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Eddy current testing reliability improvement; application to nuclear fuel cladding tubes

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Abstract

Postirradiation tests are performed on the fuel bundles of Nuclear Power Plants, in order to evaluate their performance. The Zircaloy-4 cladding, the first containment of the fission products, is a very important part of these bundles. A fundamental step of these tests is the in-pool identification of the failed bars in the “suspect” bundles. Later, once in the hot cell facility and prior to the destructive tests, it is necessary to characterize the defects in the cladding. The eddy current method provides a means for fast and reliable detection and characterization of defects unobservable in visual inspection, such as tiny cracks, pores and anomalously hydrided regions.

The probability of detection (POD) and the correct probability for characterization of detected flaws can be taken into consideration for nondestructive evaluation of high risk components regarding the shape and geometrical dimensions of the flaws. The eddy current examinations of some components from nuclear power plants, as tubular bundles from steam generators, nuclear fuel bundles, and pressure tubes in the case of PHWR, must have an extremely high degree of confidence and for this, the use of automatic systems for characterization of flaws is recommended, the human operator intervening only in case of doubt.

The project for the application of this method in postirradiation tests has been divided into three stages, namely laboratory set up and data analysis, in-pool tests and hot-cell application, the first one being described here. In this purpose, samples from nuclear fuel cladding tubes, non-irradiated, made from Zircaloy-4 with a series of artificial discontinuities similar to those that may appear during the fabrication, storage and burn-up of nuclear fuel bundles, have been taken into study.

The eddy current examinations on the non-irradiated material were made at 4 simultaneous frequencies using MAD8D - ECT with encircling coils, the relative movement transducer- specimen being produced by an automatic system with constant speed.

The principal features of the signals from some of the discontinuities, such as amplitude, phase, width of lobes, the amplitude of Fourier harmonics were determined, a signal from a flaw corresponding to a point into a n-dimensional space, where n is the number of features. Such a space is named Mahalanobis space, the classification being more correct if the matrix of this space is bigger. Other signals have constituted the testing base. This system has allowed the correct characterization of 95% from flaws for a confidence level of 95% (95/95).

Keywords: eddy current testing, fuel cladding, Mahalanobis space

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1. Introduction

Pressurized Heavy Water Reactors (PHWR) use natural low-enriched uranium pellets as nuclear fuel. These pellets are inserted in the nuclear fuel cladding, made from Zircaloy -4, both ends being closed. A nuclear fuel bundle is made from several claddings, usually disposed into an ordinate structure and that are fixed between them. The Nuclear Reactor Atucha II uses vertical fuel channels inside a pressure vessel reactor. The vertical channel is filled by fuel elements of 5.3 m active length, each containing 37 fuel rods [1]. The fuel cladding represents the first containment of the fission products.

Post irradiation tests are performed on the fuel bundles, in order to evaluate their performance. A fundamental step of these tests is the in-pool identification of the failed bars in the “suspect” bundles. Later, once in the hot cell facility and prior to the destructive tests it is necessary to characterize the defects in the cladding. The eddy current method provides a means for fast and reliable detection and characterization of defects unobservable in visual inspection, such as tiny cracks, pores and anomalous hydride regions [2-4].

The eddy current examination of nuclear fuel cladding is usually made using differential encircling transducer operating at one or more frequencies [5]. The system must allow the emphasizing of small discontinuities on the nuclear fuel cladding with high probability of detection for a high reliability coefficient. In addition, this system must classify the signals into classes and severities, by automatic or manual procedures. This paper proposes the development of an automatic system for processing and post-processing data provided by multi-frequency PC-based eddy current equipment in the examination of nuclear fuel cladding which will have double role:

- Maximization of the probability of detection of flaws
- Their automatic classification

2. Theoretical principles

The proposed system for the maximization of the probability of detection and automatic classification has the scheme presented in Figure 1.

The scheme presented below consists of two blocks: the pre-processing section and the post-processing section. This organization has the advantage that only the signals with the maximum probability of being flaw indications will be selected and automatically analyzed, thus minimizing the calculation time and memory requirement.

The data provided by the eddy current equipment is sampled and digitized in the data acquisition block. Prefiltering is necessary to remove the high frequencies due to digitization noise. This block uses the filtering with the average over a sliding window as working principle.

The sampled digital eddy current signal provided by the equipment can be written as

$$S(i) = A(i) + n(i), \qquad i = 1, 2, ..., N \tag{1}$$

where A represents the complex signal due to the presence of a flaw, n represents the complex noise considered as additive noise, N is the total number of samples of the signal S.

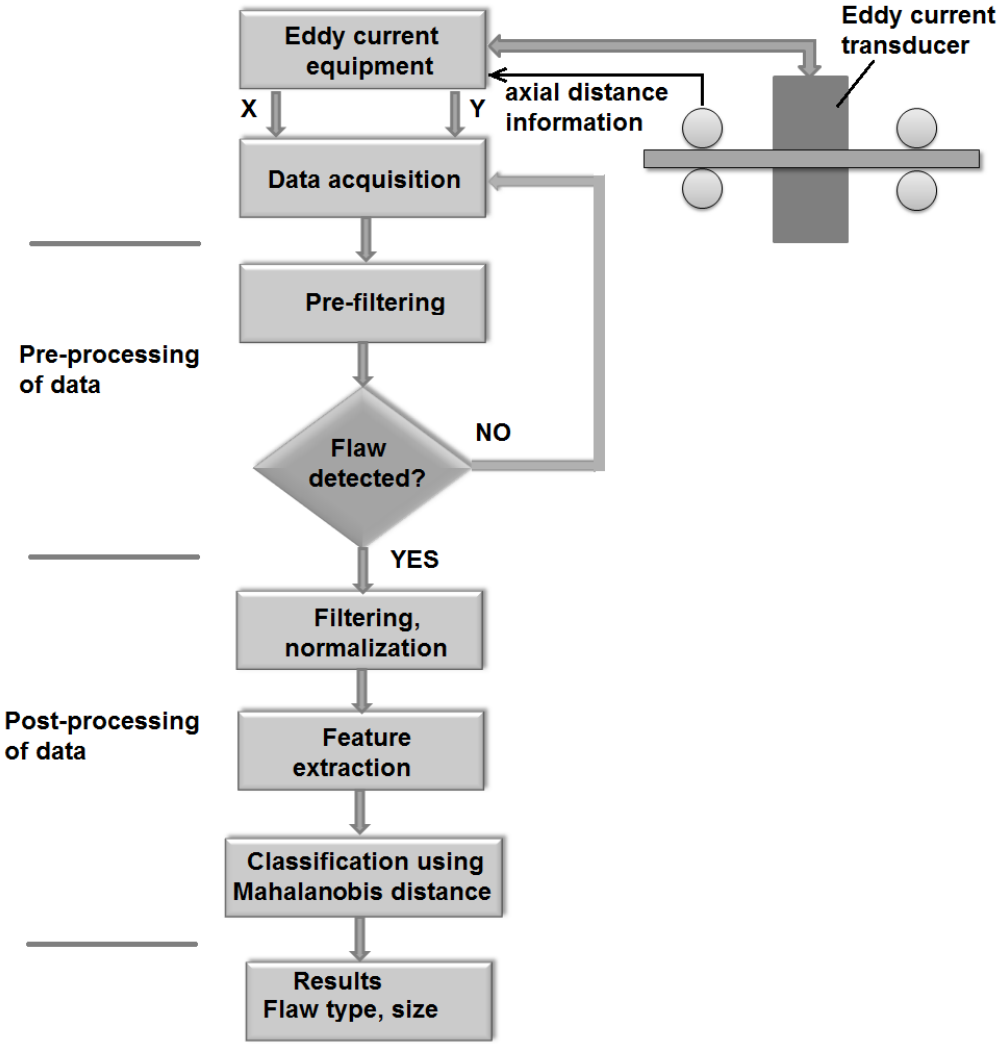


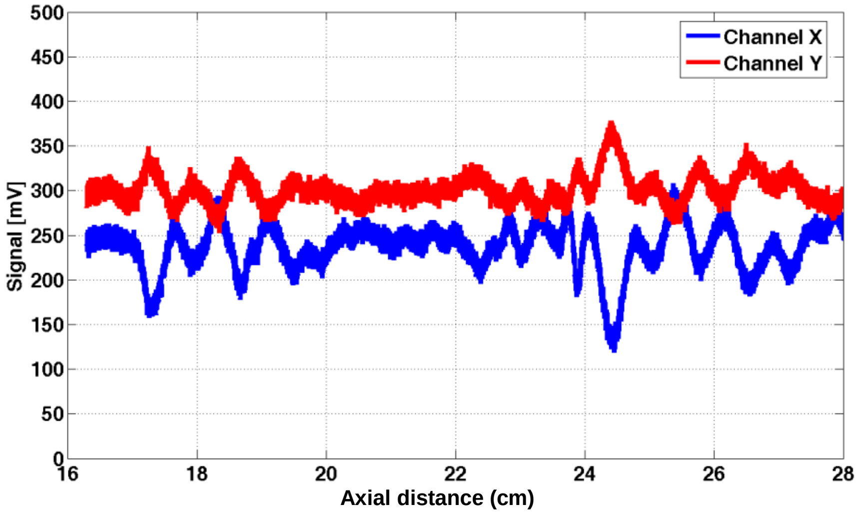
Figure 1. Scheme of the system for maximization of the probability of detection and automatic classification

In order to minimize the digitization noise and other high frequency noises, a window of length L samples is considered.

The filtered signal will be

$$\bar{S}(i) = S(i) - \frac{1}{L}\sum_{k=-\frac{L}{2}}^{\frac{L}{2}} S(i+k) \tag{2}$$

The efficacy of this filtering is presented in Figure 2.



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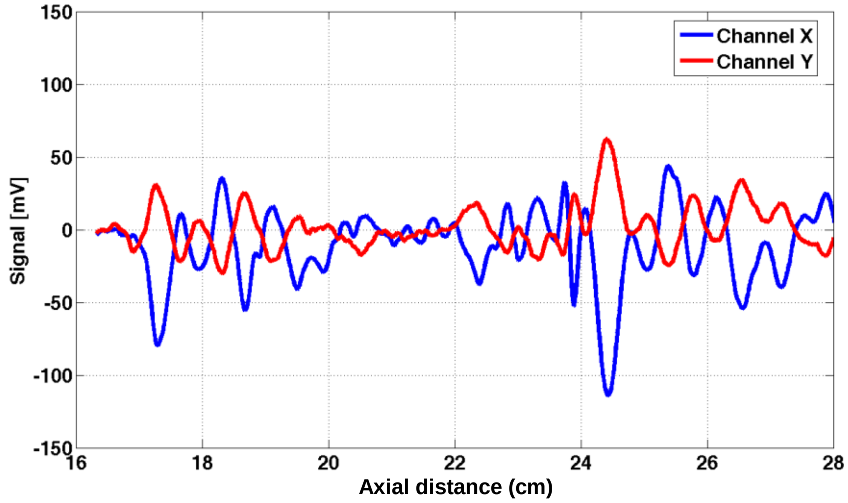

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Figure 2. The action of average filtering with a sliding window: a) the original signal; b) the filtered signal

If any other kind of noises may be present, other types of filtering can be applied. In principle, the digital filters do not modify the phase of the signal.

The Flaw Detector Block is a Neyman-Pearson detector. This detector maximizes the POD of the signal (in the presence of the noises) for a given probability of false alarm (PFA) [6]. The objective can be accomplished using a hypothesis testing approach. The hypotheses are given by

$$\begin{aligned} H_0 &: \quad S(i) = n(i) \\ H_1 &: \quad S(i) = A(i) + n(i) \end{aligned} \tag{3}$$

The Neyman-Pearson detector uses the log likelihood ratio to compute a test statistic that is used for threshold computation. The log likelihood ratio is specified as

$$T(S) = \log\left[\frac{P(S\,|\,H_1)}{P(S\,|\,H_0)}\right] \tag{4}$$

$P(S|H_1)$ is the probability distribution function (PDF) of S given H_1 and $P(S|H_0)$ is the PDF of S given H_0. If it can be assured that the noise is additive with a Gaussian distribution with zero mean and variance σ_w^2, the signal is distributed as a multivariate Gaussian with covariance C_S and mean μ_S

$$\begin{aligned} n &\sim N\left(0,\sigma_w^2\right) \\ A &\sim N\left(\mu_S, C_S\right) \end{aligned} \tag{5}$$

The test statistic can be formulated as [7]

$$T(S) = S^T\left(C_S+\sigma_w^2 I\right)^{-1}\mu_S + \frac{1}{2\sigma_w^2}S^T\left[C_S\left(C_S+\sigma_w^2 I\right)^{-1}\right]S \tag{6}$$

where I represents the identity matrix.

This test statistic is then compared to a threshold, λ_0, to determine which of the two hypotheses is true

if $T(S) \leq \lambda_0$ H_0 *is true*
if $T(S) > \lambda_0$ H_1 *is true*

The threshold is obtained using a constraint on the PFA

$$PFA = \int_{\lambda_0}^{\infty} P\left[T(S)|H_0\right]dT \tag{7}$$

Because the registered signal consists mostly of noise points with a few defect signal points, a sliding window of length M given by [8] is used.

$$y = y(n) = \left[S\left(n-\frac{M}{2}+1\right), S\left(n-\frac{M}{2}+2\right), ..., S(n), S(n+1), ..., S\left(n+\frac{M}{2}\right)\right] \tag{8}$$

With the signal with the sliding window as the input signal, the test statistic is given by

$$T\left[y(n)\right] = \frac{\sigma_S^2}{\sigma_w^2\left(\sigma_S^2+\sigma_S^2\right)}y^T y \tag{9}$$

where σ_S^2 represents the variance of total signal defined as

$$C_S = \sigma_S^2 I \tag{10}$$

Figure 3 presents the action mode of Neyman-Pearson detector on the original signal, Figure 2a, that is shown filtered in Figure 2b.

A PFA of 5% is imposed so that POD shall be 95% for a reliability coefficient of 95%. It must be remarked that this detector has identified the existent artificial flaws. The data post-processing block receives only the signals which the detector considers are produced by flaws on the nuclear fuel cladding. These signals can be eventually supplementary filtered, but without modifying the phase. After this stage, the signals must be normalized. The normalization requires the existence of a standard flaw signal characterized by its amplitude and phase. Usually, the standard flaw is a through-wall hole.

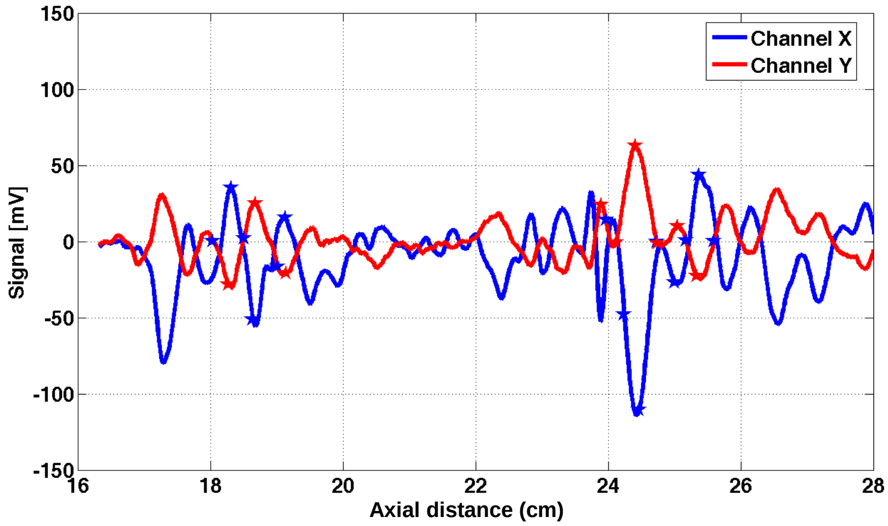


Figure 3.The effect of Neyman–Pearson on the data presented in Figure 2. The emphasized points appertain to flaws detected with POD=95%

The phase angle of the signal from a through-wall hole is adjusted to 40 degrees with the negative OX axis. In the present case a hole in accordance with the ASME code, Section V, article 8, II 860.2.2 was used, i.e. a 1.32 mm through-hole for tubes with an outer diameter less than 19 mm. Thus, for normalization, all the recorded signals must be rotated the corresponding angle, φ, leading to the modification of X and Y signals according to the relation

$$\begin{aligned} X_r &= X\cos\varphi + Y\sin\varphi \\ Y_r &= -X\sin\varphi + Y\cos\varphi \end{aligned} \tag{11}$$

where X_r and Y_r are the components of X and Y rotated with φ angle.

All the signals will also be normalized by the amplitude of the signal (X and Y components) provided by the etalon flaw. In this way, the X and Y signals are adimensional, and can be easily compared with the results of numerical simulations. The significant features are extracted from the flaw's normalized signals. Naturally, these can be the amplitude and the phase, or, as we propose in this paper, the amplitude of the 6,7,8,9 and 10^{th} order Fourier coefficients. These features represent the coordinate of a point in phase-space. Because it is extremely difficult and costly to make databases containing features of a big number of types and dimensions of flaws, it is better to use a database containing the characteristics of several signals provided from flaws by numerical simulations. It can be observed that different types of flaws create clusters. In the phase space, the distance between two clusters or between a singular point and the existent clusters is named the Mahalanobis distance.

The Mahalanobis distance from a vector $\bar{y}_j$ to a set $\chi = \{\bar{x}_1,...,\bar{x}_n\}$ is the distance from y_j to $\bar{x}$, the center of χ, weighed according to C_x, the variance matrix of the set χ, i.e.

$$d_j^2 = \left(\bar{y}_j - \bar{x}\right)' C_x^{-1} \left(\bar{y}_j - \bar{x}\right) \tag{12}$$

where

$$\overline{x} = \frac{1}{n_x}\sum_{i=1}^{n}\overline{x}_i$$
$$C_x = \frac{1}{n_x - 1}\sum_{i=1}^{n}\left(\overline{x}_i - \overline{x}\right)\left(\overline{x}_i - \overline{x}\right)' \qquad (13)$$

and the (‘) sign represents the conjugate.

The simulated data must contain a large number of types and dimensions likely to appear on nuclear fuel cladding, and, eventually, characteristics of real signals from the same category. Calculating the Mahalanobis distance between the detected flaw vector having its features as coordinates and clusters with principal types of flaws, the analyzed flaw will correspond, with maximum probability, to the same category of flaws types for which the Mahalanobis distance is minimum. This classification can be then refined taking into account the sensitivity of simulated flaws.

3. The experimental method

Samples from virgin Zircaloy 4 nuclear fuel cladding with outer diameter 13.02 mm and 0.40 mm wall thickness were used in this study. On these samples, different types of artificial flaws have been made, being presented in Table 1. Two additional samples were charged with gaseous hydrogen, at 340ºC in a Sievert device, up to the 84 and 93 wt-ppm respectively. After a 24-hour homogeneization heat treatment at 380ºC for a uniform hydride distribution [9], a localized thermal gradient was applied to each sample, in order to form a blister on the outer surface of the tube. The samples were put over a hot Al block and pressed with a 2-mm radius aluminum cold finger on the upper surface of the sample, as described in [10,11]. To improve thermal conductivity, aluminum powder was deposited between the sample and the cold finger and between the sample and the hot Al block. The temperature of the sample was measured with a J-type sheathed thermocouple. To avoid blister cracking, in one sample the cold tip was kept over the sample surface without contact and the gap was filled with a copper-silicone gasket maker to produce thermal contact without applying any pressure.

Table 1. The artificial flaws taken into study

No.	***Flaw***	***Dimensions [mm]***	***Depth [mm]***	***Depth [% of wall Thickness]***
1	Hole	0.1	through hole	100
2	Hole	0.25	through hole	100
3	Hole + fretting	0.3	through hole	100
4	Hole	0.4	through hole	100
5	Circ (Inner wall ring nut)	1*	0.1	25
6	Circ (Inner wall ring nut)	0.5*	0.05	12,5
7	Circ (Inner wall ring nut)	1*	0.2	50
8	Circ (Inner wall ring nut)	0.5*	0.1	25
9	Circ (Inner wall ring nut)	0.5*	0.15	37,5
10	Circ (Inner wall ring nut)	0.5*	0.2	50

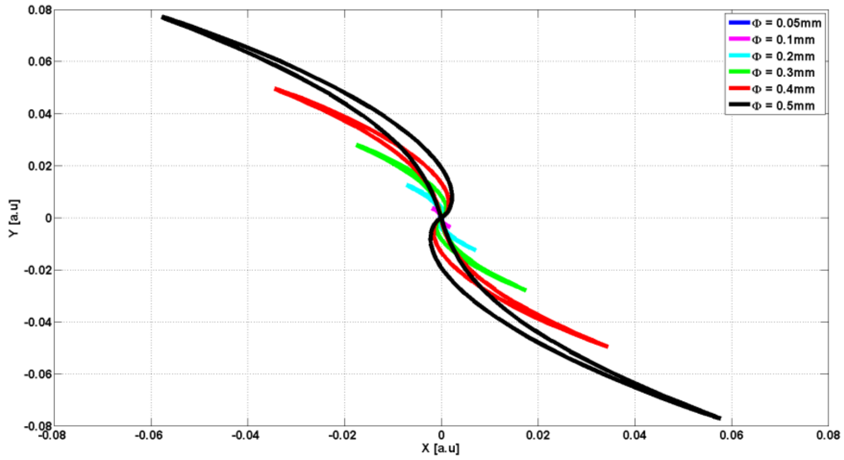
* represents the opening of the flaw

A PC- based multifrequency MAD 8D eddy current equipment from ECT-USA was used. It has up to 4 simultaneous frequencies with a sampling rate of up to 8 kHz on each channel. The displacement of the encircling coils along the tubes was made with an automatic displacing system. Data points were measured every 0.01 mm.

4. Numerical simulation of the differential eddy current transducers responses for the principal types of artificial flaws

In order to make a database for the automatic classification, the eddy current responses to the flaws described in Table 1, has been simulated using the software CIVA v.9.1 [12].

In Figures 4 a and b the eddy current responses for through holes and inner circumferential slots are presented. This response is rotated so that the signal from a through hole shall be at -40º with the X axis. The simulations have been made at the same frequencies as the experimental determinations.



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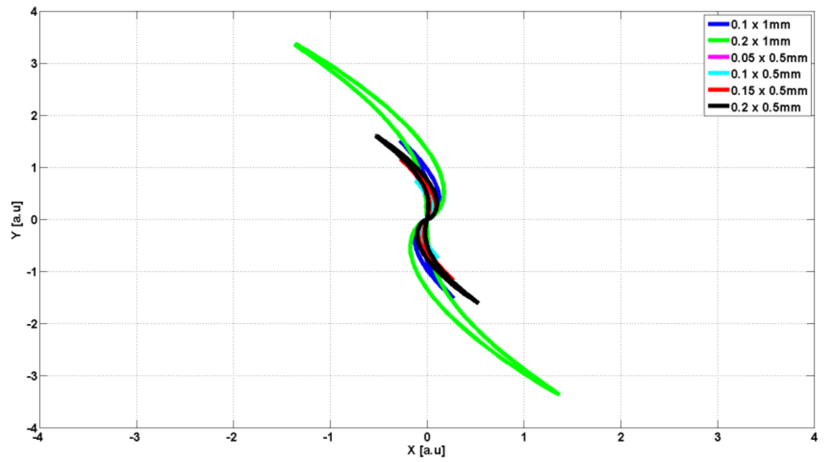

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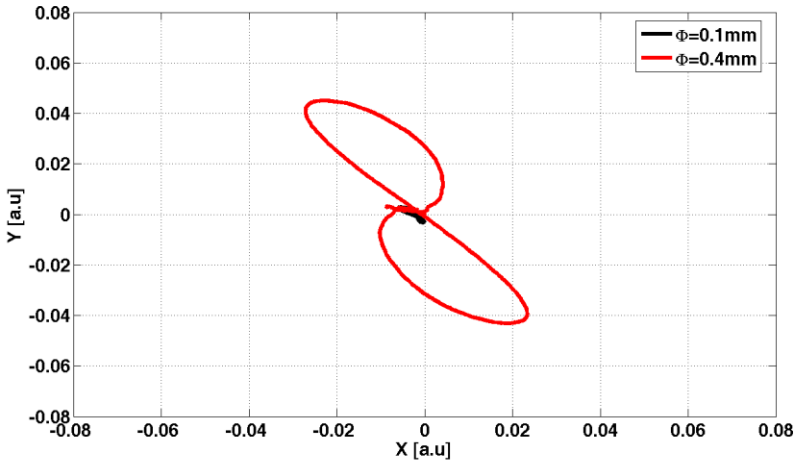
Figure 4. The eddy current response for:
a) through holes; b) inner circumferential slots

5. Results and discussion

Apriori knowledge about the eddy current signals of the defects at the frequencies at which the experiments were made has been used here. The real data can be appropriately processed, within the scheme in Figure 1. Figure 5 presents the impedance plane graphs (Lissajoux representations) of the signals from through holes (Figure 5a) and inner circumferential slots (Figure 5b) at 900 kHz. The signals were pre-processed and then normalized by a convenient phase rotation and amplitude transformation into a non-dimensional measure through division into the amplitude of the etalon signal.



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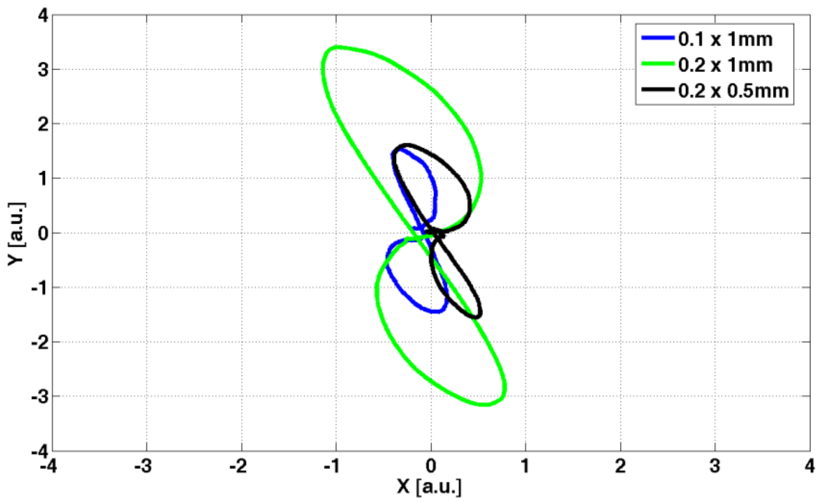

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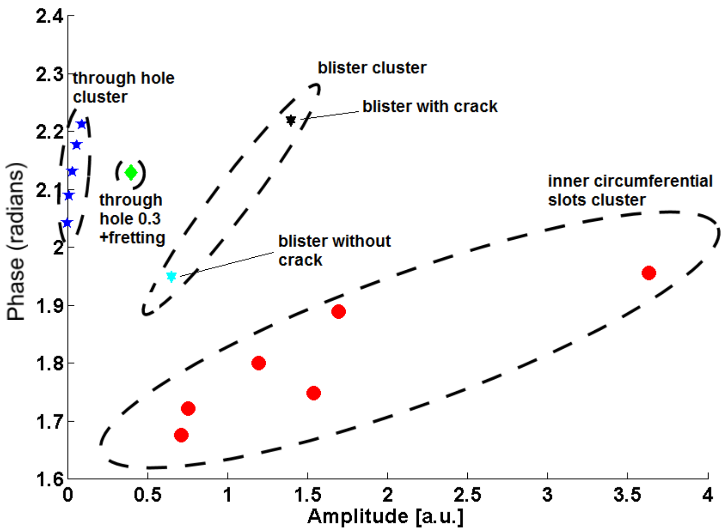
Figure 5. Real flaw signals pre-processed and normalized provided by: a) through-holes; b) inner circumferential rings

The features extraction operation is applied in two variants: classical, in which the amplitude and the phase the pre-processed signals are determined; alternatively, the amplitude of the coefficients of 6, 7, 8, 9 and 10^{th} order from the Fourier spectrum calculated by FFT procedures are determined.

In the first case, the signals from the through-holes (the simulated ones and those effectively determined on real data) form a cluster. The signals from the inner circumferential rings with different depths and widths form another cluster, well-separated from the first one. This operation can be performed before the actual eddy current nondestructive examination of nuclear fuel cladding, thus constructing the database for automatic classification. In this situation, the clusters are represented into a 2D coordinate system in which the normalized amplitude is represented in the abscissa and the phase angle in the ordinate.
If the considered features are the 6 to 10th harmonics of the Fourier spectrum, the clusters are formed in a 5-dimensional system.



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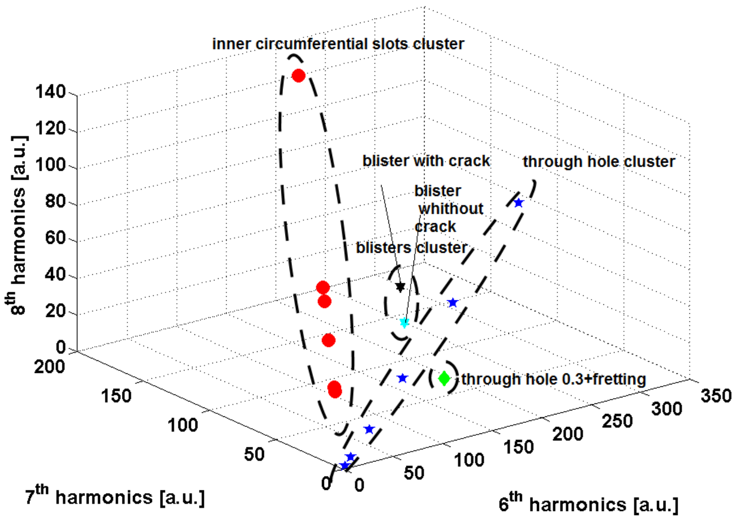

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Figure 6. The clusters of vectors provided by through-holes and inner circumferential rings, and the 0.3 mm diameter through-hole with fretting: a) amplitude–phase plane; b) 3D in 6,7 and 8th harmonics of Fourier spectrum

Any signal picked up by the block – “Flaw detected”, is considered with 95% probability to be produced by an existent flaw on the nuclear fuel cladding. After normalization and features extraction, the signal will be represented by a vector, either on the amplitude-phase plane, or in the 5-dimensional space in which the axes represent the amplitude of the Fourier harmonics 6 up to 10^{th} order.
Figure 6a presents the clusters formed by the real signals provided by through-holes, respectively inner circumferential rings, two types of hydride blisters with and without cracks, as well as by signal delivered by 0.3 mm diameter hole with fretting, in the amplitude–phase plane and Figure 6b the same clusters and the vector of the same signal but in a 3D space in which the axis represent the coefficients amplitude of the 6, 7 and 8^{th} harmonics.
The examination of data from Figure 6 shows that the signal provided by the 0.3mm diameter through-hole with fretting is not framing in the three represented clusters but the Mahalanobis distance reported to the through-hole cluster is smaller than the same distance measured regarding the inner circumferential ring cluster and hydride blisters cluster. Thus the analyzed flaw shall be considered as a through-hole over which other type of flaw, which provides a smaller signal that cannot mark the specific characteristics of through-hole cluster is superimposed. This fact is evident also in the case of using multidimensional representation based on the amplitude of Fourier harmonics from 6 up to 10^{th} order.
In this way, the signal provided by a flaw can be clarified regarding the Mahalanobis distance towards the clusters, representing the principal flaws classes that can appear in nuclear fuel cladding. If these clusters will contain a sufficient number of vectors, generated by more simulated and real flaws with known dimensions, the severity of measured flaws will be evaluated using the automatic classification system. This classification can be made with a fuzzy system [13], the fuzzification variable being the Mahalanobis distances.

6. Conclusions

The nondestructive examination of nuclear fuel cladding can be made using eddy current differential encircling transducers.
In order to increase the probability of detection, an automatic system that pre-filters the signal, uses a Neyman-Pearsons detector with imposed false alarm probability, allowing the determination of those zones from the signal provided by the eddy current equipment due to the flaws can be used.
The use of an automatic classification system allows the framing of the flaws on classes or even indications referring to its geometrical dimensions. This is made with Mahalanobis distance, the membership being assured by the minimization of this distance.

Acknowledgements
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