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Eddy-Current Signal Interpretation Using Fuzzy Logic Artificial Intelligence Technique

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Abstract

This work presents a fuzzy logic aided computer program that automatically extracts the main characteristics of Eddy-Current testing signals, which are the total amplitude and the phase angle, thus reducing the time spent by the inspector for each testing and increasing the diagnosis quality by assuring repeatability. Presently, this software is applicable to heat exchangers tubes.

The inspection using Eddy-Current electro-magnetic technique generates a large number of signals that must be analysed properly and as fast as possible. The signals analysis made by the inspector is the basis of the diagnosis. The conceived software works in the same way that an inspector does.

Most of the Eddy-Current testing signals are affected by noise, and to overcome this problem, they are automatically cleaned by the software through Wavelet analysis.

The software was tested using an Eddy-Current signals data set specially generated by a MIZ-17ET inspection equipment applied in tubes with known defects. Around 600 defects where identified at 50 inspections. These numbers are very similar to those obtained by an inspector and most of the characteristics where correctly calculated, except in those cases where the Lissajous figure is strongly distorted by noise, in those cases they are normally discarded. The easy to use graphic interface and the good results achieved by the software can make the inspection work easier, faster, cheaper and more reliable.

1. Introduction

The signals originated in the Eddy-Current (EC) Non Destructive Test (NDT) are presented as Lissajous figures in the impedance plan [(1)]. Those figures are used by specialized inspectors on defect diagnosis in rough metallic pieces as forged axes, piston roods or finished pieces as tubes and screws. The EC NDT is also applied as an inspection method for the operational condition equipment evaluation.

Typical Lissajous figures are generally “8” shaped and each side of the figure is named as a petal. EC inspectors interpret those figures by reading its phase angle and amplitude with the objective of defects dimensioning.

Figure 1 presents a Lissajous figures set obtained in a six artificial machine made defects tube inspection. Amplitude and phase angle are presented for the larger Lissajous figure.

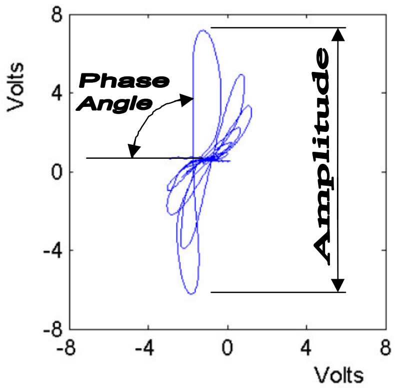

Figure 1. Typical Lissajous figure

Some Lissajous figures present noises because materials are heterogeneous, the inspection acquisition equipment interferes in the generated signals and the probe distance varies during the inspection [(2)]. Those noises make the inspection activity very difficult. In this work, Wavelet Transform is used for signal denoising.

As presented in Fig. 1, each inspection generates a lot of Lissajous figures which must be interpreted as fast as possible due to time spending restrictions. The fast inspection time is a very important task under inspection work by considering that the time spent during inspection increases production costs and bring on loss of money. Furthermore, the inspection work involves big responsibility because the inspector decision can throw into the discard of an equipment, a piece of even a set of pieces. The inspection work is a repetitive and stressing activity highly affected by psychological and physiological aspects which make difficult the inspector decision activity.

This work presents an Artificial Intelligence (AI) Fuzzy Logic aided software created to enhance the efficiency of EC inspection and reduce the time lost. The software resources make it an easy to use inspection tool. A lot of inspection signals were used to test the software and the results were compared with conventional diagnosis.

2. Noise removal

The signals generated in a EC inspection contain noises which reduce the quality of the Lissajous figures. Those noises must be removed for a correct operation of the software and reading of the phase angle and amplitude.

Some methods can be used for noise removal [3]. One of them is the Fourier analysis, a mathematical tool which allows changing the signal from a time based to a frequency based point of view through several senoidal signal decomposition. The Fourier analysis offers good results when the frequency domain information is important. However, the time information of a signal is lost and is not possible to determine when an event occurred. In stationary signals with constant period, the above mentioned deficiency is not important. However, EC signals present transitory characteristics and Fourier analysis is not adequate.

The Short Time Fourier Transform (STFT) is an adaptation of Fourier Transform which analyses a signal in steps or windows, mapping the signal as a function of time and frequency. Through this method, some information about time event occurrence is obtained but the precision is limited due to window dimensions. Under STFT analysis, the window width is fixed and is the same for all frequencies. This is an important deficiency in the noise removal process of EC signals because the window size is required for determining with more accuracy time and frequency.

Wavelet analysis, firstly proposed by Mallat [4], is the next step as it generates variable dimensions regions windows allowing high time intervals where a more accurate low frequency information is required and low time intervals for high information. Wavelet Transform (WT) decomposes the signal into several frequencies bands without losing its time dependence, allowing for a more precise and dedicated de-noising process.

This work uses the Continuous Wavelet Transform (CWT) which is the sum of an EC signal multiplied by displaced and scaled versions of a Wavelet which is a zero medium value limited in time wave, generally not regular and not symmetrical in opposition to a senoidal type wave. The results of a CWT are the wavelet coefficients *C* which are a function of scale and position. In other words, for a given EC testing signal *s(x)*, the CWT is the convolution of *s(x)* with a set of Wavelet functions ψ *scale/position (x)* resulting in a set of coefficients *C scale/position* as follows:

$$C(scale, position) = \int_{-\infty}^{+\infty} f(t)\psi(scale, position, t)dt \quad \text{......................} \ (1)$$

Multiplying each coefficient *C* by its respective shifted and scaled wavelet returns the *C* coefficients of the original EC signal.

The de-noising procedure consists of the proper selection of *C scale/position* coefficients in such a way that the higher frequencies components of the EC testing signal be removed. In this work, Daubechies (Db) family of wavelets Db1 to Db10 was used because it is the most appropriate wavelet for EC signal denoising according to recent work [5].

3. Fuzzy Logic

Fuzzy Logic is an artificial intelligence tool that uses qualitative methods when analytical solutions are not possible to be implemented [(6)]. This technique is widely used in humanistic problems solution such as Eddy-Current signals interpretation.

The principle of a Fuzzy Logic solution considers the relationship between fuzzy variables such as "*a big phase angle*" and fuzzy declarations in the *if-then* conditional way such as "*if phase angle is big then the defect is external*". In other words, Fuzzy Logic maps the input space by its relationship with the output space.

The rules of a Fuzzy Logic inference system represent the relationships between the inputs and the outputs. The rules are grouped in two sub-sets: Deepness and Size. Table 1 presents the inputs and outputs of each sub-set.

Table 1. Sub-sets inputs and outputs

SUB-SET	INPUT	OUTPUT
DEEPNESS	Phase Angle	Deepness
SIZE	Amplitude	Overall Size

The output of a Fuzzy inference system is de-fuzzyfied through a numerical fuzzy membership function. Figure 2 presents a typical de-fuzzyfied wavelet de-noising selection where the z axis shows the de-noising level, the x axis shows the number of removed noise frequency levels and the y axis shows the Daubechies wavelet used. Figure 2 shows that a high de-noising level is obtained to around five removed noise frequency levels and by using wavelets from 2 to 8.

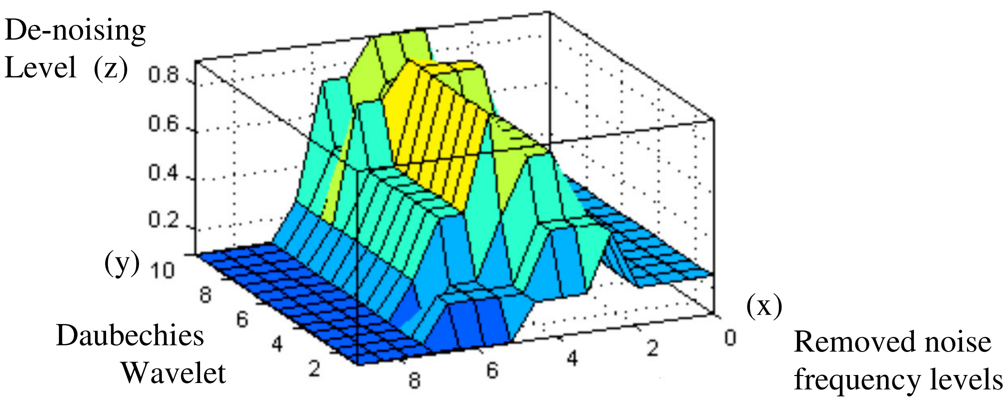

Figure 2. De-noising selection

4. Defect Identification and Sizing Software

The software conceived in MATLAB [7] language for defect detection and phase angle / amplitude readings uses an algorithm which, first of all, reads EC signals and makes their decomposition into reactance and resistance components. After that, the inductive reactance and resistance components are de-noised by using Fuzzy Logic and Wavelet analysis.

Following, defects are identified and amplitude / phase angle readings are made. The inductive reactance component of the signal is searched for defects in the Eddy-Current inspection. The inspector's positive identification of a defect is based upon two main characteristics: whether the amplitude is above a pre-set threshold and if the Eddy-Current signal morphology follows a typical pattern.

The software's defect identification process is very similar as it scans the reactance component for big amplitudes, just like an inspector, but the process is based on Fuzzy Logic. A second analysis checks if the defects so far identified have Eddy-Current signal morphology, so each defect's resistance and reactance components can be used to plot the Lissajous figure and to calculate its characteristics.

Finally, defect sizing and location are registered. Figure 3 presents the logic diagram of the software main functions.

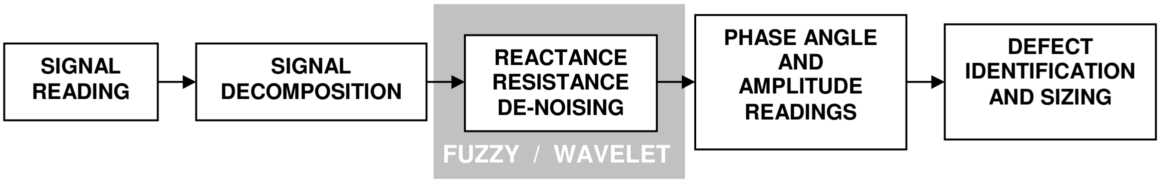

Figure 3. Software main functions

5. Results

The software was tested within 50 signal files of heat exchanger tubes ASTM A-249-316L, ∅ 19.05 mm, BWG 16, with approximately 600 known real defects. The files were generated by an Eddy-Current inspection equipment Zetec MIZ-17ET with circumferential coil probes. An Eddy-Current inspector performed the analysis of those files and read all amplitudes and phase angles in the traditional way.

The files were also read by the conceived software which found around 600 defects resulting in a despicable error. The amplitudes and phase angle readings were also made by the program and the resulting errors were around 7% for amplitudes and 9% for phase angles. Figure 4 shows a typical EC signal identification and amplitude / phase angle readings. The Fuzzy Logic aided software identified a real defect shown in the figure top (red colour, white circle rounded) despite the high signal noise. The corresponding Lissajous figure is presented (bottom, left) as well as the defect location (13273 data acquisition medium position), total amplitude (2,56 V), phase angle (114,1^{o}) which corresponds to an external tube defect with 56,5% deepness.

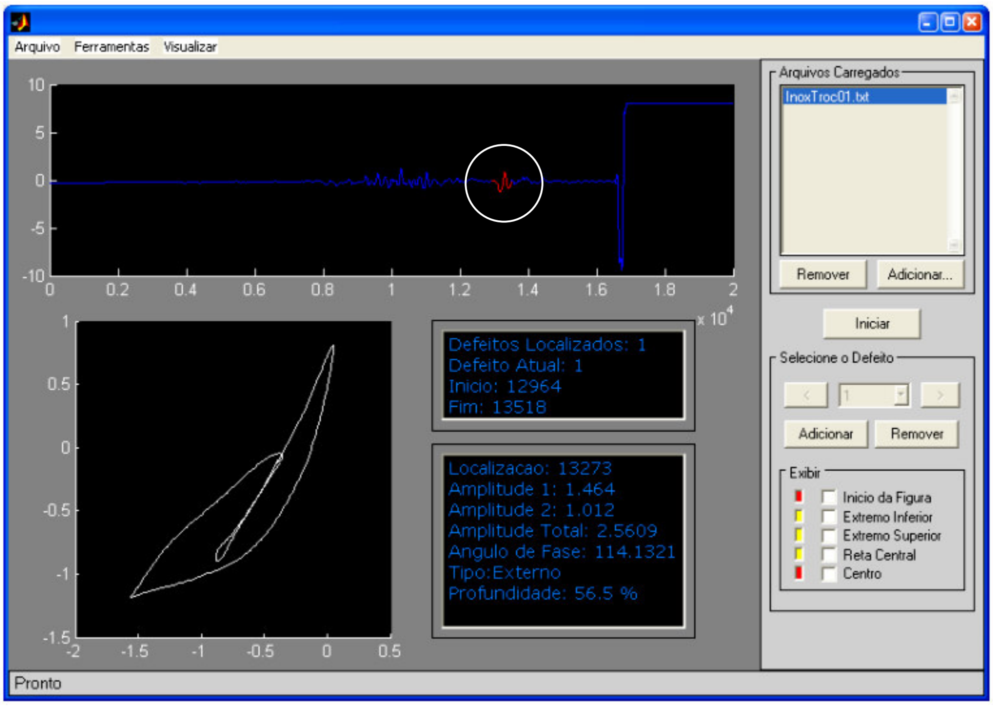

Figure 4. Typical softwafe display

6. Conclusions

As a result of this work, an automatic computational tool is presented. This tool is applied to heat exchanger tubes defects location as well as EC testing signal characteristics reading.

The software presents good results in the majority of signals used for testing. The algorithm performance was jeopardized in the analysis of seriously noise contaminated signals. As a future work it is suggested the test of the algorithm in other files besides the application of more accurate and precise acquisition signal methodology.

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