Damage Detection of Surface Cracks in Metallic Parts by Pulsed Eddy-Current Probe

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Abstract

.Transient eddy-current technique is being developed for detection of flaws located at depth within metallic structures. It uses a transient signal to induce eddy currents, which interact with flaws in a conducting structure to produce an output signal that provides information about the flaw. The technique involves a transmission/reception probe to produce an output signal centred on a given frequency.

In this work, surface crack detection is considered through modelling of eddy-current pattern which are induced by the presence of small flaws. This was undertaken by means of the finite element method under transient inductive excitation having the form of short time pulses. The proposed model included the excitation coil, the sensing coil, the tested defected plate and the ambient air. Different types of probes were simulated by changing some of the design parameters in an attempt to generate an output signal of optimum magnitude and shape.

Key words: *Transient eddy-currents, pulsed eddy-current, metallic parts, flaws, detection*

1.   Introduction

Non-destructive evaluation (NDE) techniques based on electromagnetic methods are commonly used for inspection of metallic parts [1]. Some of these inspection methods are based on eddy-currents (EC) which are a. consequence of electromagnetic induction phenomenon. In EC testing, the depth of penetration into the material is controlled by the conductivity of the tested material and the work frequency. Flaws that lie parallel to the probe may not be detectable, so proper orientation of the probes should be arranged.

Transient eddy-current (TEC), also called pulsed eddy current (PEC), is an emerging non destructive technique that employs a pulsed excitation to induce a transient electromagnetic response from defects lying deep within a conducting structure. Such defects are difficult to inspect by conventional techniques, such as harmonic eddy currents or ultrasonics. A number of publications on this subject are aimed at a theoretical understanding of the phenomenon, development of appropriate probes, and finite element (FE) modelling of the input and output signals [5-7].

The present work uses FE modelling to investigate the effect of defect location on the TEC signal for a circular probe. Comsol Multiphysics is used

2.   Analysis and modeling

The constitutive equations governing a perfect Ohmic homogeneous and isotropic conductive medium write

$$\vec{J}=\sigma\vec{E} \ , \ \vec{D}=\varepsilon\vec{E} \ , \ \vec{B}=\mu\vec{H} \tag{1}$$

where $\vec{E}$ is the electric filed, $\vec{B}$ the magnetic induction field, $\vec{D}$ the electric displacement field, $\vec{H}$ the magnetic field, ε the permittivity, μ the permeability and σ the conductivity.

In case of a metallic material, it is expedient to assume $\rho=0$ in Maxwell equations. A decoupling happens then and the following propagation-diffusion equations are readily obtained

$$\Delta\vec{E}-\varepsilon\mu\frac{\partial^2\vec{E}}{\partial t^2}-\mu\sigma\frac{\partial\vec{E}}{\partial t}=0 \ , \ \Delta\vec{B}-\varepsilon\mu\frac{\partial^2\vec{B}}{\partial t^2}-\mu\sigma\frac{\partial\vec{B}}{\partial t}=0 \tag{2}$$

A stationary and harmonic solution of equations (2) is such that $\vec{E}=\vec{E}_0 e^{j(\omega t-\varphi_E)}$ and $\vec{B}=\vec{B}_0 e^{j(\omega t-\varphi_B)}$ where $\omega=2\pi f$ is the radial frequency and f the frequency of the wave. As for most metals at 20°C, ε is of order $10^{-11}\,F/m$ and the conductivity is greater than $10^6\,S/m$, considering low work frequencies not exceeding $10^3\,Hz$ one can verify that the condition $\omega\ll\sigma/\varepsilon$ is satisfied. This enables to simplify equations (2) by neglecting the propagation terms and keeping just the diffusive parts as follows

$$\Delta\vec{E}_0-j\mu\omega\sigma\vec{E}_0=0 \ , \ \Delta\vec{B}_0-j\mu\omega\sigma\vec{B}_0=0 \tag{3}$$

Equations (1) and (3) yield the existence of a permanent density of currents that are circulating in the conductive material and having the form $\vec{J}=\sigma\vec{E}_0 e^{j(\omega t-\varphi_E)}$ these compose the EC. For a given specimen geometry, the field $\vec{J}$ can be computed by integrating equations (3) under given boundary conditions. In the presence of a singularity or a flaw in the medium, the conductivity varies and the EC distribution will show changes as

compared to the pattern associated to the intact geometry. This provides a way of using EC as indicators to monitor flaw detection in metallic parts.

The practical implementation of this technique for diagnosis purpose of flaws sets usually on two circuits. The first one constitutes the inductive part which is excited by a current pulse as that shown in Figure 1. This puts variable magnetic field in the test material. The second circuit takes the form of a single coil or multiple coils sensor. Figure 2 depicts the EC probe proposed in this work and having the form of an array of coils. These consist of coils that are influenced by the variable magnetic field created by the EC inside the test material. The receiver coils undergo impedance variation induced by the EC while the compact probe is crossing a zone with variable local conductivity.
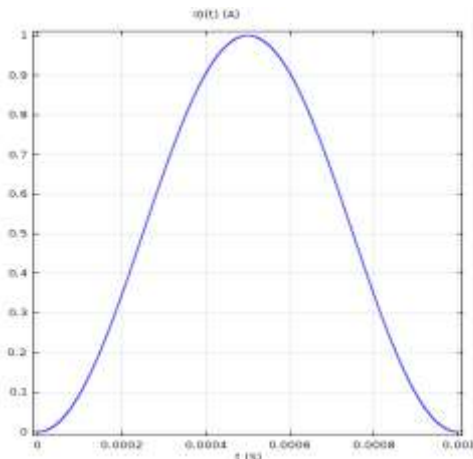

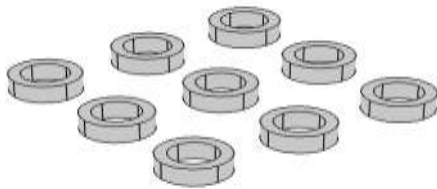Figure 1: The transmission coil excitation function

Figure 2: Details of the EC array sensor; some of the coils are inductive coils while the others are receivers

For a material with general geometry, solution of equations (3) can be achieved by means of the FEM. Comsol software provides solutions for multiphysics engineering problems. Here, use is made of the AC/DC Module of Comsol which is available for simulating electromagnetic problems.

3. Results and discussion

Let's consider a rectangular plate made from aluminum with length $L=800mm$, width $\ell=400mm$ and depth $h=10mm$ figure 3. The plate material characteristics are $\sigma=3.774\times10^7 S.m^{-1}$ and $\mu_r=1H.m^{-1}$

A defect having the form of an open parallelepiped cavity that has sides parallel to those of the plate is assumed to be present at the center of the plate. Its dimensions are taken to be: $L_d=20mm$, $\ell_d=20mm$ and $h_d=5mm$
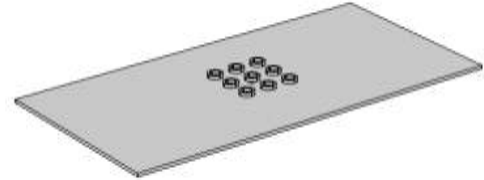

Figure 3: The test plate sample model geometry

The inductive coils are made from copper for which $\sigma'=6\times10^7 S.m^{-1}$ and $\mu'_r=1H.m^{-1}$. The coil base is circular with radius $5mm$. This coil is assumed to be formed by 1000 whorls having the section area $a_c=5.7810^{-5}m^2$. It is assumed to be excited by a pulsed current of the form $I(t)=\left[1+\cos\left(2\pi(t-T/2)/T\right)\right]/2$ for $t\in[0,T]$.

The sensor coils are made also from copper. The base of receiver coils is circular with the same diameter than that of the inductive coils.

A FEM model was developed for the system. The mesh was generated automatically by using free tetrahedral elements under Comsol. The nine elements constituting the probe-coil setup are meshed using the same element type; the maximum size was fixed at 20mm for the plate and 10mm for the coils.

As the excitation coils are coupled to the test specimen through air according to equations (2), the environmental air should also be meshed. Because meshing an infinite volume is not possible, it is necessary to specify a finite volume to mesh and solve for it. In the present study, the whole probe-coil setup was placed at the centre of a cube as shown in Fig. 3.

To avoid reflection that is susceptible to take place in a finite volume domain, the default boundary condition corresponding to magnetic insulation is used at the cube boundaries. This condition forces the field to be tangential to the exterior boundaries. The cube used in the present model has a length side of $2000mm$. The air electric conductivity is fixed at $\sigma_{air}=1S/m$. The pulse frequency is $f=1000Hz$ which correspond to $T=1ms$.

Both the inductive and the sensor coils are placed at the same distance from the top surface of the plate assumed to be planar and perfectly smooth. The air gap separating the coils from the inspected plate was fixed at $d=15mm$.
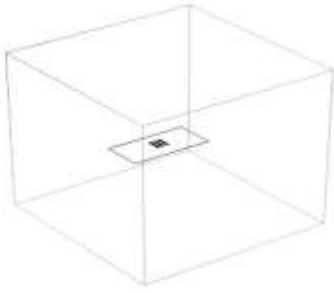
Figure 3: The complete model of the EC probe setup and test specimen

The EC intensities in the receiver coils were calculated by FEM computation. Internal boundary condition corresponding to electric and magnetic surfaces where applied and the density of charge was fixed at zero.

Figure 4 gives the obtained density of eddy-currents at time $t = 2Ts$.
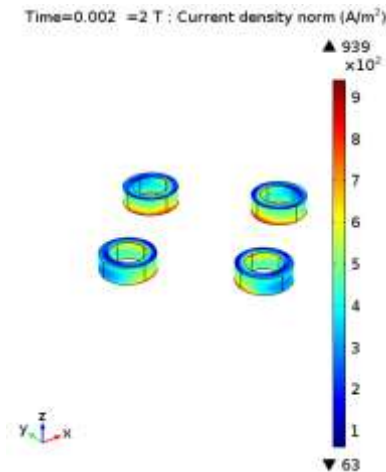

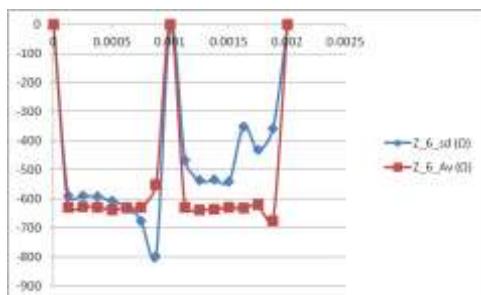Figure 4: Current density in the receivers coils at t=2T

Figure 5: Comparison of impedance of receiver coil 2 between the free defect case (sd) and the defected plate (av)

Figure 5 gives a comparison, in terms of impedance time evolution for the receiver coil 2, between the case of defect free-plate and flawed plate.

Figure 5 shows that the defect induces a signature on the time variation of coils impedance that can be monitored in order to sense the defect. A defect indicator can like this be defined in order to proceed to defect detection in metallic parts.

It should be noticed that while working with harmonic like excitation, this signature was poorer.

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