag{3}$$

The mutual inductance M_l of equivalent contours moved far away from each other is calculated by the formula

$$M_l = \frac{\mu_0 \pi R}{16}\gamma^3\left(1 - \frac{3}{4}\gamma^2 + \frac{75}{128}\gamma^4 - \frac{245}{512}\gamma^6 + \frac{6615}{16384}\gamma^8 - \ldots\right), \tag{4}$$

where $R = d_l/2$ – contour radius, m; $\gamma = 2R/x$ – equivalent contour parameter.

A similar mutual inductance of coils with a rectangular cross-sectional area of windings with parallel axes (Fig. 1, *b*) is calculated by the formula

$$M_2 = \frac{\pi}{32}\mu_0 w^2 \frac{d^4}{a^4}\left(\frac{Z_1}{b_1} - \frac{Z_2}{y}\right), \tag{5}$$

where d and a – respectively, the average diameter and length of the coils; $b_1 = \sqrt{a^2 + y^2}$; y – distance between coil axes, m; $Z_1 = \rho_2^2 - \frac{1}{2}\alpha_1^2\rho_2\rho_4 P_2(\gamma_1) + \frac{1}{8}\alpha_1^4(2\rho_6\rho_2 + 3\rho_4^2)P_4(\gamma_1) - \frac{5}{32}\alpha_1^6(\rho_8\rho_2 + 6\rho_6\rho_4)P_6(\gamma_1) + \ldots$ – calculated parameter; $\rho_n = 1 + \frac{n(n-1)}{3!}\rho^2 + \frac{n(n-1)(n-2)(n-3)}{5!}\rho^4 + \ldots + \frac{n(n-1)(n-2)\ldots2\cdot1}{(n+1)!}\rho^n$; $\alpha_1 = d/2b_1$; $P_n(\gamma) = \frac{1}{2^n(n)!}\frac{\partial^n}{\partial\gamma^n}(\gamma^2 - 1)^n$ – spherical Legendre functions of the *n*-th order [15], n – whole number; $\gamma_1 = a/b_1$; parameter Z_2 is similar to Z_1 when replacing γ_1 with $\gamma_2 = 0$ and α_1 with $\alpha_2 = d/(2b_2) = d/(2y)$.

In the course of studies using the Mathcad program, we have calculated the mutual inductance of two coils having the same number of turns $w_1 = 1000$, $w_2 = 2000$ and $w_3 = 3000$, and various geometric dimensions: $a_1 = 0.005$ m, $a_2 = 0.01$ m, $a_3 = 0.02$ m, with a change in the distance between them $y = 0.05$; 0.1; 0.15; 0.2; 0.25; 0.3, m.

As a result, we have obtained the calculated dependences of the mutual inductance of the coils on the distance under coaxial and parallel placement relative to each other, according to which a six-fold increase in the distance between the source and measuring coils leads to an exponential decrease of the mutual inductance between them by approximately two decimal order (Fig.2)

It is established that the parallel placement of inductance coils in the design of the probe leads to a decrease in

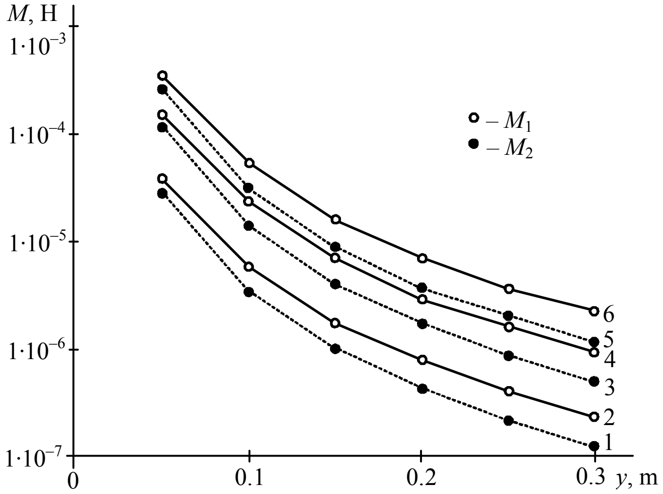

Fig.2. Calculated dependences of the mutual inductance of coils placed at some distance when they are coaxial and parallel to each other (a = 0.005 m)
1, 2 – w_1 = 1000; 3, 4 – w_2 = 2000; 5, 6 – w_3 = 3000

the mutual inductance of approximately twice as compared to coaxial coils, and at different distances between them. In addition, an increase in the number of turns in the source and measuring coils in the range from $w_1 = 1000$ to $w_3 = 3000$ allows approximately 10 times to increase the absolute values of the mutual inductance for different locations of the coils.

Based on the calculations, it was also found that an increase in the winding size from $a_1 = 0.005$ m to $a_3 = 0.02$ m results in an increase of mutual inductance of the coils in about 40 times, while maintaining the exponential dependence of its decrease with increasing distance y between the coils.

The analysis of the obtained mutual inductance dependences on the distance between the coils showed that the electromagnetic field produced by the source coil under conditions of coaxial arrangement exerts a larger side effect on the receiving coil when measuring the magnetic susceptibility. The geometric dimensions and number of coil turns affect the absolute values of the mutual inductance, while the form of the dependence remains exponential. Taking into account the data obtained to select the design of the probe and to assess its sensitivity to the controlled magnetic environment, a full-scale experiment with a metal plate

The results of a full-scale experiment to assess the sensitivity of a measuring probe to a controlled magnetic medium. The scheme of the experiment is shown in Fig. 3. With the same number of turns $w = 1000$ in source and receiving coils, a capacitor with a capacitance $C = 0.5$ µF was connected in parallel to the receiving coil through a keyswitch to obtain a parallel oscillatory circuit with a resonance frequency $f_r = 1140$ Hz.

During the research, the source and receiving coils were located at different distances from each other. A sinusoidal voltage $U_g = 10$ V with a frequency $f_r = 1140$ Hz was applied to the source coil. A digital voltmeter measured the voltage on the receiving inductor in three cases: without a ferromagnetic core, with the introduction of a ferro-magnetic core with a diameter of 1 cm into the receiving coil and when a resonant capacitor C was connected to a receiving coil with a ferromagnetic core. The magnetic medium was a metal plate of size 0.05×1.0 m, the apparent magnetic susceptibility of which could be taken to be $\chi_{\max} = 2$ SI, which was located at a distance of 0.1 m from the source and receiving coils. The distance between the coils varied from 5 to 30 cm.

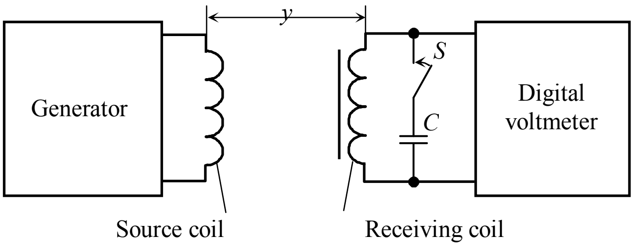

Fig.3. Experiment layout

As a result of the influence of the electromagnetic field, a voltage (in volts) of mutual induction $U_{pr} = MI_g$ arises at the clamps of the receiving inductor, where I_g is the current flowing along the source coil, A; M is the mutual inductance, H [18].

Fig.4 shows the voltage dependence on the receiving inductor from the distance to the source coil in the resonant U_{rez} and without the resonant U_{nrez} operating mode.

To assess the sensitivity of the probe with different arrangement of the coils, the dependences of the voltage increment on the receiving coil with their coaxial ΔU_{1g}, (ΔU_{2g}) and parallel ΔU_{1v} (ΔU_{2v}) placement from the distance y to the source coil in the presence and absence of a metal plate and in the absence were obtained (Fig.5).

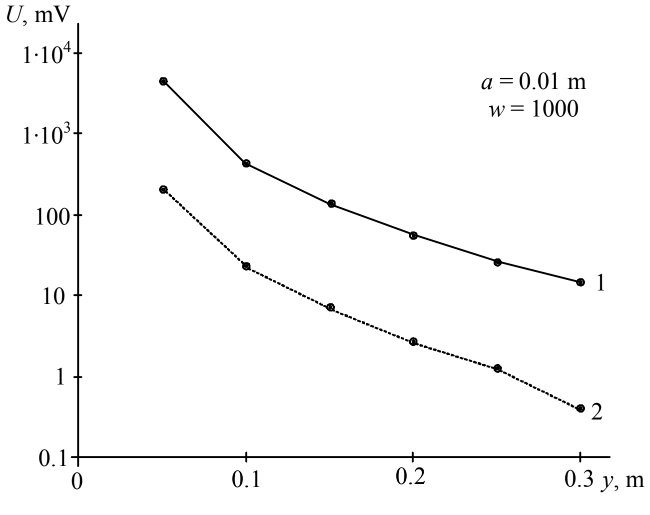

Fig.4. Dependence of voltage at receiving induction coil in resonance U_{rez} (1) and non-resonance U_{nrez} (2) mode on the distance to the source coil

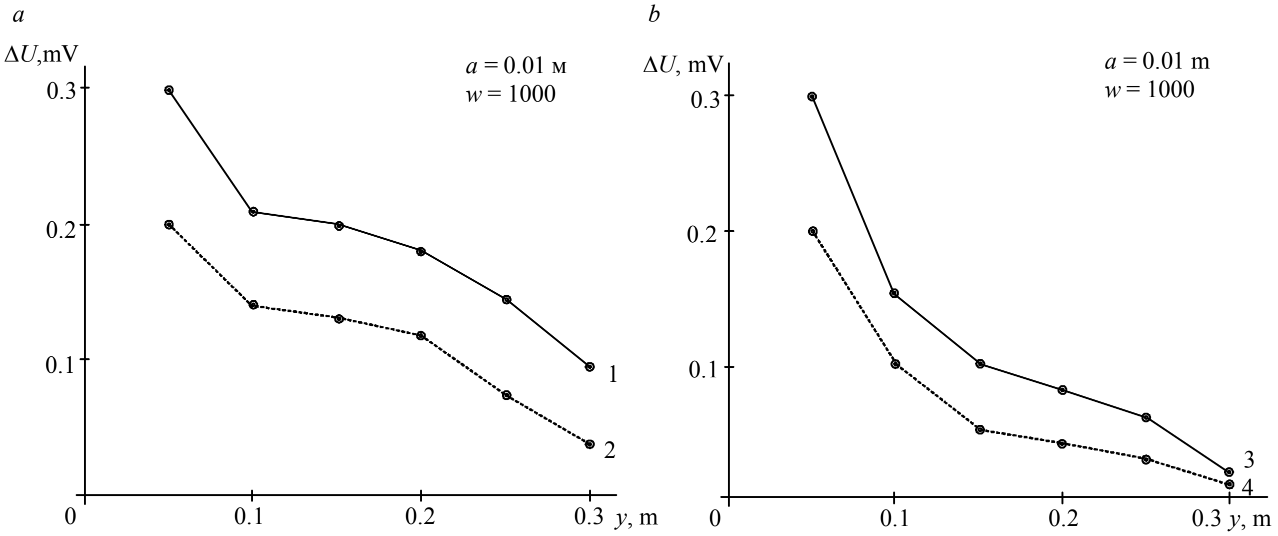

Fig.5. Dependences of voltage increment at receiving coil with coaxial and parallel placement from source coil with and without metal plate:

a – in resonance mode (1 – ΔU_{1v}; 2 – ΔU_{1g}); *b* – in non-resonance mode (3 – ΔU_{2v}; 4 – ΔU_{2g})

As a result of the carried out experimental researches it is has been established:

1) in the known scheme of the measuring probe containing the source and receiver coils without cores when the probe coils are arranged, for example, coaxially, the voltage on the receiving coil changes in the range ΔU_{nrez} = 0.41÷197 mV as the distance y between coils increases from 5 to 30 cm;

2) when the capacitance is connected, the voltage on the receiving coil operating in the resonant mode rises by approximately 30 times, and with a similar change in the distance y between the coils changes in the range ΔU_{rez} = 14.7÷4302 mV;

3) comparison of voltage increments on the receiving coil with different mutual placement of the source and receiving coils showed that the use of a parallel arrangement of the coils allows approximately 1.5 times to increase the sensitivity of the probe to the iron content (Fig. 4, *b*);

4) relative sensitivity to the iron content does not depend on the operating mode of the receiving coil and varies inversely with the square of the distance h from the coils to the metal sheet surface, however, the use of the resonance mode of operation allows to increase the absolute sensitivity values approximately in $\Delta U_{1v}/\Delta U_{2v} = 10$ times (Fig.5);

5) amplitude of the voltage on the receiving coil is proportional to the mutual induction with the source coil and decreases inversely proportional to the square of the distance between these coils, which corresponds to the calculated graphs (see Fig. 2). As a result, the voltage on the receiving coil decreases to hundreds of tens of microvolts at a distance between the coils of y = 0.3 m, which leads to instability of the results of controlling the iron content in the ore mass because of the influence of interference from the electrical equipment when the monitoring device is operating under production conditions.

A comparative analysis of the obtained results allows us to work out the practical recommendations for the development of quality control instruments for magnetite ores:

1) the source and measuring coils should be placed parallel to each other and perpendicular to the controlled surface of the ore, which allows about a 1.5-fold increase in the sensitivity of the monitoring device to the metal content in the ore mass;

2) the amplitude of the signal on the receiving coil can be increased by introducing a ferromagnetic core. In this case, the source coil should be without a core, since the intensity of the generated magnetic field $H = I_g w$ depends only on the number of turns w and the alternating current I_g [12],

and at a constant amplitude of the voltage at the generator output, the magnetizing current decreases due to an increase in the inductive resistance of the winding (from insertion of a core);

3) to increase the amplitude of the receiving coil signal, a resonance mode of operation should be used, it allows, first, to increase the level of the measured voltage and, secondly, to weaken the relative influence of industrial disturbances on the result of control.

In addition, to increase noise immunity at a large distance between the source and receiver coils, it is advisable to measure the voltage on the receiving coil by the weight function method [7, 8], which allows approximately 60 dB (or 1000 times) to reduce the effect of network interference with a frequency of 50±1 Hz on the result of control.

Practical implementation of the method of induction control of the iron weight fraction in magnetite ore. A variant of the circuit implementation of the method of induction control of the iron weight fraction in the ore is presented in Fig.6 [5]. To receive the resonance, parallel to the compensating coils (with inductance L_1 and L_2, respectively) and measuring (with inductance L_3), three capacitors are connected (with capacitances C_1, C_2 and C_3, respectively). The resistance of the formed oscillatory circuits at the resonance frequency is tens of times higher than the inductive resistance of the compensating and receiving coils, which makes it possible to significantly increase the amplitude of the signals on these contours with a change in the magnetic susceptibility of the medium.

The control device (Fig.6) works as follows. When alternating current flows from the generator of the sinusoidal voltage along the turns of the source coil, an alternating electromagnetic field is created in the surrounding space. Structurally, the receiving coil is mounted in the probe at a fixed distance l_{gp} from the source coil. The first compensation coil is located at a distance of $0.2l_{gp}$, and the second compensation coil is at a distance of $0.8l_{gp}$ from the source coil. In the air in the absence of a magnetic medium, this electromagnetic field induces on two counter-connected compensation coils equal in magnitude and EMF opposite in phase, E_1 and E_2.

When the probe is placed above the investigated medium, it is magnetized by the alternating electromagnetic field of the source coil. The secondary magnetic field that appears in this case induces a different in amplitude EMF in the receiving and compensating coils. As a result, a difference EMF ΔE_1 of the output signals of the receiving and first compensating coils appears at the input of the first amplifier, and the differential EMF ΔE_2 of the output signals of the receiving and second compensation coils at the input of the second amplifier. After the amplification of the differential EMFs ΔE_1 and ΔE_2 by amplifiers and their rectification by synchro-

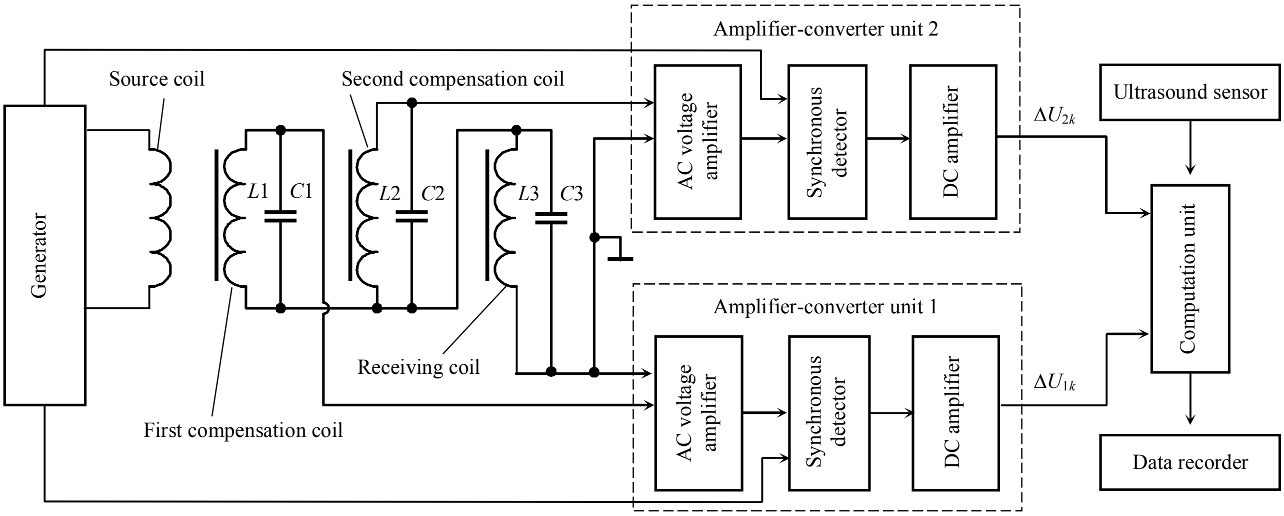

Fig.6. A sample of layout for implementation of method of induction control of iron weight fraction in magnetite ore

nous detectors, constant or slowly varying signals are amplified by direct current amplifiers and fed to the first two inputs of a calculating unit based on a microcontroller containing an input switch and an analog-to-digital converter for obtaining and processing control results in digital form. The third input of the calculating unit receives pulses from an ultrasonic sensor that determines the distance h from the probe to the medium to correct the conversion results that are output to the recorder. The magnitude of the digitally fixed result determines the magnetic susceptibility of the medium.

When the probe is placed above the flat surface of the medium under study, the difference EMFs $\Delta E_1 = E_0 G_1 \chi$ and $\Delta E_2 = E_0 G_2 \chi$ depend on the product of the EMF E_0 induced in the air, the geometric factors of the probe G_1, G_2 and the magnetic susceptibility of the medium $\chi = I / H$ proportional to its magnetization I on the strength H of the electromagnetic field. The values of the geometric factors of the probe G_1, G_2 depend on the arrangement of the compensation coils relative to the source coil and vary over a wide range of values, depending on the ratio of the distance to the investigated medium and the probe length h / l_{gp}.

The difference EMFs ΔE_1, ΔE_2 are amplified and detected by amplifying-conversion blocks with conversion coefficients K_1, K_2, so the voltages at the two inputs of the computational block are

$$\Delta U_{1k} = K_1 E_0 G_1 \chi , \tag{6}$$

$$\Delta U_{2k} = K_2 E_0 G_2 \chi . \tag{7}$$

To obtain the same maximum values of the measured voltages $\Delta U_{1\max}$ and $\Delta U_{2\max}$, it is necessary to fulfill the condition $K_1 G_{1\max} = K_2 G_{2\max}$, that when using amplification-conversion blocks with equal conversion factors $K_1 = K_2$, is reduced to providing equal maximum values of the geometric factors of the probe $G_{1\max} = G_{2\max}$. This equality can be achieved by reducing by 4 times the number of turns in the first compensation coil in comparison with the number of turns in the second one (provided they are placed at distances $0.2 l_{gp}$ and $0.8 l_{gp}$ from the source coil).

The use of an ultrasonic sensor makes it possible to create a resonant method for controlling the iron weight fraction in magnetite ore, which is invariant to the geometric factor. The ultrasonic sensor detects the distance h from the probe to the studied medium and applies pulses of different duration to the third input of the calculating unit, which automatically changes the conversion factor of the signals ΔU_{1k} and ΔU_{2k} coming from the direct current amplifiers, compares them and extracts the highest one, its value is used to calculate the magnetic susceptibility of the studied medium for its output to the data recorder.

An increase in the amplitude of the signals on the two compensating and one receiving loops makes it possible to use amplifiers of alternating voltage with small gain factors and to generate voltages per unit volt at the inputs of synchronous detectors. This reduces the effect of instrumental errors of synchronous detectors and the temperature drift of DC amplifiers on the accuracy of the conversion.

Almost by increasing the amplitude of the signals at the outputs of the compensating and receiving oscillation circuits, the relative influence of external interference and interference is further weakened, and the random error of the transformation decreases.

To evaluate the effectiency of the proposed technical solution, the device was simulated on a PC in the Electronics Workbench Pro software, which resulted in the following:

1) when a sinusoidal voltage with amplitude $U = 10$ V and frequency $f = 1$ kHz is supplied to the source coil, a change in the inductance of one of the compensation coils by 10% relative to the initial value of $L = 0.1$ H leads to the appearance of a differential voltage $\Delta U \approx 2.28$ mV;

2) when connecting capacitors with the same capacitance $C = 200$ nF parallel to the compensation coils, a change in the inductance of one of them by ±10% changes the differential voltage to

$\Delta U_r \approx 80$ mV at the resonance frequency $f_r = 1$ kHz contours at input impedances of the AC voltage amplifiers of 10 kΩ, i.e. the amplitude of the measured signal increases approximately in $K = \Delta U_r / \Delta U = 80.2/2.28 \approx 35$ times.

Conclusion. The paper has described the method of induction control of the iron weight fraction in magnetite ore, its theoretical justification is presented, and effectiveness for instruments of magnetite ores quality control is proved experimentally.

It is established that the use of the resonance mode of operation of the receiving and compensating circuits makes it possible to increase the sensitivity of the monitoring device by a factor of tens to the change in the electromagnetic field and makes it possible to increase the sensitivity of the device by more than 30 times.

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Authors: **Ivan N. Bazhenov**, *Employee*, *bazhen-orel77@mail.ru* (*Russian Federation Security Guard Service Federal Academy*, *Orel*, *Russia*); **Oleg O. Basov**, *Doctor of Engineering Sciences*, *Employee*, *oobasov@mail.ru* (*Russian Federation Security Guard Service Federal Academy*, *Orel*, *Russia*).

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