Rail flaw detection,
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ESTIMATED MATHEMATICAL MODEL OF CRACKS IN MAGNETIC INSPECTION OF RAILROAD RAILS

A model of crack was developed to provide possibility for magnetic field over the defect, and signal that will be inducted in the searching coil depending on its parameters, spatial orientation and height above rail head to be calculated. This allows to analyze the shape of the signals and the ratios between their amplitudes for all three components of the magnetic field caused by crack depending on its shape and location in the rail and to predict signals in multichannel systems of rail flaw detection.

MODEL MATEMATYCZNY DO WYZNACZANIA PĘKNIĘCIA SZYN KOLEJOWYCH W DEFEKTOSKOPII MAGNETYCZNEJ

Opracowano model pęknięcia, dla którego wyznaczono pole magnetyczne nad defektem (pęknięciem), oraz sygnał, który uzyskuje się w poszukującej go cewce pomiarowej w zależności od jej parametrów, przestrzennej orientacji i wysokości nad główką szyny. Pozwala to analizować przebiegi sygnałów i współzależności między ich amplitudami dla wszystkich trzech składowych pola magnetycznego pęknięcia w zależności od jego formy i rozkładu w główce szyny, a także prognozować sygnały w wielokanałowych systemach defektoskopii szyn.

1. INTRODUCTION

Diagnosis of technical condition of facilities ensures their safe operation and timely detection of defects. This is especially true in the diagnosis of objects, whose defects can cause considerable material losses or casualties. These objects include railroad rails. Timely detection of defective rails can take measures to prevent rail break under the train, which increases safety and economic efficiency of rail transport in general.

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Currently, ultrasonic and magnetic flaw detectors are used for high-speed rails diagnostic, which complement each other. In particular, magnetic flaw detectors has better performance for detecting transverse crack, which is especially dangerous because it can cause rails fracture under a moving train [1].

Increased intensity of train traffic and increased requirements for safety raises a question of automating the collection and processing of diagnostic information, since at present the reliability of defects detection depends on the experience of the person, who operates a system of diagnosis [1]. Perspective is the use of three-component sensors and multichannel systems which significantly increases the amount of information to be processed [2-4]. The aim of developing new systems should not be the complete elimination of operator in making decision about defect presence. Instead, using modern methods of collecting and processing of diagnostic information system should facilitate the operator work to take objective decisions on each suspicious signal. It is very important to develop algorithms for distinguishing signals from various types of defects and other related signals which are not caused by defects.

It is known that in magnetic flaw detection systems amplitude and waveform of the defect depends on the rail characteristics, magnetization system parameters, speed, sensor parameters, area of the defect plane, its opening and depth. Also, this signal will depend on the angle of the plane of the defect and its displacement relative to the rails axis and flatness of defect walls. Besides defects can form groups, which also affects the signal. All these factors cause a large number of waveforms from defects [5] and complicate the work of detection and distinction.

The works are performed to establish systems and algorithms for automated detection of defects [2-4] can be effective only if they will have the greatest possible number of variants of signals from the defect. Some data on the waveform caused by the longitudinal component of magnetic field above the defect is described in [5, 8]. However, information on the waveform from the other two orthogonal components of the field as well as the signals in a multi-channel sensor is not enough.

Obtaining such a large number of signals experimentally requires a lot of time and financial costs. Therefore, it is an actual task to create mathematical model of the defect, which would allow calculating the amplitude and shape of the signal depending on the geometrical parameters of the defect, its position in the rail head and the type of applied sensor.

2. ARGUMENTATION OF MATHEMATICAL MODEL OF CRACKS

To determine the waveform that occurs in the searching sensors the magnetic field scattering from the defect must be determined first. There are many mathematical models describing this field. In the simplest case of a field defect can be described as a field of two-wire line distance between the conductors of which corresponds to a height defect [6]. However, this model can not consider, for example, displacement of the defect relative to the rails axis.

In other works a field of a pair of magnetic charges or magnetic moment is used for the description of the crack [7]. In [8], for example, a combination of the two charges is uses. This model is a two-dimensional, it suppose that the defect is transverse and distributed throughout the width of the head rail.

To solve the task the best approach is a three-dimensional model. Then by the known distribution of magnetic charges on the walls of the defect we can calculate all the components of the field depending on the kind of system geometrical parameters of the defect and form a signal that the occurs in the searching sensors.

The model described in [5] was used for the basis. Defect is represented as a small internal region in the rail filled with material with relative magnetic permeability μ_2, which is considerably less than the permeability of the material μ_1 of the rails, resulting in the magnetization of the material J_2, which fills this area is much smaller than magnetization J_1 of rest areas of the rail. The part of the magnetization vectors in the rail body are interrupted at the border of area with magnetic permeability μ_2 and begin again at another border in area with the same permeability μ_1. Each end of magnetization lines acts as a positive magnetic charge, and each beginning - as a negative [5].

However, the magnetization is more convenient to calculate using absolute magnetic permeability of environments where the magnetic field propagates. Then magnetizing system of the flaw-wagon, rail and defect or set of defects can be represented as a magnetic circuit, and integrated Ohm's law for magnetic circuit can be used to determine the parameters of field. As a result, the expression on which you can determine the magnetic flux in this circuit will have the following form [9]:

$$\Phi = \frac{w \cdot I}{\sum R_{mk}} = \frac{w \cdot I}{\sum \frac{L_k}{\mu_0 \cdot \mu_k \cdot S_k}}, \tag{1}$$

where: w – number of turns of coils of magnetizing system;
I – current in the coils of magnetizing system;
R_{mk} – magnetic resistance of the k-th magnetic section;
L_k – length of the k-th magnetic section;
μ_0 – absolute magnetic permeability of free space ($4\pi\cdot10^{-7}$ H/m);
μ_k – relative magnetic permeability of k-th magnetic section;
S_k – area of the k-th magnetic section.

This magnetic flux field in defect area Φ_D, which occupies only part of the rail head crosscut, can be determined taking into account the influence of parallel magnetic resistance of defectless part of rail crosscut area.

As a result, each elementary area ΔS of defect wall can be considered a point source of magnetic field with magnetic flux Φ_n such that the condition

$$\Phi_D = \sum_{n=1}^{N} \Phi_n , \tag{2}$$

where: N - number of elementary areas, which divide the defect wall.

Induction of each such source, on spherical surface of radius r can be calculated using the expression [9]:

$$B_n = \Phi_n / 4\pi r^2 \, , \tag{3}$$

and then using superposition it is possible to determine all components of the magnetic field of the defect and the corresponding signals that are in search sensor.

Fig. 1 shows magnetizing system of flaw detector with the sensor, which is located on inductor cart.

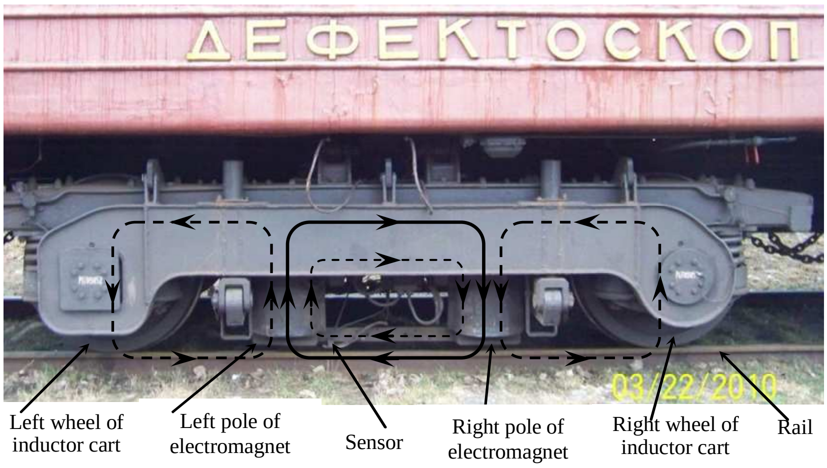

Fig. 1. Magnetizing system of flaw detector with the sensor

Closed solid line arrow shows the main magnetic flux through the rail investigated. Dotted lines show other magnetic flux stimulated with magnetizing system. For example, scattering flow through the air between the poles of an electromagnet, and flows through the rail, wheels and chassis of inductor cart. At a given value of magnetomotive force I·w these magnetic flux will make lower the absolute value of the magnetic field of the defect, but their influence on the shape of the signal from the defect can be ignored. As a result, the magnetizing system flaw detector wagon with the defective rail under study is presented in the form as shown in Fig. 2.

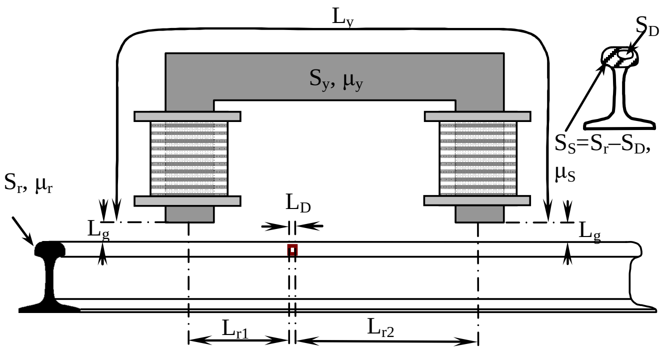

Fig. 2. Magnetizing system of flaw detector with the rail under study

The system consists of two magnetizing coils with the number of turns w/2 with the current I, yoke with length L_y, area S_y and magnetic permeability μ_y, forming an electromagnet, two air-gap with length L_g and the effective area of S_g, rail segment with length L_{r1} and magnetic permeability μ_r between the left pole of the electromagnet and the defect, the rail segment length L_{r2} with magnetic permeability μ_r between the right pole of the electromagnet and the defect, the defect itself as crack opened on L_D, with S_D area and magnetic permeability of free space. Part of the magnetic flux bypass defect through defectless part of the same rail head, which is considered using the shunt area length $L_S = L_D$, area $S_S = S_r - S_D$ and magnetic permeability μ_S, which may differ from the rail permeability μ_r. Here S_r - cross sectional area of the rail head.

Each of these sections is characterized by the corresponding magnetic resistance with the result that you can make a substitution scheme of magnetizing system rail flaw detector with a magnetic circuit (Fig. 3). [9].

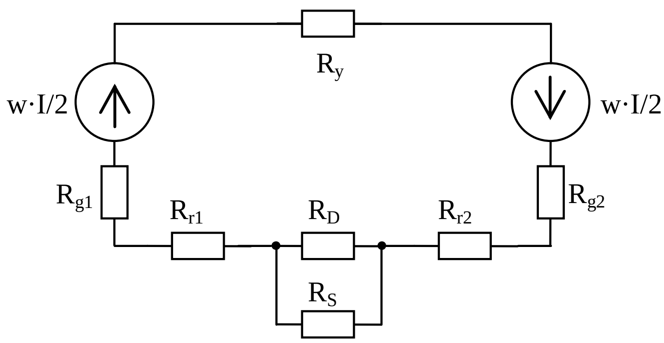

Fig. 3. Substitution schematic of magnetizing system with a rail as a magnetic circuit

On Fig. 3 R_y - magnetic resistance of the yoke, R_{g1} and R_{g2} - magnetic resistance air gaps, R_{r1} and R_{r2} - magnetic resistance rails, R_D - magnetic resistance of the defect, R_S -

magnetic resistance of the shunt section of the rail. Magnetic resistance has dimension (ohm •sec) $^{-1}$.

A model allows you to easily calculate the magnetic flux Φ_D in the plane of the defect:

$$\Phi_D = \frac{w \cdot I}{\frac{R_D \cdot R_S}{R_D + R_S} + R_y + R_{g1} + R_{g2} + R_{r1} + R_{r1}} \cdot \frac{R_S}{R_D + R_S}, \quad (4)$$

where all symbols are described above.

This circuit, by considering the impact of changing magnetic flux in the movement of flaw detector, on the value of the magnetic resistance of individual sections of the track, allows its influence on the shape of the signal to be additionally taken into account.

3. DESCRIPTION OF CRACK MODEL CALCULATION GEOMETRY

In the proposed model (Fig. 4) the crack with opening L_D is represented by two spatial arrays of positive $\Phi_a(x, y, z)$ and negative $\Phi_b(x, y, z)$ point sources of magnetic field, that are in the body of the rail head and are shown with points. The surface of the rail head, which is conventionally shown translucent plane matches with the plane x0y, and its axis matches with the direction of the axis y. The trajectory of movement of the search sensor is defined by Y axis set above the head track and shown with dotted line.

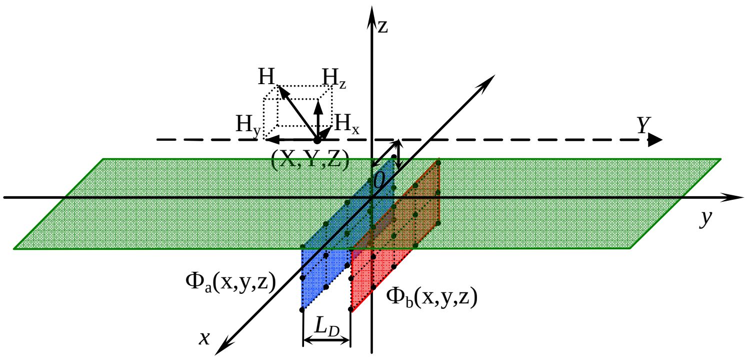

Fig. 4. Geometry of crack model

Number of point sources along the x axis is M, and along the axis z - K. Each point source located in the corresponding node of square mesh and has its coordinates in space and value. Changing these parameters you can simulate cracks surface of any shape. Besides of transverse cracks you can build a model inclined at arbitrary angle cracks and fissures, with the surface which have a different shape and form, for example, a cavity.

Considering the influence of crack shape on the character of distribution of the signal realized through the corresponding intensity distribution of the flow from each source.

The magnetic field at any point over the rail head with coordinates (X, Y, Z) is a superposition of field from all sources, and three orthogonal magnetic field components H_x, H_y and H_z for the point defined as the total projection of the vector to the corresponding axis of coordinate system. When moving the sensor along the coordinate Y each component of the field corresponds to a signal - under E_x (Y), E_y (Y) and E_z (Y).

The position of each search sensor, which can be both point and integral sensor, is defined by coordinates (X, Y, Z). For each sensor coordinates X and Z are constant, and Y - variable. Also it is considered that the velocity of the sensor is constant. Therefore, electromotive force, which is inducted in it determined with considering the changing magnetic field around the sensor by integrating in the volume of sensor within its size. For example, for signal E_y (Y), this expression has the form:

$$E_y(Y) = -\upsilon\mu_0 w_0 \frac{d\iiint_V H_y(X,Y,Z)dXdYdZ}{dY} \tag{5}$$

where: υ – velocity of the sensor,

μ_0 – absolute magnetic permeability of free space,

w_0 – number of coils per unit length of the sensor,

V – volume of the sensor.

For signals $E_x(Y)$ and $E_z(Y)$ there is the same expressions. The model allows calculating the waveform for the three orthogonal components of magnetic field, depending on the form of crack, size, depth and angle of its plane relative to the axes.

4. RESULTS OF CALCULATION OF CRACK WAVEFORM

To implement the calculation of waveform of cracks on the basis of present model program developed in Delphi. Graphical user interface developed for this program allows you to quickly set such crack parameters as opening of a crack, the depth of its position relative to the surface of the rail head, angles and rotation of the crack and the sensor height above the rail head (Fig. 5).

In the program window the segment of rail in the coordinate system and three projections are given that allows the user to visualize the crack position relative to rail head. The result of the program - a distribution of three orthogonal components of the magnetic field of the crack and the corresponding signals of the search sensors.

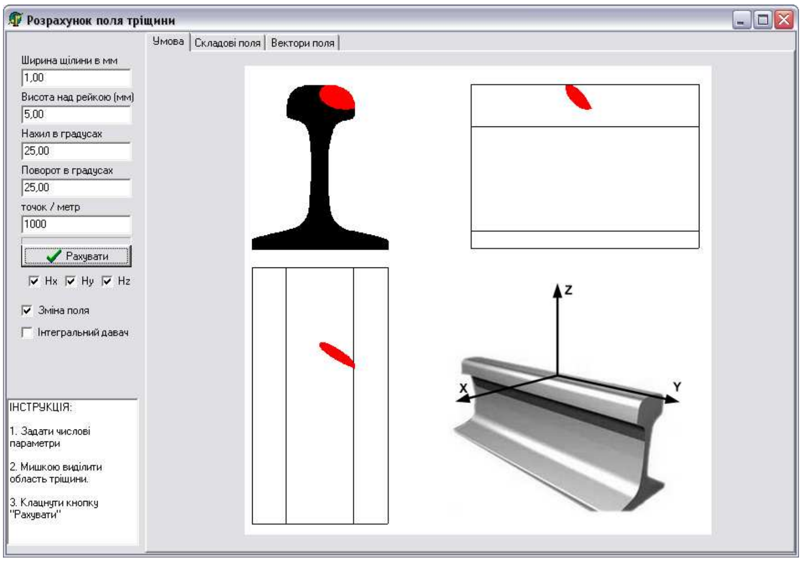

Fig. 5. Graphical user interface of developed program

As an example, Fig. 6 shows the simulation results of three orthogonal signal components of the transverse cracks, the parameters and location of which is shown in a box in Fig. 5, in the case of a point sensor, which moves along the Y coordinates of the middle of the rail.

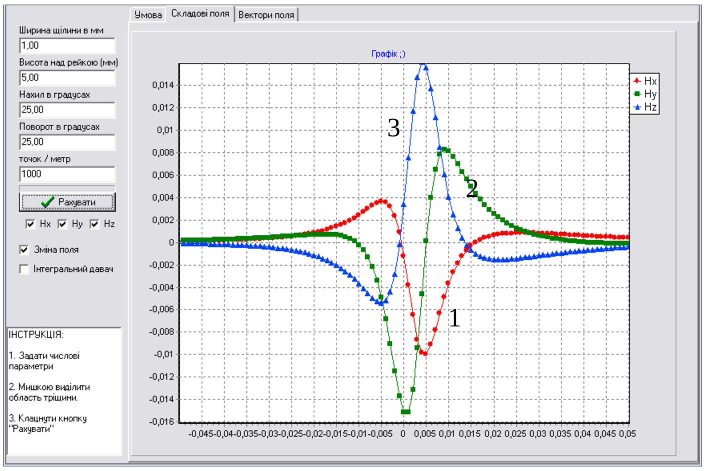

Fig. 6. Three orthogonal signal components using a point sensor

Fig. 7 presents similar signals from the same crack when using integrating sensor, which moves along the coordinates of Y. The results of the simulation match well with the data of [5, 8].

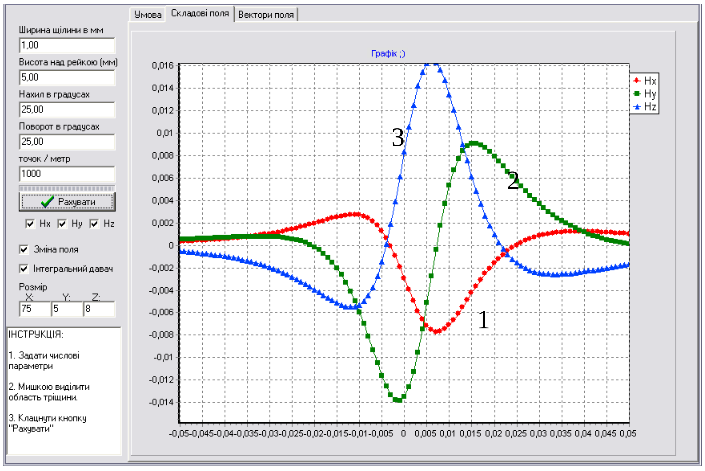

Fig. 7. Three orthogonal signal components using integrated sensor

In all the graphs in Fig. 6 and Fig. 7 curve 1 is a signal $E_x(Y)$ component of the field H_x, curve 2 – signal $E_y(Y)$ from the field component H_y and curve 3 – signal $E_z(Y)$ from the field component H_z. In most cases, high-speed magnetic rail flaw analysis is performed on a signal from the longitudinal field component $E_y(Y)$ (curve 2). However, as shown in Fig. 6 and Fig. 7 significant additional information about the parameters is in signal $E_x(Y)$ (curve 1) of the transverse field component H_x, which can not be determined when using two-dimensional models.

5. CONCLUSION

An estimated mathematical model of the crack using equivalent circuit of magnetizing system with the rail was developed. This allows simulating the distribution of the three orthogonal components of the magnetic field of the crack and the corresponding signals from sensors for any geometrical parameters of crack and any type of sensor. A small calculation will complement the program to simulate signals from the defect as a set of cracks, which are located nearby.

Using the proposed a mathematical model for multichannel defectoscopic systems the optimum number of sensors can be determined according to their geometric dimensions and parameters.

This also allows you to create basis functions for wavelet analysis to their further use for automatic recognition of signals of rail defects - cracks and more accurately predict the type of cracks from waveform.

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