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Pulsed Eddy Currents: A New Trend in Non-destructive Evaluation of Conductive Materials

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Abstract- Pulsed eddy current (PEC) is a new technique of non-destructive material evaluation (NDE). In comparison with other eddy current techniques, PEC uses pulsed excitation that is characterized by wide frequency content and thus the response carries more complex information about a tested object. PEC method is used in many NDE common applications such as inspection of defects, measurement of conductivity and estimation of material thickness. This article deals with the conventional and the pulsed eddy testing method as a new trend in electromagnetic nondestructive evaluation of conductive materials. Numerical simulations as well as selected experimental results are carried out to study correlations between the driving and the response signals regarding the defect classification. The gained numerical and experimental results are presented and discussed in the paper.

I. Introduction

Among the testing methods developed for maintenance and inspection purposes, non-destructive testing (NDT) techniques present the advantages of leaving the components undamaged after inspection. Such techniques find applications for example in the aerospace, transport, nuclear and off-shore industries. The main purpose of NDT is detection of various material properties, especially inhomogeneities or defects, without mechanical damage of a tested object. Nowadays, non-destructive evaluation (NDE) is more preferable, because the maintenance requires not only detection but also characterization of a detected defect. In NDE, it is ambition to detect, classify, and quantify defects that can be found in various structures. Especially fatigue cracks and corrosions are concerned. Different physical principles are utilised for NDE of materials. One of the conventional electromagnetic methods, originating from the electromagnetic induction phenomena, is eddy current non-destructive inspection (Eddy Current Testing, ECT), [1], [2]. Principle of the method underlies in the interaction of induced eddy currents with structure of an examined body, Fig. 1.

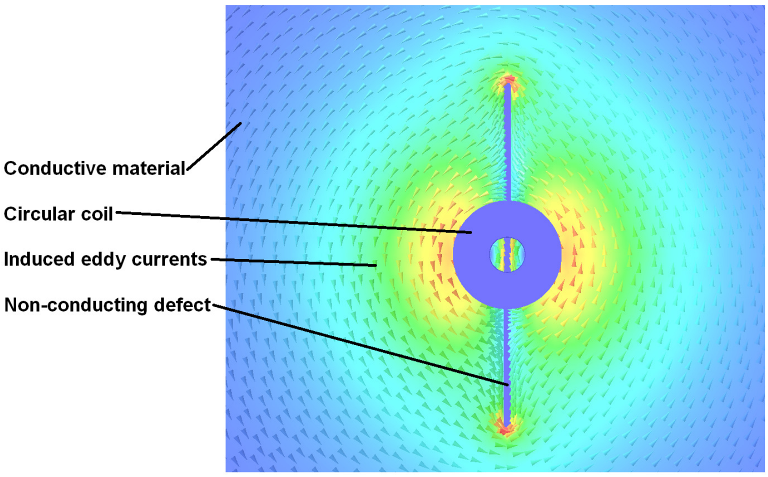


Figure 1. Principle of the ECT method

II. ECT with harmonic excitation

Conventional eddy current systems have generally been limited to a small number of discrete frequencies in order to allow for maximum test speeds and despite the advent of automated analysis systems, the primary mode of analysis is pattern recognition by highly trained analysis. Conventional ECT encounters difficulty in finding crack / corrosion indications in the presence of layer edges and gaps and also low frequency signal degradation.

The major characteristics of conventional ECT with harmonic excitation are: application of discrete frequencies, large dynamic range, accurate flaw sizing, high speed and signal analysis by pattern recognition [3].
Presence of a crack in a tested material affects the amplitude and the phase change of the EM field and thus of the coil induced voltage, see Fig. 2.

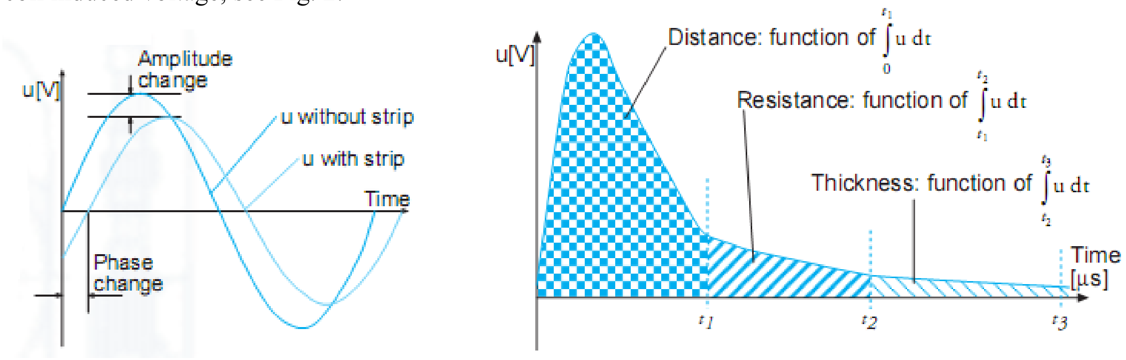


Figure 2. Conventional ECT, change of the coil induced voltage due to a crack (left) and the time dependence of the coil induced voltage under the pulse excitation (right), [3]

III. ECT with pulsed excitation

Using conventional eddy current techniques to inspect materials for flaws that may occur at various depths, inspectors must establish multiple excitation frequencies. In commercial applications, these tests are typically done in two ways: by taking multiple measurements at different frequencies using a single-frequency instrument or by using a multiple-frequency instrument. Before measuring, the user must set up the probe and perform a calibration for each frequency. With a multiple-frequency instrument, the technician can select from a number of frequencies, which the probe will use simultaneously in a single measurement. To a certain extent with either method, users must have some knowledge of the material's properties, the types of flaws expected and the depth to select the appropriate frequencies [4], [5].
A new technology, pulsed (or transient) eddy current (PEC), uses a shaped waveform rather than a continuous sine wave to excite the coil and generate an eddy current pulse in the structure. Because the pulse represents the sum of sine waves for a broad band of frequencies, one test pulse can contain all the frequencies needed to perform the tests at different depths. The real advantage is the fact that pulsed eddy current is rich in low-frequency components which allows to see near-surface and deeper flaws at the same time. PEC method offers an advantage over multiple-frequency probes because users don't have to select the scanning frequencies. In comparison with eddy currents with harmonic excitation, transient eddy current captures data covering all the frequencies in the bandwidth, whereas multiple-frequency eddy current only captures certain specific frequencies. This means that the optimum frequencies for any part of the structure will always be available from any transient eddy current scan. For a multiple-frequency scan, the optimum frequencies would be determined in advance and they will be different for each different structure, requiring several scans over complex structural changes [3], [6], [7]. PEC technology thus offers more information about the structure and defects than multiple-frequency eddy currents. PEC probe is also much easier to use. The same probe and simple setup can be used over a wide range of structural thickness, thus speeding up the data acquisition process. Compared to inductive coils, the use of Hall-effect sensors as field detectors improve the spatial resolution and detection ability of deeper defects. Pulsed eddy current equipment has been successfully applied in corrosion detection for several years now. Whereas field experience on insulated objects has grown significantly, the technique's characteristics make it also highly suitable for other field situations where the object surface is rough or inaccessible. When using PEC, square, triangular and ¼-sine shape of the driving pulse is usually used for the eddy current excitation. The shape of the driving signal influences the response. Basic parameters of the driving signal that need to be adjusted are amplitude of the signal, time duration and repetition rate. Repetition rate have to be set properly regarding to the time constant of a circuitry.

IV. Numerical investigations

Numerical simulations of both the ECT methods based on the Finite Element Method (FEM) using OPERA software have been carried out. A conductive specimen, shown in Fig, 3, having the electromagnetic parameters of the stainless steel SUS 316L is inspected in this study. The material has the conductivity of $\sigma = 1.35$ MS/m and the relative permeability of $\mu_r = 1$. The specimen contains a non-conductive defect. Parameters of the defects, i.e. its depth and length are varied according to Fig. 3. All of the simulated non-conducting defects represent the electric-discharge machined notches (EDM) in reality. A coil of absolute type shown in Fig. 4 with $N = 600$ number of turns is used to drive eddy currents and to detect the response signal. The conductivity of the coil winding is set to $\sigma = 56$ MS/m (copper conductivity). The coil is placed over the centre of the specimen normally to the specimen surface with the lift-off of 1 mm. The PEAK signal (Fig. 4) was used to driving the coil with the peak time of $t = 1$ ms. The signal contains smooth curves and it does not contain sharp changes, like for example the square signal. The smooth curve means smooth derivative and thus, the induced voltage (U=L·di/dt).

Specimen No. 1			
	a [mm]	b [mm]	c [mm]
# 1	0,2	10	1
# 2	0,2	10	2
# 3	0,2	10	3
# 4	0,2	10	4
# 5	0,2	10	5
# 6	0,2	10	6
# 7	0,2	10	7
# 8	0,2	10	8
# 9	0,2	10	9

Specimen No. 2			
	a [mm]	b [mm]	c [mm]
# 1	0,2	10	5
# 2	0,2	12,5	5
# 3	0,2	15	5
# 4	0,2	17,5	5
# 5	0,2	20	5
# 6	0,2	22,5	5
# 7	0,2	25	5
# 8	0,2	27,5	5
# 9	0,2	30	5

Specimen No. 3			
	a [mm]	b [mm]	c [mm]
# 1	0,2	3	1
# 2	0,2	6	2
# 3	0,2	9	3
# 4	0,2	12	4
# 5	0,2	15	5
# 6	0,2	18	6
# 7	0,2	21	7
# 8	0,2	24	8
# 9	0,2	27	9

Figure 3. Geometry of the simulated defects

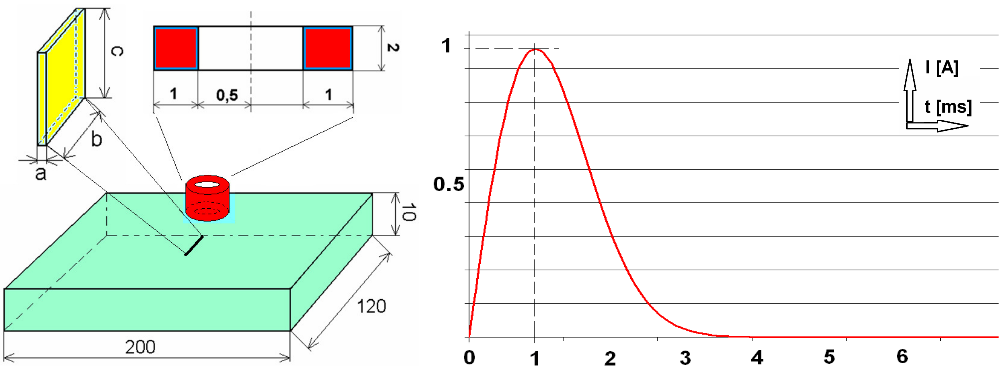
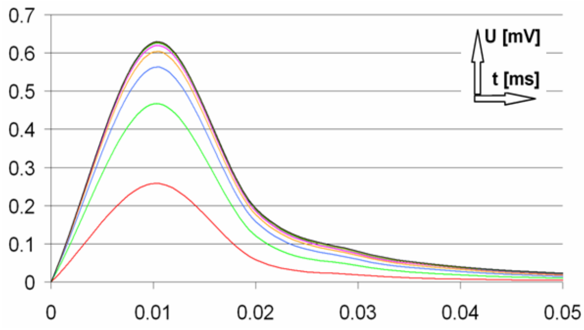


Figure 4. Configuration of the inspection system (left) and driving signal of the coil (right)

V. Numerical simulation results

Following PEC simulation results shown in Figs.5 – 6 present the dependences of the differential response signal on the geometry of the defect. Dimensions of the defect are shown in Fig. 3 according to the notation displayed in Fig. 4. It can be seen that if only one parameter of the defect, its depth in this case, is changed (specimen No.1) the signals start to saturate when the defect is deeper than approximately 4 mm. Even, deeper defects can be detected but can not be precisely evaluated from the measured responses. Simulation results concerning the specimen No.2 (Fig. 5), where only the length of the defect changes are slightly different than the previous ones. The defect has a depth of 5 mm and the differential response signal starts to saturate when the defect is approximately 25 mm in length. When both the depth and the length of the defect are varied at the same time, specimen No. 3 (Fig. 6), the differential response signals of the defects are clearly separated from each other up to a defect depth of 9 mm. The main aim of these simulations was to inspect and to compare changes in the response signals due to the changes in the defect geometry. Of course, a material defects that occur in practical cases of inspected materials belong to simulated defects of the specimen No. 3.



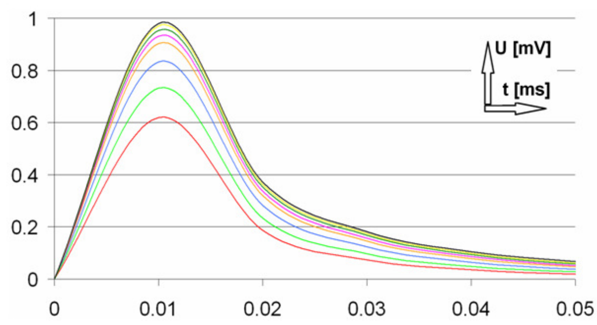


Figure 5. Differential responses, PEC method, specimen No.1 (left), specimen No.2 (right)

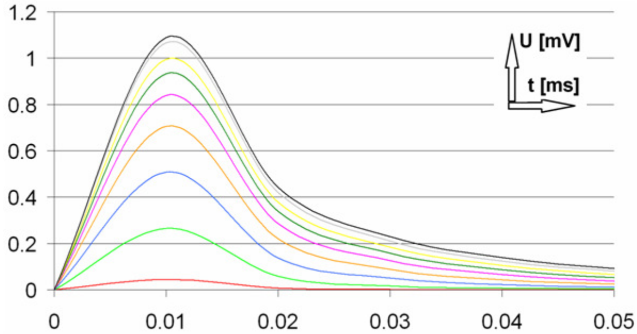


Figure 6. Differential responses, PEC method, specimen No.3

Following simulation results shown in Figs. 7 - 8 present comparison between the conventional and the pulsed ECT signals in relative scale. As can be seen, the results obtained for the conventional ECT method with using of three different frequencies of the driving signal are similar to the PEC ones, with using of three time durations of the driving signal. Of course, the non-harmonic PEC signals offer more complex information about the defect when analyzing in a frequency domain.

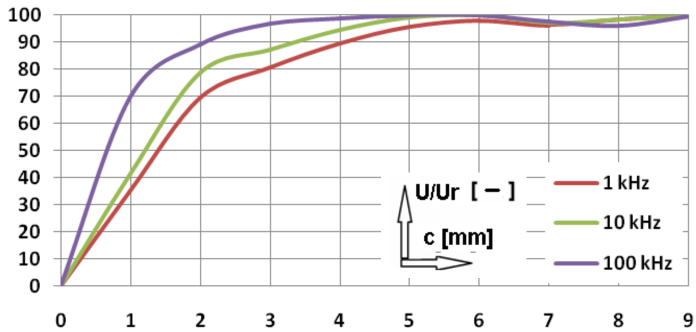


Figure 7. Differential responses, conventional ECT method, specimen No.3

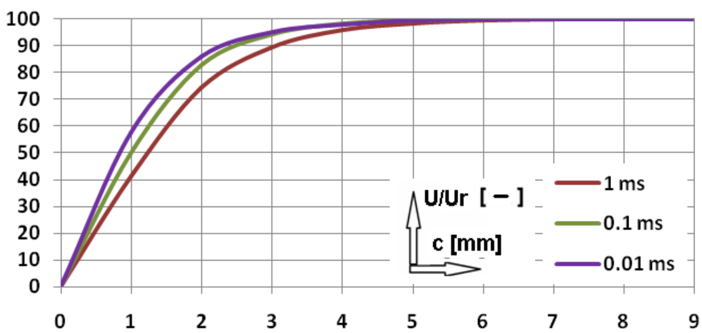


Figure 8. Differential responses, PEC method, specimen No.3

VI. Selected experimental results

Following experimental results using harmonic excitation are carried out to show the dependences of the signal changes due to the defects in a complex plane. Experiments were performed using two different types of the probes. Probe No.1 was realized according to the dimensions of the probe used for numerical simulations (Fig. 4). Probe No.2 was the commercial probe KA 2-1 (by Rohmann). Dimensions of the second probe as well as the characterization were not known. ECT analyzer B300 (by Rohmann) was used for the experiments. As can be seen from the results, Figs. 9 – 10, using of the first probe, with excitation frequencies of f = 50 kHz and f = 100 kHz have appropriate information value. On the other hand, the results obtained with the commercial probe, the ECT signals have information value only at higher frequencies. The first type of the probe thus can be used for the conventional ECT measurements as well as for the PEC ones.

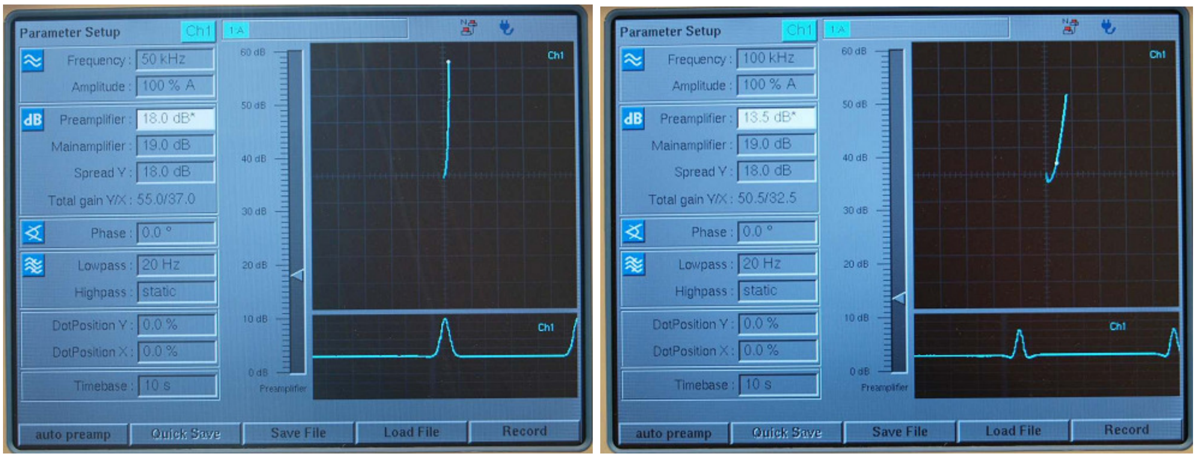


Figure 9. ECT with harmonic excitation, defect # 9, f = 50 kHz (left) and f = 100 kHz (right), used probe (Fig. 4)

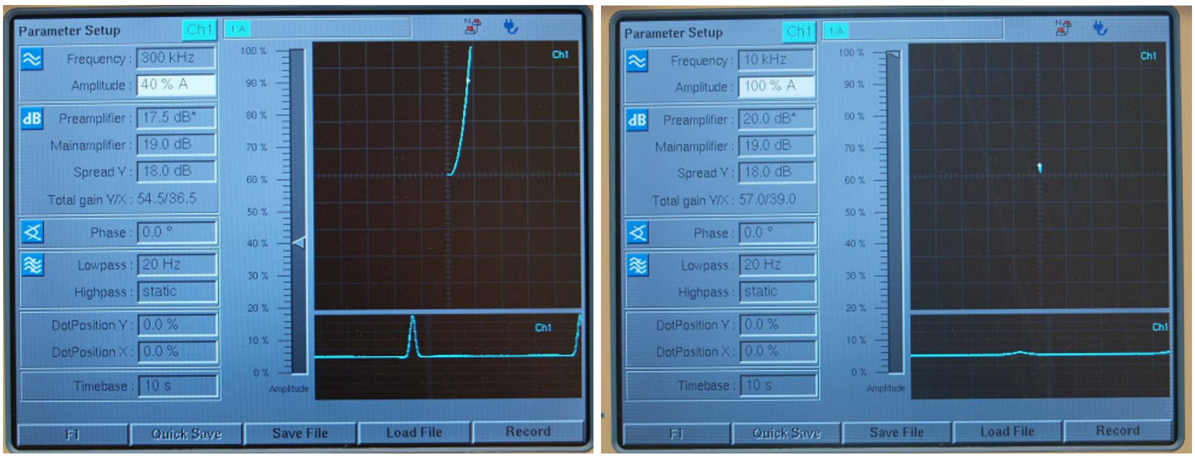


Figure 10. ECT with harmonic excitation, defect # 9, f = 300 kHz (left) and f = 10 kHz (right), commercial probe KA 2 - 1 (Rohmann)

VII. Conclusions

Non-destructive testing of conductive materials using the eddy current techniques plays very important role at the present time. The maintenance and the inspection bring prolongation of the functionality of such materials. This article presents comparison between the conventional and the pulsed ECT method. Selected numerical simulations and the experimental results are carried out. As can be seen from the results, the PEC method is more suitable for detection of the deeper cracks, and due to the principle of the method, more complex information about the defect can be obtained. Based on the performed simulations it can be concluded that parameters that influence less significantly the PEC response signal are: the shape of the driving signal (influences only shape of the resulting signal), variations of the lift–off parameter (influences value of the resulting signal). More significant influence on the response signal have following parameters: the time duration of the driving signal and set-up of the ratio of the duty cycle with respect to the repetition frequency of the driving signal. Performing of the PEC experiments and comparison with the conventional ones, as well as the parametric analysis of the PEC signals are the main aims of our future work.

Acknowledgment
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