Models of Signals of Eddy-Current Transducers above Defects of the Continuity of Metal

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Abstract. The shape of real signals of eddy-current transducers of electromagnetic flaw detectors obtained over continuity defects in the process of monitoring the surface of steel products and metal structures depends both on the type of eddy-current transducer and on the type of continuity defects in the metal (single defects, a group of cracks, pitting corrosion). When solving practical problems of eddy-current flaw detection of steel products and metal structures, there is a need for mathematical modeling of the measured signals of eddy-current transducers of different types (absolute, differential, overhead, throughput) over continuity defects in the metal. Signal models of eddy-current transducers are also important from a methodological point of view, since they allow one to study the transformation of the eddy-current transducer signal shape with an arbitrary change in the parameters of real continuity defects in the metal, which facilitates the analysis and interpretation of flaw detection results.

It is shown that the signal waveform of an overhead eddy-current transducer of an electromagnetic flaw detector above a continuity defect is determined by its type, while for an absolute overhead eddy-current transducer it has a unipolar character, the extremum of which is located above the center of the continuity defect; for a differential overhead eddy-current transducer, it has a bipolar character, the extremes of which are located symmetrically on opposite sides of the center of the continuity defect.

To describe the signal waveform of the indicated types of overhead eddy-current transducers, mathematical models based on simple algebraic functions have been proposed that have two tuning parameters. It is shown that these tuning parameters are related to the amplitude and half-width of the measured signal for the absolute overhead eddy-current transducer, and with the distance between the extremes for the measured signal of the differential overhead eddy-current transducer over the continuity defects such as a crack in the metal.

On the basis of these functions, mathematical models of signals of overhead eddy-current transducers above a group of cracks are proposed. It is shown that a change in the interval between continuity defects and their number in a group of cracks leads to a significant transformation of the signal waveshape of the overhead eddy-current transducers.
1. Introduction

Electromagnetic (eddy-current) flaw detectors are used to detect metal continuity defects in steel products and metal structures, which are highly sensitive to surface defects such as cracks and metal pitting corrosion. The signal waveform of eddy-current transducers (ECT) of electromagnetic flaw detectors obtained over continuity defects in the process of testing the surface of steel products depends both on the type of ECT and on the type of continuity defects in metals (single defects, a group of cracks) [1, 2].

When solving practical problems of eddy-current flaw detection of steel products, there is a need for mathematical modeling of the measured signals of ECT of different types (absolute, differential, overhead, throughput) over the continuity defects in the metal. ECT signal models are necessary in the development of mathematical methods for processing and interpreting the results of eddy-current testing of steel products and metal structures.

They are also important from a methodological point of view, since they allow one to study the transformation of the ECT signal shape with an arbitrary change in the parameters of real continuity defects in the metal. This is very important for recognizing real ECT signals above a group of cracks in a metal, usually having a complex shape, against the background of extraneous noise and interference present in the measured signal [2, 3].

2. Simulation of a signal of an overhead ECT

The signal waveform of the overhead ECT of an electromagnetic flaw detector above continuity defect like a crack is determined by the ECT type, while:

- for the absolute overhead ECT, it has a unipolar character, the extremum of which is located above the center of the continuity defect;
- for a differential overhead ECT, it has a bipolar character, the extremes of which are located symmetrically on opposite sides of the center of the continuity defect.

Experimental studies of the signals of overhead ECT over defects of continuity such as cracks in metal show that the shape of the ECT signal can be described using algebraic functions (Fig. 1) [4]:

- for the signal of the absolute overhead ECT transformer type:

  \[ U(x) = J \frac{z}{x^2 + z^2}, \]

- for the signal of the overhead differential ECT of the parametric type (imaginary/real signal):

  \[ U_1(x) = J \frac{x}{x^2 + z^2}, \]

where \( J, z \neq 0 \) - parameters of an algebraic function, point coordinate \(|x| < \infty\).

The parameters of the algebraic functions (1) are determined on the basis of the parameters of the measured signals of the overhead ECT over the defects of continuity, in this case, two experimentally measured parameters are sufficient for this.
It can be shown that:
- in formulas (1), the parameter J of the algebraic functions determines the values of the extremes of the functions. In this regard, this parameter in algebraic functions (1) can be determined from the values of the extremes in the real measured signals of the absolute and differential overhead ECT;
- in formula (1a), the parameter z of the algebraic function is equal to the half-width of the function $U(x)$, that is, $z = x_{1/2}$ (where $x_{1/2}$ is half the width of the signal of the absolute overhead ECT, set at half the amplitude). Therefore this parameter of the algebraic function (1a) can be determined by the half-width of the measured signal of the absolute overhead ECT;
- in formula (1b), the parameter z of the algebraic function is equal to half the distance between the extremes of the function $U_1(x)$, that is, $z = x_{\text{max}} = -x_{\text{min}}$ (where $x_{\text{max}}$, $x_{\text{min}}$ are the coordinates of the extremes of the function $U_1$). Therefore, this parameter of the algebraic function (1b) can be determined from the distance between the extremes of the measured signal of the differential overhead ECT.

From formula (1a) it follows that for the signal of the absolute overhead ECT parameter J is determined as follows (with known signal half-width $z$, established experimentally):

$$J = \frac{U_m z}{2},$$  \hspace{1cm} (2a)

where $U_m$ - signal amplitude of the overhead ECT above the crack (at point $x=0$).

From formula (1b) it follows that for the imaginary and real signal of the differential overhead ECT, the parameter J is determined as follows (for a known distance between the signal extremes $x_{\text{max}} = -x_{\text{min}} = z$, established experimentally):

$$J = 2z U_{1m},$$  \hspace{1cm} (2b)

where $U_{1m}$ - extremum (maximum) of the imaginary (real) signal of the overhead differential ECT above a crack in the metal.

Thus, indeed, the parameter J is determined by the values of the extremes of functions (1).

It also follows from formula (1a) that for the value of the coordinate $x = z$, the value of the function $U(x)$ is equal to half the amplitude of the function:

$$U(z) = J \left[ \frac{z}{x^2 + z^2} \right]_{x = z} = \frac{J}{2z} = \frac{U_m}{2},$$

where $U_m = J/2$ - the amplitude of function (1a), which corresponds to a point with a coordinate $x=0$ (Fig. 1). Thus, indeed, the parameter $z$ is equal to the half-width of the function $U(x)$ (1a).

The extremes of the function $U_1(x)$ (1b) satisfy the condition:
\[
\frac{\partial U_1(x)}{\partial x} \bigg|_{x = x_{\text{ext}}} = 0,
\]

where \( x_{\text{ext}} = \{ x_{\min}, x_{\max} \} \) - the coordinates of the extremum points of the function (1b). Substituting function (1b) into this condition, we obtain the following equation:

\[
\frac{\partial U_1(x)}{\partial x} \bigg|_{x = x_{\text{ext}}} = J \frac{z^2 - x^2}{(x^2 + z^2)^2} = 0,
\]

whence it follows that \( x_{\max} = - x_{\min} = z \).

Thus, indeed, the parameter \( z \) is equal to half the distance between the extremes of the function \( U_1(x) \) (1b).

Formulas (1)–(2) are a mathematical model of overhead ECT signals over a separate defect of continuity such as a crack in the metal. They can also be used to describe the signals of absolute and differential overhead ECT over a set of joints.

Let us represent the signal of the absolute overhead ECT over the group of joints \( U(x) \) in the form of a superposition of the ECT signals over individual cracks \( U_{\text{k}}(x) \) (1a), assuming in the first approximation that the formation of signals over the set of joints occurs without their mutual influence:

\[
U(x) = \sum_{k = -N}^{N} U_{\text{k}}(x) = \sum_{k = -N}^{N} J_{\text{k}} \frac{z_1}{(x - x_{\text{k}})^2 + z_1^2}, \tag{3a}
\]

where \( U_{\text{k}}(x) \) - signal of the absolute overhead ECT over the \( k \)-th defect in a set of joints, \( x_{\text{k}} \) is the coordinate of the location of the \( k \)-th crack in the metal, \( J_{\text{k}} \) is the parameter \( J \) and \( z_1 \) is the half-width of the overhead ECT signal over a separate \( k \)-th crack.

It should be noted that it is known from the experimental data that the half-width of the signal of the overhead ECT over an individual crack in the metal is \( z_1 \approx 2.5 \text{ mm} \ldots 3 \text{ mm} \).

With an equidistant arrangement (with a constant interval \( \Delta \)) of cracks in the metal and with the same depth \( h \), formula (3a) has the form:

\[
U(x) = J_0 \int_{-N}^{N} \frac{z_1}{(x - k \Delta)^2 + z_1^2} \, dk, \tag{3b}
\]

where \( J_0 \) - parameter \( J \) for the absolute overhead ECT signal above an individual crack.

Let us represent the signal of the differential overhead ECT over the set of joints \( U_1(x) \) in the form of a superposition of ECT signals over individual cracks \( U_{1\text{k}}(x) \) (1b), assuming in the first approximation that the formation of overhead ECT signals over the set of joints occurs without their mutual influence:

\[
U_1(x) = \sum_{k = -N}^{N} U_{1\text{k}}(x) = \sum_{k = -N}^{N} J_{\text{k}} \frac{x - x_{\text{k}}}{(x - x_{\text{k}})^2 + z_1^2}, \tag{4a}
\]

where \( U_{1\text{k}}(x) \) - signal of the differential overhead ECT above the \( k \)-th defect in a set of joints, \( x_{\text{k}} \) is the coordinate of the \( k \)-th crack in the metal, \( J_{\text{k}} \) is the \( J \) parameter and \( z_1 \) is the distance between the extremes of the differential ECT signal above an individual crack (\( z_1 \approx 2.5 \text{ mm} \ldots 3 \text{ mm} \)).

With an equidistant location (with a constant interval \( \Delta \)) of cracks in the metal and with the same depth \( h \), formula (4a) has the form:

\[
U_1(x) = J_0 \int_{-N}^{N} \frac{x - k \Delta \, dx}{(x - k \Delta)^2 + z_1^2}, \tag{4b}
\]
where $J_0$ - parameter $J$ for the signal of the differential overhead ECT over a separate crack.

Formulas (3)-(4) are a mathematical model of overhead ECT signals over a group of surface defects such as cracks in the metal.

From the presented models (3)-(4) it follows that, in the first approximation, the half-width of the signal of the overhead ECT $z$ over a group of $n$ cracks located in the metal with a constant interval $\Delta$ is determined by the following formula:

$$z = z_1 + \frac{1}{2} \Delta (n - 1),$$

where $z_1$ - half-width of signal of the overhead ECT over a separate crack.

In formula (5), it is assumed that the width of the cracks is much less than the interval between them, while the parameter $\Delta(n-1)$ is equal to the width of the region where the set of joints is located on the metal surface.

It follows from formula (5) that the half-width of the overhead ECT signal over a set of joints always exceeds the half-width of the overhead ECT signal above an individual crack in the metal and increases linearly with an increase in the interval between continuity defects and their number in a set of joints.

3. Results and its discussion

Figures 2, 3 show the graphs of the signals of overhead ECT over a set of 3 joints of the same depth, but located at different intervals, obtained by the calculation formulas (3)-(4).

The signals of the overhead ECT above a set of joints are determined by the superposition of the ECT signals over individual fractures (in Fig. 2, 3, the colored curves correspond to the ECT signals above an individual crack).

It can be seen from the presented models of the overhead ECT signals that when the interval between the cracks in the metal changes, a significant transformation of the ECT signal shape over the set of joints occurs.

From the model of the signal of the absolute overhead ECT (3) it follows that when a set of joints approaches (with a decrease in the interval $\Delta$), a significant increase in the amplitude of the ECT signal is observed, while the signal shape is similar to the signal of the absolute overhead ECT over an individual crack (Fig. 2a). A set of joints in the metal is not resolved in space by the signal of the overhead ECT, since there is only one extremum in it (cracks are not separated for perception).

A similar situation is observed for the signal of the differential overhead ECT over a set of joints (Fig. 3a). A set of joints is not resolved in space by the ECT signal, since it contains only extremes characteristic of a separate defect of continuity (cracks are not separated for perception).

In the practice of eddy-current flaw detection, the case of spatial non-resolution of a set of joints in a metal leads to an erroneous interpretation of the signal of the overhead ECT. It will be perceived as an ECT signal above a separate crack with a greater depth, which corresponds to a signal of greater amplitude (which will not correspond to reality), that is, the over reject of the controlled steel products will be carried out.

It also follows from the model of the absolute overhead ECT signal (3) that when a set of joints moves away from each other (with an increase in the interval $\Delta$), there is a significant change in the shape of the overhead ECT signal, which in this case is not similar to the ECT signal above a separate crack (Fig. 2b).

Local extremes appear in the signal of the overhead ECT, the number of which corresponds to the number of continuity defects in the set joints, and the location of the extremes coincides with the centers of the defects continuity in a set of joints. Studies have shown that with increasing the interval between cracks decreases the difference between the values of local extremes in the signal of the absolute overhead ECT.
Figure 2. Model of the signal of the absolute overhead ECT over a set of 3 joints with their non-resolution (a) and resolution (b) in space.
These factors, present in the signal of the absolute overhead ECT, create favorable conditions for the spatial resolution of a set of joints in the metal (they are separated for perception).

![Signal model of differential overhead ECT over a set of 3 joints with their non-resolution (a) and resolution (b) in space.](image)

**Figure 3.** Signal model of differential overhead ECT over a set of 3 joints with their non-resolution (a) and resolution (b) in space.

From the signal model of the differential overhead ECT (4) it follows that when a set of joints moves away from each other, a significant transformation of the signal shape of the overhead ECT takes place, which takes on a noise-like character with many oscillations, and it is not similar to the signal of the overhead ECT over a separate crack (Fig. 3b).
Local extremes appear in the signal of the differential overhead ECT, the number of which is associated with the number of continuity defects in the set of joints.

Calculations have shown that an increase in the interval between cracks leads to a decrease in the difference between the values of the extremes in the signal of the differential overhead ECT. However, this difference remains significantly larger than the extremes in the signal of the absolute overhead ECT. This circumstance leads to the fact that it is difficult to determine the exact location of the continuity defects in the set of joints by the location of the extremes in the signal of the differential overhead ECT.

In practice of eddy-current flaw detection, the indicated features of the differential overhead ECT signal above a set of joints will lead to certain difficulties in their visual analysis and interpretation.

Comparison of the presented models with real signals of the overhead ECT over the continuity defects in the metal shows their good qualitative convergence.

4. Conclusions

1. Mathematical models of signals of overhead ECT over a separate defect of continuity such as a crack in a metal, described by simple algebraic functions, are obtained.

2. Models of overhead ECT signals over a set of joints in a metal are obtained, presented as a superposition of ECT signals over individual cracks.

3. It is shown that a change in the interval between a set of joints leads to a significant transformation of the signal shape of the overhead ECT:
   - if the defects of continuity are located close in a set of joints, they are not resolved in space;
   - with an increase in the interval between continuity defects, local extremes appear in the signal of the overhead ECT, creating conditions for the spatial resolution of a set of joints.

4. It is shown that the half-width of the overhead ECT signal above a set of joints always exceeds the half-width of the ECT signal above an individual crack in the metal. It increases linearly with an increase in the interval between continuity defects and their number in a set of joints.

5. References

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