Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2021, № 3 (103) https://doi.org/10.33108/visnyk_tntu2021.03
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 681.518.5:519.7:666.3/.7

MATHEMATICAL FUNDAMENTALS OF THE METHOD OF IDENTIFICATION OF METAL INCLUSIONS IN RAW MATERIALS WITH AUTOMATIC DETERMINATION OF THEIR COORDINATES

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Summary. *The article deals with the actual problem of theoretical substantiation of the method of identification (diagnosis) of metal inclusions (hereinafter referred to as metal inclusions) in bulk raw materials under the conditions of a conveyor belt. The presence of metal inclusions in the raw material transported by the conveyor belt can lead to both emergencies and deterioration in the quality of the output product. The identification method provides for diagnosing the presence of metal inclusions, determining its dimensions, type of metal and coordinates relative to the cross-section of the conveyor belt. The results of theoretical and experimental studies of the method for identifying metal inclusions based on a scanning signal and an additional excitation coil are considered. A mathematical model has been developed for determining the position of metal inclusions on a conveyor belt relative to a line perpendicular to the axis between two excitation coils, including two trajectories for determining coordinates for three excitation coils and two receiving coils.*

Key words: *metal inclusions, conveyor belt, theoretical and experimental research, mathematical model, identification method, coil system.*

https://doi.org/10.33108/visnyk_tntu2021.03.023 *Received 17.08.2021*

Statement of the problem. Most of the ceramic industries engaged in the processing of raw materials for the manufacture of ceramic products, in particular bricks, ceramic tiles, etc., require high-quality clay as raw material. Despite the improvement of the clay preparation process, different types of metal inclusions which differ in the type of metals, shape and weight can be found in it. The presence of metal inclusions in raw material is a major threat to the technical condition of the technological equipment and adversely affects the quality of the final products. It is also a typical problem for a number of other industries, such as the process of manufacturing of building materials, recycling, storage and processing of agricultural products.

The metal inclusions get in the raw material during various technological stages of its preparation. The inclusion of metal wires in the raw material often leads to emergency situations and, as a consequence, to significant financial costs for the elimination of emergencies and downtime of technological lines, as well as reducing the quality of the initial products [1, 2]. Therefore, the task of developing a method of identifying (diagnosing) the metal inclusions in the raw material transported by conveyor belt with the possibility to automatically determine their coordinates and dimensions requires its theoretical justification.

Analysis of available research. The analysis shows that at most of the brick production plants the existing automated process control systems of preparation of raw materials provide the placement of permanent electromagnet of various models (in particular P100M) above the conveyor line. This situation does not allow to ensure the purity of the raw material to the full extent, especially in the case of inclusion of non-ferrous metals, or in the case of inclusion of metals, the weight of which does not actuate the electromagnet. The existing methods of

Corresponding author: Ivan Levitskyi; e-mail: LETIS@ukr.net identification of metal inclusions do not allow to determine their dimensions and coordinates of position on the conveyor belt. Thus, in [3, 4] for the identification of metal inclusions the LDC series chip is used, which acts as a coordinator of work with the receiving coil, performs amplification and normalization of the received signal. However, they do not provide sufficient sensitivity. In other works [5, 6], the pulse method is used for metal inclusion identification, however, as in the previous case, the problem of increasing the sensitivity of the receiving coil has not been solved. In order to increase the sensitivity of detectors, specialized approaches to signal generation for excitation coils are used [7, 8]. Though this approach has increased the sensitivity of the receiver coil, it is insufficient for industrial applications.

The use of methods for identification of metal inclusions using high frequencies in the range of 1–1.5GHz [9, 10] is a promising trend; however, their use is very expensive and requires specialised equipment and complex data processing algorithms. In [11, 12] amplitude and phase characteristics of the received signal were studied; we used them in developing the method of identifying metal inclusions in raw material. Thus, when a non-ferrous metal inclusion is present in the excitation coil area, the signal from the receiving coil changes not only the signal amplitude but also the signal phase that is relative to the excitation signal. This property allows us to identify non-ferrous metal inclusions in the flow of raw material.

Objective of the investigation. The objective of the research is the theoretical and experimental substantiation of the method of identification of metal inclusions in raw materials for manufacture of ceramic products and bricks, transported by conveyor belt. The created method of identification can be the basis for the system of diagnosing the presence of metal inclusions, determining its dimensions, type of metal and coordinates relative to the cross section of the conveyor belt. Integration of such a system of identification of metal inclusions into the automated control system of processing of raw materials will improve the quality of the initial products.

Statement of the task. To study the propagation of electromagnetic waves in the «clay layer – metal-insulator» system it is necessary to develop a mathematical model that takes into account the electromagnetic permeability of the medium and metal inclusions and is based on the formation of electromagnetic field after passing through the metal inclusion with distinctive electrical and magnetic properties. It is based on a method based on generation of magnetic field with moving maximum of excitation coil intensity amplitude, proposed in [13]. It allows the registration of secondary vortex flow fields, which occur in objects with ferromagnetic properties under the influence of the primary low-frequency magnetic field. In this case, the magnetic field is generated by means of coils supplied with alternating current. The generated eddy currents primarily depend on the current strength of the excitation coil, its frequency and the properties of the metal inclusions (geometric dimensions, type of metal). The developed method of identification of the metal inclusions in the raw material is based on the improved electromagnetic method, which is devoid of its main drawback – the magnitude of the receiving signal is inversely proportional to the sixth power of the distance between the diagnostic system and the object of diagnosis (metal inclusion).

Development findings. Electromagnetic waves, which pass through the medium with certain electromagnetic properties, are transformed. At the exit of the medium these transformations are described by the formula

$$H_2 = H_0 \cdot e^{(\alpha + jk)}, \tag{1}$$

where α is is the coefficient of attenuation of the wave, H_0 is the magnetic field strength at the entrance of the medium, k is the wave number. Wave number depends on properties of the medium:

$$k = \omega \cdot \sqrt{\varepsilon_a \cdot \mu_a} \,. \tag{2}$$

It is obvious that the estimation of electromagnetic field at low frequencies gives an integral estimation of the medium and, if different materials are present, an average estimation will be obtained, (Fig. 1.)

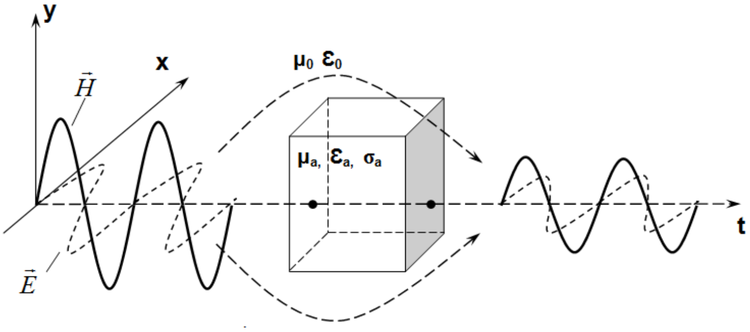

Figure 1. Model of the formation of an electromagnetic field after passing through an object with distinctive electromagnetic properties Figure 1. Model of the formation of an electromagnetic field after passing through an object with distinctive electromagnetic properties

Depending on the trajectory of a particular magnetic field line, it will have its own length and propagation coefficient. In this case all lines will be added and the total field H_2 will have an integral estimation of all lines between the emitting and receiving coils.

In order to theoretically justify the developments of a method of identification of metal inclusions such as steel, aluminium and copper, an experimental device has been developed (Fig. 2). Experiments on the experimental device included determination of electromagnetic wave attenuation coefficient and wave number.

The experimental device contains a sinusoidal signal generator connected to one of the coils. The coil generates an electromagnetic field which propagates, passes through a metal inclusions and reaches the receiving coil. The wave number is determined using a phase meter and the attenuation coefficient is determined by the ratio of the amplitude values using a detector [14].

With the help of this device a study of the interaction of copper and aluminium metal inclusions with the electromagnetic field was carried out. This investigation involved measuring the change in signal amplitude ratio at the receiving coil with the sample of metal inclusion and without it. The study also involved measuring the phase change when introducing into the space between the coils metal inclusions of different size and different metals [15].

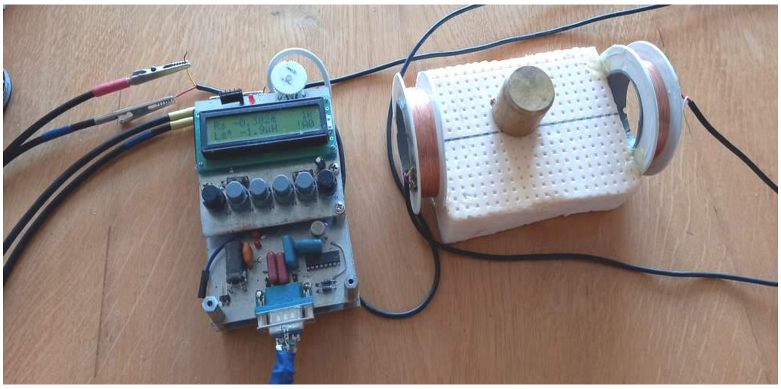

Figure 2. Photo of the experimental device

As a result in Fig. 3 and Fig. 4 with the help of an oscilloscope we obtained hodographs in the presence of the metal inclusion (copper, 120 grams) and without it.

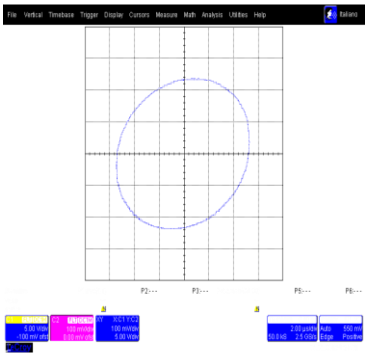

Figure 3. Screenshot of the oscilloscope in the absence of metal in the control area

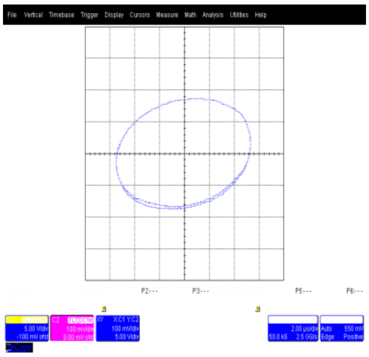

Figure 4. Screenshot of the oscilloscope in the presence of metal (copper) in the control area

As a result of the experiments (Fig.5) it was found that when the size of the aluminium metal inclusion increases, the signal phase approaches 2 degrees compared to the signal without metal inclusion and the signal amplitude decreases to 0.8. In the case of copper metal inclusion, the maximum amplitude ratio is 0.5. If steel metal inclusions are analyzed, the ratio increases to 2. The results obtained allow us to state that after interaction of metal inclusions with the electromagnetic field, the magnetic field strength changes the phase and the amplitude ratio. The magnitude of these changes depends on the magnetic and electrical properties of the metal. These properties can be taken as a diagnostic indication of the presence and properties of a metallic inclusion in an electrically non-conductive medium [16].

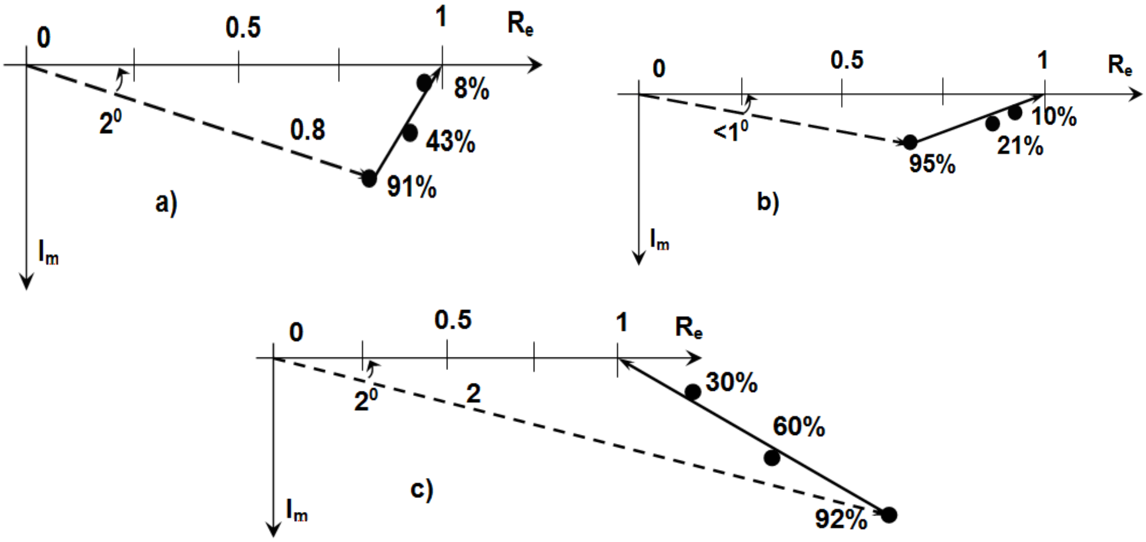

Figure 5. Diagrams of the dependence of the phase shift angle and the amplitude of the received signal on the size and type of metal inclusion: a – aluminum part, b – copper part, c – iron part

A mathematical model has been developed to determine the induction of the magnetic field of a two coil system. Using the principle of superposition, the process of calculating the induction of the two coils has been decomposed into two components. These induction components are determined separately for each coil. Then the fields of the two calculations are added and thus the field of the two coils is formed, Figure 6.

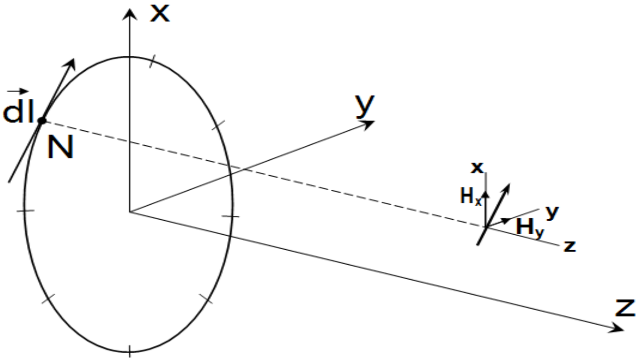

Figure 6. Model for calculating the induction of the magnetic field at any point in the plane

The current coil is divided into a certain number of segments, which form the field emission areas *dl* [17]. The number of sections determines the accuracy of the result. As their number increases, the length *dl* decreases, but their number increases. The system is directed along the axis of coordinates Z. Therefore at each point in the plane the value will be determined by the coordinate along the Z axis. The components must be defined as the sum of the effects of all the segments of the coil with current. Thus we have to find the distribution of inductances from the two coils. And then we have to find the sum of inductions at each of the calculated points.

A simplified simulation of the total magnetic field without taking into account phase shifts, which are neglected at low frequencies, is carried out using a third coil the centre of which is located at a certain point in space. At this point, the field induction will be generated by the two current coils. This induction will create a secondary field that is proportional to the magnetic properties of the area. These magnetic properties depend on the size and magnetic properties of the metal inclusion.

By adopting a generalised coefficient that takes into account size and properties, we look for the equivalent current that generates the secondary field. After that, we have to find the distribution of the induction of the secondary magnetic field. The simulation results can be observed as a three-dimensional model of distribution of the induction of the magnetic field, according to simulation results in MatLab environment, Fig. 7.

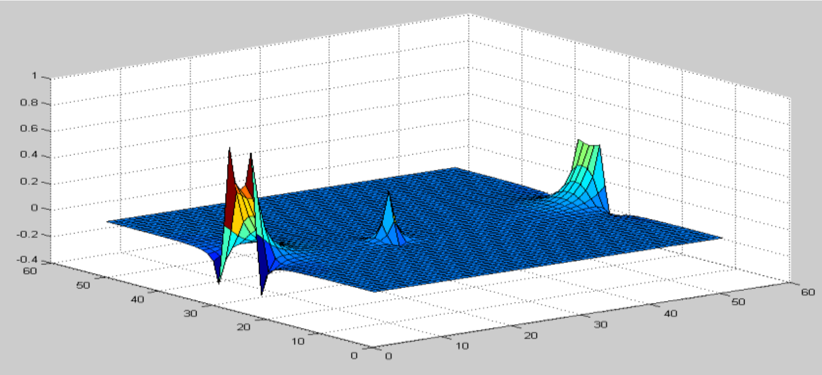

Figure 7. Distribution of current values of magnetic field strength in the developed system of coils in the presence of a model of metal inclusion

The graph shows that due to the large size of the excitation coils the field around them is complex. Therefore, in order to measure the field induction, the receiving coil is placed at a certain distance from the end of one of the excitation coils. As a result of the measurements carried out, we obtained graphs of the dependence of EMF in the receiving coil on the position of metal inclusions of different sizes along the axis perpendicular to the axis of the coils with different magnetic properties (Fig. 8). In order to study the metal inclusions of different sizes, a signal value was introduced, which indicates the ratio of the geometric size of the metal inclusions in relation to the distance between the excitation coils. The graphs of the studies of the copper or aluminium metal inclusions have shown that their amplitudes are attenuated, but they do not differ significantly in amplitude from each other, so they partially overlap.

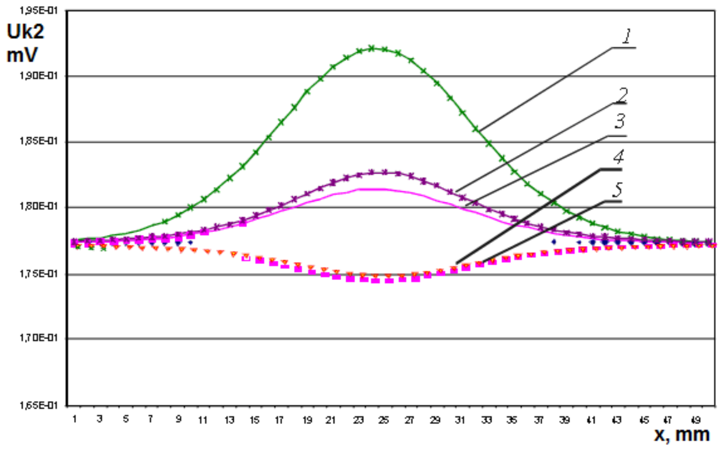

Figure 8. Dependence of the EMF on the position of metal inclusions of different sizes with different magnetic properties: 1, 2, 3 – iron of different sizes (12%, 18%, 68%), 4 – copper (36%), 5 – aluminum (34%)

From the graphs of the relationship between the position of the metal inclusion and the magnetic field strength, it is possible to find its distance from the axis between the two excitation coils, which is as follows:

$$U_a = K \cdot \frac{y}{y^2 + x^2}, \qquad (3)$$

where U_a is the EMF at the output of the receiving coil, K is the coefficient of proportionality, x is distance of the metal inclusion from the axis between the two excitation coils K_{11} and K_{12}, y is the generalizing coefficient of the coil parameters.

Figure 9 shows a scheme of the experiment. The graph (Fig. 10) shows the measurement result which is invariant to the axis of symmetry. Therefore, with this coil system it is impossible to determine the exact position, only the displacement relative to the axis of the excitation coil.

Analyzing dependence (3), to determine the position of the metal inclusion it is not enough to have a voltage at the output of the receiving coil. It is necessary to determine the value of the other two components. The coefficient y depends on the coil parameters and its value can be pre-determined by calibrating the coil system. The coefficient K can be determined by using an additional measuring coil system which operates simultaneously but at different frequencies.

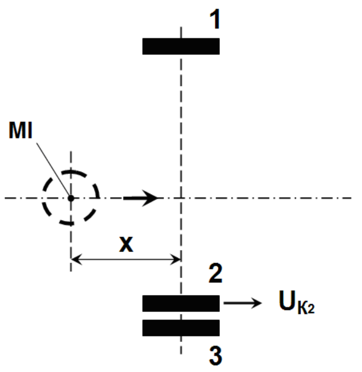

Figure 9. Scheme of the experiment: MB – metal inclusion, 1, 3 – excitation coils, 2 – receiving coil

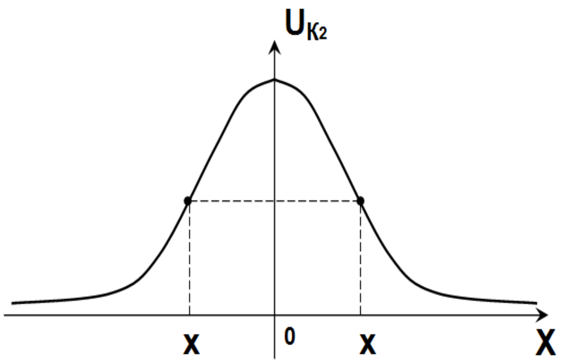

Figure 10. The graph of the dependence of the voltage Uk2 of the receiving coil on the position of the metal inclusion X

To determine the position of the metal inclusion between the coils, the measurements are performed using the parallax method [18]. The method involves simultaneous measurement of EMF by two coils shifted in space by a fixed magnitude. For simultaneous measurement, excitation is performed at different frequencies for each pair of coils (Fig. 11). The EMF (U_{k2}) from the two receiver coils (2, 4 in Figure 11) was measured. The results obtained are given in Fig. 12.

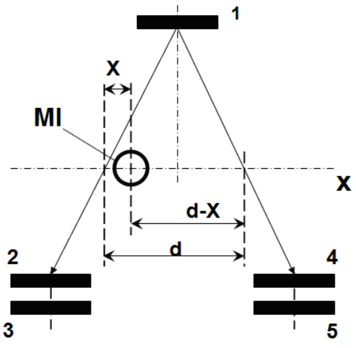

Figure 11. Layout of the coils: 1, 3 – excitation coils of the first trajectory; 1, 5 – coils of excitation of the second trajectory, 2, 4 – receiving coils

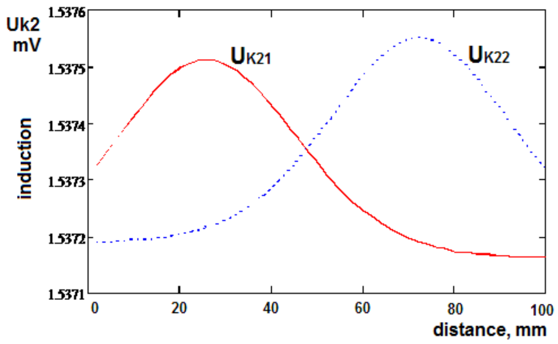

Figure 12. Graphs of the dependence of the EMF of the two receiving coils K_{21}. and K_{22} from the position of the metal inclusion between them

In order to fit the graph in dependence (3), the passive component, which is formed by the excitation coil, was subtracted. The dependence graphs after subtracting the established value caused by the non-informative components and the approximated dependence are given in Fig. 13.

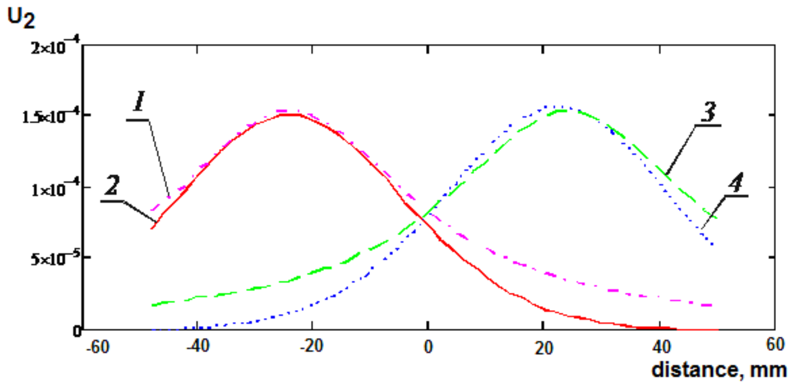

Figure 13. Approximation of the found EMF by the selected function: 1, 3 – measured values, 2, 4 – approximated values

As a result, to calculate the position of the metal inclusion, which is located between the axes of the receiving coils, it is necessary to perform two independent measurements. Thus we obtain a system of equations, assuming the distance between the coils as *d*:

$$\begin{cases} U_{a1} = K \cdot \left(\dfrac{y}{y^2 + x^2} \right) \\ U_{a2} = K \cdot \left(\dfrac{y}{y^2 + (d - x)^2} \right) \end{cases} \tag{4}$$

Expressing from the first equation of the system (4) coefficient *K* and substituting it into the second equation of the system we get:

$$U_{a2} = \left[U_{a1\cdot} \left(\frac{y^2 + x^2}{y} \right) \right] \cdot \left(\frac{y}{y^2 + (d - x)^2} \right). \tag{5}$$

$$\frac{U_{a2}}{U_{a1}} = \frac{y^2 + x^2}{y^2 + (d - x)^2} = G. \tag{6}$$

$$x_1, x_2 = \frac{G \cdot d \pm \sqrt{Gd^2 + 2Gy^2 - G^2 y^2 - y^2}}{G - 1}. \tag{7}$$

As a result of simplification, we obtain a mathematical model for determining the position of the metal inclusion relative to the axis of the excitation coils:

$$x_1, x_2 = \frac{G \cdot d \pm \sqrt{Gd^2 - y^2 (G - 1)^2}}{G - 1}. \tag{8}$$

The solution of the equation provides two values of coordinates, but we choose the positive and less than distance *d* as the final one. If neither of them meets this criterion, then the metal inclusion is outside the measuring coil system.

Approbation studies have been carried out with raw materials used at «Ceramicbudservice» Ltd, (Ivano-Frankivsk, Ukraine). Several times the metal inclusions of heterogeneous metals were present in the raw material, and their coordinates relative to the conveyor belt cross-section were fixed in advance. The measuring system, with the help of the developed mathematical model, performed identification of metal inclusion, which included the fact of metal inclusion detection, determination of metal inclusion type, calculation of metal inclusion coordinates. The deviation of calculated coordinates from the actual ones was not more than 3 cm with the conveyor belt width of 60 cm.

Conclusions. The results of the experiments, using the developed research device, confirmed the possibility of using the properties of changes in the amplitude and phase of the measured signal of the receiving coil as a diagnostic feature for identification of metal inclusions both by type of metal and by their size. The empirical dependence of metal inclusion on the conveyor belt in relation to its axis between the two excitation coils has been established. A mathematical model for identification of metal inclusions, which includes two trajectories of determining their coordinates, using the parallax method and additional excitation coils, has been developed. Using it, it is possible to diagnose the presence of metal inclusion by its position in relation to the axis of the excitation coils and by the type of metal inclusions (iron, aluminum or copper). The mathematical model is the basis of the proposed system for removal of identified trace metal inclusions [19], which is integrated into the plant automated control system of the raw material processing.

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УДК 681.518.5:519.7:666.3/.7

МАТЕМАТИЧНІ ОСНОВИ МЕТОДУ ІДЕНТИФІКАЦІЇ МЕТАЛОВКЛЮЧЕНЬ У СИРОВИНІ З АВТОМАТИЧНИМ ВИЗНАЧЕННЯМ ЇХ КООРДИНАТ

Леонід Заміховський; Іван Левицький; Микола Николайчук; Юрій Стрілецький

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Резюме. *Розглянуто актуальну задачу теоретичного обґрунтування методу ідентифікації (діагностування) металевих включень (далі за текстом – металовключень) у сипучій сировині в умовах конвеєрної стрічки. Наявність металовключень у сировині, що транспортується конвеєрною стрічкою, може призвести як до виникнення аварійних ситуацій, так і до погіршення якості вихідної продукції. Металовключення потрапляють у сировину на кожному етапі руху сировини технологічною лінією виробництва. Метод ідентифікації передбачає діагностування наявності металовключення, визначення його габаритів, типу металу й координат відносно поперечного перерізу конвеєрної стрічки. Розглянуто результати теоретико-експериментальних досліджень методу ідентифікації металовключень на базі скануючого сигналу й додаткової котушки збудження. Розроблено математичну модель визначення положенням металовключення на конвеєрній стрічці відносно лінії, перпендикулярній осі між двома котушками збудження, що включає дві траєкторії визначення координат для трьох котушок збудження і двох приймальних котушок. Математична модель базується на паралексному методі визначення координат металовключення по отриманих сигналах із приймальних котушок. Дослідження взаємодії магнітного поля з металовключенням показали наявність залежності між розміром самого металовключення, виду металу й амплітудою прийнятого сигналу, величиною зсуву фази між сигналом випромінення й прийнятим сигналом. Запропоновано додаткову котушку збудження, яка забезпечує паралельність ліній напруженості магнітного поля і збільшує чутливість приймальної котушки. Результати моделювання в програмному середовищі MatLab підтверджують достовірність отриманих даних. Розроблена модель передбачає можливість масштабування системи шляхом нарощування кількості приймальних котушок і котушок збудження вздовж лінії перерізу конвеєрної стрічки.*

Ключові слова: *металовключення, конвеєрна стрічка, теоретико-експериментальні дослідження, математична модель, метод ідентифікації, система котушок.*

https://doi.org/10.33108/visnyk_tntu2021.03.023 *Отримано 17.08.2021*