INVERSION OF EDDY CURRENT DATA AND THE RECONSTRUCTION
OF FLAWS, PART 1: ACQUISITION OF DATA

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INTRODUCTION

Measuring the eddy currents in a material induced by an exciting field can provide useful information about the shape of the material. Several methods of nondestructive evaluation using eddy currents do not utilize a uniform exciting field over the area of interest [1]. When a non-uniform exciting field is used, the presence or absence of a flaw in the material is detected. However, some applications require more specific information about the size and shape of the flaw. If reconstruction of the flaw is required, current mathematical algorithms [2,4] require that the magnetic field due to eddy currents induced by a uniform exciting field be accurately measured. The magnetic fields can be measured by placing small inductive pickup coils in the vicinity of the material. Several different frequencies can be used to take advantage of the skin depth effect in conductors. Low frequencies can be used to look for flaws relatively deep beneath the surface; high frequencies can be used to look for "shallow" flaws.

In this project our goal is to develop a system to gather data for quantitative reconstruction of flaws in stainless steel tubing. Our sets of data are to be used by Sabbagh Associates for the purpose of high resolution inversion of the flaws and calibration of their computer model. A number of sensors are needed to span the inner perimeter of the tube. Sensors must be oriented to measure primarily the axial (parallel to tube axis) and radial (perpendicular to tube axis) magnetic field components [3]. The computer model requires that twenty five frequencies be used. A sensor spacing of approximately 0.03" in a 0.8" ID tube is required.

EXPERIMENTAL PROCEDURE

Refer to Figure 1 for a diagram of the probe assembly. A solenoidal exciting coil of approximately 4" length and 0.4" diameter was used to produce an electric field which was uniform and in the axial direction near the sensors. Eight small
sensors fabricated using a photolithographic technique were encapsulated around the perimeter of the exciting coil. Axial and radial magnetic fields were measured by suitable orientation of the sensors around the exciting coil.

Multi-channel signal conditioning circuitry was developed to amplify and measure the signals from several sensors simultaneously. Phase-sensitive detection was used to perform phase and magnitude measurement. Signals from the sensors were first preamplified, then fed into the phase detector circuitry. The phase detector produced two DC outputs, one which was proportional to the in-phase field component, and one which was proportional to the quadrature component. The two DC outputs were measured by analog-to-digital converters.

A lab computer was used to control the data acquisition by stepping the function generator through the different frequencies, selecting the proper gain setting on the mixer circuit, positioning the probe by turning a stepping motor, and recording the A/D converter voltages. The set of data was stored on floppy disk and later transferred to a larger computer for analysis.

ELECTRONICS AND SENSORS

The computer model requires using 25 frequencies in the range of 100KHz to 5MHz. The required spatial resolution limits the sensor dimensions to about 1mm x 1mm. This small sensor size limits the available signal. Amplification must be sufficient to obtain a measurable signal from a flaw anywhere in the wall of the tube. Crosstalk and other noise must be kept small enough not to interfere with the measurements.
Phase shift in the electronics must be characterized so that the data can be properly rotated to extract true in-phase and quadrature information. The computer model developed by Sabbagh Associates utilizes the in-phase, as well as the quadrature, information. A small phase error can cause significant measurement error in the smaller of the two signals.

To improve noise performance, we preamplified the signal from the inductive sensors before passing the signals to the phase detecting electronics. The preamplifier, based on the MC1733 video amplifier, gave a gain of about 40dB. The phase detector was a circuit based on the MC1596 balanced modulator IC. The overall gain of the system (peak-to-peak input to DC output) was selectable between 88dB and 108dB. Mixing signals were the voltage driving the exciting coil and the trigger signal from the signal generator. This trigger signal was 90 degrees out of phase with the exciting coil voltage. A lowpass filter at the output of the MC1596 extracted the phase information.

The sensors we used were small inductive pickup coils. Ideally such a coil is perfectly flat so that there is no pickup of orthogonal fields. The first sensors we used were hand wound from magnet wire. These sensors had a very low source impedance, so there was negligible signal loss at the preamplifier input and thermal noise was low. It was very difficult to control the geometry of the hand wound coils. The hand wound coils also were larger than the spatial resolution desired. The next coils we used were fabricated using a photolithographic technique. These sensors had a consistent geometry and were flat, and had a source impedance of approximately 100 Ohms.

Sensors oriented to sense the axial field pick up a large background field resulting from magnetic coupling to the exciting coil. This background signal limits the dynamic range of the measured signal by causing the amplifier to saturate at a low value of the exciting field strength. This problem can be overcome by using a bridge arrangement to subtract the background signal from the sensor before amplification. A large "background coil" is used to sense the average axial field inside of the tube. The background signal is subtracted from the sensor signal at the input to a differential amplifier.

Figure 2 presents a block diagram of our eight-sensor data acquisition system. We accomplish the spatial resolution by placing eight sensors on the probe and making three runs of data acquisition. Successive runs have slightly different azimuthal rotation angles. The data from these successive runs are used to obtain measurements spaced on a uniform grid near the flaw. The eight signals from the sensors are fed into a preamplifier box. Eight coaxial cables connect the preamplifiers to the phase detectors. Each of the eight phase detectors is built on a printed circuit board, and has an amplifier, an in-phase mixer, and a quadrature mixer. Each board has two gain settings, selectable by computer. A phase detector board produces two DC outputs. The sixteen DC outputs from the eight mixer boards are read by an A/D converter. A program was written to control all aspects of taking data. A photograph of the experimental setup appears in Figure 3.
EXPERIMENTAL RESULTS

We used our system to obtain axial and radial field data from several electro-discharge-machined (EDM) flaws in the 0.8" ID tube ranging in dimensions from 10 mils to 200 mils. The peak-to-peak flaw signal induced in the sensor ranged from about 25 nanovolts to a few microvolts. This resulted in DC signal outputs in the range of about 10 mV to 10 V. We present some of this data, and compare the data with calculations from a computer model developed by Sabbagh Associates.

Figure 4 shows a small flaw on the inner wall of the tube with dimensions 0.203" long by 0.019" deep by 0.022" wide. In Figure 5 we present our measured data for a frequency of 500 KHz. Figure 6 shows the corresponding computer model data.
The data plot represents the quadrature field measured beneath a section of tube 1 inch long in the axial (z) direction, and spanning 192 degrees in the azimuthal (phi) direction. We have normalized the DC outputs to correspond with the EMF calculated with the computer model. We notice a very close qualitative agreement; the experimental and the model data plots both exhibit the same characteristics. The signal magnitude is also very close to the expected; thus there is at least some quantitative agreement.

Measurements were also made using axial field sensors. The flaw used for the axial experiment measured 0.200" long by
0.039" deep by 0.020" wide. Two sets of measurements were made; one using the background coil method discussed above, and one using the unimproved axial signal. Two plots of the axial magnetic field that is 90 degrees out of phase with the exciting coil current at 500 KHz appear in Figure 7. Figure 7(a) was obtained using the unimproved axial sensor, and Figure 7(b) was obtained using the background-reducing coil. The improvement in signal-to-noise ratio is noticeable in the Figure 7(b). The axial measurements presented here agree qualitatively with the computer model calculations.

CONCLUSIONS

Our goal of flaw inversion appears to be very feasible based on the qualitative and quantitative agreement between measured data and computer model data. Further development of the inversion algorithm by Sabbagh Associates is expected to result in high resolution inversion of the flaws. Measurement of the axial signal was sufficiently accomplished by using a bridge circuit to subtract the background signal; this technique improved the signal-to-noise ratio. We noticed that the flaw signal from the radial sensor was, in general, about two to three times as large as the corresponding (for the same exciting field) axial signal. This is partly due to the fact that the sensor is much closer to the wall of the tube [3]. Flaw fields were successfully measured at different frequencies by small sensors in the presence of a uniform exciting field.
Several improvements to the system would probably improve performance and result in better data. Better cable shielding and grounding might help eliminate stray RF pickup, resulting in smaller background signals and less noise. It would also be beneficial to somehow eliminate the effect of variation in the tube diameter. Natural variations in the wall of the tube give false signals which might be interpreted as flaws. The voltage from the axial background coil could be used to monitor the exciting field strength. This might provide information about variations in the tube diameter. Perhaps changing the probe design would keep the sensors a more uniform distance from the wall of the tube. It might be possible reduce the effect of tube variations by using a bridge-type sensor arrangement. Also, digital filtering or number processing might improve the signals from the electronics for use by the computer model.

In summary, we have taken eddy current measurements to be used for high-resolution reconstruction of flaws in a stainless steel tube. Magnetic field measurements were made at many frequencies with small sensors in the presence of a practically uniform exciting field. Sensor design and electronics were developed to make the acquisition of large amounts of data feasible. Plots of the magnetic fields were compared with model calculation plots generated by Sabbagh Associates, and were found to show good promise of reconstruction.

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REFERENCES


