ELECTROMAGNETC PHENOMENA AS THE PRINCIPLES OF MATERIAL NONDESTRUCTIVE EVALUATION

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Summary In the paper the principles and application of nondestructive evaluation by both electromagnetic acoustic transducer (EMAT) and the eddy current (EC) methods are introduced. The ultrasonic testing (UT) and the electromagnetic nondestructive testing (NDT) are presented with their fundamental properties and the experimental results concerning the defects of conducting object characterization are shown.

Keywords: material non-destructive evaluation, ultrasonic testing, eddy current testing, EMAT

1. INTRODUCTION

Nondestructive testing (NDT) represents an important activity in various areas of modern society from nuclear power plants, fluid raw material transportation to aerospace. NDT methods and devices help to enhance safety, environmental protection and economy in production. The main aim of NDT realization is to find out anomalies in the tested material without destroying the tested object. Such testing can avoid damages to the objects and some NDT techniques may also be used for monitoring the growth of defects size up to a critical level. Nondestructive evaluation (NDE) methods can be used also for providing real time information of products quality during the production process.

The basic principles of material NDT consist in most physical phenomena, e.g. mechanic, acoustic, electromagnetic, optic, etc. Each principle possesses certain advantages for certain application areas.

Our paper deals with the two basic groups principles of NDT consisting in the acoustic and electromagnetic approaches.

The general diagram of NDE system is shown in Fig.1. In some special application the excitation and detection device can be the same one. Signals representing the field/anomaly interaction are then measured.

Defect characterization can also involve signal classification when they are classified into certain classes (good, bad, normal, abnormal) while the abnormal signals need to be analyzed and the defect signals need to be characterized.

The acoustic (ultrasonic) NDT use to be realized by various techniques differing mainly by the way of the excitation and detection of acoustic signal. The widely known acoustic NDT techniques use the acoustic transducer probe (volume or surface acoustic wave), or transducer array mostly for quickly scanning of a device and also electromagnetic acoustic transducer (EMAT) which works on the principle of anomalous electromagnetic wave generation in conducting objects.

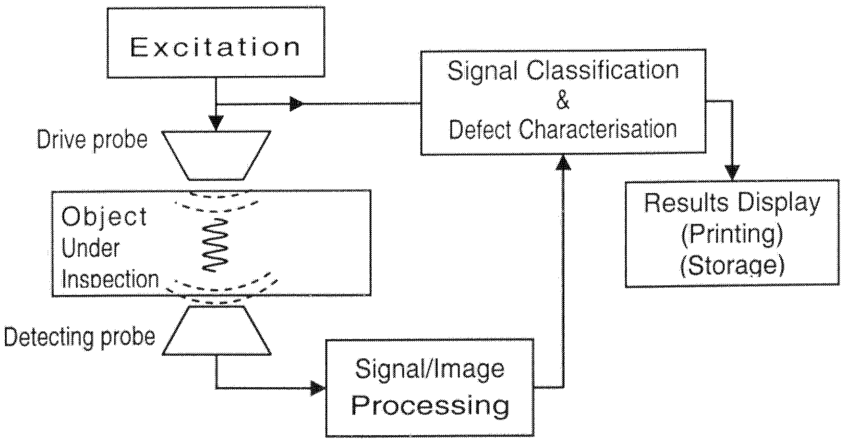

Fig. 1. General diagram of NDE system.

The electromagnetic NDT principles follow from Maxwell equations and they are classified by their frequencies as magnetostatic, magneto-stationary, quasi-static and wave. The typical electromagnetic NDT methods are magnetic flux leakage method and eddy current testing (ECT).

This paper will deal with the ultrasonic testing using EMAT and with the electromagnetic nondestructive evaluation by ECT method.

2. EMAT PRINCIPLE AND USE IN NDT.

In the presence of a constant magnetic field an RF electromagnetic wave incident on a surface of a conducting object can generate an acoustic excitation, which propagates as an acoustic wave in the object. The generated acoustic wave excites an accompanying slow electromagnetic wave, which can be radiated from the surface of the sample into the surrounding space and detected by a pick-up probe, [1], [2], Fig. 2.

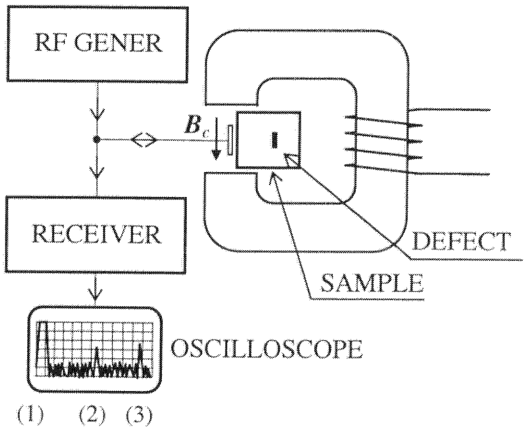

Fig. 2. NDE arrangement by EMAT.

The EMAT is a complex device consisting of the electromagnet (or magnet) being source of the constant bias magnetic field B_c, the generating (drive) and detecting (pick-up) flat spiral coil connected with an RF amplifier. The one probe pulse system is used here. During the short RF generating pulse the coil serves as a generating (exciting) one and between two successive generating pulses the same coil detects the reflected response pulses from the anomalies of the tested conductive sample, Fig.2. The detected signal is visualized by the oscilloscope. The first pulse (1) corresponds to the generating one and the others (2) and (3) to the signals reflected from the defect of the sample and from the back side of the sample, successively.

The EMAT generates and detects acoustic waves by means of the EM conversion without need of any coupling material. This fact eliminates measurement errors caused by contact and coupling influences. The EMAT can operate in a wide frequency range of application using the same device.

The EMAT method was used for nonmagnetic materials inspection, [1], [2]. In the case of ferromagnetic materials the magnetic phenomena must be considered additionally.

3. ECT PRINCIPLE AND USE IN NDT

The ECT principle consists in electromagnetic induction of eddy currents by driving coil supplied by an alternating current.

Traditional ECT methods are based on the measurements of a probe coil impedance, which is given as $\mathbf{Z} = R + j\omega L$, where R is resistance of the coil, ω is angular frequency, L is self-inductance of the coil, which is defined by the ratio of the total flux linked by each turn of the coil and the current in the coil.

When an alternating current of certain frequency is applied to probe coil placed close to a conducting object, the induced eddy current in the object alters the magnetic field and the total flux, linked by coil. Therefore the coil impedance of an EC probe is a function not only of the coil parameters, but also the object conductivity and geometry, which means that the impedance of an EC probe is related to the material properties of the object under inspection. If the probe consists of a single coil, it is called as an absolute EC probe.

Anomalies on the surface of a conducting object also alter the induced current and change the probe coil impedance. The EC probes may also consist of

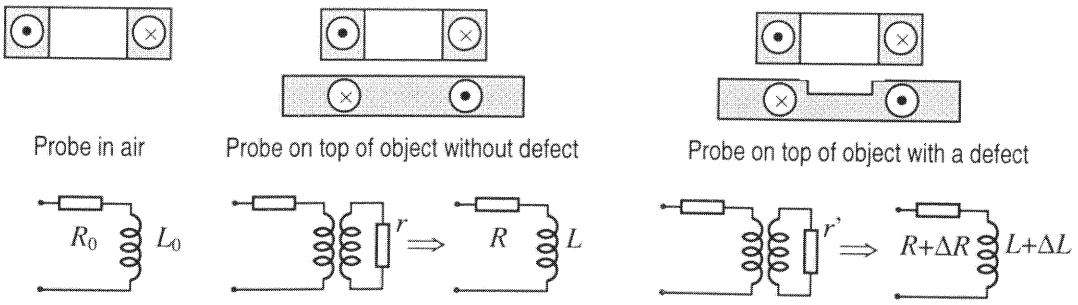

Fig. 3. Equivalent circuit of the EC probe.

two coils connected in differential mode to enhance its sensitivity and are called differential EC probes. A simplified approach to describe the impedance variation is the equivalent circuit of a transformer, Fig. 3. The probe coil can be regarded as the primary side of the transformer while the conducting object is regarded as its secondary side. The Fig. 3 represents three possibilities: the probe in air, the probe on top of an object without defect and the probe on top of an object with a defect.

The existence of an anomaly in the object alters the resistance R and, consequently, changes the coil impedance. The ECT method typically displays changes in impedance on an impedance plane, [3], [4].

For successful ECT different type sensors such as pancake probe, plus-point probe, etc. have already been developed with various success. The signals are different according to different probes.

In the next part the pancake type probe is considered, Fig. 4. It is placed at the center of a flat plate with the given lift-off and frequency. The simulated crack (defect) is treated as a group of impenetrable elements (zero conductivity). Regarding position of the defect in general two main cases can be considered. They are inner defect, when the crack and the probe are from the same side of the conducting plate, and outer defect when the crack and the probe are on the opposite sides.

Numerical analysis of ECT signals of cracks is carried out in two steps. The first step represents computation of a 3D eddy current distribution inside conducting plate, using finite elements method (FEM). The second step includes computation of the changes of the induced electromagnetic force inside the pick-up coil due to the changes of the generated eddy current distribution around the crack using the Biot - Savart law.

In order to detect the existence of a crack inside the conductor it is possible to evaluate the signal generated as a result of the changes in the intensity and the phase of the electromotive force. The variable used to solve the problem is the magnetic vector potential $\mathbf{A}_c$. Applying the Biot - Savart's law the magnetic vector potential inside the pick-up coil region can be expressed using the following equation

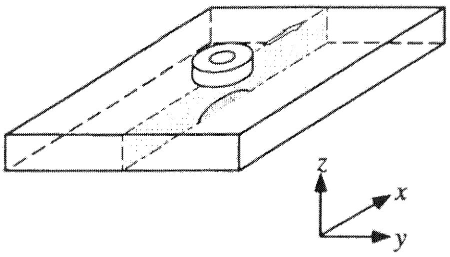

Fig. 4. Arrangement of ECT by pancake probe.

$$\mathbf{A}_c = \frac{\mu}{4\pi}\sum_{k=+}^{n_e}\sum_{j=1}^{n_i}\frac{w_{j,k}\,\mathbf{J}_{j,k}\,V_k}{\left|\mathbf{r}_{c,j}\right|}, \qquad (1)$$

where $w_{j,k}$ is the weight of the j-th integration point of the k-th finite element, V_k is the volume at the k-th element, and $\left|\mathbf{r}_{c,j}\right|$ is the distance from the integration point j to the measured point inside the pick-up coil region c. In the above equation n_e, n_i and μ are the total number of finite elements inside conducting region, the number of integration points per one element, and the permeability, respectively.

The scanning is usually made in perpendicular and parallel directions to the crack. A repertory of signals, described by their phase angle and amplitude in the complex plane, is obtained.

The changed impedance of the pancake coil is

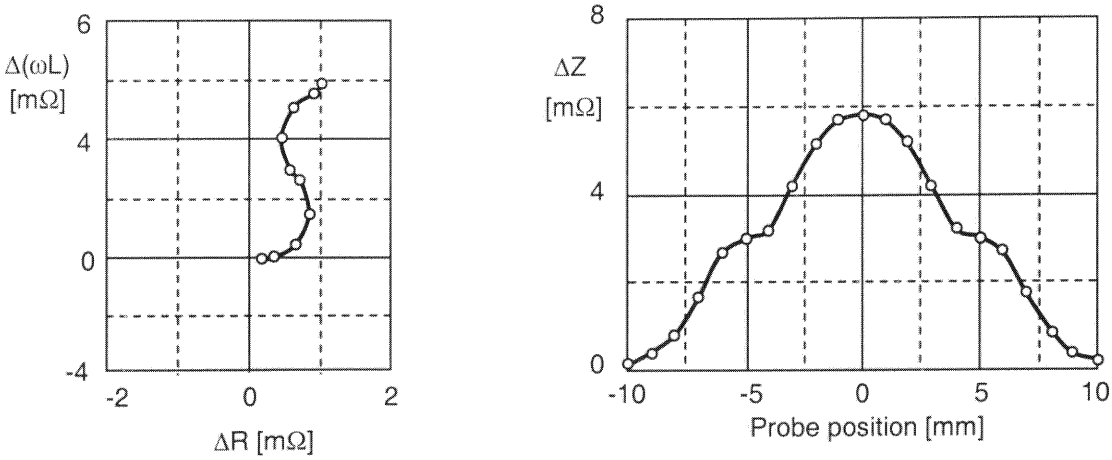

Fig. 5. The computation results of ECT by FEM.

expressed as [5]

$$\mathbf{Z} = -\frac{\mathrm{j}\omega N}{I} \oint_{c} \mathbf{A}_{s}\, \mathrm{d}l \,, \tag{2}$$

where N is the number of turns, I is the current per turn, and $\mathbf{A}_{e}$ is the magnetic potential due to eddy currents.

In order to detect the existence of a crack inside the conductor, we have to evaluate the signal generated as a result of the changes in intensity and the phase of the induced electromotive force.

The computation results of the ECT by the finite element method (FEM) are shown in Fig. 5. Both impedance trajectory changes and the impedance versus probe position dependence during the testing are illustrated.

Although the pancake probe exhibits the largest ECT signal, the determination of the crack size, its position, depth and width is quite difficult to be achieved using this of ECT probe. The reason is the fact that the eddy currents induced by this probe do not easily permeate inside the external conductors.

According to the signal's amplitude, position of the peaks in the signal, its symmetrical shape and trace one can easily determinate not only the existence of the crack inside the conductor, but also the position, length, depth and even the shape of the crack.

The topics to be discussed in the solution of the ECT problems are the operational frequency range, scan above the test piece without crack, scans over various inner and outer cracks, investigation of the lift-off noise, investigation of the tilting noise.

4. CONCLUSION

The main aim of the paper has been to show electromagnetic phenomena, which determine the operation principles of various material NDT methods. Especially, acoustic and electromagnetic methods have been described. The EMAT method of acoustic nondestructive testing has been explained and experimental arrangement for conducting nonmagnetic material investigation has been introduced.

The defectoscopy using the EMAT makes possible to investigate the material structure without any acoustic coupling, which is advantageous for the scanning method of the sample structure visualization. The coils made on different substrates are usable in the wide temperature range, as well.

The important advantage of conductive materials NDT by EMAT probe is no limitation of defects evaluation with respect to their position under the surface due to the skin-depth effect.

The NDE by EC techniques have been described for defect characterization in conducting objects. The computations by FEM and obtained simulation results have been presented for the pancake probe arrangement. The major advantages of the EC method are its simplicity and its sensitivity to tight defects. The disadvantage of ECT is its insensitivity to defects that are deeply embedded below the surface of a tested object.

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