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Eddy current method for characterizing the tubes under pressure in CANDU PHWR

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Abstract
This paper proposes to present the methods and the algorithms for the data analysis, and the results obtained at the inspection of non irradiated steam generator tubes, made from Incoloy 800 and pressure tubes samples made from Zr2.5%Nb. The data acquisition has been made using two types of transducers: the rotating probe and the inner eddy current transducer with rotating magnetic field.
Keywords: eddy current, automatic system, signal processing, PHWR, tubes samples

Introduction

The NDE operations can be considered as getting into development in two steps:

- a physical field (selective forces, electromagnetic field, etc) actions over examined object and an adequate transducer convert the answer of the system into a size that can be sampled and quantified for storing on a compiler. This stage can be named data acquisition.
- the stored data are interpreted to could answer to the following questions: the flaws exist or not, and, in case in which one of the signals or the images obtained in the first stage have been interpreted as flaws, which is its severity. This stage can be named data analyses.

For a very long period of time, the attention of the non-destructive evaluation (NDE) community was focused on design and production of high quality equipments, this desideratum being reached therewith the development of the computing systems, as well as of the signal and image digital processing methods [1], [2], [3].

It was clearly that, if the signals and images resulted from NDE operation contain a low noise level, the adequate trained operators would interpret them correctly, detecting the flaws and more, being able to evaluate them with high accuracy. A series of round-robin tests [4], [5] has shown that the situation is more complicated, the errors of the human factors being more numerous than the initial estimation.

The Nuclear Power Plants with Pressurized Heavy Water Reactor (PHWR) has foreseen, approximately once an year, an outage, with this occasion a large number of NDE operations being effectuated [6], especially the eddy current examination of the tubes bundles from the steam generators, as well as of a series of fuel channels. Because the number of data from the examination is extremely large, and for avoiding the errors that the human factors might commit, especially under the circumstances of the stress conditions, theoretical principles, algorithms and numerical codes for the automatic data analysis have been developed [7],[8] [9].

The data delivered by the control equipment and the eddy current transducers shall fulfill certain quality criterion, in order that the automatic data analysis systems function correctly.

This paper proposes to present the methods and the algorithms for the data analysis, and the results obtained at the inspection of non irradiated steam generator tubes, made from Incoloy 800 and pressure tubes samples made from Zr2.5%Nb. The data acquisition has been made using two types of transducers: the rotating probe [11], [12], and the inner eddy current transducer with rotating magnetic field. [13] , [14].

Studied samples

There have been taken into study tubes made from Incoloy 800 with 15.8×1.12mm diameter, on which different types of discontinuities have been practiced, using the electro discharge machine. Because in steam generators the tube sheet, and the anti-vibration bars are made of ferromagnetic steel, their presence has been simulated by inserting them in the wholes with 16mm diameter, practiced in a ferromagnetic steel plate.

In order to develop an automatic data analyzer system for eddy current evaluation of the pressure tubes in PHWR, tubes samples made from Zr2.5%Nb, with the diameter of 103x4.1mm on which there were made artificial discontinuities and scratches that simulates the effects of fuel - loading - unloading machine, have been taken in study.

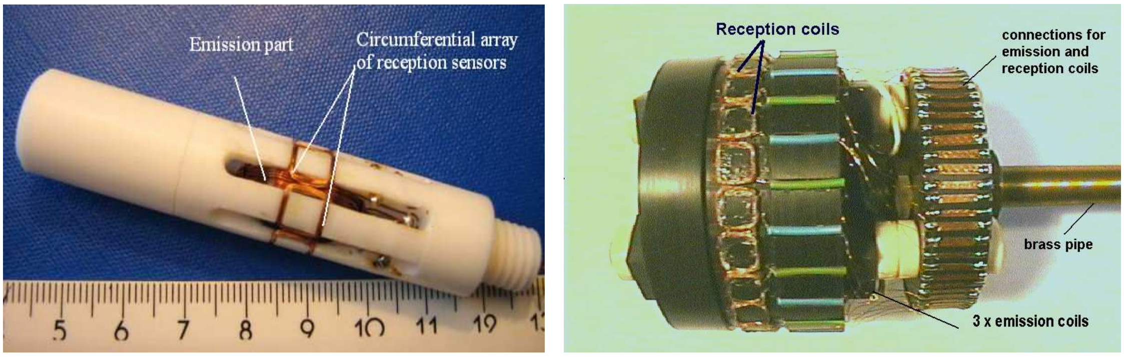
Experimental set-up

The eddy current transducers have been made in the Non Destructive Testing Laboratory from the National Institute of Research and Development for Technical Physics (NIRDTP) Iasi, Romania. Because the rotating probe are well-known in usually practice, in Figure 1 are presented the two variants of eddy current transducers with rotating magnetic field.

The displacement of the transducers inside the examined tubes have been made using an X-Y displacement system, produced by Newmark USA, which has the possibility of rotation, being connected with a PC using a RS232 interface.

The output signal of the transducer has been measured with Network/Spectrum/ Impedance Analyzer 4395A produced by Agilent USA, connected to the same PC using a PCIB interface, IEEE 482.2 type. The same PC will acquires and save the results of the control into a convenient manner.

The multi-frequency control was used. In the case of the tubes from the heat exchangers, the frequencies were 10 kHz, 100 kHz, and 200 kHz. The checking of the functioning and tuning were made taking into consideration the ASME standards, section V, art. 8, app1 and 2 [15].



a b

Figure 1. Eddy current inner transducers with rotating magnetic field:
a) the transducer for examination of steam generator tubes; b) the transducer for examination of pressure tubes

In the case of the examination of the pressure tubes samples, only two frequencies were used: 64 kHz and 200 kHz. The calibration flaws correspond to the standards [6].

Data analysis principle

The proposed data analysis scheme is presented in Figure 2.

The data provided by the equipment and by the eddy current transducers utilized are pre-processed. This stage can contain a variable number of tasks, depending on the type of transducer used and the object to be controlled.

We will give an example for the case of the steam generator tubes control in PHWR nuclear power plants (Figure 3)

In case of using the rotating probe, the angular position of the transducer is determined by the special synchronization impulses. In the case in which, due to different causes, the rotation of the transducer is non-uniform, through the operation of synchronization it is followed the restoration of the impulses fronts, as well as the signal processing that will allow the obtaining of the 2D images of the unrolled tube.

During the transducer’s displacement in the tube, it can reach in zones where anti-vibration grids are. These zones are extremely visible when 10 kHz low frequency of is used. Therefore, using the segmentation, the regions in which the anti-vibration grids exist will be clearly marked, the remaining operations following like in the multi-frequency method. The operation of calibration implies the scaling of the obtained data and the corresponding phase shift, in order that the data shall correspond qualitatively with the data obtained from the ASME standard.

In the case in which the transducer with the rotating magnetic field is used [14], the pre-processing schema is similar. Because the transducer doesn’t have to rotate in order to examine the entire circumference of the tube, the stage of the synchronization does not exist.

Because the number of the reception coils of the transducer is limited due to the constructive reasons, the signals will be interpolated to obtain a sufficient number of voxels on the image.

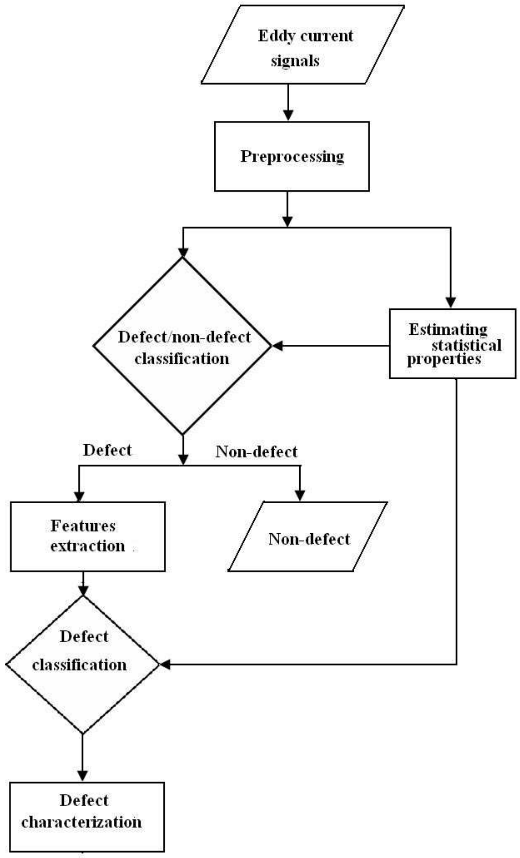


Figure 2. Data analysis flow chart

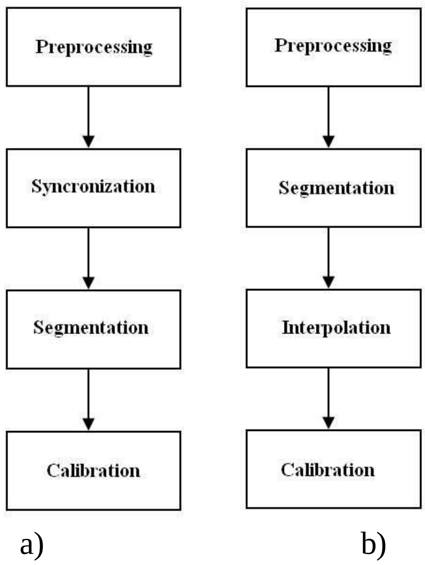


Figure 3. Processing scheme: a) for the rotating probe;
b) for the transducer with rotating magnetic field.

The classification block, defect - non defect type is based on the using of the information delivered by the block for estimation of the statistical properties of the signals/images. An auto-adaptive threshold it is used, as well as the Neyman-Pearson criterion that can be formulated in the following way for the problem of eddy current examination: the probability of detection is maximized, maintaining the probability of false alarm at least at a specified level.

We will detail the functioning of this block.

Let $\bar{y}_i$ be the signal given by the equipment during the control. We consider that $f(\bar{y}|H_0)$ and $f(\bar{y}|H_1)$ are the densities of $\bar{y}$ conditioned by the following hypothesis:

H_0: the signal given by a non-defect zone has a Gaussian distribution with null average and the dispersion σ_{nd}

H_1: the signal given by a defect zone has also a Gaussian distribution, with the μ average and σ_d dispersion

Considering that the two signals contain N samples, it can be written that:

$$f(\bar{y}|H_0) = (2\pi\sigma_{nd})^{-\frac{N}{2}} \exp[(-\sum_{i=1}^{N}(y_i^2/(2\sigma_{nd}^2))] \quad (1)$$

$$f(\bar{y}|H_1) = (2\pi\sigma_d)^{-\frac{N}{2}} \exp[-\sum_{i=1}^{N}(y_i-\mu)^2/(2\sigma_d^2))] \quad (2)$$

Using the Neyman –Pearson lemma, the likelihood ratio can be written as:

$$L(\bar{y}) = \frac{f(\bar{y}|H_1)}{f(\bar{y}|H_0)} \quad (3)$$

The optimum detector using (3) is:

$$\sum_{i=1}^{N} y_i : \begin{cases} < T \Rightarrow H_0 \\ > T \Rightarrow H_1 \end{cases} \quad (4)$$

where:

$$T = \sqrt{N} \cdot \sqrt{\sigma_{nd}\sigma_d}\,\Phi^{-1}(1-\alpha_0) \quad (5)$$

and: α_0 =the maximum probability of false alarm

$\Phi(1-\alpha_0)$ = the cumulative distribution function

In the same time, the threshold T must be greater or equal that the signals provided by the discontinuities with the severities less than 10% of the thickness of the wall, discontinuities that in general are not reported.

Once that through the proposed method it is considered that the signal provided by the transducer in a certain region of the controlled tube is coming from a defect, it will appear the problem of their classification. The corresponding modulus from the flaw chart presented in figure 2, represents a neural network with a hidden layer presented in Figure 4.

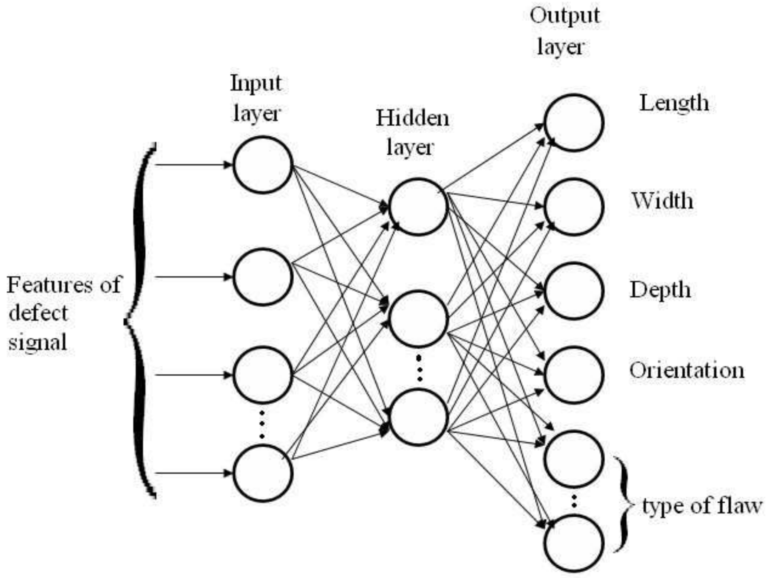


Figure 4. Neural system for automatic data analyses

The number of neurons from the input layer is equal to the number of the features of signal provided by the defect. The number of neurons from the output layer provides the information about the geometrical dimensions of the defect, its orientation, and the type of degradation: ODSCC (Outer Diameter Stress Corrosion Cracking), ID IGA (Inner Diameter Intergranular Attack), pitting, thinning and wear.

For a correct classification of the data, the neural network must be trained using a ‘learning base’ made from much more signals given by the defects completely characterized by other means. Usually, the data base for the training contains thousands of signals [16].

Because in our research we have used only the defects of EDM type practiced on steam generator tubes, and on non-irradiated pressure tubes, we did not simulate the ODSCC, ID IGA, but only the pitting, thinning, and wear.

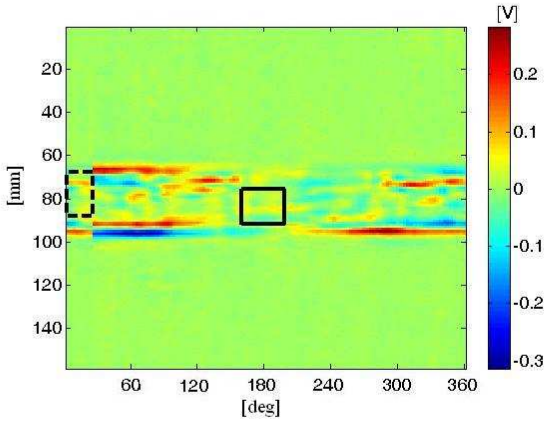
The features extraction from a signal can be made using two procedures:

a) As close as possible to the methods of defect analysis that are using the human operator; the features in this case can be: the maximum and the minimum of the magnitude, phase information, etc.

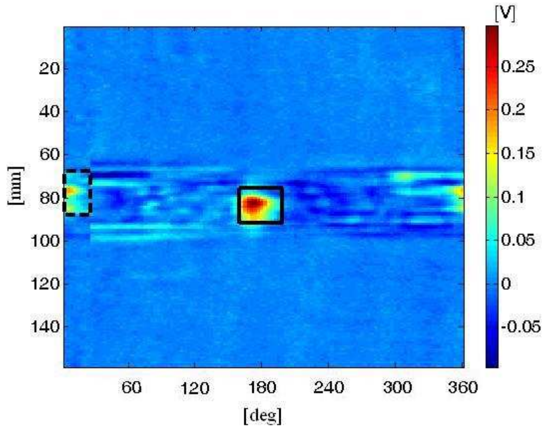
b) Without an intrinsic connection with the parameters used by the human operator, in this case the real and the imaginary components of the signal can be decomposed using different typical methods of digital signal/image processing. We used the wavelets decomposition of the two components, using only the mother wavelets-Daubechy 2 [17]. Due to the orthogonally of the signals, the decomposition is cubic, and will admit inverse transform.

Experimental results

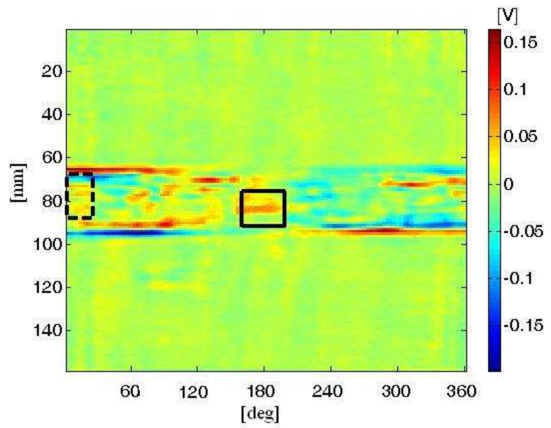
In figure 4 a, b, c, d are presented the real and the imaginary components of the signal delivered by a transducer with the rotating probe, at 100 kHz, and 200 kHz frequencies after the minimization of the effect of the anti-vibration grids.



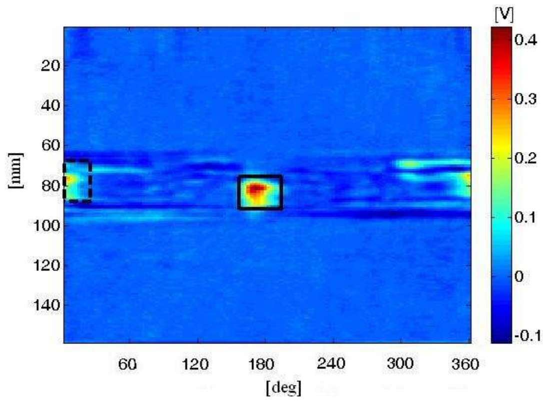
a) the real component for 100 kHz



b) the imaginary component for 100 kHz



c) the real component for 200 kHz

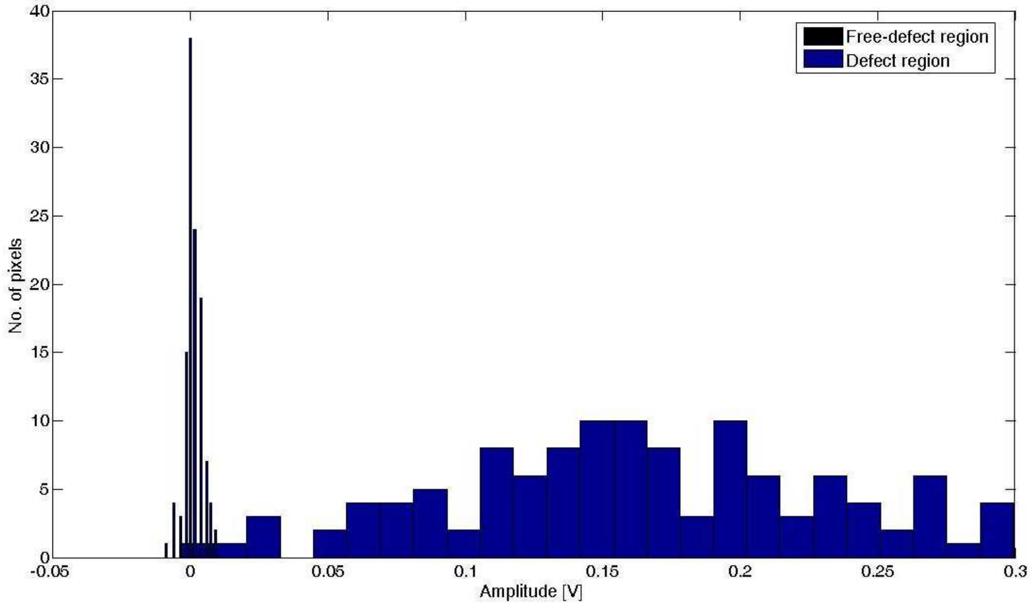


d) the imaginary component for 200 kHz.

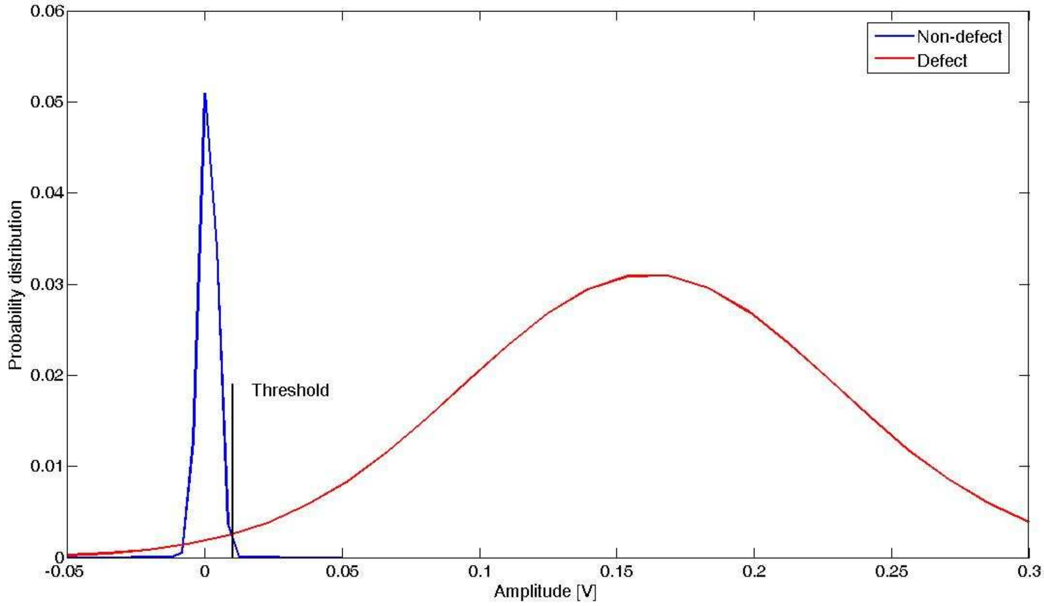
Figure 5

On the images have been marked two regions of interest (ROI boxes), the region marked with continuous line contains indeed a defect information, while the one marked with dash line contains a high amplitude indication, which will be proved as not being an indication of defect.

In Figure 6 a we present the histograms of the values of the pixels (amplitude of the signal) for the two ROI boxes, for the frequency of 100 kHz, being analyzed only the imaginary component of the signals. In figure 6 b it is presented the mode of establishing the auto-adaptive threshold, if it exist a false alarm probability of 5%.



a) Histogram of the amplitude of the signal from the 2 ROI boxes
for the imaginary component using the frequency of 100 kHz.



b) The density of probability and choosing of the auto-adaptive
threshold defect-non defect, for a probability of false alarm of 5%.

Figure 6

Feature extraction has been made using a specialized toolbox of Matlab 7.0, programming environment in which all the calculus were effectuated , and the neural system for the data analyzer have been created.

The data base for training and testing is presented in Table 1

Table 1. The structure of the database

Classification	Training	Testing	Total
Non-defect	19	8	27
Axial slots	10	6	16
Circumferential slots	10	6	16
Pitting	7	3	10
wear	6	2	8

The results obtained with the proposed automatic system are presented in Table 2.

Table 2. The results of automatic classification

Classification	Number of correction indicators	Number of obtained classification	Deviation (%)	Observations
Non -defect	8	8	0	-
Axial slots	6	7	+17%	A pitting was indicated as being an axial slot
Circumferential slot	3	3	0	-
Pitting	3	2	-33%	A pitting signal was identified as being an axial slot
wear	2	2	0	-

Automatic data analyzer works correctly enough even in the case of the examination of the pressure tube samples, the results being presented in [14].

Conclusions

1) Samples of tubes from steam generators and pressure tubes from PHWR have been tested with eddy currents, using rotating probes and inner transducers with rotating magnetic field.
2) All the artificial defects practiced on the two types of tubes have been correctly identified, the signal/noise report being better than 5:1, the auto-adaptive threshold method being correct.
3) The feature extraction method using mother Wavelets Daubechy 2, even if it has a reduced physical signification for the non destructive eddy currents operators, proves to be correct.
4) The neural system developed is working correctly, even if the base for training and the base for testing are small.

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