APPLICATION OF WAVELET TRANSFORM IN DE-NOISING EDDY CURRENT TESTING SIGNALS OF HEAT EXCHANGER TUBES

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Abstract. *Eddy Current Testing (ECT) signals from heat exchanger tubes inspections are usually corrupted by a large amount of noise. These signals are usually presented in the complex impedance plan (Lissajous figures) and are processed to extract some characteristics related to defects dimensions, e.g., phase angles for diagnostic purposes. However, the noise in ECT signals can blot and deform Lissajous figures making any characteristic extraction impossible or, even worse, it can mask the characteristic inducing to wrong conclusions. Noise removal is therefore a critical step to obtain reliable diagnostic in Eddy Current Testing. Wavelet transform is a relatively new and efficient signal processing technique applied to remove noise. As defects captured by ECT generate transient signals, conventional frequency domain filters are inappropriate to filter these signals. This paper presents the results of several Discrete Wavelet Transform (DWT) applied to remove the Signal Acquisition Noise (SAN) of heat exchanger brass tubes. The ECT signals were obtained from experimental data in one laboratory tube specimen prepared with localized artificial defects. Different de-noising strategies using different Wavelets functions, levels of decomposition and thresholds were parametrically tested. The results of DWT applications for noise removal are compared and the limitations of this technique are presented.*

Keywords. Eddy Current Test, Wavelet Transform, De-noising

1. Introduction

Heat exchangers frequently present unexpected leaks in their tubes resulting in losses of time and money. These tubes can be inspected through several Non Destructive Testings (NDT). The Eddy-Current Test (ECT) is an electromagnetic method largely applied to volumetric defect detection (with loss of material) or not [1]. In the ECT, a bobbin coil probe is introduced into the tube and signals are generated allowing the localization and sizing of defects, resulting in a safe heat exchanger operation.

The signal interpretation in general is made by inspectors. However, these signals are usually corrupted by several types of noise [2] resulting in decision doubts and early tubes plugging. So, reducing signal noises, signal analysis is more accurate and bad decisions are minimized. One of the signal noises that make signal analysis difficult is the Signal Acquisition Noise (SAN). This type of noise can blot defect Lissajous figure, making defects detection and sizing difficult.

In this paper, Discrete Wavelet Transform (DWT) is used to remove efficiently SAN without compromising signal information provided by Eddy Current signals [3].

The results of several DWT applications to SAN removal of ECT signals are compared. The signals were generated by inspections in one ASTM B-111-687, ∅ 19.05 MM, BWG 16 brass tube sample, with several volumetric artificial defects as shown in Figure 1.

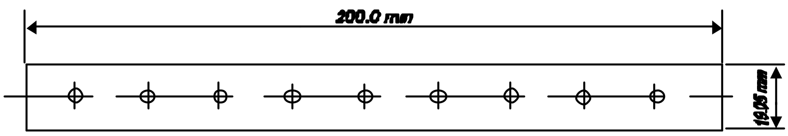
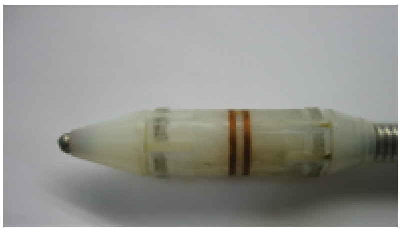


Figure 1: Tube sample

The signals processed in this work were generated by Zetec Eddy Current inspection equipment MIZ-17ET. Figure 2a shows the complete hardware used to data acquisition. The probe used in this work (Fig. 2b) has two circumferential bobbin coils connected to a differential self-compared mode.

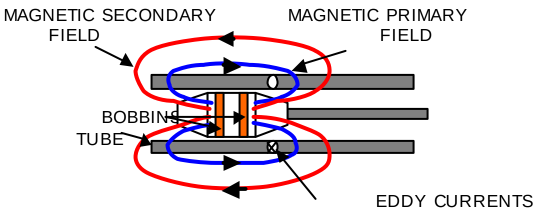


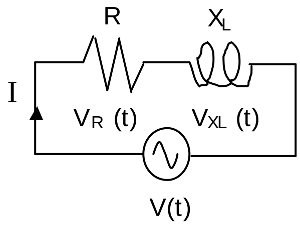
(a) (b)

Figure 2: Data acquisition hardware

2. ECT principles

The ECT is a fast and widely used inspection method based on the magnetic induction of circular Eddy Currents in the tube as consequence of an primary magnetic field generated by a bobbin coil probe [4] as shown in Figure 3a. The ECT has an RL circuit (Fig. 3b) in which R (Resistance) and X_L (Inductive Reactance) share part of the probe and tube concomitantly.





(a) (b)

Figure 3: ECT operation and electric circuit

The tension in this circuit is:

$$V(t) = V_R\ (t) + V_{XL}(t) = Z\ .\ I(t) \tag{1}$$

where Z is the total impedance that can be represented in the impedance complex plan as shown in Figure 4 in which

$$\vec{Z} = \vec{X}_L + \vec{R} \tag{2}$$

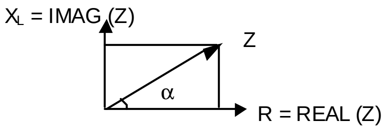


Figure 4: Impedance complex plan

The phase angle (α) is defined as:

$$\alpha = \arc\tan \frac{X_L}{R} \tag{3}$$

The impedance variation as the probe moves through the tube generates a "8" shape Lissajous figure as can be seen in Figure 5. The SAN corresponds to the abrupt deviation from the continuous Lissajous figure line that can obstruct any computational signal characteristic acquisition.

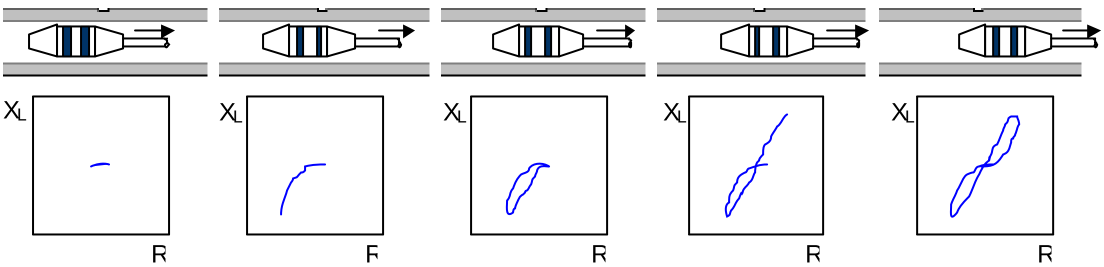


Figure 5: Lissajous figure formation

3. DWT applied to SAN removal

Discrete Wavelet Transform (DWT) applied to signal processing is a relatively new technique which allows local analysis of non stationary signal characteristics such as ECT signals [3],[6],[5]. That is the great advantage of DWT when compared with other analysis tools such as Fourier Transform in which, generally, are based on the signal periodicity to obtain an acceptable answer. DWT presents sensitivity to temporal discontinuities, that is a typical characteristic of ECT signals.

DWT is considered a multi-level and multi-resolution analysis method. The Eddy-Current signal s(x) is studied at several frequency levels with several resolutions.

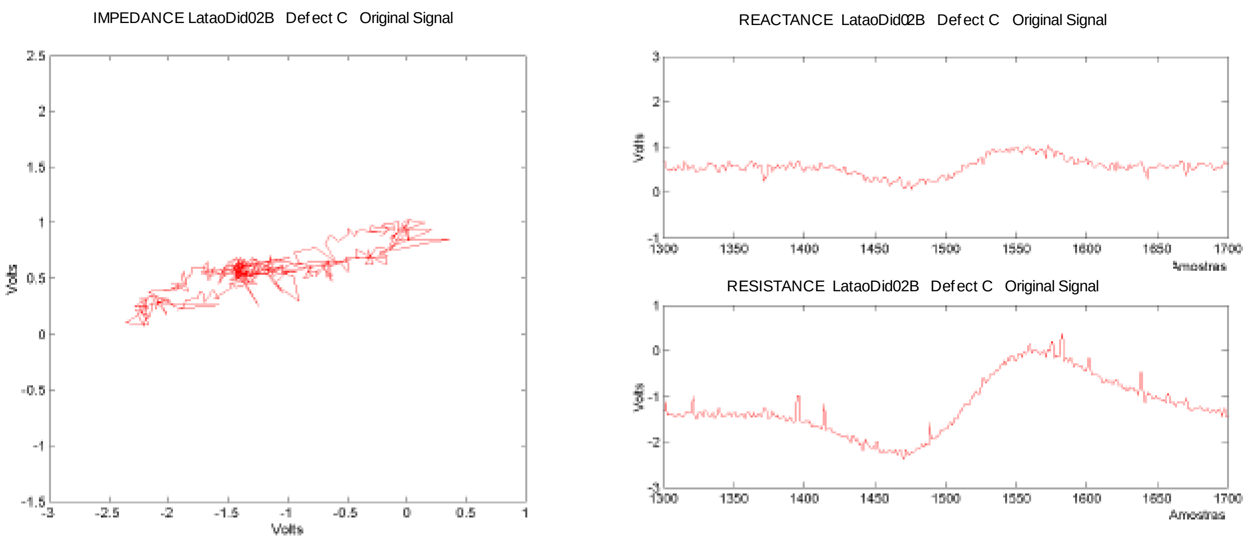
DWT of an Eddy-Current signal s(x) [7] is defined as the signal projection on the set of analysis functions $\psi_{a,b}(x)$

$$DWT_{s(a,b)} = \int_{-\infty}^{+\infty} s(x)\ \psi_{a,b}(x)\, dx \tag{4}$$

as a result, many $C_{(scale,\ position)}$ coefficients are generated

$$C_{(scale,position)} = \int_{-\infty}^{+\infty} f(t)\ \psi_{(scale,position,t)}\ dt \tag{5}$$

SAN is a high frequency and low amplitude noise and in general is a consequence of a high signal gain which can blot Lissajous figure. Figure 6a presents the signal of tube sample, defect C, seriously corrupted by SAN. To remove this noise, the impedance plan signal is decomposed into resistance and inductive reactance as presented in Figure 6b.



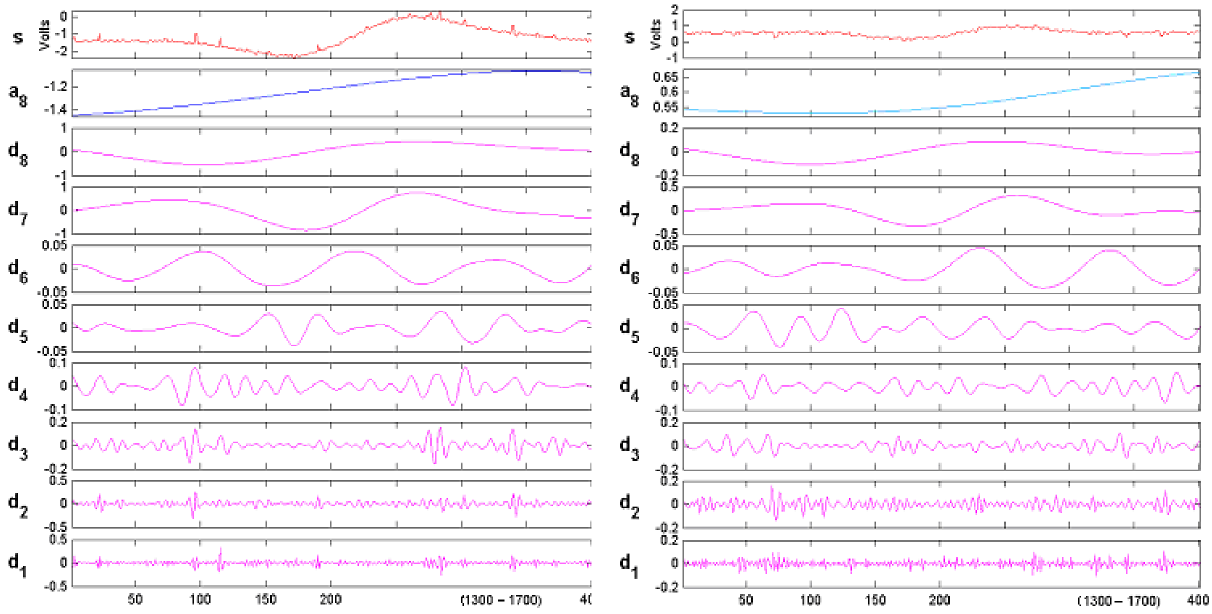
(a) (b)

Figure 6: Lissajous figure with SAN and R and X_L signal components

The resistance and the inductive reactance are decomposed through DWT in several frequency levels as presented in Figures 7a and 7b through an appropriate selection of a basic Wavelet function $\psi_{a,b}(x) \in L^2$ (R):

$$\psi_{a,b}(x) = \frac{1}{\sqrt{|a|}}\ \psi\left(\frac{x-b}{a}\right) \tag{6}$$

in which a is the scaling parameter, b is the shifting parameter and a , $b \in$ R, $a \neq 0$.



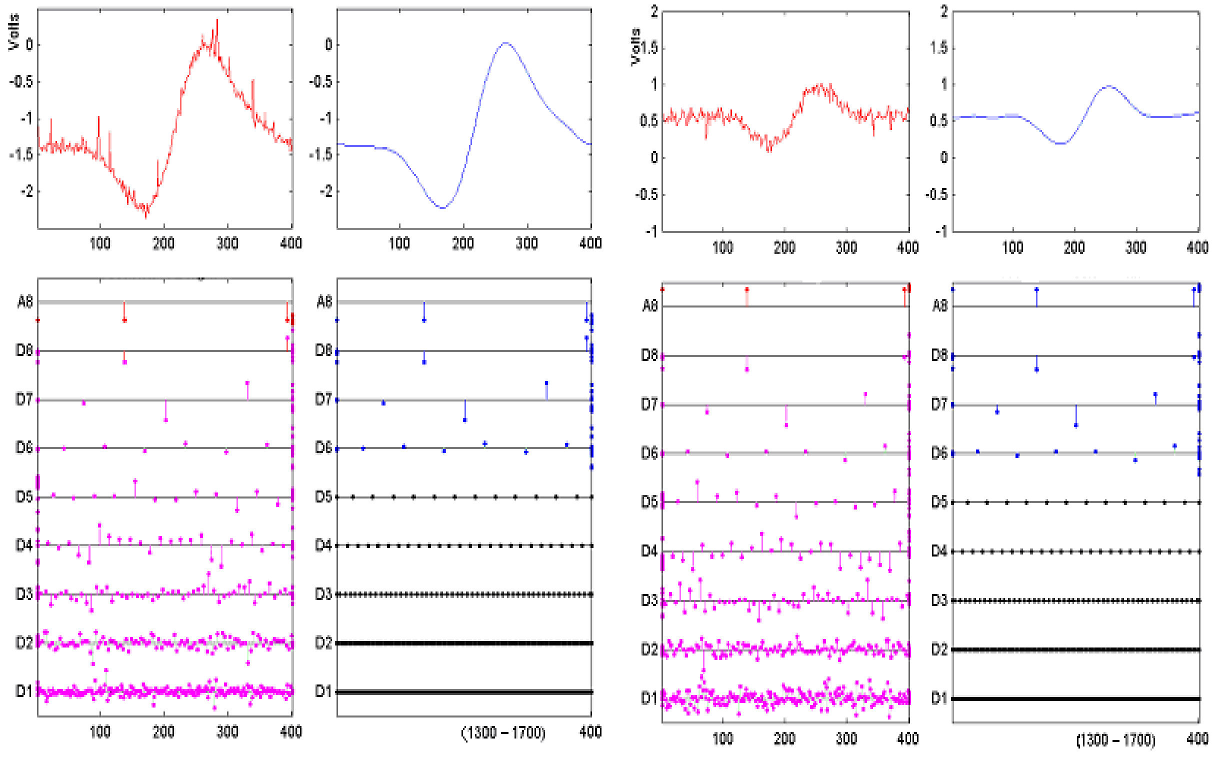
(a) (b)

Figure 7: R and X_L component decomposition

In the multi-level frequency decomposition a signal is decomposed into two components A and D in which A is the signal approximation (high scale and low frequency) and D is the signal detail (low scale and high frequency) [7].

After decomposition, the ECT signal is reconstructed by means of Inverse Discrete Wavelet Transform (IDWT). Scale and position coefficients are selected to remove high frequency signal components.

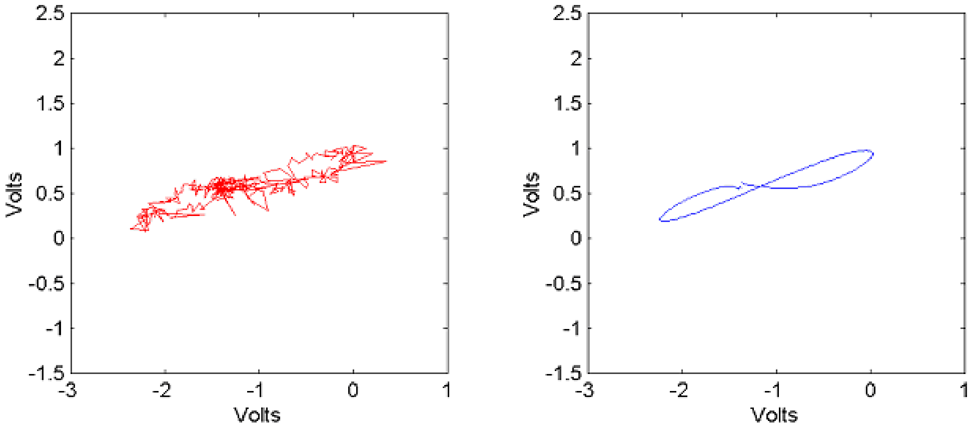
Figures 8a and 8b show the result of the high frequency coefficients manual selection.



(a) (b)

Figure 8: R and X_L coefficients selection

Finally, R and X_L de-noised components are combined in the impedance plan as presented in Figure 9b, given as a result a Lissajous figure without SAN.

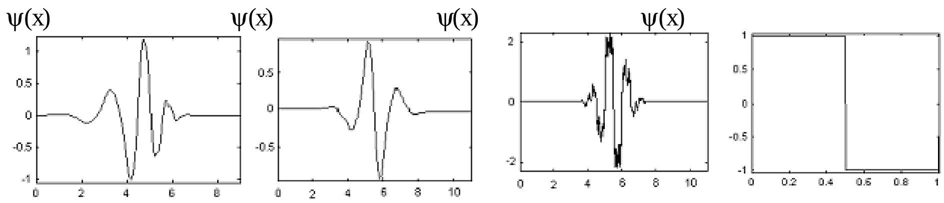


(a) (b)

Figure 9: De-noising through Daubechies 10

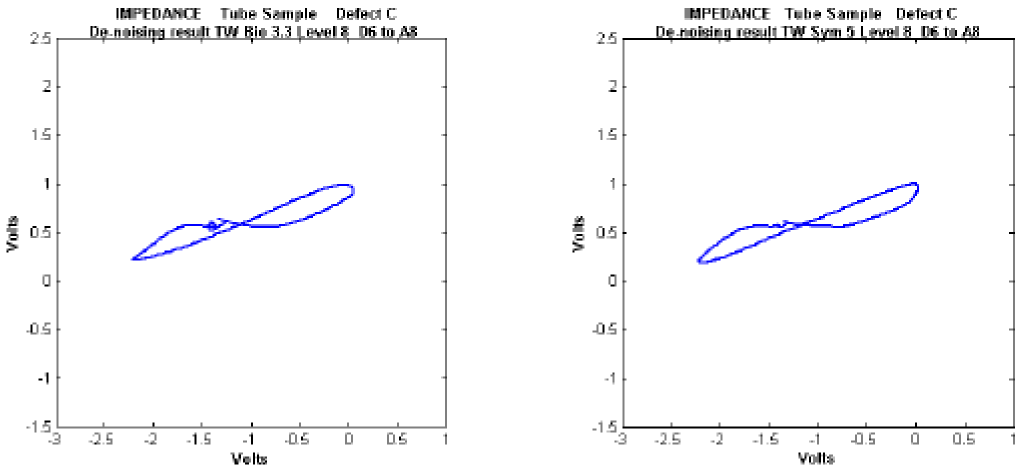
4. Wavelet function selection

The wavelet function selection is made by comparing de-noised signals. A de-noising result is considered as a good result when Lissajous figure denting is removed as above shown in Figure 9. This task can be obtained through several wavelet functions. SAN presented in Figure 9 left was successfully removed through Daubechies 10 wavelet (Fig. 10a). Good de-noising results through Biorthogonal 3.3 (Fig. 10b) and Symlet 5 wavelets (Fig. 10c) are depicted in Figures 11a and 11b respectively.



(a) Daubechies 10 (b) Biorthogonal 3.3 (c) Symlet 5 (d) Haar

Figure 10: Wavelet functions



(a) (b)

Figure 11: De-noising through Biorthogonal 3.3 and Symlet 5 wavelets

IMPEDANCE Tube Sample Defect C

However, wavelet functions like Haar wavelet (Fig. 10d) do not present good results as depicted in Figure 12.

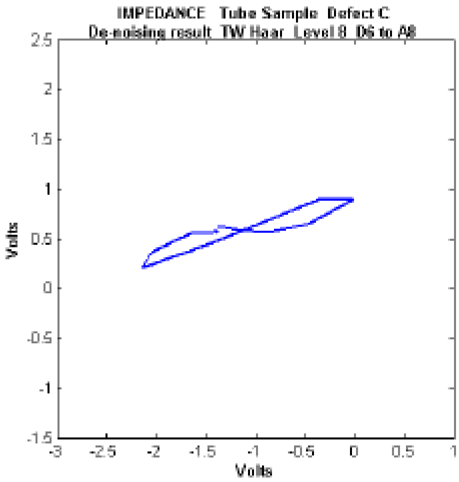


Figure 12: De-noising through Haar wavelet

5. Frequency level selection

Likewise wavelet function selection, frequency level selection is obtained by comparing de-noising results.

Frequency level signal decomposition affects de-noising results as depicted in Figures 13 and 14 in which SAN was removed through Biorthogonal Reverse 6.8 wavelet in 5 and 9 frequency levels.

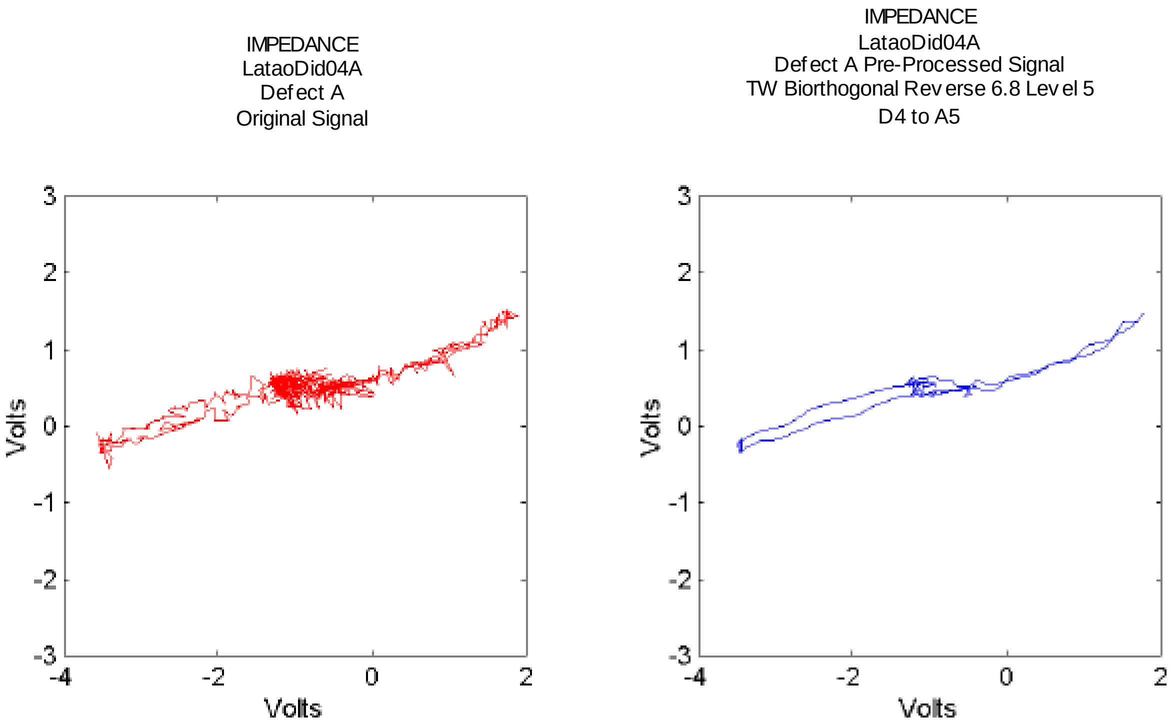


Figure 13: Frequency level influence (Biorthogonal Reverse 6.8 Level 5)

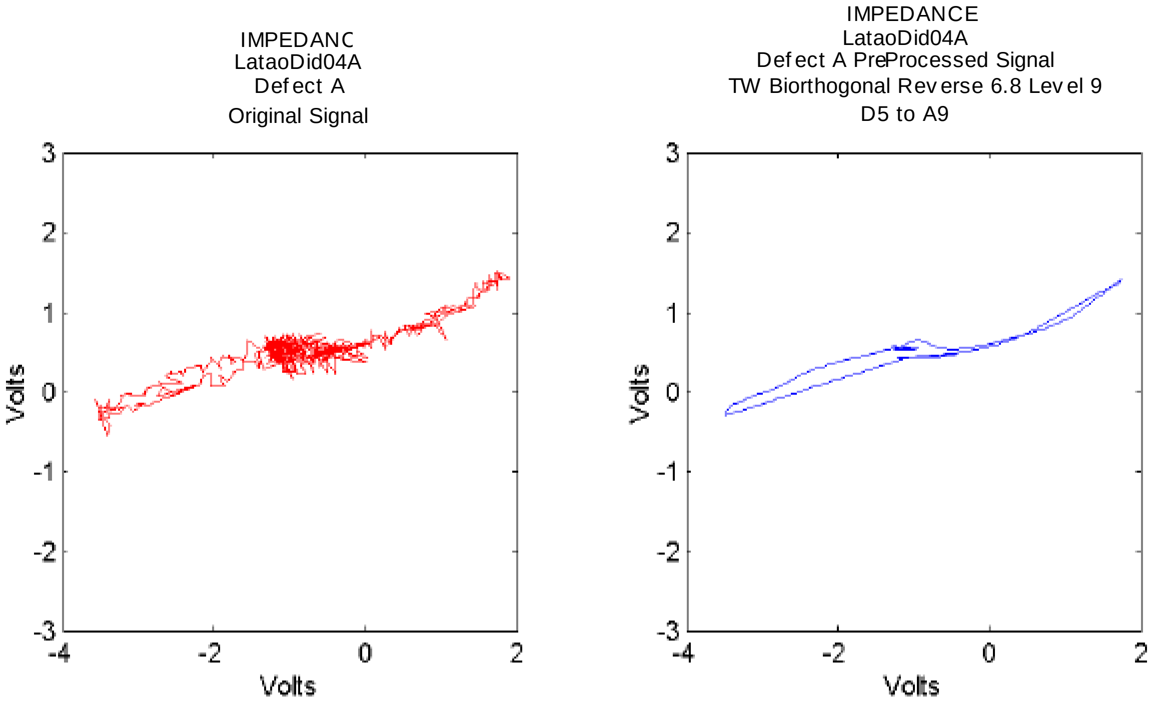


Figure 14: Frequency level influence (Biorthogonal Reverse 6.8 Level 9)

6. Conclusion

As presented, Wavelet Transform can be used successfully in de-noising Eddy-Current signals. Daubechies wavelet offers the best results due to its non symmetry characteristic which is better adjusted to the transient nature of Eddy Current signals.

Except for Haar wavelet, any other wavelet function can basically be used to SAN removal.

High levels of frequency signal decomposition such as 10, offer better results than medium or low levels (until 5) as it provides more possibilities of SAN removal.

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