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WAVELET TRANSFORM FOR EDDY-CURRENT SIGNAL PROCESSING

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ABSTRACT

The paper describes the difficulties of steam generator heat exchanger tubes eddy-current testing data analysis due to noise levels and the presence of numerous interfering parameters. One of the main interfering parameters is structural elements. The paper considers continuous wavelet transform for reliable flaw isolation under structural elements.

Index Terms – Wavelet transform, eddy-current testing, eddy-current signals

1. INTRODUCTION

Operation reliability requirements of nuclear power plants (NPP) are significantly improved nowadays. Steam generator (SG) functionality is one of the most important aspects of safe water-moderated water-cooled reactor (VVER) powered NPP operation. Horizontal SG maintenance indicates that heat exchanger tubes (HET) are the main part of the generator to consider while evaluating the service life. Austenitic stainless steel HET damage analysis shows that the most probable corrosive processes are: stress corrosion cracking (SCC), single and multiple pitting corrosion. HET damage intensity varies for different steam generators and is determined mainly by water-chemical conditions.

2. EDDY-CURRENT TESTING

Structural integrity of SG heat exchanger tubes NPPs during operation process is currently evaluated by means of multifrequency eddy-current testing (ECT). Eddy-current testing is based on analysis of interaction between external electromagnetic field excited by the inductance coil with alternating current and the electromagnetic field of eddy currents induced by the coil in the test object (TO). Distribution and density of eddy currents are determined by the source of the electromagnetic field, geometrical and electro physical parameters of the TO. As a result of eddy current appearance in the TO, the active and inductive resistance of the coil (eddy-current probe ECP) is changing. Thereby, the changes in active and/or inductive resistance of the probe allow inspecting the geometrical parameters of the test object.

Multifrequency eddy-current testing generally allows detecting the flaw and analysing its depth and location. ECT results become the basis for decision making concerning the remaining life of a SG and the replacement necessity. Furthermore, maintenance experience has indicated that it is impossible to timely detect corrosion process activization in SG without ECT. Under such circumstances the requirements for testing quality and results processing and interpretation increase significantly.

According to ECT results flawed tubes are preventively cut off. It allows avoiding possible expansion of the located flaw towards becoming through and, consequently, leakage from the primary coolant circuit to the secondary.

3. STRUCTURAL ELEMETNS

Multifrequency ECT data analysis entails significant difficulties due to the presence of numerous interference parameters as well as noise in the signal.

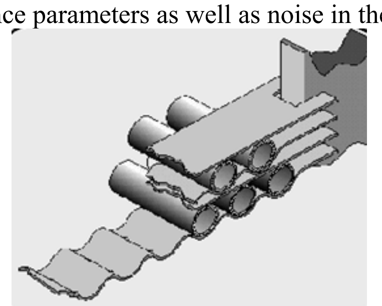

Figure 1 Spacer grid and heat exchanger tubes

One of the main interfering parameters during flaw isolation are structural elements, notably spacer grids (Fig. 1) that hold the heat exchanger tubes in the right position inside the steam generator.

4. STEAM GENERATOR HEAT EXCHANGER TUBE MODEL

Finite element method is used to compute the distribution of electromagnetic field in the heat exchanger tube with a flaw positioned under the spacer grid. Tube and spacer grid model is presented on Fig. 2. Electromagnetic field distribution is calculated for different eddy-current probe positions relative to the grid. As the sensor moves, the field distribution changes as well as the induced voltages in each coil. Calculation is conducted for absolute (voltage calculation for a single coil) and differential (voltage difference calculation between the coils) voltage.

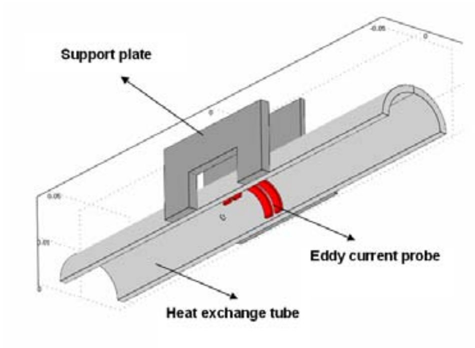

Figure 2 Model of steam generator heat exchanger tube with spacer grid

Resulting eddy-current signals simulate maintenance inspection of steam generator tubes.

5. FLAW SIGNAL ISOLATION METHODS

Comparison of model spacer grid signals against experimental data indicates that the signals are identical in shape on all frequencies. Based on model data analysis a signal isolation algorithm was suggested to localize the flaws under spacer grids. Flaw isolation on on a free tube fragment is based on various thresholding algorithms. Those algorithms are not suitable for locating a flaw under the grid, because the signal amplitude from a grid may be greater than from a flaw. As an example Fig. 3 demonstrates a flaw signal under a spacer grid.

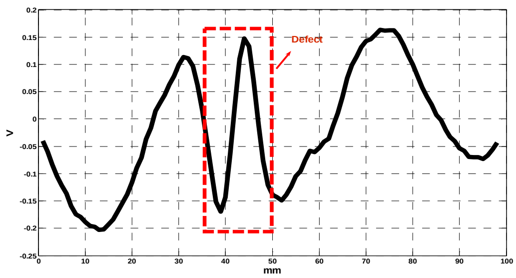

Figure 3 Signal from a flaw under the grid on a frequency of 130 kHz

During filtering flaw signal is strongly distorted because flaw and grid signal bandwidth intersect. Various algorithms are used to suppress the interfering parameters [1], e.g. linear balance method for interference suppression. This method doesn't always provide the correct signal, because rotation (for complex signals) may create fake signals which have defect-signal properties.

5.1. Continuous wavelet transform

The paper considers continuous wavelet transform [2, 3, 4, 5, 6, 7, 8] for nonstationary signals. Continuous wavelet transform (WT) $W_\psi(a,b)$ is a two-dimensional integral transform that represents a convolution of signal f(x) with a so called mother wavelet, function $\psi_{a,b}$.

$$W_\psi(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{+\infty} f(x) \cdot \psi\left(\frac{x-b}{a}\right), \quad (1)$$

where a – is a scale factor, b – x axis displacement parameter. Wavelet transform is used when signal analysis result should contain not only a simple list of its typical frequencies (scale factors), but the information regarding definite coordinates at which those frequencies are detected as well [9].

5.2. Application of continuous wavelet transform

The choice of wavelet $\psi_{a,b}$ was based on the resemblance between flaw-signal form and mother wavelet. Gauss wavelet was used for analysis.

$$\psi(t) = (-1)^n \frac{d^n}{dt^n} e^{\frac{-t^2}{2}} \quad (2)$$

The higher the order of the wavelet *n*, the thinner (high frequency) the structure of the signal that can be inspected with this wavelet. An order 6 wavelet is used for analysis, because the peak regions of scale factors for flaws and grid are farther apart on a spectrogram $W\psi(a,b)$ (Fig. 4).

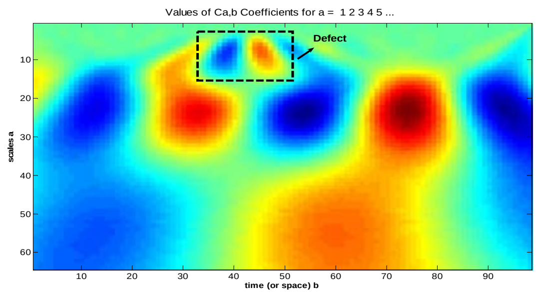

Figure 4 Spectrogram for the flaw signal under the grid

Local extrema on a wavelet spectrogram are the result of strong correlation between wavelets and signal components. Flaw area is marked with a dotted line on Fig. 4. Spectrogram shows that the defect is located in the low-scale range and the area of the grid is in the higher scale range. It allows locating the flaw by analysing only significant scale factors. The signal/noise energy ratio of the source signal (Fig. 3) after constant component removal is 0.23. The calculation of signal (flaw signal) to noise (grid signal) energy ratio for every scale factor showed that it reaches its maximum at the scale from 3 to 10 (Fig. 5). Therefore the determination of flaw coordinates is based on smooth thresholding of wavelet coefficients at 8 scale factors. Coordinates of wavelet coefficients correspond to flaw coordinates (Fig. 6).

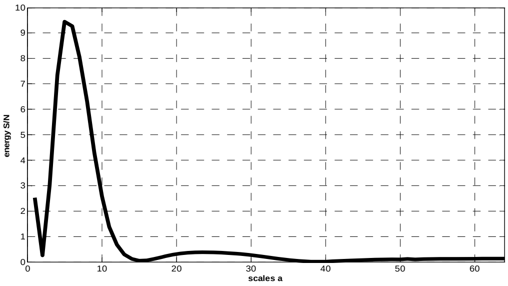

Figure 5 Signal to noise energy ratio for scale factors

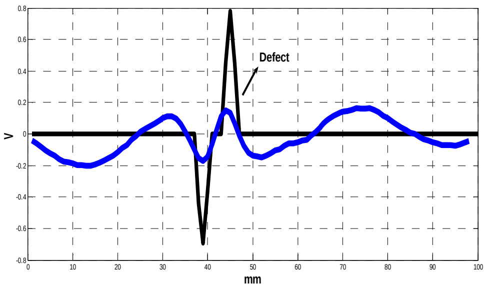

Figure 6 Signal from a flaw under the grid and flaw area isolation result

Since heat exchanger tube inspection is conducted by multifrequency ECT, differential (complex) signals were analysed on several frequencies: 130 kHz, 280 kHz and 60 kHz. Imaginary component of the signal on the frequencies of 130 kHz and 280 kHz appeared to be the most informative for algorithm application.

6. CONCLUSION

The trial of suggested method was conducted on signals acquired during planned maintenance on russian NPPs. Trial results showed that out of 250 analysed signals of grids with flaws the flaw coordinates are correctly determined in 90% of cases.

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