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V. Lunin / A. Zhdanov

Inversion of Eddy Current Field Data for In-service Inspection of WWER Steam Generator Tubes

INVERSE FIELD PROBLEMS AND OPTIMISATION

Introduction

Previous experience in the operation of WWER type reactor has shown that steam generator tube bundle is one of the most critical components. The tube walls are the only boundary between the primary (radioactive) and secondary circuits. Therefore, the integrity of the steam generator tube wall is of prime importance. Damages of tubes result in unplanned shutdowns, expensive corrective actions including plugging or repair, and in some cases even in the replacement of steam generator. Therefore, the timely detection of defects and preventive corrective measures are of significant importance for the reliable and safe operation of nuclear power plants.

The most convenient method in respect to quality and time for inspection of steam generator tubes is multi-frequency eddy current method. This method has several advantages in comparison with other methods such as ultrasonic inspection or leak testing. The most common eddy current technique applied for steam generator examination is standard bobbin coil technique.

All recorded data are transferred to data analysis tool and analyzed in order to invert these experimental signals. For this, we developed software package called PIRATE (Program for Identification & Recognition of defects through signal Analysis in Testing by Eddy current), which allows to increase speed and quality of data analysis based on inversion algorithm which views this task as recognizing responses from one of several predefined classes. The most important analysis problem is how to extract defect influenced field, taking into account the fact that the perturbation of the electromagnetic field due to defects is usually small portion of the total field. Besides of this, the bobbin coil probe signal may be distorted by influence of large massive ferromagnetic components (tube support and tube sheet plates) and so-called pilger-noise (figure 1).

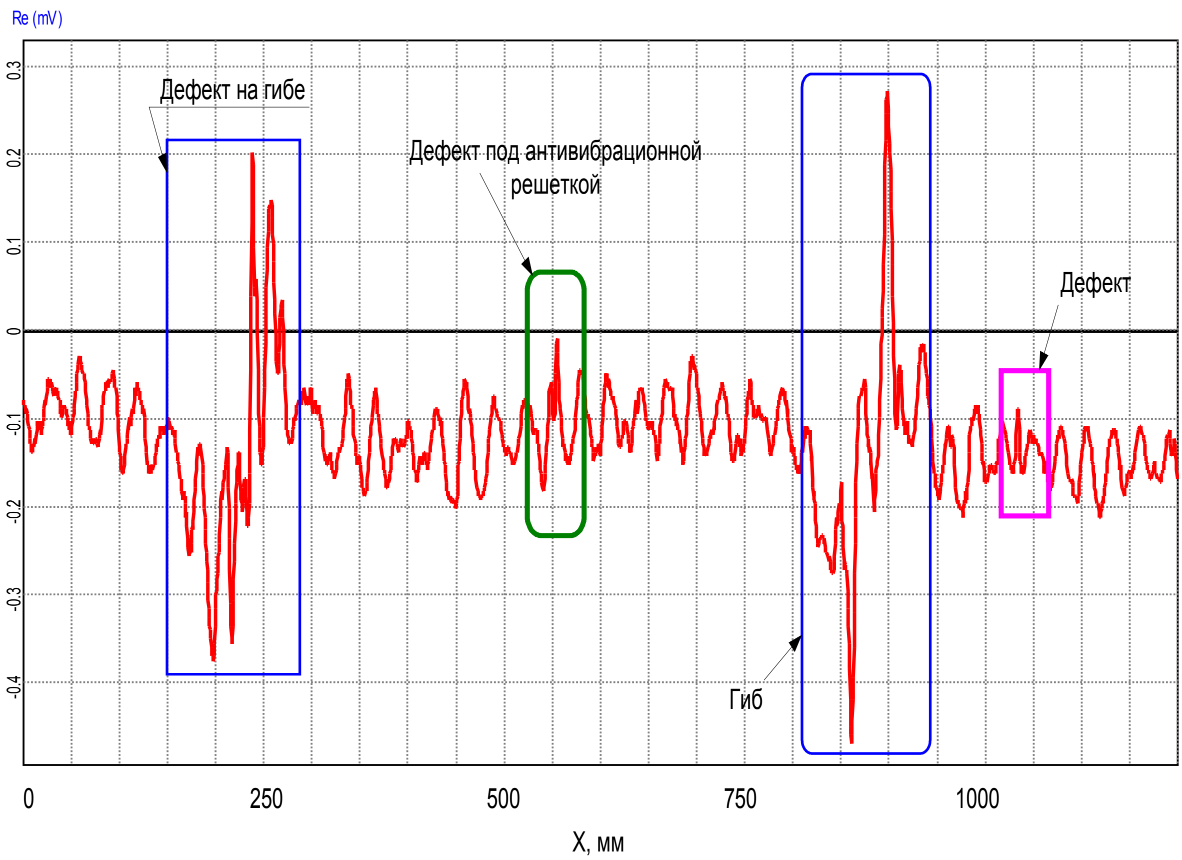

Figure 1 Typical field eddy current signal from inspected tube

Main features of software

The key features of PIRATE (see working window in figure 2) are:

- visualization of testing results (imaginary and real signal components in time dependence mode, impedance plane trajectory);
- preprocessing of experimental data (adaptive and wavelet filtration, calibration, suppression of unwanted factors influence – pilger-noise, support structures, anti-vibration bars, U-bends);
- analysis of diagnostically significant signal parts, in automatic and also in manual modes;
- inversion of data - evaluation of depth and axial size of detected defect automatically and interactively (with expert);
- edition of interactively obtained analysis results;
- creation of final report in Microsoft Excel format.

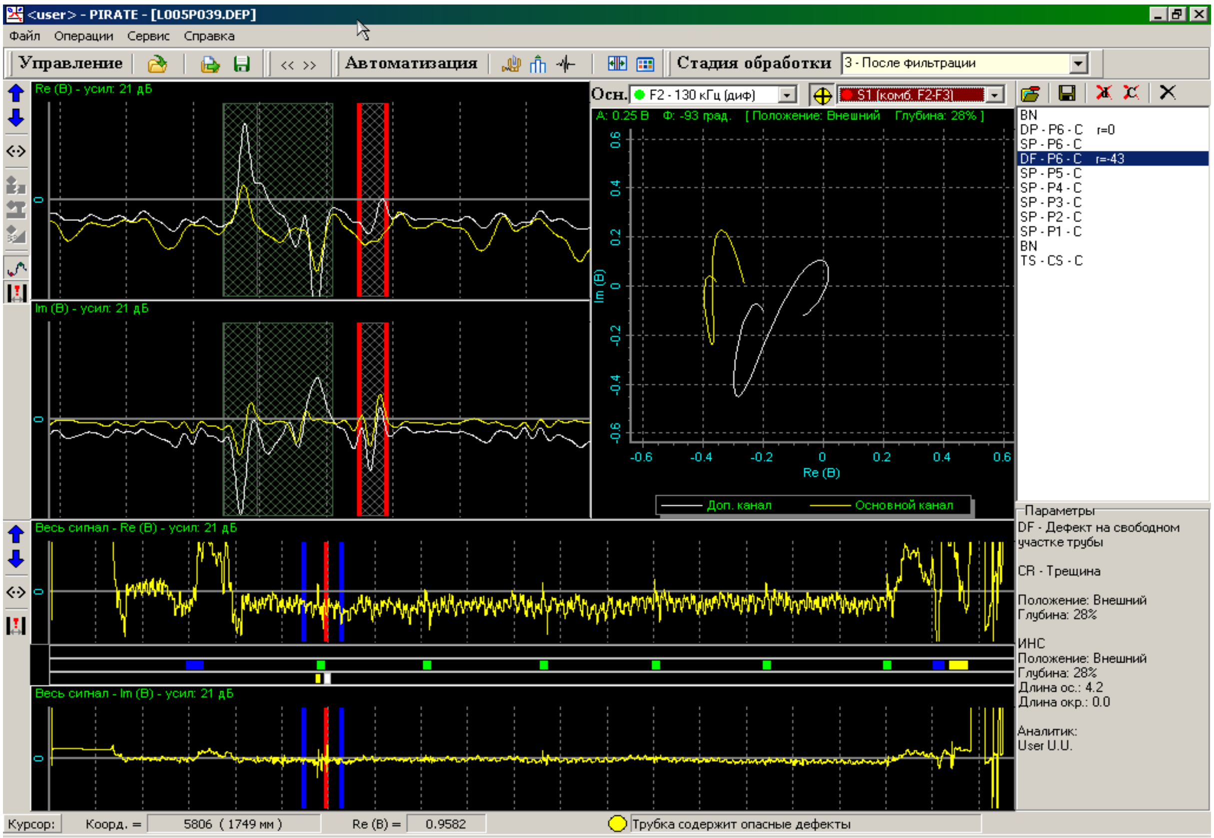

Figure 2 Example of field signal analysis with extracting portion from axial crack

Short description of analysis algorithms

Block diagram of analysis algorithms is shown in Figure 3. The raw eddy current inspection data from bobbin coil probe is first applied to preprocessing stage that filters the data and makes it insensitive to pilger-noise and structural elements influence.

Calibration is necessary to provide a reference for defect sizing. A calibration tube of the same material and dimensions as the tubes to be inspected is used for calibration. The calibration tube contains reference defects whose dimensions are known. Sample signals are then collected from both the calibration tube, as well as from inspected tubes, using the same instrument settings. Signals from a reference defect are phase-rotated and scaled to a standard angle/amplitude.

The enhanced data with extracted diagnostically significant signal parts is then applied to a feature extraction algorithm to identify features containing discriminatory information. Features selected are then applied to inversion algorithm, where defect signals are divided into some classes according to defect position (on outer or inner surface) and to defect depth level (small, dangerous, critical). Defect signals in each class are then analyzed to determine the true defect geometrical parameters (defect depth, axial and azimutal lengths).

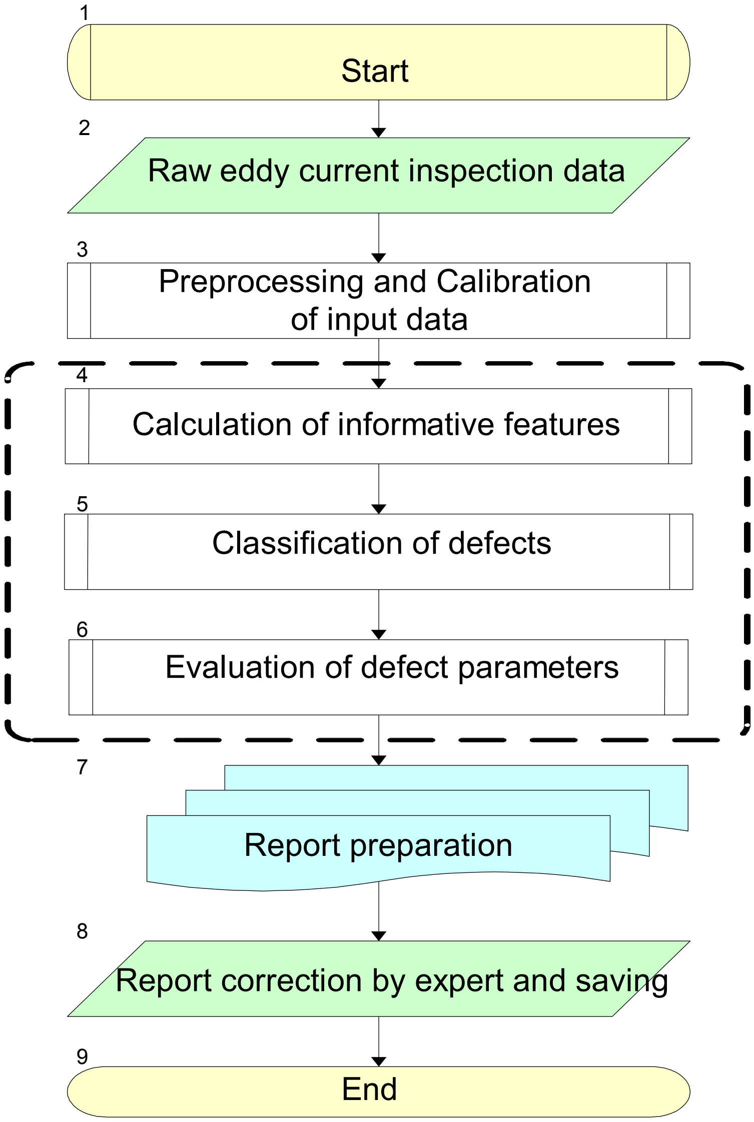

Figure 3 Block diagram of signal analysis algorithms

As mentioned above, successful detection and geometry evaluation of steam generator tube defects using through-pass differential probe is a very difficult problem because of great number of interfering factors and disturbances. These interfering factors resulted from a number of structural elements of heat exchanger tubes being inspected (the presence of support plates, anti-vibration bars, U-bends, collector sheet, corrosion deposits). Moreover, details of probe construction and noise of eddy current measurement circuits have certain influence on experimental signals.

Illustration of a typical one-dimensional inspection signal of standard differential bobbin probe is shown in figure 1. A common situation is where a defect can exist on outer or inner surface of a tube and can be positioned under a ferromagnetic tube support, anti-vibration bar or near U-bend area. The purpose is to detect and classify such defects.

Effective algorithms for separation defect signals from interfering factors were investigated and introduced to increase the validity of eddy current testing while designing the automated signal analysis system.

Suppression of pilger-noise

The goal of signal preprocessing is to eliminate the influence of the main interfering factors and to bring the experimental data to signal which is directly caused by defect. For example, the elimination of low frequency quasi-periodical distortions, caused by so-called pilger-noise, is achieved by combination of different frequency signals application. Additional technique is successfully used for rejection the low frequency trend, in which the approximation by low-power polynomial is subtracted from the signal. Figure 4 illustrates these procedures.

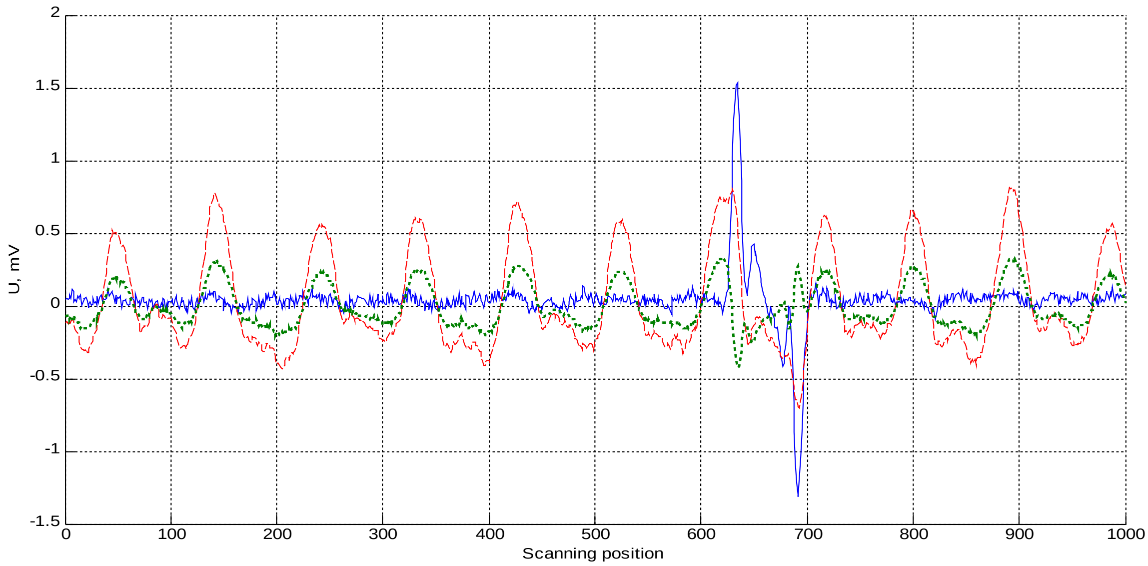

Figure 4 Result of suppressing pilger-noise

Suppression of support plate signal

The possibility of selecting defect caused signal from constructive element influence (support plates and anti-vibration bars) is probe signal from these elements is stable enough in its impedance shape. A parametrical approximate function is plotted for rejecting the constructive element influence, which describes the “clean” signal from the element (figure 5). Free parameters of approximate function are selected particularly for each element using the simplex algorithm of residual minimum searching [1].

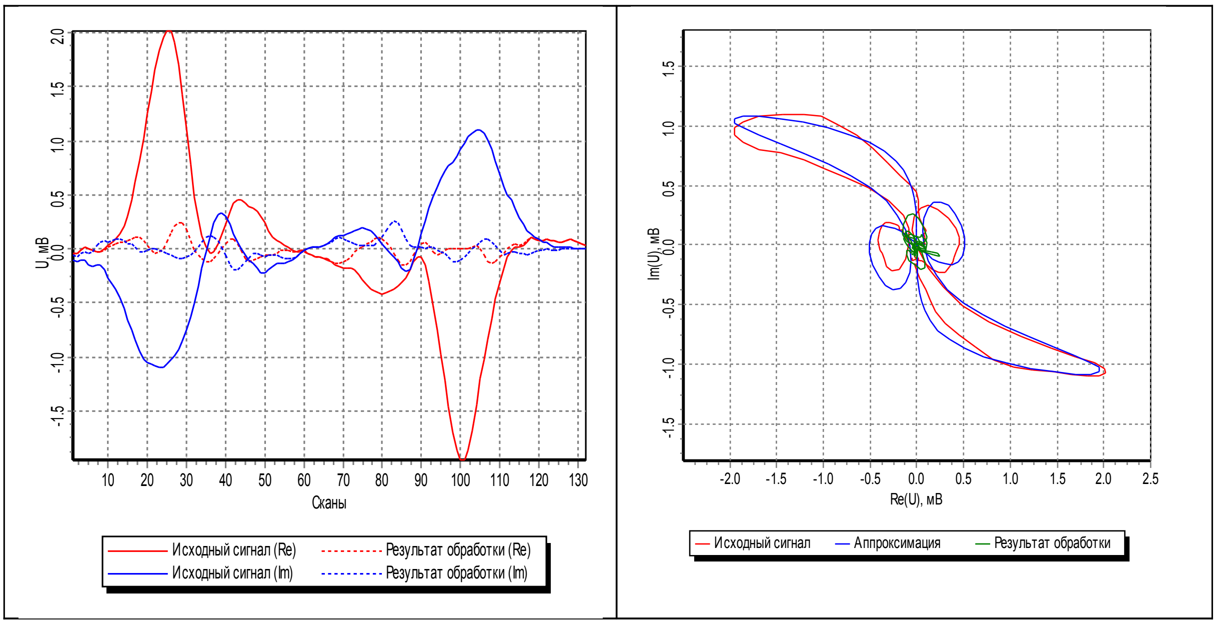

Figure 5 Result of selecting an appropriate approximation function

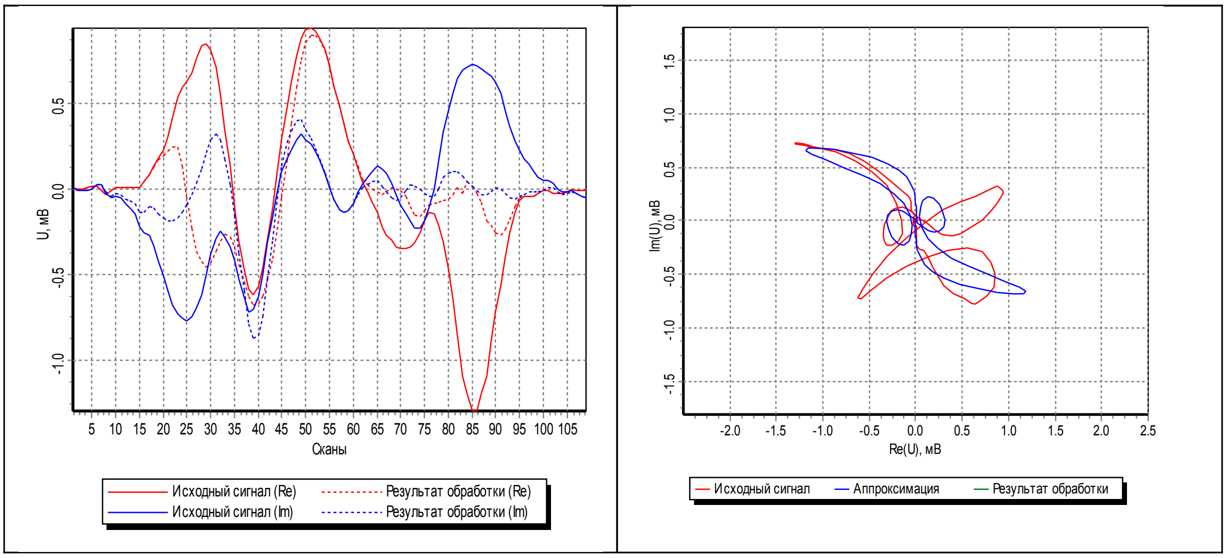

Figure 6 Result of suppressing support plate signal by selected appropriate approximate function

Numerical experiments were carried out on data obtained during in-service inspection of steam generator tubes. As investigations showed, in most cases the present technique allows successful extraction of diagnostic signal from data to be made and the defects presence to be detected (figure 6). The analysis was made for signals from 32 tubes (more than 450 structural elements) and 140 defects were revealed; 20 of them are dangerous (with depth of more than 70% of tube wall thickness), and 38 defects had the depth within the range from 40% to 70% of the wall thickness. The results of the algorithm fit well with the expert estimations.

Neural Network Based Inversion Scheme

Neural network based inversion algorithm for identification and estimation of defect parameters (shape, sizes, orientation) was developed with use of theoretical, based on accurate physical and mathematical model of inspection procedure, and experimental, based on test-samples and field tube measurements. We developed effective modeling algorithm for inspection procedure considering axisymmetrical nature of source field and electro-physical properties of structural elements, possible shapes and geometrical parameters of defects, presence of interfering factors in the form of support plates, anti-vibration bars, bends, corrosion deposits, probes (bobbin coil and array), measurement schemes of diagnostic signal (absolute and differential). It has allowed to predict probe signals during scanning of tested tube (figure 7, [2]).

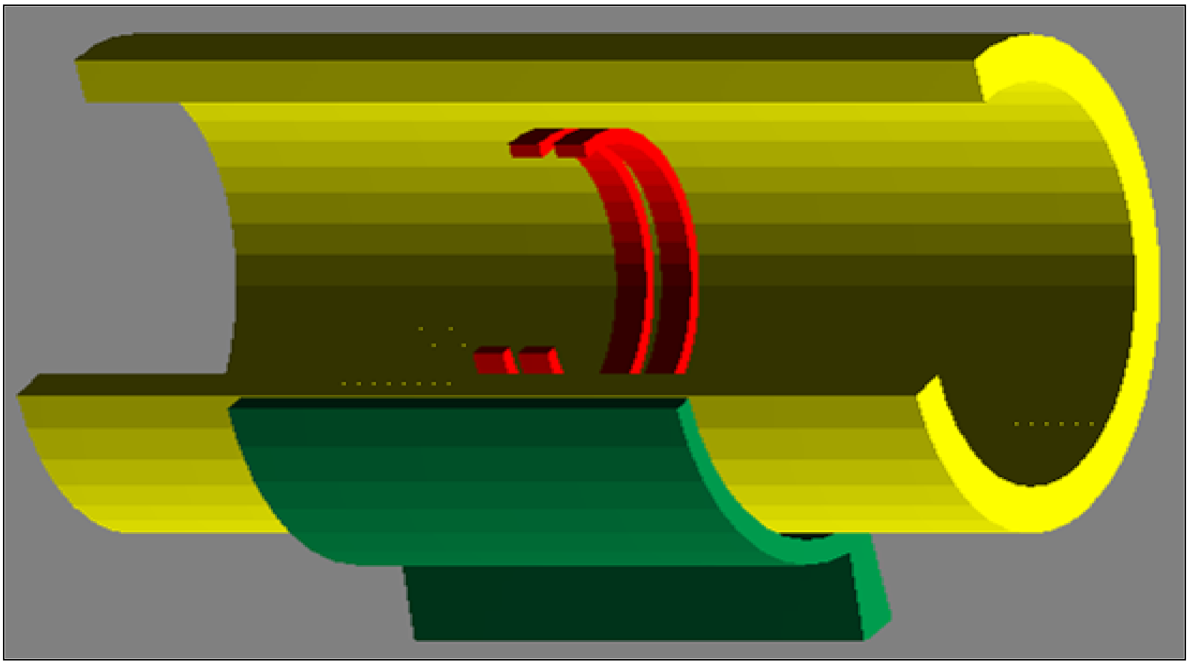

Figure 7 Finite element model of eddy current inspection of tube with support plate

The extensive signal base from a wide spectrum of defects (pitting, stress-corrosion crack, corrosive wear) was created. Automated signal inversion system uses feature based method. The approach consists of two steps. The first step is feature extraction, where characteristic features in the signal that have discriminatory information are extracted. The second step is the recognition of the feature vector using neural network algorithm.

A hierarchical neural network scheme was used for inversion of eddy current data. At first, the hierarchical system classifies data as either a defect or a non-defect. Defects are further classified into one of several classes using additional hierarchical classifiers. We use multilayer perceptron neural networks in each case. The main advantage of the hierarchical scheme is its modularity.

Field examination of inversion algorithm

Field examination of inversion algorithm included in PIRATE was carried out at one russian NPP during regular operating inspection regime. The purpose was overall verification of developed software in solving defect classification and parameterization tasks. In particular, analysis of eddy current data from “hot” collector tubes was demonstrated. For this, data from series of more than 1000 tubes were analyzed in automatic mode. The PIRATE results in detecting all construction elements and defects were very promising.

Automatic and manual data evaluations by PIRATE were compared with results obtained by experts from the NPP with using standard analysis software. Number of overcalls during automatic analysis was 1001 or 1,05 per one inspected tube. For comparison, number of overcalls during expert analysis was 836 or 0,87 per inspected tube. Forty five in-service-degraded tubes with critical defects (depth no less than 75% made by standard software) were included in testing set. Comparing results of defect classification and parameterization showed that for detecting critical defects the results coincided in 80% cases.

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