Subminiature Eddy Current Transducer for Detect Violations of the Internal Structure in Steels

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Abstract. This paper presents the design of the transducer, the action of which is based on the principles of eddy currents and is designed to identify closely located violations of the internal structure in steel parts. According to the authors of the study, the converter operates in conjunction with a specialized software application that includes hardware and software for amplifying the signal and suppressing spurious noise from the eddy current transducer. The application allows you to process the signal received from the device with digital algorithms, which positively affects the ability of the system to differentiate internal structural disturbances. The study included the results of a series of scans of samples with known cracks that are at different distances from each other. The practical limits of applicability and effectiveness of the system are illustrated in terms of detecting various structural violations. Including those located close enough to each other, in particular, closer to the maximum possible resolution distance of defects, determined solely by the geometric parameters of the eddy current transformer circuits, without taking into account mathematical processing.

1. Introduction
Violations of the internal structure such as cracks are among the critical defects, since their presence in the metal can lead to unpredictable consequences.

The timely detection of fatigue crack formation in many engineering applications such as railways, bridges, aircraft, and pipelines is crucial for safety, extended service life, and reduced maintenance cost. Cyclic loading can produce fatigue, which occurs progressively and locally, leading to sudden failure below the yield stress limit.

The presence of cracks is one of the key factors in the destruction of devices and objects both in everyday life and on a production scale. In this case, the risk level of undesirable consequences is due to the depth of surface cracks. In this regard, the identification and determination of the depth of defects is of high practical importance [1].

Crack monitoring activities using crack-detecting sensors can complement visual inspections and provide information about crack damage. As such, extensive research has been performed in flaw-detecting sensors and many nondestructive evaluation and testing methods have been developed. A few methods to detect cracks in metallic materials have been developed. One of the most common and effective methods to detect flaws and cracks is using angle beam ultrasound [2]. The ultrasonic wave...
can be generated by wireless inductively-coupled piezoelectric transducers. This wave is reflected back to the transducer by some form of discontinuity, such as another surface or a crack. Typically, crack inspection with this method requires an experienced operator and it is manually performed by moving the transducer across the surface at different orientations. Another mature technology is the usage of eddy currents where the alternation of the electromagnetic field generates magnetic lines of force that reveal hidden defects. This method is very effective in determining subsurface cracks due to its great penetration depth [3, 4]. Other technologies that have been patented or are commercially available include ultrasonic flaw detectors [5], magnetostrictive sensors, surface-mount piezoelectric paint sensors [6, 7], probe-pump-based loud sensor systems [8], coaxial cable sensors, and fiber-optic sensors, among others [1]. However, the use of these methods for long-term monitoring of crack patterns in larger scale civil infrastructure is time-consuming and expensive.

To solve this problem, two approaches are mainly used that implement non-destructive testing methods: the electro-potential method and eddy current methods. The method of eddy currents, based on a change in the parameters of the current passing in the area with a defect, is non-contact and finds its application both to identify and to establish the parameters of surface cracks.

Structural defects, in addition to immediate danger, can affect the error of scanning systems if they are close to each other, and the error can be associated with the relative position and characteristics of individual cracks. This circumstance necessitates the improvement of existing non-destructive testing methods. The problem of establishing the parameters of defects located at a short distance from each other has various approaches to solving and is mentioned in a number of works [9, 10].

At the same time, there are a number of technical issues accompany the scanning process. For separate identification of the eddy current signal from each of the defects, it is necessary to increase the locality of the transducer, including by reducing its diameter. Moreover, the extension of the measuring range of the depth of defects, on the contrary, should be accompanied by an increase in the diameter of the ECT. The practical experience of scanning defects of fatigue origin suggests an acceptable level of effectiveness of this method, due to the large ratio of crack lengths to their depths.

In a number of publications [11, 12], the authors managed to achieve significant results when scanning the parameters of defects observed in the structures of equipment operating in extreme conditions of nuclear energy. At the same time, in the work was noted the fact the scanning system could not determine the depths of some defects. For example, those defects that lie below the defects used at the calibration stage.

The effect of two parallel defects with equal depth is reflected in [13]. The measurements made it possible to establish the difference between the signals received from one and two defects in the frequency range from 0.1 Hz to 10,000 Hz.

Xie et al developed a frequency domain summation method combined with an interpolation strategy to predict pulsed EC signals [14], and estimated stress corrosion cracks using artificial neural networks (ANN), tabu search, simulated annealing and a genetic algorithm (GA) [15]. Li et al used the finite element method (FEM) to predict the EC response of 3D volume defects, and employed a simulated annealing local search technique combined with a canonical GA to improve the convergence rate of GA [16]. The main drawback of these methods is how slow they are [17].

These circumstances determine the problem of developing a scanning system that can take into account the influence of closely spaced defects on each other and measure their depths.

2. Materials and methods

The eddy current approach to non-destructive testing is actively used in the manual detection of surface defects due to its simplicity and effectiveness. The implementation of the method is based on the dependencies of the voltage supplied to the measuring circuit of the transducer. The defect depth is evidenced by the ratio $U_1 / U_0$, where $U_0$ is the voltage on the measuring circuit when scanning the defect-free portion of the test object, $U_1$ is the voltage when scanning the portion with the defect.

When scanning metal alloys, there is a significant nuance: the $U_1 / U_0$ ratio should not depend on various electro-physical properties in the areas of the test object with and without cracks. In this
regard, it is necessary to ensure the mutual compliance of the electrical conductivity parameters of these sites.

The specificity of establishing the parameters of surface defects is the nonlinear nature of the correlation of the voltage and the depth of the crack applied to the measuring circuit of the ECT. This contributes to the measurement error. In the framework of this study, it was possible to significantly increase the linearity of the characteristics by determining the nature of the interaction of the overhead ECT with a crack.

The scanning system is a transformer with three circuits: exciting, compensating and directly measuring. All windings were impregnated with a compound closed with a thin-walled aluminum casing and assembled on a core made of Permalloy 81NMA and having a pyramidal shape. The initial magnetic permeability served as a key reason for choosing this material as the core; subsequently, this characteristic was further increased by the previously developed annealing and cooling method [18-20].

The conceptual principles of the ECT operation when scanning a sample with a defect are as follows: an alternating sinusoidal current, with a frequency of 500-10000 Hz, is supplied to the exciting circuit placed above the scan object. In the absence of cracks in the sample, eddy currents in the scanning object pass along circular paths coaxial with the exciting circuit. The presence of defects affects the paths, causing eddy currents to flow around them. In turn, eddy currents induce induction EMF on the measuring circuit of the ECT. The signal from this EMF, which contains information about the internal structure of the scanned sample, is amplified and cleared of noise by the system for suppressing spurious noises, after which it is fed to an amplitude detector and to the input of an analog-to-digital converter. The received data is processed by digital algorithms and displayed on the screen in graphical and digital form.

The developed system employs an ECT with an effective winding diameter of D e. = 1 mm and D e. = 0.25 mm. The frequency of the excitation current was selected taking into account the provision of acceptable sensitivity to the depth of the defect to values of 5 mm. The working gap was ensured by the use of aluminum foil 0.1 mm thick. The ETC was controlled using a specialized hardware-software complex with functionality for automatic compensation and graphical indication of the output signal. The output amplitude was the voltage amplitude at the ECT measurement circuit, and the suppression of stray noise was carried out on the basis of a two-stage feedback Delyann filter.

3. Results and discussion
In order to verify the reasoning and calculations, a series of scans of steel samples with a central crack with a depth of h₁ and a side crack with a depth of h₂ parallel to it located at a distance of l₁ was performed in parallel (Fig.1).

![Figure 1. The steel samples with a central crack with a depth of h₁ and a side crack with a depth of h₂ parallel to it located at a distance of l₁ was performed in parallel.](image-url)
The width of both defects was 2 mm. The defect parameters were selected so that the width did not affect the ECT signal. The coordinate of the ECT position in the crack region varied discretely, with a step of 0.5 mm, and was counted as the distance from the left to the right edge of the object. The influence of a lateral defect was determined by comparison with the measurement results without it.

The calibration of the hardware-software complex which determines the optimal amplification and filtering values within the framework of the task was carried out before the start of the scans and consisted in measuring a sample that obviously had no cracks. An analysis of the results showed that the influence of a lateral defect on the ECT signal begins to be felt at a distance \( l_1 \) less than the equivalent diameter of the ECT winding, calculated by the formula: 
\[
D_{ec.} = \frac{D_{exc.} \times D_{eff.}}{2}
\]

Additionally, measurements were made of the mutual influence of the parameters of the central and lateral defects placed at a distance of \( D_{e} / 2 \). During the scan, data were obtained indicating a significant effect of the lateral defect in the case when the central defect has a depth of up to 2 mm (Fig. 2).

![Figure 2. Results of steel samples inspecting (\( h_1 \) – 1 mm, \( l_1 \) – 0.5 mm).](image)

As part of the study, the lateral defect ranged from 1 to 5 mm in increments of 2 mm. It is noteworthy that with an increase in the depth of the central defect to values greater than 2 mm, the significance of side cracks decreased (Fig. 3, 4.). To illustrate the conclusions, we give the following data. With a central defect of 1 mm deep, the influence of a lateral defect was 25% with parameters of 5 mm. With a central defect of 4 mm deep, the influence of a side defect was 5% at the same depth. At the same time, the presence of lateral defects led to a significant decrease in the voltage, across the measuring circuit of the transducer, in comparison with samples where such a defect was absent.
As the distance \( l_1 \) between the defects decreases, side cracks exerted an ever-increasing influence on the transducer signal.

Similar correlations between the transducer signal and the distance \( l_1 \) equal to 0.25 D e. are shown in Figures 5-7. They illustrate well the effect produced by the defect of the side, which persists up to the values of the central defect of 4 mm, in contrast to the effect at a distance of \( l_1 = 0.5 \) D e.. Significant in this case is the ratio between the depth of the central defect and the influence of a lateral crack: at a depth of 1 mm it is more than 50\%, and at 4 mm it is already about 20\%. When the depth of the central defect is more than 4 mm, the influence of a lateral crack not observed.
Figure 5. Results of steel samples inspecting (h₁ = 1 mm, l₁ = 0.25 mm).

Figure 6. Results of steel samples inspecting (h₁ = 4 mm, l₁ = 0.25 mm).
The obtained results provide grounds for assessing the prospects for measuring depths of adjacent defects in the framework of the application of the developed compact transducer based on the eddy current effect with $D_e$ of the order of 0.25 mm. With such linear parameters, the effect of a defect of the side located at a distance of more than 0.125 mm (0.5 $D_e$) is not significant, and the results of the measurements obtained can be considered reliable within the framework of the stated task.

4. Conclusion
The created compact hardware-software complex, including the ECT, has shown high efficiency in the measurement of nearby surface defects. It has been established that with a large locality of the sensor, with an effective winding diameter of 1 mm or less, the possibility of identifying and distinguishing signals from various defects and separately evaluating their total contribution to the ECT signal is reduced. Solving the inverse problem will open up prospects for determining the depth of defects located relative to each other at distances of not less than 0.25 from the effective diameter of the ECT windings. Further localization of the magnetic field of the transducer will reduce this gap and provide identification of the signal from closer defects.

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