EDDY CURRENT IMAGING FOR MATERIAL SURFACE MAPPING

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INTRODUCTION

For most nondestructive inspections, quantitative evaluations have to be performed to correlate the measured signals and the desired material properties. In some applications, the relationship between the signals and the material parameters is simple and straightforward. An analytic mathematical function can be easily constructed and solved to describe the interaction. The inverse function also can be readily determined to transform the measured data into the desired information. In some cases, such as defect characterizations, the interaction between the sensing field and the test object is often too complicated for such an approach. Advanced signal analysis techniques with complex assumptions, approximations, and computations are required to interpret the signals. Such an intricate approach is frequently time consuming and beyond general comprehension. Alternative methods that enable the direct correlation of the signals with the test piece are being sought. Imaging techniques which provide a unique capability of correlating NDE signals with component geometry, are gaining in popularity.

Major manufacturing operations such as material processes, component machining and field service often unavoidably cause geometric marks, stress concentrations, and structural defects. These variances in term induce localized changes in electric conductivity and magnetic permeability of the material. Eddy current are sensitive to these electromagnetic parameters. Thus eddy current NDE techniques are widely used to characterize material properties in various applications.[1-4] Incorporated with a mechanical scanning mechanism, an eddy current image can be constructed to map out material surface properties and identify various features. Eddy current imaging can be a vital technique for signal discrimination, classification, and interpretation.[5,6]

An analog eddy current imaging system which is capable of real time material surface mapping has been developed and integrated. Eddy current signals and positional information are superimposed by a special designed mixer/amplifier. Outputs from the signal mixer/amplifier are then used to drive an analog X-Y recorder for the generation of 3-D eddy current images.

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Experiments on machining features, residual stresses, and surface defects are studied using the system. The images obtained have demonstrated positive results in mapping and recognizing signatures of the described structural effects. Other potential applications are discussed. A digital system is proposed for data manipulation, image analysis, pattern recognition, and advanced signal processing.

BACKGROUND

Eddy current NDE techniques utilize electromagnetic induction effects to characterize the material properties.[7] As it is well known all electromagnetic phenomena are governed by Maxwell's equations. With appropriate boundary conditions, exact analytic equations and solutions can be obtained to describe the eddy current effects. A mathematical transformation can be obtained to invert the eddy current signal to the desired material parameters. However, in practice, it is often very difficult to define the proper boundary conditions to model the specific eddy current interaction. Eddy current imaging method is an effective approach to correlate eddy current signals with specimen coordinates. Theoretical analysis of the general eddy current phenomena has been discussed by many researchers.[8-11] We shall examine only the theoretical background as it is applied to eddy current imaging.

The fundamental operating principle of the eddy current imaging system is to utilize the eddy current impedance measuring technique to detect the induced changes of the electrical conductivity, magnetic permeability, and geometries due to residual stresses and surface defects in the electrically conductive materials. The impedance change of the sensing coil due to the presence of a pertubation field can be written as

$$dZ = 1/I^2 \int_s (E \times H' - E' \times H)\, ds \tag{1}$$

where dZ is the variation in eddy current coil impedance, I is the current flow in the coil, E and H are the unperturbed electric field and magnetic field, E' and H' are the perturbed electric and magnetic fields, and s is the area enclosed in the fields. The impedance Z is a complex quantity and is generally witten as $Z=R+jX_L$, the sum of the resistance R and reactance X_L. By correlating the variations in coil impedance dZ ($= dR + j\, dX_L$) with the specimen coordinates, an eddy current image can be generated.

Also, the depth penetration of the eddy current field in the material is inversely proportional to the square root of the conductivity, the permeability and the operating frequency.[12] It can be expressed as

$$\delta = (2\pi\mu\sigma f)^{-\frac{1}{2}} \tag{2}$$

where δ is the skin depth, f is the operating frequency, σ is the electric conductivity, and μ is the magnetic permeability of the material. Since eddy current field is divergent, the measurement is an integrated effect to the depth of the field. The material surface up to the desired depth thus can be examined by operating at the specifically selected frequency.

In our particular application of eddy current imaging, only the relative changes in impedance dZ with the scanning X-Y coordinates are monitored. Advanced analysis of the impedance amplitude and phase measurments can provide additional information of the material characteristics. Combining the advanced signal analysis capability with the imaging mechanism, detailed structural images of the material may be shown.

EXPERIMENTS

The block diagram of the laboratory configuration of this eddy current material surface mapping system is shown in Figure 1. The instruments used are a Staveley Nortec NDT-25L Eddyscope, an Aerotech Unidex III controller with ATS406 X-Y scanning axes, a Hewlett-Packard 7045B X-Y recorder, and a specially designed signal mixer/amplifier controller. The functional diagram of this signal mixer/amplifier controller is shown in Fig. 2. The eddy current probes used are standard absolute pencil probes typically with 2 MHz, 1 MHz and 500 kHz in frequencies.

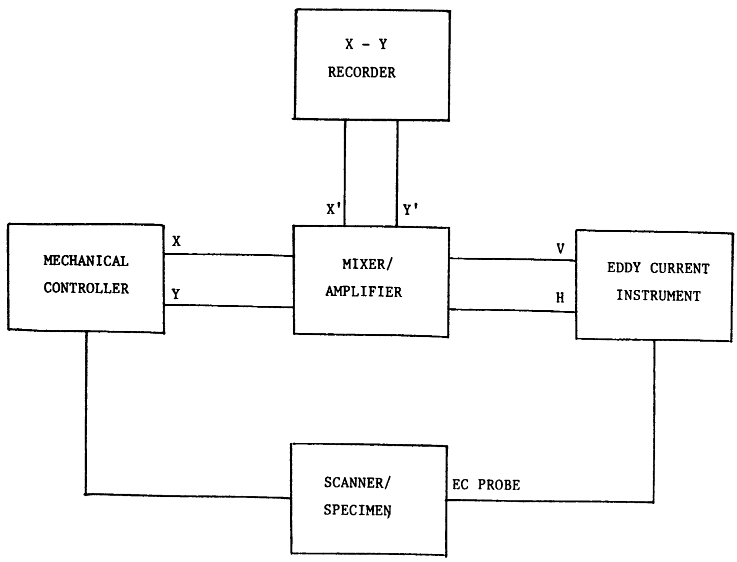

Figure 1. Block Diagram of the Eddy Current Surface Mapping System Configuration

The mechanical scan plan is programmed into the Aerotech controller with numerical control (NC) codes. The scan plan is designed to scan on X axis with the speed of 1 cm/sec and index on Y axis with 0.4 cm increments. The parameters of the NDT-25L eddy current instrument are set by nulling the system at the specimen and calibrating to a liftoff amplitude of 10 V. Experimentally, nulling the system at the specimen surface removes the dc component of the eddy current signal. This procedure enables the monitoring of signal variations with higher sensitivity.

The mechanical X and Y raster scanning voltage signals, and both vertical and horizontal eddy current signals are input to the signal mixer/amplifier assembly. The output signals from the mixer/amplifier, X' and Y' are used to drive the X-Y recorder for imaging plotting. Where X' is X plus Y cosΘ, Y' is y sinΘ plus the arithmetic sum of the two measured impedance components as described in Fig. 2. A three dimensional image is generated in real time while the probe is scanning across the surface of the specimen. In addition to an X-Y recorder which allows the real time tracking of signal variation, a grey scale amplifier can also be used to

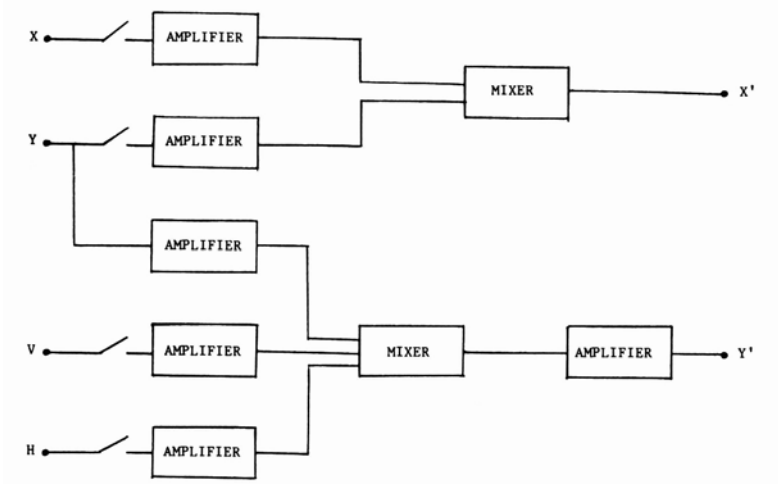

Figure 2. Functional Diagram of the Signal Mixer/Amplifier Controller

present the image. A typical result of the eddy current material surface property mapping image is shown on Figure 3. The surface structures from electrostatic-discharge machined (EDM) notches and machining features are clearly shown.

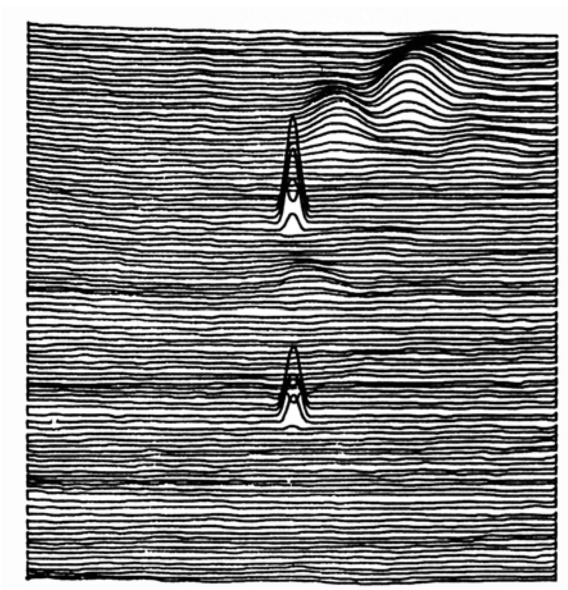

Figure 3. A typical Eddy Current Image from the Material Surface Mapping System.

RESULTS AND DISCUSSION

The results of the experiments are summarized in three technical areas: (i) "electromagnetic microscope"; (ii) surface stress mapping; (iii) defect characterization. Each subject is described and discussed as follows.

Electromagnetic Microscope

The function of a scanning electron micrscope (SEM) is to study the metallurgical structure of the surface within a few thousandths of a centimeter, while the function of an acoustic microscope (A/M) is to study the acoustic structure from a surface dead zone of about two tenths of a centimeter down to a few centimeters for most of the materials. The Electromagnetic Microscope can investigate surface and subsurface regions which cannot be investigated by either SEM or A/M nondestructively. With the use of different frequencies to vary the depth of penetration, various depths of the material electromagnetic properties can be magnified and studied. Figure 4 shows an magnified eddy current image of a 0.015 inch (0.381 mm) deep, 0.030 inch (0.762 mm) long, and 0.003 inch (0.076 mm) wide EDM notch. Figure 5 shows the "electromagnetic" grain boundary of an aluminum specimen with various grain structures.

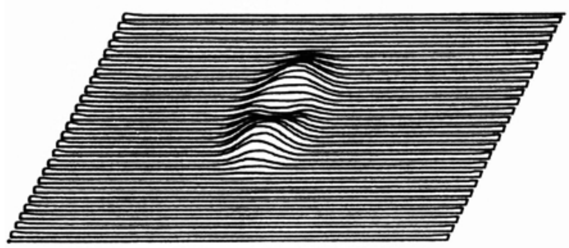

Figure 4. An Eddy Current Image of a 0.015 inch deep, 0.030 inch long, and 0.003 inch wide EDM Notch

Surface Stress Mapping

Localized static or dynamic stress concentrations generated by uneven distribution of applied and residual stresses, can cause fatigue cracks to initiate and propagate. Applied stresses and residual stresses induced changes in material properties such as acoustic and electrmagnetic parameters. Using the eddy current imaging mechanism, the stress distribution across the material surface can be easily mapped out. The localized high stress areas, i.e. potential crack initiation sites, thus can be identified and corrected to prevent the failure. Figure 6 shows an area with residual a stress distribution created by applying external stresses on legs of an H-shaped aluminum specimen.

Defect Characterization

Surface breaking defects such as porosities, fatigue cracks and electrostatic-discharge machined (EDM) notches cause an abrupt change in the secondary electromagnetic field induced in the material by an eddy current sensor. Various surface discontinuities are all different in nature. For example, a fatigue crack which is a "close" surface discontinuity has a higher frequency eddy current response than an "open" EDM notch. The shape and size of the discontinuity can also be depicted by the imaging system.

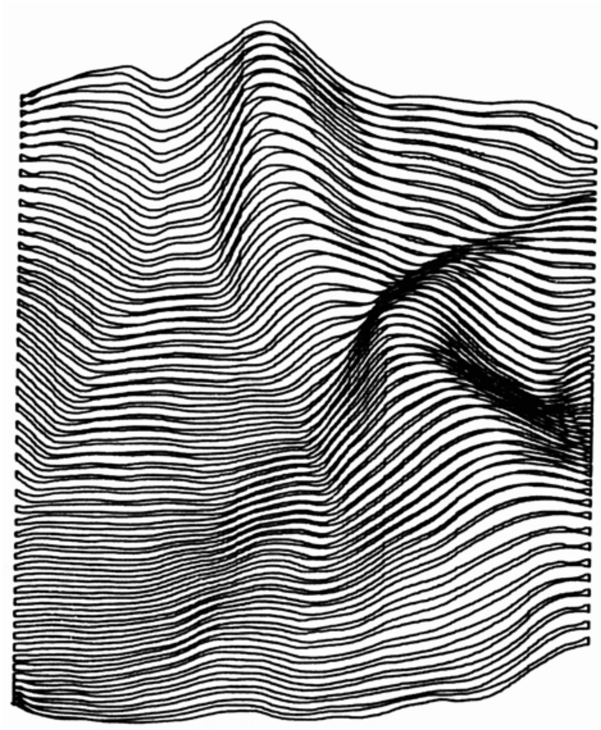

Figure 5. The "Electromagnetic" Grain Boundary of an
Aluminum Specimen with Many Grain Structires

Fatigue cracks, machining marks, and geometric features thus can be identified and categorized. Figure 7 shows the eddy current image obtained from a 0.006 inch (0.1524 mm) diameter hole on a 5/8 inch (15.875 mm) thick flat specimen. The image of a 0.024 inch (0.610 mm) fatigue crack is shown in Figure 8.

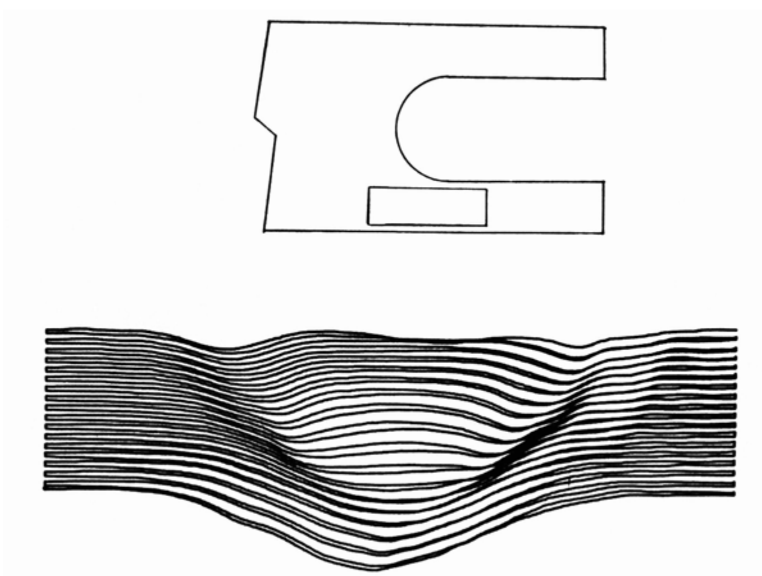

Figure 6. An Image of a Residual Stress Distribution

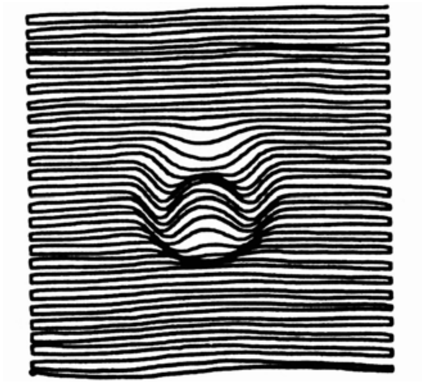

Figure 7. An Eddy Current Image of a 0.006 inch (0.152 mm) Diameter Hole on a Flat Specimen

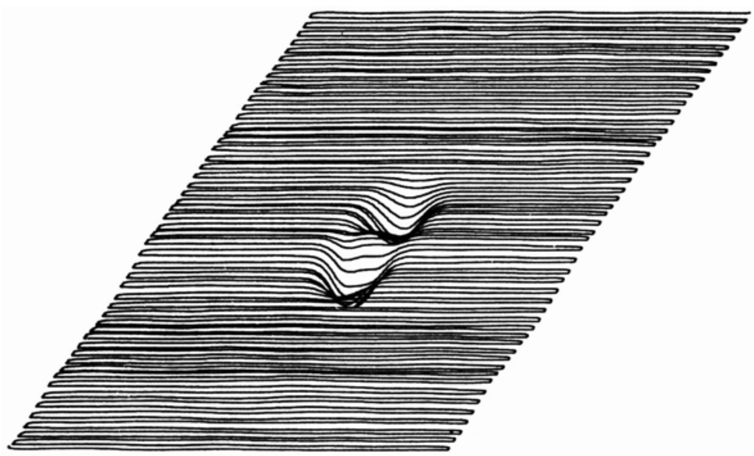

Figure 8. The Eddy Current Image Obtained from a 0.024 inch (0.610 mm) Long Fatigue Crack

The eddy current images can be presented with either the conventional grey scale approach or a continuous line X-Y 3-D approach. The continuous line approach which allows the tracking of the varying signal has the significant advantage over the conventional grey scale approach in which only discrete levels of signal amplitudes can be set and observed. The stress induced changes in conductivity and permeability are more slowly varying in nature, i.e., lower frequency, compared to abrupt continuity changes of surface breaking flaws. The system can discern stress responses from crack responses. This capability enables the prediction and monitoring of the initiation and propagation of surface cracks.

In summary, analog eddy current imaging techniques can undoubtably improve the system detection and evaluation capabilities. However, to fully utilize the capacity of imaging approach, a digital eddy current imaging system is proposed. The data storage and manipulation, imaging processing, signal enhancement, and other advanced analysis capabilities of the digital system will greatly facilitate the potential developments and applications of eddy current imaging.

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