CALIBRATION AND CHARACTERIZATION OF EDDY CURRENT PROBES BY

PHOTOINDUCTIVE FIELD MAPPING

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INTRODUCTION

The calibration of eddy-current measurement systems is a long-standing problem in nondestructive evaluation. Eddy-current probe calibration is needed for several reasons: to compensate for different probe sensitivities, to set detection thresholds, to validate instrument setup and operation, and to perform quantitative flaw sizing. The most frequently used calibration method is to scan the probe being calibrated over simulated defects such as electrical-discharge-machined (EDM) slots, saw cuts, or laboratory-produced fatigue cracks. This method has the virtue of calibrating probe and instrument at the same time and it can be performed on the same material as that to be inspected. But it has a number of disadvantages as well. First, a large number of artifact standards must be generated, certified, and maintained, resulting in considerable expense. Second, the signals from EDM slots and saw cuts are not equivalent to the signals from actual defects. Third, it is questionable whether quantitative flaw sizing can be performed using such a calibration method. Even if laboratory-produced cracks were to be used for routine calibration (a prohibitively expensive option), the accuracy of calibration or quantitative sizing could be compromised by the occurrence of crack closure effects.

Another approach to the calibration problem is to map the magnetic field of the probe to be calibrated. Previous eddy-current probe field mapping techniques have been based on the use of Hall probes, SQUID probes and small pickup coils, and small defects of known geometry. However, these approaches suffer from several drawbacks: poor noise immunity, large sensor size, introduction of significant perturbations to the probe field, or insensitivity to the tangential component of the H field. An ideal field-mapping technique would use an infinitesimal probe of the tangential component of H that introduces no field perturbations.

Previous work by Moulder et al. has demonstrated that the photoinductive (PI) effect
may be used to map eddy-current probe fields. This method meets the requirements of an ideal field-mapping technique. In principle the technique can attain spatial resolution on the order of microns, does not perturb the incident field significantly, and is sensitive to the tangential component of the electric field. We have begun applying this technique to the mapping of commercial eddy-current probes with a view to its eventual application to probe calibration.

In this paper we describe a prototype eddy-current probe calibration instrument based on the photoinductive field measurement technique. The advantages of this electro-optical calibration method are discussed in relation to more conventional approaches. We show the correlation between photoinductive measurements of probe field strength and quantitative measurements of probe impedance changes caused by artifact standards, demonstrating the ability of the instrument to calibrate probes. We also illustrate the amount of variability to be found among commercial eddy-current probes by using the instrument to map their fields. The pronounced variability we observed in field strength among probes of identical specifications (ferrite, number of windings, inductance, liftoff, etc.) demonstrates that predicting the performance of eddy-current probes from these parameters alone is not possible. Thus, it seems that measurement of a probe's field by some means will be essential for quantitative flaw sizing. We feel that the PI technique will serve this need. It will also be useful for probe standardization and the development of novel eddy-current probe designs.

THEORY OF PHOTOINDUCTIVE PROBE CALIBRATION

The photoinductive (PI) effect has been described previously by Moulder et al. The physical principles underlying it are illustrated in Fig. 1, which shows the coil of an eddy-current probe carrying a current I placed in close proximity to a thin metal film supported on an insulating substrate. We refer to this film-substrate combination as a witness plate. A modulated laser beam is focused on the thin conductive film from below. The resulting temperature fluctuation induces a highly localized change in the conductivity of the metal foil, which in turn induces a change in the impedance of the eddy-current probe. It can be shown from Auld's reciprocity relation that this impedance change is

\[ \Delta Z = \frac{1}{\mu_0} \int \left\{ \frac{\partial \sigma}{\partial T} E^2 + i \omega \frac{\partial \mu}{\partial T} H^2 \right\} \Delta T \, dV \]  

(1)

where V is the entire volume of the metal film, E and H are the electric and magnetic field intensities in the metal film, \( \omega \) is the eddy-current frequency, \( \Delta T \) is the temperature fluctuation in the film, and \( \sigma \) and \( \mu \) are the conductivity and permeability of the film. For our experiment a gold film was used so that \( \frac{\partial \mu}{\partial T} = 0 \) and the \( H^2 \) term vanishes. In the quasi-static approximation only the tangential components of E and H contribute to Eq. 1. Furthermore, in the thin film limit (\( \tau \ll \delta \)) the values of H and E obtained are essentially those of the vacuum case.

In practice \( \Delta T \) is a function of x and y that is strongly peaked at the location of the laser beam. Thus, Eq. 1 indicates that \( \Delta Z \) is determined primarily by the values of E and H at the position of the laser spot. Therefore, the photoinductive technique permits mapping E and H with spatial resolution that is governed only by the size of the thermal spot, one of the chief
advantages of the PI technique over other methods of mapping magnetic fields.\textsuperscript{5-7} In our experimental setup the thermal spot size is on the order of 200 \( \mu \text{m} \) and the probe dimensions are on the order of several millimeters.

**PHOTOINDUCTIVE CALIBRATION INSTRUMENT**

The instrument we designed and built to demonstrate the feasibility of calibrating and characterizing eddy current probes using the photoinductive technique is shown in Fig. 2. The probe to be calibrated is clamped into a positioning fixture and then lowered until the probe face is in contact with the gold film of the witness plate. The laser source is a 0.5 W infrared diode laser, which is collimated and focused onto the gold film from below. The laser output is electronically modulated with a 50\% duty cycle square wave, variable from 1 Hz to 250 Hz.

The laser and associated optics are scanned under the stationary probe in a raster-fashion with computer-controlled stepping motors. The value of \( \Delta Z_{PI} \) for the eddy-current probe is then measured at points on a two-dimensional grid by detecting only the changes in the probe impedance which are synchronous with the laser modulation. A commercial eddyscope is used to demodulate the eddy-current impedance signal. The demodulated output of both horizontal and vertical channels of the eddyscope is then supplied to lock-in amplifiers synchronized to the laser modulation frequency (see Fig. 2). The in-phase and quadrature components of each lock-in are acquired and stored in the computer for later analysis and display.

Two modes of operation are possible with the instrument: one-dimensional scans along either of the two orthogonal axes and full two-dimensional scans of the active area of the probe. Scans of up to 50 x 50 mm may be performed, limited by the range of motion of the positioners. Although the most information about a probe is obtained with two-dimensional scans, the amount of time this requires (typically 5-30 minutes, depending on area scanned, density of points, and amount of signal averaging) is too long for routine
calibration purposes. But scans across a probe’s diameter provide sufficient information to calibrate the probe and can be performed in less than one minute.

RESULTS

We have used the photoinductive eddy current calibration instrument to study a wide variety of standard commercial probes as well as several custom-designed probes. These have included absolute, differential, and reflection probes in sizes ranging from 1.5 to 30 mm in diameter and at frequencies from 5 kHz to 2 MHz.

An example of the results obtained using this instrument in the field-mapping mode of operation is shown in Fig. 3(a). This 3-D surface plot represents the electric field distribution for a 2 MHz commercial surface probe. The general shape of the response is common to most absolute eddy-current probes: a circular pattern of current flow with a dead spot in the center, hence the term “eddy” currents. The apparent tilt at the top of the conical response surface is not expected. Nevertheless, we did observe this behavior in many of the probes we studied, although it was usually less pronounced. We believe that this tilt results from a coil that is not aligned parallel with the central axis of the probe housing. We have seen evidence in x-rays of similar probes of this occurring because of misalignment of the coil inside the probe. In other cases it is caused by the surface of the probe face not being perpendicular to the probe axis. As a practical matter, if an excessive amount of tilt is present in a probe it can cause the probe to give varying responses to a flaw depending upon how it is oriented relative to the flaw. For this reason, for critical inspections it may be desirable to discard probes with too much tilt.

![Diagram](https://example.com/diagram.png)

Fig. 2. Prototype eddy current probe calibration and characterization instrument based on photoinductive field mapping.
To demonstrate that photoinductive measurements of a probe’s field intensity are equivalent to conventional calibration procedures, it is important to correlate PI measurements of a probe’s field with measurements made on flaws. Such a comparison of an eddy-current flaw signal to PI measurements is shown in Fig. 3(b). The eddy current probe used for this comparison is the probe shown in Fig. 3(a). The eddy current flaw measurements were taken on a 1.3-mm long by 0.6-mm deep EDM notch in 7075 aluminum. The PI scan is a slice along the x-axis, through the center of the field map shown in Fig. 3(a). The flaw scan was taken with the probe in the same orientation, but with the direction of scanning reversed. Because the length of the flaw is less than the diameter of the probe, the flaw scan produces a double-peaked response. As shown in the figure, when the stronger part of the probe field is intercepted by the flaw, the eddy current signal is greater than on the other side of the probe where the relative tilt makes the field weaker. This result clearly illustrates how the flaw signal from a probe with a tilted coil can produce different results on the same flaw depending upon the orientation of the probe.

One of the key findings of our study of commercial eddy-current probes is the wide variability we observe in the electric field intensity of nominally identical probes. This is demonstrated in Fig. 4, which displays the field maps obtained from a series of six commercial 2-MHz surface probes purchased from the same manufacturer at different times over the last five years. The peak field intensities of the strongest and weakest probes among these six vary by 240 percent. According to the manufacturer, the probes were built to the same specifications: type of ferrite, number of turns, inductance, etc. Clearly, the performance of
these probes could not have been predicted from these parameters alone. Among other series of probes we examined the variation was not as great. For example, for a set of six 100-kHz surface probes purchased from the same manufacturer over the same period of time, the maximum variation in peak PI signals was about 37 percent.

Results from further studies of the correlation between PI measurements and flaw signals are shown in Fig. 5. Results from the two sets of commercial eddy-current probes discussed above are shown in the figure. One set is composed of 2 MHz surface probes, the other set is composed of 100 kHz surface probes. For the former set, the peak PI signal is plotted against the peak eddy current signal from a 1.3-mm long EDM notch. For the latter set of probes, the peak PI signal is plotted against the peak eddy current signal from a 2-D EDM slot 0.5 mm deep. The lines plotted in the figures are linear least-squares fits to the data. The linear response functions evident in Fig. 5 are further support for the conclusion that the photoinductive field measurements obtained with this instrument are suitable for calibration of eddy current probes.

Fig. 4. Comparison of field maps of six commercial eddy current probes, obtained from the same manufacturer at different times over a five year period.
Fig. 5. Correlation of peak photoinductive signals with peak flaw signals for two sets of probes. Left, six 2 MHz surface probes; right, six 100 kHz surface probes.

SUMMARY

This report has described the design and operation of a prototype eddy-current probe calibration instrument based on photoinductive mapping of the probe's electromagnetic field. Since the calibration method is electro-optical in character, calibration can be accomplished quickly and reliably under computer control. The method offers a means to determine the electric field intensity of eddy-current probes, a quantity that is directly related to their performance for flaw detection and characterization. Since the eddyscope that is used with the probe for flaw detection is used in the calibration circuitry, both the instrument and the probe are calibrated. Besides revealing the strength (or sensitivity) of a probe, this new method also can reveal defective probes by the overall shape and symmetry of their fields. This information is not available from ordinary calibration methods.

We have used our prototype instrument to study a wide variety of eddy-current probes, both commercial and custom-designed probes. The results demonstrate that the features of photoinductive field maps of the probes correlate well with the qualitative features of eddy current signals obtained from EDM slots. We have also demonstrated the ability of the instrument to detect imperfections in the eddy-current probe fields such as tilt. Quantitative correlation between PI field maps and eddy-current flaw signals has been demonstrated for two separate families of probes. The transfer function between PI signal strength and flaw signal is linear and this shows that PI signals can be used to calibrate the response of eddy-current probes to flaws.

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