PULSED EXCITATION IN EDDY CURRENT NON-DESTRUCTIVE TESTING OF CONDUCTIVE MATERIALS

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Summary The paper deals with eddy current non-destructive testing of conductive materials. Basic principle of the method is explained. Two types of eddy current excitation, the harmonic one and the pulsed one, are discussed. The characteristics, advantages as well as disadvantages of the two excitation methods are compared. It is explained that the pulsed excitation gives more complex information about a tested object. Experimental results of the pulsed eddy current testing of a defect in an Aluminium plate are presented.

1. INTRODUCTION

Non-destructive testing (NDT) play an important role in different industrial applications. The main purpose of NDT is the detection of different material properties, especially non-homogeneities 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.

Eddy current testing (ECT) is one of the electromagnetic non-destructive methods. The ECT works based on the electromagnetic induction. Eddy currents are induced in a tested object using time-varying electromagnetic (EM) field. Usually, harmonic excitation is utilized for the purpose. Perturbation field due to changes in the eddy current flow pattern is sensed.

The paper deals with pulsed excitation of eddy currents. The two excitation methods are discussed and compared. It is explained that the ECT with the pulsed excitation provides more complex information about a detected defect. Experimental results of the inspection of an artificial notch in an Aluminium plate are presented.

2. PRINCIPLE OF ECT

The principle of the ECT is based on the electromagnetic induction phenomenon, see Fig. 1. A coil supplied with a time-varying current generates the time varying EM field in its vicinity. If there is a nearby conductive object, time-varying electromotive force is induced there. Consequently, eddy-currents flow in the object according to the electromotive force [1], [2]. The EM field generated by the eddy currents has the opposite direction in comparison with the exciting EM field generated by the coil. If there is a defect in presence, it influences the flow pattern of the eddy currents. The impedance of the coil changes due to this fact. By measuring the changes in the coil impedance, information about the material defect are obtained.

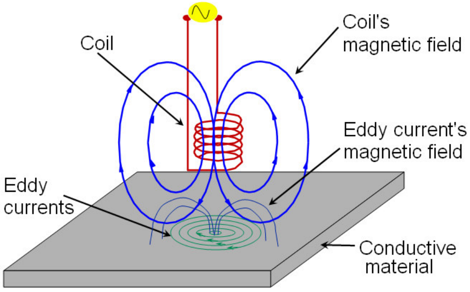

Fig. 1 Principle of the ECT

3. MODELLING OF ECT

ECT is modelled using the quasi-stationary approach. Usually, this approach gives reliable results when the time changes of EM field are relatively slow, so the displacement current can be neglected ($\mathbf{J} >> \partial \mathbf{D}/\partial t$). EM field in conductive materials fulfil this condition also at higher frequency range because the conductive current is much higher than the displacement current.

The quasi-stationary EM field is described by the four Maxwell's equations in the following form:

$$\mathrm{rot}\,\mathbf{H} = \mathbf{J}\,, \quad (1) \qquad \mathrm{rot}\,\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}\,, \quad (2)$$

$$\mathrm{div}\,\mathbf{B} = 0\,, \quad (3) \qquad \mathrm{div}\,\mathbf{D} = \rho_0\,, \quad (4)$$

where: $\mathbf{H}$ [A.m^{-1}] is the magnetic intensity vector, $\mathbf{E}$ [V.m^{-1}] is the electric intensity vector, $\mathbf{B}$ [T] is the magnetic flux density vector, $\mathbf{D}$ [C.m^{-2}] is the electric displacement vector, $\mathbf{J}$ [A.m^{-2}] is the conducting current density vector and ρ_0 [C.m^{-3}] is the volume density of free charges. The materials' relations between the vectors of EM field are:

$$\mathbf{D} = \varepsilon\,\mathbf{E}, \ (5) \qquad \mathbf{B} = \mu\,\mathbf{H}, (6) \qquad \mathbf{J} = \sigma\,\mathbf{E}, \ (7)$$

where ε [Fm^{-1}] is the permittivity, μ [H.m^{-1}] is the permeability and σ [S.m^{-1}] is the conductivity of a material.

The EM field can be analyzed using the potential functions:

$$\mathbf{B} = \mathrm{rot}\mathbf{A}\,, \quad (8) \qquad \mathrm{grad}\,V = -\mathbf{E} - \frac{\partial \mathbf{A}}{\partial t}\,, \tag{9}$$

$$\mathrm{div}\mathbf{A} = 0\,, \tag{10}$$

where **A** [T.m] is the magnetic vector potential and V [V] is the electric scalar potential. Then the potential equations have the following form:

$$\text{in air region:} \qquad \nabla^2 \mathbf{A} = 0 \tag{11}$$

$$\text{in coil region:} \qquad \nabla^2 \mathbf{A} = -\mu \mathbf{J} \tag{12}$$

$$\text{in conductor region:} \quad \nabla.\sigma\left(-\nabla V - \mathrm{j}\omega \mathbf{A}\right) = 0 \tag{13}$$

$$\nabla^2 \mathbf{A} - \mathrm{j}\omega \mathbf{A} - \mu\sigma\nabla V = 0 \tag{14}$$

4. ECT WITH HARMONIC EXCITATION

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.

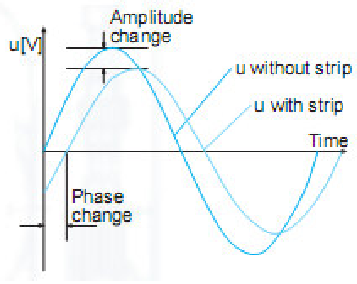

Fig. 2 Conventional ECT, change of the coil induced voltage due to a crack [4]

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.

5. ECT WITH PULSED EXCITATION

Pulsed eddy current testing (PEC) allows:

- excitation of a wide spectrum of frequencies with a single pulse,
- effective subsurface cracks detection and corrosion detection,
- reduction of power consumption,
- possibility of multi-frequency analysis after scan is completed and other features.

Because of multi-frequency inspection, more complex information about a material defect is obtained. For example, to measure the thickness of a plate, three parameters must be taken into account: the distance between the coil and the specimen, the electrical resistance and the thickness of the metal plate, Fig. 3 [4]. However, one of the parameters must be kept constant.

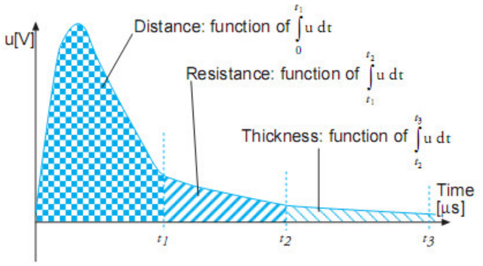

Fig. 3 Time dependence of the coil induced voltage under the pulse excitation [4]

PEC testing applies a broad band pulse and analyzes the transient voltage response, which can yield a signal with frequency content from DC to 100 kHz or higher. Because the penetration depth of eddy currents depends on excitation frequency, thus PEC testing provides more volumetric inspection and fetches more information. Pulses can be easily generated and controlled by the intensity of excitation and starting time for data synchronization and interpretation, Fig. 4. Responses of a pulse often come when step excitation is over and no over lap between excitation and response will occur, so PEC testing is more robust to interference [5]. By performing the Fourier transformation, the response obtained by the probe can be displayed as a variation of the amplitude spectrum. By sampling different delay times within a pulse, different parts of the spectrum can be evaluated [5].

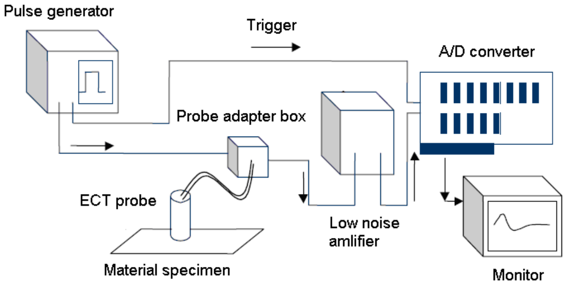

Fig.4 PEC apparatus

The method has the potential advantages of deeper penetration, the ability to locate discontinuities from time-of-flight determinations and a ready means of multi-frequency measurement. The apparatus is somewhat complicated in design and not readily usable by the average operator experienced with the conventional eddy current equipment. Its main successes are in the testing of thin metal tubes and sheets as well as metal cladding, for measuring thicknesses and for the location and sizing of internal defects.

6. EXPERIMENTAL RESULTS

An Aluminium plate specimen, shown in Fig. 5, having the width of 100 mm, the length of 100 mm and the thickness of 2 mm is used in experiments. The material has the conductivity of $\sigma = 3{,}538.107\ \mathrm{S.m^{-1}}$ and the relative permeability of $\mu_r = 1$. An artificial notch with the length of 10 mm, the depth of 0,4 mm and the width of 0,2 mm is introduced in the plate. The notch is inspected using eddy currents with pulsed excitation.

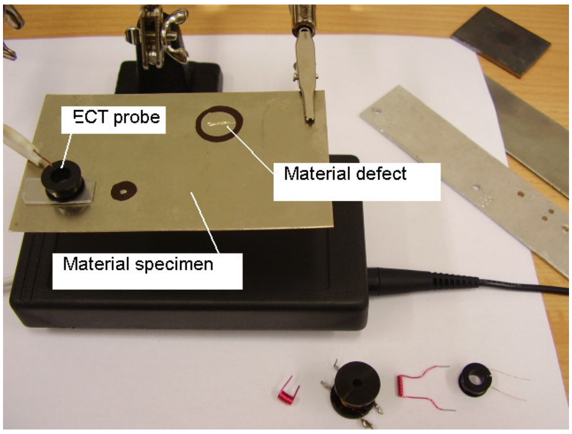

Fig. 5 Experimental setup

Configuration and dimensions of the pancake probe are shown in Fig. 6. The probe has 400 turns and its free-space inductance is 433 µH.

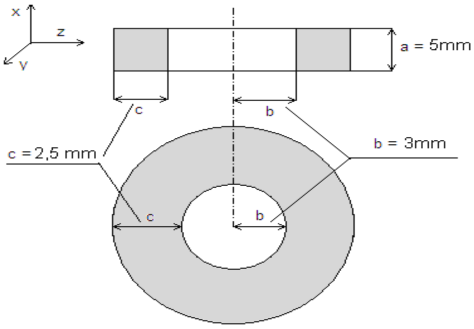

Fig.6 Configuration and dimensions of the pancake probe

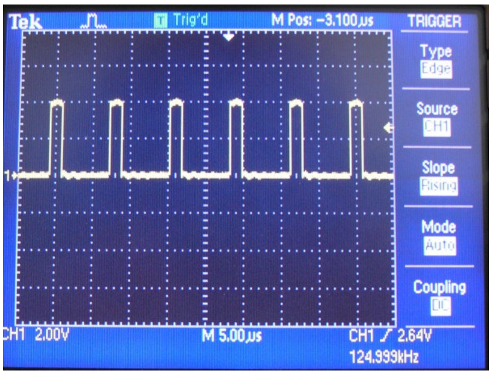

Fig. 7a Driving signal

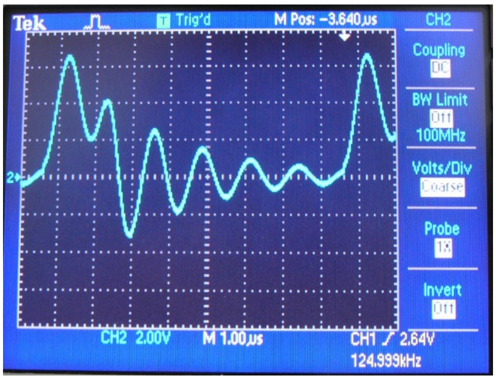

Fig. 7b Detected signal without the material defect

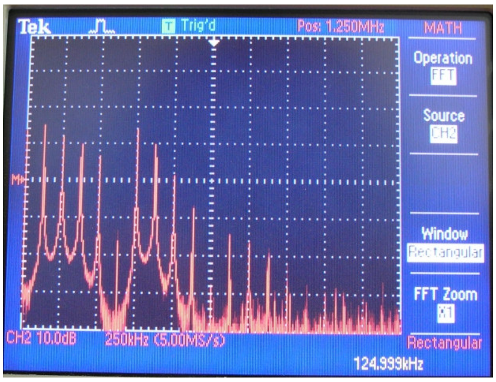

Fig. 7c Detected signal without the material defect

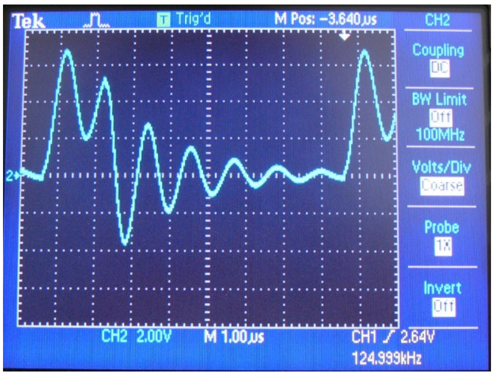

Fig. 7d Detected signal with the material defect

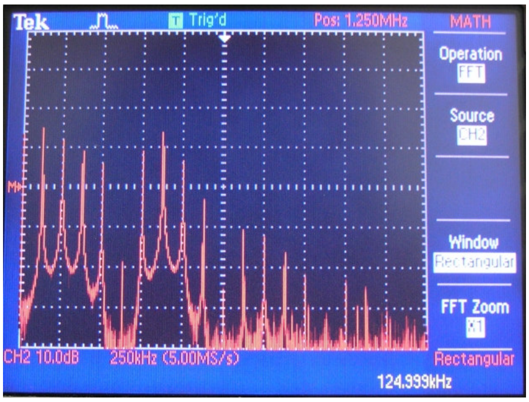

Fig. 7e Detected signal with the material defect

The amplitude of the driving voltage is $U = 2$ V, time duration of the pulse is $t = 2{,}5$ μs and the frequency is $f = 125$kHz. A function generator AGILENT 33220A is used for the driving. Figure 7a displays the driving voltage waveform. The waveform of the coils induced voltage is shown in Fig. 7b and 7d without and with defect, respectively. Corresponding amplitude spectrums of the induced voltages are shown in Figs. 7c and 7e. As it can be seen, the coil induced voltage with material defect and without material defect is different. However, the difference is not so significant, because the driving signal is only 2 V. Measured data are obtained with the oscilloscope Tektronix TDS 2012. By analyzing (discrete Fourier transform, cross-correlation function etc.) the differences between both the spectra, the material defect can be evaluated.

7. CONCLUSION

Eddy current testing is wide-spread electromagnetic method for non-destructive evaluation of conductive objects. This method is suitable for detection of surface braking cracks. However, under the harmonic excitation, the signal saturates when the crack gets deeper and thus the crack evaluation becomes more difficult. Pulsed eddy current method in contrast to conventional eddy current testing represents new approach of eddy currents driving.

Pulsed eddy current testing possesses many advantages comparing to the conventional eddy current testing, mainly more extended depth evaluation, rich information about defects and high robustness of anti-interference. Obtained information is more complex because conductive material objects is multi-frequency tested in real time. Requirements on pulsed eddy current measuring apparatus are higher in contrast with the conventional eddy current testing. It is important to ensure low noise level at all their components. Pulsed eddy current testing has a limited dynamic range and a slow repetition rate while conventional eddy current instruments have a limited number of discrete frequencies and complex analysis. The dynamic range of pulsed eddy current systems is limited by the fact that the available drive power is shared by the entire applied frequency spectrum and the input must be scaled to fit the highest response over that spectrum. Current systems also have a relatively low repetition rate limited by the settling time of the waveform.

When comparing the pulsed method with the conventional eddy current technique, the conventional technique must be regarded as a continuous wave method for which propagation takes place at single frequency or, more correctly, over a very narrow frequency bandwidth. With pulse methods, the frequencies are excited over a wide band, the extent of which varies inversely with the pulse length. The total amount of energy dissipated within a given period of time is considerably less than for continuous waves having the same intensity. Thus considerably higher input voltages can be applied to the exciting coil for the pulsed operation than for continuous wave operation. It is also important for suitable design of probes windings. Current flowing over them can reach up to tenths of amperes at very short time intervals, depending on used drive pulses.

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