Study of closely spaced cracks in steel by eddy current method

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Abstract. The article describes the design of an eddy-current transducer intended for studying the effect of closely spaced cracks in steel parts. The eddy-current transducer runs under the control of the developed hardware-software complex with a system for suppression of noise and amplification of signal received from the eddy-current transducer. Signal processing makes it possible to separate the effects of closely spaced cracks on the eddy-current transducer signal and evaluate the contribution of each crack separately. The results of experiments conducted on the samples with cracks of different depths located at different distances from each other have been presented, and the feasibility of finding different cracks located closer than the distance determined by the geometric dimensions of the windings of the eddy-current transducer has been shown.

1. Introduction

Structure health monitoring (SHM) is the process of implementing a damage-identification strategy for civil infrastructures and mechanical parts [1].

Among the most critical defects of metal alloys are the continuity defects like cracks. They are the main reasons of destruction of industrial and civil facilities. The criticality of surface cracks directly correlates with their depth. In this connection, the information of the surface cracks depth is necessary for assessing the technical condition of the product. Various non-destructive test methods are used for identification and evaluation of the characteristics of surface cracks, however, the electric potential and eddy current methods based on changes in the electric current flowing through an area of crack location are the most commonly used.

The eddy current method is a non-contact one being used both for cracks identification and determination of their characteristics. The electric potential method is used, if it is necessary to monitor areas under significant load or assess the depth of cracks located by some other methods.

These methods make it possible to determine the depth of a single surface crack, however, the problem of measuring the depths of closely spaced cracks is still understudied. The influence of neighboring cracks leads to an additional error in their depth estimation, which depends on the parameters and mutual position of the cracks, which is not always taken into consideration.

The comparative vacuum monitoring (CVM), a process developed by the Structural Monitoring Systems (SMS) Company, has been used for monitoring on surface cracks in metallic structures [2].

Giant magnetoresistive (GMR) sensor using uniform linear eddy current excitation and GMR field measurement has been developed to detect fatigue cracks around fasteners in multilayer structures [3, 4]. Eddy current non-destructive evaluation techniques have been widely used in the inspection of conduction structures for the detection of surface and near-surface cracks [5]. The basic eddy current (EC) is a cylindrical coil used to generate and sense the electrical current in the metallic part.
simultaneously. Almeida et al. propose a new type of eddy current probe with enhanced lift-off immunity and improved sensitivity and estimates a new NDT system [6]. Vishnuvardhan et al. conduct structure health monitoring of anisotropic plates with single-transmitter multiple-receiver (STMR) eddy current sensor array [7].

The importance of determining the parameters of closely spaced surface cracks was reported in a number of works [8], where it was solved by various methods, including those previously mentioned. When scanning such defects, it is necessary to increase the locality of the ECP, particularly by reducing its diameter, for separate recording of the eddy current signal from each of the cracks, while for expanding the range of measurement of the depth of cracks, an increase in the diameter of the ECP is required [9].

However, practice shows that good flaw detection results can be obtained when evaluating the depth of cracks of fatigue origin due to their sufficiently large length to depth ratio [10].

Papers [11, 12] reported about the success achieved in assessing the depth of cracks observed in elements of equipment operating in extreme conditions of a nuclear power plant. However, the authors note that the eddy current method does not allow to measure the depth of a crack if it is deeper than the cracks used for calibration of the eddy-current transducer.

The mutual influence of two parallel cracks having the same depth was studied in as research [13]. The performed studies made it possible to estimate the difference between the signals received from one and two cracks in the frequency range of 0.1 Hz to 10,000 Hz.

In this connection, the task of developing a software and hardware complex that would allow to take into account the mutual influence of neighboring cracks and measure their depths.

2. Materials and methods

For manual control, the eddy-current method is successfully applied for measuring the characteristics of surface cracks. It is quite simple to implement and is based on the dependence of the voltage introduced into the measuring winding of the eddy-current transducer. Using this method, the depth of the crack can be inferred by the $U_{1}/U_{0}$ ratio, where $U_{0}$ is the voltage in the measuring winding when scanning a defect-free section of the test object, and $U_{1}$ is the voltage when scanning a section with a crack.

When studying metal alloys, it is important that the $U_{1}/U_{0}$ ratio would not depend on various electrophysical properties in defect-free and defective areas of the test object. To achieve this, the agreement between the electrical conductivity values of these areas is necessary.

The problem of determining the depth of a surface crack is in the significant nonlinear dependence of the voltage introduced into the measuring winding of the ECT on the depth of the crack. This leads to a significant increase of error in estimating the depth of the crack. In the course of this work, it was possible to significantly increase the linearity of the characteristic as a result of a study of the interaction of an applied ECT with a crack.

ECT was represented by a transformer with the exciting, measuring and compensation windings wound around a pyramidal core made of 81NMA permalloy. The choice of core material is conditioned by its high initial magnetic permeability, which was additionally increased by using the previously developed method of 81NMA permalloy annealing and cooling (Figure 1). To protect the windings, they were impregnated with a compound and covered with a thin-walled aluminum casing [14, 15].

When scanning an object with a crack, the general scheme of the ETC operation is as follows: an eddy current exciting coil is placed above a conductive object with a surface crack. Sinusoidal alternating current with a frequency of 500-10000 Hz flows through the turns of the coil. The eddy currents excited in the defect-free test object flow along the circular paths coaxial with the exciting coil. If the crack is located under the ECT, the eddy current paths change, flowing around the crack. Eddy currents induce an electromagnetic field that induces the induction EMF on the measuring winding of the ECT. EMF is a signal that carries information about the test object. This signal is amplified in a special amplifier and cleared from noise by a noise reduction system, following which it arrives at an amplitude detector and the input of an analog-to-digital converter. The obtained values are displayed on a computer screen in digital and graphic forms.
In measurements, an eddy-current transducer with an effective winding diameter \( D_e = 1 \) mm were used. The frequency of the exciting current was selected in such a way as to maintain sensitivity to the crack depth of up to 5 mm. As a working gap, 0.1 mm thick aluminum foil was used. The ECT operated under the control of the developed hardware-software complex having the functions of auto-compensation and graphical indication of the output signal. The measuring winding voltage amplitude of the eddy-current transducer was used as the output signal. In order to suppress the external electromagnetic interference, a system of preliminary amplification of the ECT signal and noise reduction was used, which was designed on the basis of a two-stage closed loop Delyann filter.

To simulate the influence of closely spaced cracks on the eddy-current transducer signal, samples representing steel objects with a central crack with \( h_1 \) depth, a side crack with \( h_2 \) depth located parallel to it at a distance \( l_1 \) (Figure 2).

The lengths of the cracks were chosen so that their value did not affect the ECT signal. The widths of both cracks were 2 mm. The coordinate of the ECT position in the defect area varied discretely, with a step of 0.5 mm, and was counted as the distance from the left to the right edge of the sample. To determine the influence of a side crack on the ECT signal, the results of measurements made are also presented in the absence of a side crack are also presented. To calibrate the hardware-software complex,
the defect-free area of the sample was scanned, and the parameters of the amplification and filtering system optimal for scanning this type of object were determined prior to measurements.

3. Results and discussion

The analysis of the ECT voltage dependences when passing over the central crack shows that a side crack begins to influence upon the ECT signal at a distance $l_1$ less than the equivalent diameter of the ECT winding calculated by the $D_e = (D_{ex} \times D_{meas})/2$ formula, $D_{ex}$ - diameter exciting winding, $D_{meas}$ - diameter measuring winding.

Also, a study of the mutual influence of the depths of the central and side cracks located at a distance of $D_e/2$ was conducted. During scanning of a central crack with a depth of up to 2 mm, it was established that the influence of the side crack depth is very great (Figure 3).

![Figure 3](image)

**Figure 3.** Results of a samples inspecting (central crack – 1 mm, $l_1$ – 0.5 mm).

The depth of the side crack was varied from 1 to 4 mm in increments of 2 mm. However, when the depth of the central crack was increased to more than 2 mm, this effect weakened (Figure 4, 5). For instance, for a 1-mm deep central crack, the influence of a 5-mm deep side crack was 25%, whereas for a 4-mm deep central crack, the influence of a 5-mm deep side crack was only 5%. At that, the presence of a deep lateral crack resulted in a substantially sharper voltage drop on the measuring winding of the ECT as compared with the voltage drop in the absence of a side crack.

With decrease of the $l_1$ distance between the cracks, the influence of a side crack on the ECT signal increases significantly. Figures 6-8 show similar dependences of the ECT signal at $l_1$ distance of 0.25 $D_e$. 


It is clearly seen that the influence of the side crack is kept up to the depth of the central crack of 4 mm, in contrast to the influence at \( l_1 \) distance of 0.5 \( \text{De} \). It is important to note that the contribution of a side crack to the ECT signal with a central crack depth of 1 mm is more than 50\%, whereas it makes about 20\% at a central crack depth of 4 mm. The influence of a side crack at a central crack depth of more than 4 mm has not been reported.
Figure 6. Results of inspecting samples (central crack – 1 mm, $l_1$ – 0.25 mm).

Figure 7. Results of inspecting samples (central crack – 4 mm, $l_1$ – 0.25 mm).
Based on the above mentioned, it is possible to judge the possibilities of determining the depth of closely spaced cracks using the developed subminiature eddy-current transducers with \( D_e \) of about 0.25 mm. With such dimensions of the transducer, the contribution of a side crack located at a distance of more than 0.125 mm (0.5 \( D_e \)) from the central one can be considered insignificant, and the results obtained using such transducers can be considered reliable for solving the stated problem of determination of depths of closely spaced cracks.

4. Conclusion

The developed subminiature eddy-current transducer operating under a hardware-software complex providing signal cleaning from noise has shown high efficiency in the study of closely spaced surface cracks. It has been established that with a large locality of the sensor and an effective winding diameter of 1 mm or less, it becomes possible to separate the signals from each of the closely spaced cracks and evaluate their contribution to the ECT signal. Solving the inverse problem will make it possible to determine the depth of the crack even when it is located close to another crack provided that these cracks are separated by a distance of not less than 0.25 of the effective diameter of the ECT windings. Further localization of the ECT magnetic field will enable to reduce this gap and ensure separation of signals from closer cracks.

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