Design of multiprobe for fuel-elements cladding eddy current testing

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Abstract. This article presents a study of the eddy current flaw detector (ECFD) numeric model in order to choose the necessary parameters for zirconium pipes control. As a result of mathematical modeling, the multiprobe ECFD was designed and the eddy flaw control conditions were found. The analysis of defect signals with various geometrical parameters leads to a conclusion that the presence of discontinuity registration needs a phase method of data processing.

1. Introduction

Despite the rapid development of alternative methods of generating electricity, the share of nuclear power in global electricity production remains one of the most significant today. It is difficult to overestimate the need for nuclear safety. Thus, the development and improvement of non-destructive testing for components and elements of nuclear power plants is an urgent task today at the production stage and during operation. The article is devoted to the problem of detecting local defects of small volumes of shells of fuel elements at the manufacturing stage.

The object of testing is a shell of fuel element, which is a tube of zirconium alloy with an outer diameter $D_{out} = 9$ mm and with an inner diameter $D_{inn} = 8$ mm. Electric conductivity is $\sigma = 2.44$ MSm/m. During rolling local defects of small volumes can occur on the outer surface of shells of fuel elements. Subsequently, these defects can lead to a malfunction of the fuel element. Such defects must be identified and localized at the production stage.

The eddy current method of non-destructive testing is one of the main methods for monitoring the quality of shells of fuel elements. The advantages of the eddy current method are high performance, sensitivity, and contractlessness. Sensitivity and performance depend primarily on the type of eddy current sensor. Encircling eddy current transducers are most widely used. The studies [3, 4, 5, 6] describe examples of using these probes. Encircling eddy current probes are easy to use and can effectively identify longitudinal defects, but at the same time, practically do not respond to transverse defects or defects of small volumes. The signal received from the encircling eddy current transducer can be used to evaluate the cross section of the object of testing as a whole. Determining the location and the number of defects in the cross section is not possible. Such diagnostic data do not give an accurate idea of real defects in the object and a possible violation of the technological process.

In order to improve the quality of diagnostic data and the possibility of detecting defects of small volumes, it is necessary to localize eddy currents in a small region of the shell of fuel element. Such currents can be created by surface eddy current probes with ferromagnetic cores. The authors examine
single surface eddy current transducers moved manually along the object of testing in the works [9, 10]. This method of eddy current testing has a low productivity. To a large extent, this feature is compensated by the system using the surface eddy current transducer rotating around the shells of fuel element [11]. Nevertheless, when using such a system to testing the entire surface of object of testing, it is necessary to take into account the ratio of the angular and linear velocities of the surface eddy current (EC) transducer movement, as well as to tie the angular position of the surface EC transducer and the linear coordinate of object of testing when a defect is detected for its localization, which complicates the hardware and software parts of the system.

Modern multichannel eddy-current flaw detectors allow the use of multi-element surface EC probes, consisting of several stationary single surface EC probes located around the shells of fuel element. In this case, to eliminate the mutual influence of the converters, the principle of multiplexing is used – quick sequential switching of the same measuring channel to different probes. Such an approach allows achieving the highest performance of eddy current testing with the relative simplicity of the scanning system (the shell of fuel element performs only translational motion through a stationary multi-element surface EC transducer).

Great attention is paid to digital signal processing of signals received from multi-elements surface EC transducer. Examples are described in the works [12, 13]. Efficiency, speed and simplicity of digital signal processing methods depend on the quality of the information received. The development of a unique multi-elements surface EC transducer is necessary for various testing conditions. The sensor must meet the conditions and provide high quality primary data. Therefore, the urgent tasks are development and improvement of multi-elements sensors design methods. The article presents an approach to the design of sensors for eddy current testing of shells of fuel elements using mathematical modeling. This approach can be extended to other tasks of the eddy current testing method; in which it is appropriate to use the multi-elements surface EC probes.

2. Mathematical Modeling
The mathematical model (MM) of the eddy current testing of shells of fuel elements was constructed using the finite element method in the Comsol Multiphysics software package. The problem is quasi-stationary and is solved with respect to the vector magnetic potential \( \mathbf{A} \), the distribution of which is described by the expression:

\[
\nabla^2 \mathbf{A} + k^2 \mathbf{A} = -\mu_o \mathbf{j}_{ct},
\]

where \( \mathbf{j}_{ct} \) is the density of external currents, \( \mu_o \) is the absolute magnetic permeability of object of testing, \( k^2 = -j \omega \mu_o \sigma, j = \sqrt{-1}, \omega \) is the cyclic frequency of the excitation current.

The multiplexing principle mentioned earlier allows us to simplify the mathematical modeling and improve the quality of sampling: it is enough to study the interaction of only one surface EC probe with object of testing. The results will be valid for all transducers included in the multiprobe transducer.

To calculate the parameters of surface EC probe, modeling was carried out in two stages. At the first stage, MM of absolute surface EC probe was built, using the model study, the working frequency of the eddy current testing, the diameter of the ferrite core was selected, and the nature of the influence of the gap on the magnitude of the signals from defects was revealed. At the second stage, an MM of a differential converter was constructed, consisting of two absolute surface EC probes included in the bridge circuit (bridge surface transducer), the converter base and the number of MNP elements were calculated, and signals from defects were received.

In the modeling process, testing defects (CD) of the enterprise standard sample (SS) of Chepetsk Mechanical Plant were used. SS contains local small-volume CDs made in the form of a through radial hole with a diameter of 0.15 mm (CD1) and in the form of a blind radial hole with a diameter of 0.15 mm and a depth of 0.2 mm (CD2).
Geometry. MM is symmetric, which allowed improving the quality of sampling and reducing the calculation time. Figure 1 shows the MM geometry of an absolute surface EC transducer, and figure 2 shows its partition into finite elements.

Given the specification of the Elotest PL-500 flaw detector, to which the multiprobe transducer will be connected, a wire for winding with a diameter of 0.11 mm was selected to ensure a sufficient value of the voltage increment from the defect ($U_{in}$). The number of winding layers is 3. The number of turns of the surface transducer coil is 90. The magnitude of the exciting current of the coil is 15 mA. The height of the core should be sufficient to accommodate a coil on it, while the coil should not come close to its edges, thereby reducing the localization of the electromagnetic field. Based on this, the core height $h_{core}$ was chosen equal to 6 mm and did not change during the simulation.

At all external boundaries of the model, the condition of magnetic isolation was set:

$$\vec{n} \times \vec{A} = 0,$$

where $\vec{n}$ is the normal vector to the boundary under consideration.

For all internal boundaries, the continuity condition was introduced:

$$\vec{n} \times (\vec{H}_1 - \vec{H}_2) = 0,$$

where $\vec{H}_1$ and $\vec{H}_2$ are the magnetic field vectors on opposite sides of the considered boundary.

The average quality index of the splitting of MM into finite elements $q_{middle}$ was equal to 0.68, minimum $q_{min}=0.21$. The partition does not affect the solution of the model for $q>0.1$ [15].

The choice of the working frequency of the EC transducer

The effective penetration depth ($d$) of a plane electromagnetic wave in an object of testing is determined only by the physical parameters of the object of testing [2]. A plane electromagnetic wave is an ideal theoretical model with a number of assumptions. MM allows you to take into account the real front of propagation of the electromagnetic wave and calculate the real penetration depth. As an example, figure 3 shows the distribution of eddy currents (ECs) in an object of testing at a frequency $f = 1200$ kHz. In order to detect the presence of defects over the entire thickness of the wall of the cladding of a fuel rod, it is necessary that the value of the effective depth of penetration of ECs approaches 0.5 mm. Therefore, based on the determination of the effective depth of penetration of an
EC into an object of testing, it is necessary to find such a frequency of the exciting current at which the value of the density of the EC on the inner surface of the wall of the object of testing is less than the density of the EC on the outer surface by more than a factor of $e$. This condition is achieved at a frequency of 1.2 MHz (figure 4).

![Figure 3. Eddy current density distribution (A/m²) in the object of testing at f = 1200 kHz.](image)

**Figure 3.** Eddy current density distribution (A/m²) in the object of testing at f = 1200 kHz.

**Figure 4.** Dependence of the effective penetration depth on the frequency of the exciting current.

**Ferrite core diameter selection**

Defect CD2 was included in the mathematical model to calculate the diameter of the ferrite core (figure 5). Signals were obtained from the defect CD2 when it was moved along the X axis under the surface eddy current transducer for various values of $D_{core}$. The signal is understood as the introduced defective voltage $U_{in}$. Figure 6 shows the signal for $D_{core} = 1$ mm. The defect is located under surface EC core at $X = 0$. The signal has a symmetrical shape with respect to the Y axis and a dip of width $c$. This dip is explained by the fact that the defect has a small diameter and is located under the ferrite core; it falls into the region where eddy currents are practically absent (figure 5). Thus, it is necessary to minimize the width of the dip, but at the same time to keep $U_{in}$.

![Figure 5. Defect CD2 under the surface EC transducer.](image)

**Figure 5.** Defect CD2 under the surface EC transducer.

![Figure 6. Signal from a defect CD2 with $D_{core} = 1$ mm.](image)

**Figure 6.** Signal from a defect CD2 with $D_{core} = 1$ mm.
From the dependences presented above (figure 7 and 8), it follows that with decreasing $D_{\text{core}}$, $p$ decreases and at the same time, $U_{\text{in}}$ decreases. When this value of $U_{\text{in}}$ at $D_{\text{core}} = 1$ mm and $D_{\text{core}} = 1.5$ mm practically do not differ. Therefore, a ferrite core with a diameter of 1 mm will provide the maximum voltage introduced but the defect and the average value of the dip.

The study of the influence of the gap between the object of testing and the surface EC transducer

When using the surface EC transducer, one of the main interfering factors affecting the reliability of the data obtained is the inconsistency of the air gap between the surface EC transducer and the surface of the testing object. For this reason, it is extremely important to know how the change in the gap affects the informative signal from the defect.

Figure 9 shows the hodographs of the received signals for various values of the gaps. The scatter of hodograph phases with a change in the gap does not exceed 2°, while the amplitude of the hodographs decreases by 4 times with an increase in the gap value. To identify defects in small volumes, it is necessary to maintain the maximum signal amplitude, which means to ensure the smallest possible gap value, therefore, taking into account the design requirements in the manufacture of multiprobe transducers, for further calculations, the air gap was taken to be 0.1 mm.

Calculation of the base of bridge surface EC transducer

To reduce the effect on the informative signal of the physical and geometrical properties of the shell of fuel element slowly varying along the axis, as well as environmental conditions, it is advisable to use two absolute surface EC transducer included in the bridge circuit. An important parameter for such a switching circuit is the base of the EC transducer ($b$). Under the base refers to the distance between the axes of the cores of two surface EC transducer (figure 10). Its value should be such that the eddy currents generated by one of the coils have a minimal effect on the eddy currents created by the second coil, but at the same time, the distance between the coils should be as small as possible in order to reduce the effect of inhomogeneities of the material OK and be able to accurately localize identified defects.

To determine the base, signals were obtained from the defect CD2 for various values of $b$. Given the symmetry of the signal, the defect moved from a central position between the coils towards one of the coils strictly below it (figure10). Figure 11 shows the dependence of the absolute values of the signals on the X coordinate of the defect for different values of the base. Each of the dependences has
two maxima $U_{1\text{max}}$ and $U_{2\text{max}}$, which is explained by the passage of a defect in two regions with a high density of eddy currents. The larger the difference between the maximum values of the same dependence, the stronger the influence of the coils on each other for a given value of $b$. Table 1 shows the maximum values for each of the dependencies.

**Table 1.** The values of the maximums and the ratio of their difference to $U_{1\text{max}}$ for all $b$.

| $b$, mm | $U_{1\text{max}}$, mV | $U_{2\text{max}}$, mV | $(U_{2\text{max}} - U_{1\text{max}}) / U_{1\text{max}}$ | mV $\cdot$100% |
|---------|----------------------|----------------------|----------------------------------|----------------|
| 2       | 0.192                | 0.261                |                                  | 35.9          |
| 3       | 0.249                | 0.263                |                                  | 5.6           |
| 4       | 0.261                | 0.263                |                                  | 0.7           |

The influence of the coils on each other is great at $b=2$ mm, and at $b=4$ mm, there is no effect. Therefore, the base value for bridge surface EC transducer was chosen equal to 3 mm. This is the value at which the coils are located as close as possible to each other, without exerting a significant mutual influence.

The validity of the calculation is confirmed by theoretical calculations from the article [14]. The total number of the bridge surface EC probe ($n$) that are part of the multiprobe transducer is also determined by the formula (4) from [14] and is equal to 10.

$$n = \frac{\pi D_{\text{ex}}}{2\varepsilon r_{\text{core}}}$$

**Figure 10.** Eddy current density distribution of bridge surface EC transducer (A/m²).

**Figure 11.** Dependencies of the absolute values of the signals on the $X$ coordinate of the defect for different values of the base.

**Experimental confirmation of the results of mathematical modeling**

To experimentally confirm the results of mathematical modeling, three versions of coils for the bridge surface EC transducer with $D_{\text{core}} = (1, 1.5, 2)$ mm were made (figure 12 (a)). The manufactured coils were mounted on the chassis (figure 12 (b)), designed for manual movement along the cladding of a fuel rod, installed in a special recess of the platform along which the chassis moves. Coils were included in the bridge circuit shown in figure 13. Resistors have the following ratings: $R_1 = 750$ Ohm, $R_7 = R_8 = 261$ Ohm. To calculate the base of each of the manufactured bridge surface EC transducer, the principle described in article [14] was used. The base of the bridge surface EC transducer with $D_{\text{core}} = 1$ mm is 3 mm, the base of the bridge surface EC transducer with $D_{\text{core}} = 1.5$ mm is 4.5 mm, the base of the bridge surface EC transducer with $D_{\text{core}} = 1$ mm is 6 mm.
Experimental selection of the EC transducer frequency.

To simplify the experiments on one of the samples of the cladding of the fuel rods, a special defect was made in the form of an external circular groove 0.3 mm deep and 0.3 mm wide. To select the working frequency of the EC transducer, hodographs of signals from the groove were obtained at various frequencies at $D_{\text{core}} = 1$ mm. To reduce the random error at each frequency, the defect passed under the surface EC transducer 10 times. Figure 14 shows the dependence of the average value of the hodograph amplitude on the frequency of the exciting current. This dependence has a pronounced maximum at a frequency of about 1200 kHz, which confirms the validity of the result obtained at the stage of mathematical modeling.

Experimental choice of the diameter of a ferrite core

To select $D_{\text{core}}$ for each bridge surface EC transducer, signals from the defect CD2 were obtained. The signal for the bridge surface EC transducer with $D_{\text{core}} = 1.5$ mm is shown in figure 15. In the signals obtained using bridge surface EC transducer with $D_{\text{core}} = 1.5$ mm and $D_{\text{core}} = 2$ mm, dips are observed.
Figure 16. Experimental and model dependences of hodograph amplitude on air gap size.

The ratio of the amplitude of the dip to the amplitude of the useful signal from the defect is 18% and 39%, respectively. In the signal obtained using bridge surface EC transducer with \( D_{\text{core}} = 1 \) mm, there is no dip, while the amplitude of the useful signal decreased by only 4% compared to \( D_{\text{core}} = 1.5 \) mm. Thus, the experimental choice of \( D_{\text{core}} \) coincides with MM.

An experimental study of the effect of the gap between testing object and the surface EC transducer

To study the effect of the gap between testing object and surface EC transducer, signals were obtained from CD2 using the bridge surface EC transducer with \( D_{\text{core}} = 1 \) mm for various values of the gap. The gap was changed by placing plates of various thicknesses under the carriage wheels. For each gap value, 5 signals were obtained and average values of the hodograph amplitude were found. Figure 16 shows the experimental and model dependences of the average values of the hodograph amplitudes on the magnitude of the amplitude-reduced amplitude at zero clearance. Dependencies are identical. The discrepancy with a gap of 0.2 mm is 6 %, and with a gap of 0.4 mm is 35 %.

Two reasons contributed to an increase in the discrepancy between the experimental and model dependences with an increase in the gap: the difficulty of providing large gaps in the experiment and the increase in the measurement error of the decreasing hodograph amplitude for large values of the gap. In general, an experimental study of the influence of the gap confirmed the validity of the results of mathematical modeling.

Production of a multi-element overhead converter

Based on the results of mathematical modeling and experimental studies, the multiprobe transducer was designed and manufactured as shown in Figures 18 and 19. Multiprobe transducer consists of 10 bridge surface EC transducer placed on a cylindrical frame 10 cm long, installed in a metal case.

Using multiprobe transducer and the multichannel eddy current flaw detector Elotest PL-500, experimental signals from defects were obtained on real samples of claddings of fuel elements. Table 2 presents the geometric parameters of the defects used. The obtained experimental signals were compared with the model ones. For visual comparison, model signals were amplified. In Figure 17 shows the hodographs of the experimental and model signal from a defect in sample № 3. The difference between the amplitudes and phases of the experimental and model hodographs does not exceed 10 % for all defects, which confirms the validity of the results obtained using MM.
Conclusion
The article proposes a flexible approach to the design of multiprobe transducers using the example of EC testing of shells of fuel elements. The approach is based on mathematical modeling and allows taking into account various geometric and physical properties of the object of testing and defects at the design stage. The validity of the proposed approach is confirmed experimentally. The result of the work described in the article was the creation of a complex of eddy current testing of the shells of fuel elements, including not only hardware, but also software, not described in this article.

For the developed multiprobe transducer, the algorithm for determining the volume of randomly located local defects was adapted and applied [13], which allows one to determine the volume of defects located not only under the bridge surface EC probe, but also between the surface EC probe included in the multiprobe transducer.

The main interfering factor in the determination of small volume defects using multiprobe transducer is the change in the gap between the surface of the testing object and surface EC transducer included in the multiprobe transducer. Therefore, a promising direction in the field of design and application of multiprobe transducer is the development of improved DSP methods and gap stabilization systems, the combined use of which will allow the detection of defects of smaller volumes.

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