Signal Processing in an Eddy Current Non-Destructive Testing System

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Abstract **-** Nowadays, eddy current non-destructive testing requires highly skilled operators that using hand-operated eddy current testers are able to recognize defects in conductive materials. The objective of our work is to overcome this problem by implementing a microcomputer based system to detect and estimate the size of cracks and other defects in conductive non magnetic material, with minimum operator intervention. In order to reach the best solution different hardware implementations have to be investigated. This paper compares the results obtained with three techniques already tested: using a commercial lock-in amplifier, a dedicated electronic signal processing circuit and a data acquisition board (DAQ).

The implementation using the DAQ requires more digital signal processing after the analog conversion than the other methods. In particular, cross correlation and sine-fitting of the sampled signals are used to estimate the phase difference between the excitation current and the sensing coils output signals. The results obtained are presented and compared within the paper.

I. Introduction

In order to detect and characterize cracks and other defects in conductive specimens several techniques based on eddy currents theory can be used [1, 2]. In all of them the eddy currents are induced in the specimen under test by a magnetic field produced by an excitation coil carrying a time-varying current. These loop currents are proportional to the conductivity distribution and create a secondary magnetic field that contains the information about the defects in the specimen. To sense the electromotive force induced by the total time-varying magnetic field two differential coils are used.

But to fully characterize the defect profiles from testing signals, it is necessary to solve the inverse problem of the physical phenomenon under test i.e., the calculation of the unknown conductivity distribution using the measured data. This is an ill-posed problem and thus to obtain a unique solution, patterns must be classified and bi-univocally correlated with the different types of material defects [3, 4]. To identify patterns a huge amount of data is essential and experimentation is necessary in order to investigate the assumptions of the technique. Thus a new computer based eddy current testing system with minimum human operation is being developed. With this new measurement system an enhanced performance is expected by increasing the test speed and avoiding errors due to human failure such as inexperience and inconsistency.

This paper compares different hardware and software processing techniques tested in the conception and implementation of the system. Three techniques are presented: using a commercial lock-in amplifier, a dedicated electronic signal processing circuit and digital signal processing after analog to digital conversion with a data acquisition system (DAQ). Experimental results obtained with each technique are presented.

II. System Description

The block diagram of the setup being used to obtain the information about aluminum plates using eddy current probes is depicted in Figure 1.

The system uses differential-type reflection probes (ECT probe). In this type of probes the eddy currents are produced by a coil and the signals containing the information about the defects in the plate are detected by two separate coils with opposite winding directions connected in series. The output voltages from these two coils can be subtracted meaning that they are cancelled out when both coils

experience identical conditions. The height of the excitation coil is 15 mm and its diameter 15 mm. Inner sensing coils diameter is 2 mm and their height is 5,5 mm. There is a 1 mm gap between the two coils. The sensing coils have 400 turns using a 0.05 mm diameter copper wire. Excitation coil has 240 turns and uses a 0.18 mm diameter copper wire.

The ECT probe scans a conductive aluminum plate using a XY-positioning system that works under a motion control device provided with a GPIB interface. In order to reach the best solution different data acquisition blocks (DAQ-block) have been used, either using a commercial lock-in amplifier, a dedicated electronic signal processing circuit or a DAQ board.
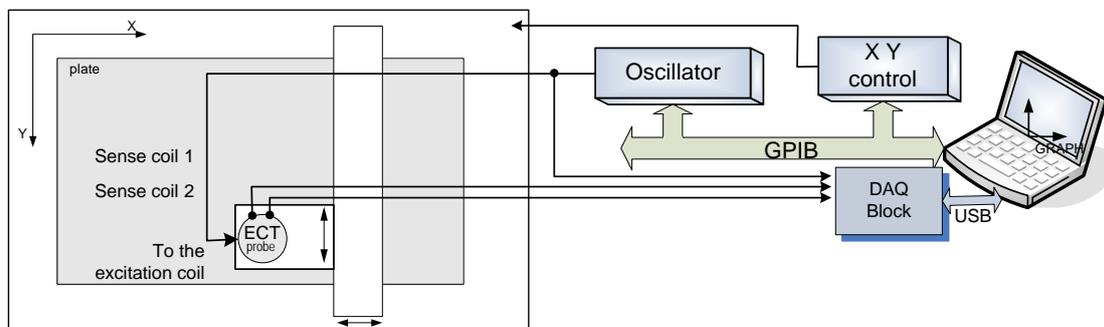

Figure 1. Eddy current automatic measurement system

The specimen under test is an aluminum aircraft plate with the length of 29 cm, 14.5 cm width and a thickness of 1 mm depth. On this plate there are artificial defects with different depths and widths as depicted in Figure 2. 2nd, 4th and 6th defects have 0.5 mm width; 1st, 3rd and 5th have 1 mm width; 1st and 2nd perforate the plate and others go half the plate's thickness.

The field penetration depth δ varies with frequency ω, material permittivity μ and conductivity σ according to:

$$\delta = \sqrt{\frac{2}{\mu \omega \sigma}} \qquad (1)$$

To search for defects at different levels a frequency range that allows the field to penetrate more or less inside the metal must be chosen. The frequency of 7 kHz was chosen. In case of the tested material this frequency corresponds to a depth of penetration of approximately 1 mm [5].
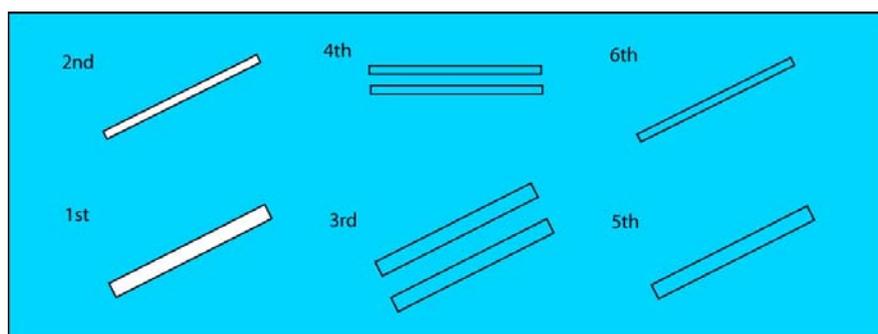

Figure 2. Defects of the aluminum plate under test

A. Case study 1: using a lock-in amplifier

The oscillator output of the SRS Model SR-530, lock-in amplifier instrument feeds the HP 467A Power Amplifier which excites the excitation coil of the ECT probe with a 6.1 mA current and an operating frequency of 7 kHz. This signal is used as the lock-in reference input.

The sensing coils are connected to the lock-in in a true-differential mode using its two voltage signal inputs. In this manner the lock-in uses as the input signal the voltage difference between the output voltages of the sensing coils. This input signal is filtered by selecting a line frequency notch, a 2x line frequency notch and an auto-tracking bandpass filter. The resulting signal is then multiplied in two

phase sensitive detectors (PSD), one driven by the reference signal and the other by a signal phase-shifted 90 degrees from the reference. The resulting signals after passing a low-pass filter represent the input signal as a vector relative to the lock-in reference oscillator. The signal amplitude and the phase between the input signal and the reference, containing the information about the plate defects can be selected as the lock-in output quantities.

Figure 3 depicts the results obtained for the data of the amplitude and phase of the voltage difference between the output voltages of the sensing coils that constitute the ECT probe measured with the lock in amplifier when the scanned area corresponds to the 2nd artificial defect of the aluminum specimen. Sensibility of the lock-in was adjusted to 20 mV(full-scale) and the low-pass filter to 3 ms, with no pos-filter.
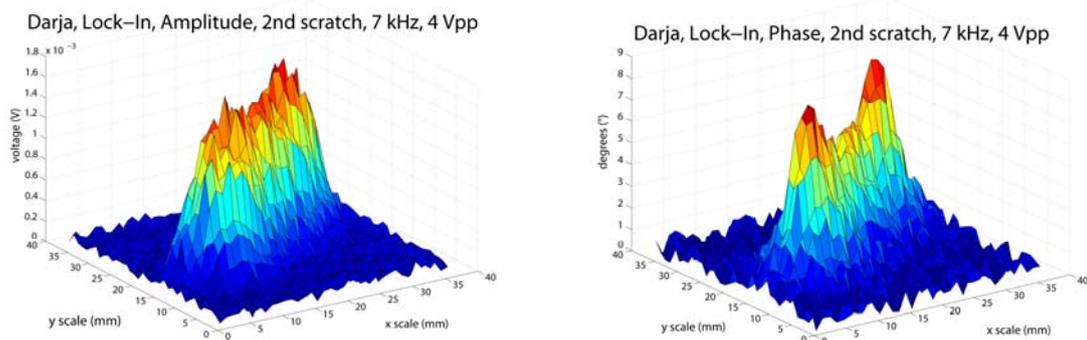

Figure 3. Amplitude and phase of the voltage difference obtained using the lock-in amplifier when 2nd defect is scanned

B. Case study 2: using a dedicated signal processing circuit

To avoid the use of an expensive commercial lock-in amplifier a dedicated signal processing circuit has been implemented. In Figure 4 the block diagram the signal processing circuit for one coil is depicted (another circuit like this is used to process the signal from the second sensing coil). This circuit represents the input signal as a vector relative to the reference with one component "in phase" with the reference and other "in quadrature". The circuit is repeated to observe the output voltage of the other sensing coil.
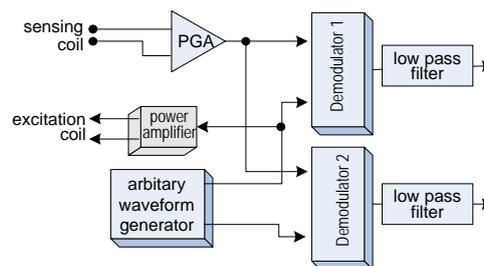

Figure 4. One signal of the signal processing circuit

The arbitrary waveform generator (TGA1242) feeds the power amplifier and provides the current to the excitation coil. This signal and a 90º phase shifted signal also available in the generator are the references of demodulators (AD630) one and two respectively. The other input signal of the demodulators is the output of a high precision instrumentation amplifier with programmable gain (AD620) used to amplify one hundred times the output voltage of the sensing coils. The demodulator output is low-pass filtered in order to extract the DC component and then sampled by a multifunction data acquisition board (NI cRIO-9215) controlled by the USB port of a PC. The board has four 16 bit resolution simultaneously sampled analog input channels and an input range ±10V. Maximum sampling rate is 100 kHz per channel.

The output signals from the four demodulators of the full implemented circuit correspond to the components "in phase" and in "quadrature" of the voltages of the two sensing coils. In order to obtain

the signal containing the information about the defects in the plate information the vectorial subtraction of the voltages is determined and then the amplitude and phase of the result are computed.
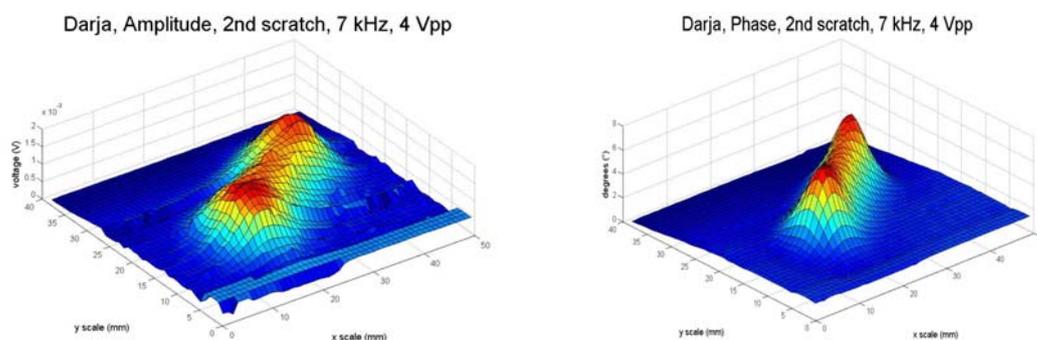The result is depicted in Figure 5 for the scan of the 2nd defect.

Figure 5. Amplitude and phase of the voltage difference obtained using a dedicated circuit

C. Case study 3 : using digital signal processing

A more agile solution is obtained using the multifunction data acquisition board (NI cRIO-9215) and some post digital signal processing: seven-parameter sine fitting, filtering and shape preserving interpolation. The board has four 16 bit resolution simultaneously sampled analog input channels and an input range ±10V. Data is acquired during some periods of the excitation current (frequency is 7 kHz) at the maximum sampling rate of the board, 100 kHz per channel. In order to have higher resolution two high precision instrumentation amplifiers with x100 gain are placed before the A/D converter for the two sensing coils. The excitation current is measured using a 220 Ω sensing resistor. Figure 6 presents raw data obtained for each sensing coil when the area around 2nd defect is scanned.
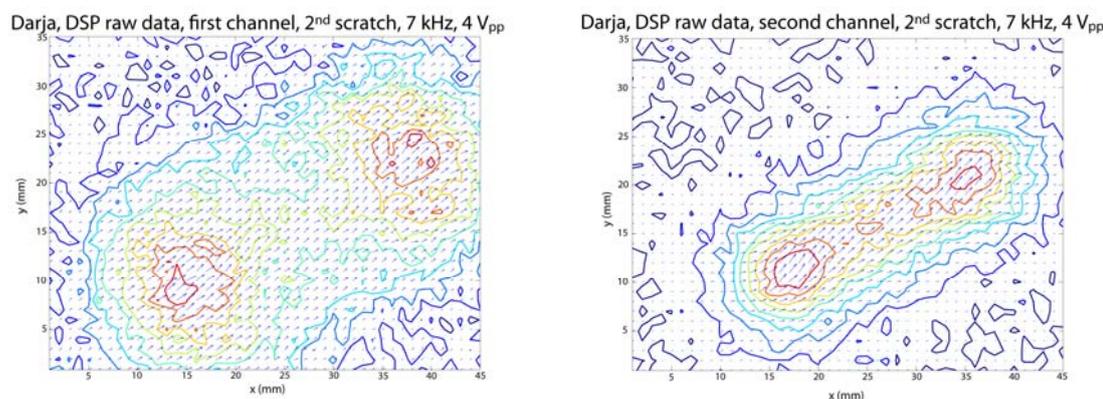

Figure 6. Contour plots of the normalized voltage amplitudes and an arrow representation
of the normalized amplitudes and phases of the output voltages sensing coils

In this case degradation of the measurement resolution is avoided by using digital signal processing. After being filtered by a digital low-pass filter to remove the white noise (with null mean value) and by a bandpass filter centered at the reference frequency provided by the excitation current to remove noise at frequencies other than the reference, the amplitude and phase of the sensing coils voltages must be computed. The methods described in section III have been investigated and due to the superior performance of the 7-parameter sine-fitting algorithm [6] it was decided to adopt this method to determine the required quantities.
The 7-parameter algorithm is an iterative least square sine fitting algorithm that works with two waveform records that are known to have the same frequency. The algorithm estimates the amplitude, phase and the DC component of each of the waveforms and the common frequency (i.e., in total it estimates seven parameters of the waveforms). Compared to applying the well known 4-parameter sine fitting algorithm [7] to each channel separately, the 7-parameter algorithm gives phase estimates with

lower uncertainty. The higher uncertainty of phase estimation in case of the 4-parameter algorithm is caused by the slightly different frequency estimate the method returns for each waveform.

With the sine amplitudes and the phases of both channels the difference between the output voltages of the sensing coils is computed. The output value corresponds to the data containing the information about the conductivity of the plate. This value is then related to the voltages that control the positioning system. A matrix with the XY locally conductivity value is thus obtained.

For representing the results some more data processing is useful. To remove individual data points (outlier values correction) or all data points that do not fulfil a certain expression filters may be included (linear or median) (classical or statistical). As the information about the defects in the plate is hidden in tenths of a thousandth part of a degree the phase shift must also be normalized. An algorithm of preserving shape interpolation can also be used.

Figure 7 presents the amplitude and phase of the voltage obtained subtracting the voltages computed from the raw data of Figure 6 using the 7-parameter sine fitting algorithm.
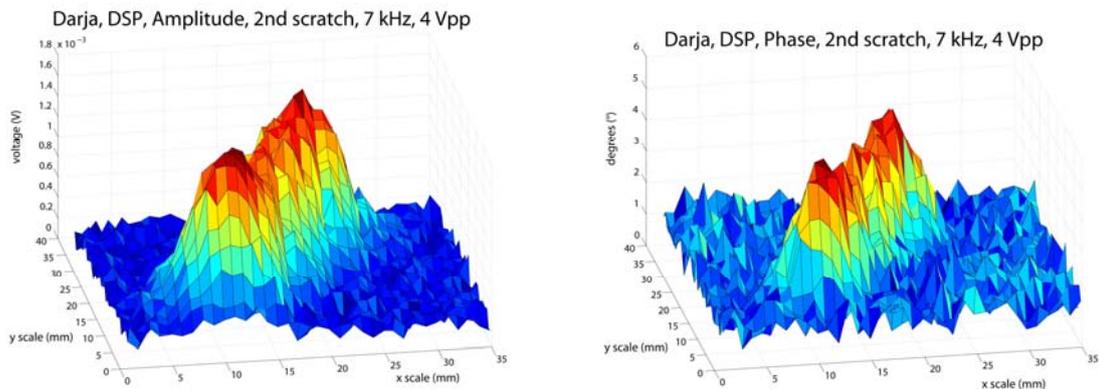

Figure 7. Amplitude and phase of the voltage difference obtained using a data acquisition board

III. Comparison between cross correlation and sine-fitting

To create eddy-currents inside the metallic body a time varying magnetic field is applied to the body. In our case sinusoidal currents applied to the excitation coil is employed to create that field. The output signals from the sensing coils are noisy sinusoids whose amplitude and phase have to be precisely determined. It is worth to remember that the material defects cause very small deviations of those parameters from their mean values. The behaviour of two different algorithms was investigated to extract the phase information from the discrete values acquired.

In this section we give special attention to the measurement of phase. For that purpose we assumed a sampling frequency $f_s = 100$ kHz , corresponding to our hardware. Eight values of the signal frequency were tested: 100; 200; 500; 1000; 2000; 5000; 10000; 20000 Hz. These frequencies correspond to different numbers of points per period ranging from 1000 points for the lower frequency to 5 points for the highest. For each one of the frequencies under test a various number of periods were generated and to each signal random noise with a normal distribution was added in order to obtain signal to noise ratios of 40 dB. Each frequency was tested 1000 times and the maximum value for the phase error was recorded.

The first tested method to be tested was based on the cross-correlation between the two arrays of values corresponding respectively to the acquired values of excitation current and detected voltage. The cross correlation was performed using the Matlab function '*xcorr*(.,.)'. The second method used seven parameters sine-fitting algorithm to extract the phase information. The results are displayed in Figure 8.
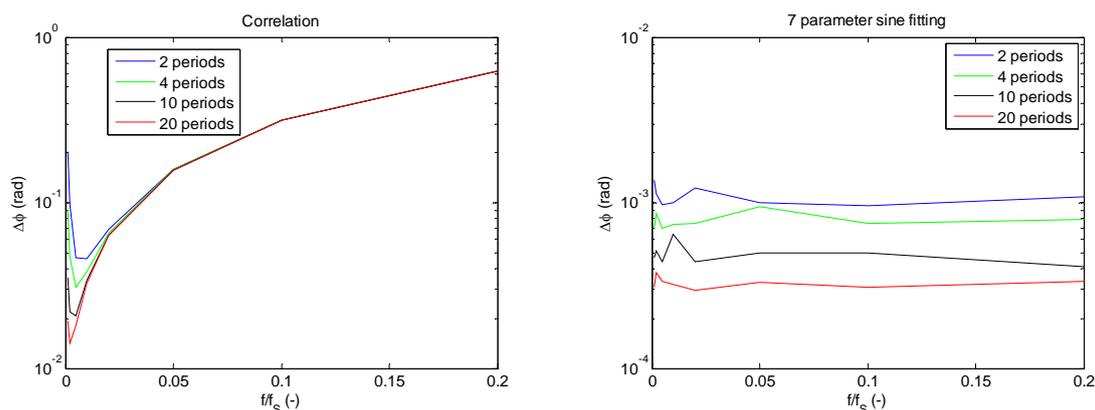
Figure 8. Maximum phase error versus normalized frequency using correlation and 7-parameter sine-fitting.

IV. Conclusion

This paper presents three different techniques to obtain information about cracks and other defects on metallic plates. Experimental testing using these techniques was performed with the same probe, for the same frequency and scanning the same defect.

The results are consistent and repeatable. Nevertheless a calibration of the system wasn't yet performed and the specifications not concluded. The XY positioning system has to be replaced because its low performance compromises the specifications.

The most agile solution uses digital signal processing over the raw data obtained with a data acquisition board. Using the 7-parameter sine fitting algorithm to obtain the amplitude and phase of the output voltage of each sensing coil leads to more accurate results than the application of cross-correlation. Although more processing methods are intended to be tested to improve data accuracy, the results presented show clearly that the method is adequate.

The use of the implemented dedicated circuit is faster and provides the amplitude and phase of each output voltage from the sensing coils. A disadvantage when compared with the use of the data acquisition board is that the DAQ is included in the automated microcomputer based system being developed to detect and estimate the size of cracks and other defects in conductive non magnetic material, with minimum operator intervention.

Future work is required in order to evaluate crack geometries from testing signals. It implies the resolution of the inverse problem of the physical phenomenon under test.

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