

A SELF-CALIBRATING EDDY-CURRENT INSTRUMENT

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INTRODUCTION

The calibration of eddy-current measurement systems is a long-standing problem in nondestructive evaluation. Calibration serves a number of purposes: for equipment setup and validation, for equalizing responses from different probes and instruments, for setting detection thresholds, and for quantitative flaw sizing. The most commonly used calibration method is to scan the probe to be 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 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 in the typical inspection organization; this can result in considerable expense. Second, the signals from EDM slots and saw cuts are not equivalent to the signals from actual defects, as discussed in another paper in these proceedings [1]. Third, quantitative flaw sizing can only be accomplished over a limited range with such calibration methodology, and the accuracy of sizing flaws with this method is brought into question by the aforementioned inequality of slots and cracks. Even if laboratory-produced cracks were to be used routinely for calibration (a prohibitively expensive option), quantitative sizing could be compromised by the occurrence of crack closure effects [2].

Other methods have been suggested in the past, but they have not found wide acceptance in the NDE community. These include electrical calibration with a small resistance in series with the probe to be calibrated [3], quantitative calibration by comparing theoretical calculations with measurements of either liftoff or EDM slots [3], and mapping of eddy current probe fields with magnetic field sensors such as SQUIDS, Hall probes, or search coils [4].

The possibility of using the photoinductive (PI) effect to map probe fields for calibration purposes was first discussed by Moulder et al. [5]. The PI effect is the small change in the impedance of an eddy-current probe caused by laser-induced temperature fluctuations in conductive materials. Because the laser can be focused to a very small point and does not significantly perturb the eddy-current probe's field, it is an ideal method for mapping probe fields. Application of the PI effect to eddy-current probe field-mapping is the subject of another paper in this volume by Hughes et al., which also provides a brief review of the theoretical basis for the photoinductive effect in thin conductive

films [6]. In that paper, the correlation between PI signals and eddy current flaw signals is demonstrated, establishing the basis by which an instrument based on the PI effect could be used to calibrate eddy current measurement systems (both probe and instrument).

In this paper we describe a prototype calibration instrument based on the photoinductive effect. Because the calibration instrument incorporates the eddyscope in the signal acquisition circuitry, calibration of an eddy-current probe also calibrates the eddy-current instrument. Since the calibration feature is designed into the eddy-current instrumentation, we call this instrument a self-calibrating eddyscope. First we discuss three possible approaches to carrying out calibration of an eddy-current probe using the PI effect. Then we show preliminary results obtained using the prototype instrument to accomplish this objective.

APPROACH

A ΔZ equation derived from reciprocity relations describes an eddy-current probe's response to localized laser heating of a thin conductive foil [5,7],

$$\Delta Z_{PI} = -\frac{1}{I^2} \int \Delta T \left(\frac{\partial \sigma}{\partial T} E^2 + i\omega \frac{\partial \mu}{\partial T} H^2 \right) dV, \quad (1)$$

where ΔZ_{PI} is the change in probe impedance, I is the probe excitation current, ΔT is the laser-induced temperature change in the foil, σ is the conductivity of the foil, μ is the permeability of the foil, ω is the eddy current frequency, and E and H are the electric and magnetic fields in the foil. This equation shows that the electromagnetic fields in a thin foil produced by an eddy current probe may be determined by observing the thermally induced change in probe impedance. Furthermore, for thin, non-magnetic, conductive foils, theory predicts that these probe impedance changes are directly proportional to changes in the squared electric field intensity.

It is well known that the shape and intensity of the electromagnetic fields incident on a flaw in a conductive material control the eddy-current probe's response to the flaw [8,9]. The relationship is given by Auld's reciprocity formula:

$$\Delta Z_{FLAW} = \frac{1}{I^2} \int (\vec{E} \times \vec{H}' - \vec{E}' \times \vec{H}) \cdot \hat{n} dS, \quad (2)$$

where ΔZ_{FLAW} is the flaw-induced change in probe impedance, I is the excitation current, \hat{n} is a unit vector normal to the surface of integration, and \vec{E} and \vec{H} are the incident electric and magnetic fields, where primed quantities refer to the fields in the presence of the flaw and unprimed quantities refer to fields without a flaw present. As this equation shows, knowledge of the fields incident on a flaw of known shape is sufficient to determine the flaw signal. Thus, if we can use the PI effect to determine the intensity and distribution of a probe's electromagnetic field, it will provide enough information to predict the flaw signals that would be produced by the probe. Although the PI measurement will provide only the square of the electric field (therefore being insensitive to the direction of the field), in most cases the symmetry of the probe will enable this information to be inferred. Knowing the electric field, it is possible to recover the magnetic field intensity from Maxwell's equations. Because both the photoinductive signal and the flaw signal are dependent on the electromagnetic field of an eddy-current probe, measurement of the PI signal will, in principle, provide the same information that would be obtained by measuring the signal from a calibration artifact standard.

We have examined three different approaches to the problem of eddy-current probe calibration using the PI effect. The first approach we considered was to use a theoretical inversion scheme to obtain a simulated eddy-current flaw scan. Calibration would be based on a first-principles derivation of absolute field intensity from the ΔZ equation for laser-induced perturbations (ΔZ_{PI}), followed by a theoretical prediction of flaw signals using the ΔZ equations for ordinary, flaw-generated perturbation (ΔZ_{FLAW}). Such an approach would have the advantage of full quantitative calibration based on absolute physical quantities. However, a calibration method based on inference of the absolute field intensities is neither practical or desirable in most cases. Determining the incident fields for a particular workpiece of arbitrary shape and conductivity from the PI signal is not a trivial computation, nor is the calculation of flaw signals from the incident fields. Such computations are possible, but at the limits of the state of the art. Hence, a calibration device intended for field applications that depends upon extensive computations is not attractive or practical.

The second approach we considered is based on the idea of using the PI measurement as an electronic transfer standard. In this approach each eddy current probe would be used to measure a traditional calibration standard such as an EDM notch, then the same probe would be characterized by measuring its PI signal. A comparison of ΔZ_{FLAW} and ΔZ_{PI} would then provide magnitude and phase adjustment factors that could be used in future calibrations. Essentially, this first measurement comparing flaw and PI signals for the probe would characterize the transfer function that relates PI signal to flaw signal for a given EC measurement system and one particular flaw. This measurement would only need to be performed one time or, at most, at infrequent intervals. After the transfer function has been determined, only a single PI scan is required to completely calibrate the eddy-current probe.

This approach, whereby each probe is calibrated on a case-by-case basis, is the most general method because of its ability to calibrate any probe that can currently be calibrated using standard methods. The drawbacks to this approach manifest themselves in the need to make eddy-current flaw scans for each and every probe. This means that it will be necessary to maintain an inventory of artifact standards, although the number required might be less than the number presently maintained. Furthermore, unless the flaw scanning procedure is automated, the requirement to scan a flaw could introduce error into the calibration caused by human factors.

Some questions about the implementation of the case-by-case method remain. Foremost among these is the question of how to select an appropriate artifact standard to determine the transfer function. It seems likely that the best procedure would be to select the smallest flaw that needs to be detected for calibration purposes, and then the gain settings for larger flaws could be derived from empirical studies of the relative magnitudes of flaw signals. However, measurement accuracy would be limited somewhat by calibrating on extremely small flaws. Thus, it remains to define the best procedure if only one flaw is to be used.

Another issue that needs further study is the question of whether the electronic transfer standard measured for a particular probe can be used for nominally identical probes of similar manufacture. Preliminary evidence suggests that it may be sufficient to choose one probe from a particular family with which to make eddy-current flaw scans. Then all other probes in the same family could be calibrated with PI measurements alone.

The third approach to eddy-current calibration we have considered is to develop an empirical model for the functional relationship between PI signal and EC flaw signal for any probe. This model would represent the transfer function from PI probe measurement space to eddy-current flaw measurement space, embodied in a response function. Such a model would obviate the need for any flaw measurements on the part of the end user, but would require a large number of measurements to adequately determine the response function. In practice, the eddy-current flaw measurement space has many more dimensions than PI space. This raises the need for a

statistically determined set of eddy-current flaw measurements in order to cover the necessary parameters with the fewest possible experiments. Such a set of experiments has been designed and is presently being carried out in our laboratory.

IMPLEMENTATION

Figure 1 depicts the instrumentation used to detect and process photoinductive signals. This detection system uses a commercial eddyscope, two lock-in amplifiers, and a simple two-axis scanning stage controlled by a personal computer to acquire data in raster scan fashion. The equipment is capable of obtaining two-dimensional electric field intensity maps of all types of eddy current probes at any frequency attainable by the eddyscope; probes studied to date include absolute, differential, and reflection type probes. An example of this type of field map for a 100 kHz absolute eddy current probe is shown in Fig. 2. By using the eddyscope together with the probe in the calibration instrumentation, both the eddyscope and the probe are calibrated at the same time.

For the purposes of routine probe calibration, we have found that complete field maps require too much time to complete (15-30 minutes). It is much quicker to acquire one-dimensional profiles of the probe's field by scanning the laser in orthogonal directions across the probe face. This type of scan requires very little time (on the order of 2-3 minutes) and produces much less data for analysis, although the information so obtained is sufficient for calibration purposes. Figure 3 shows the results of such one-dimensional scans of three commercial eddy current probes.

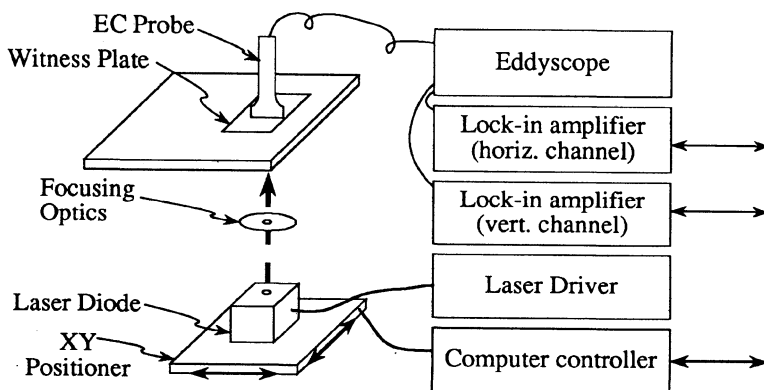


Fig. 1. The benchtop PI measurement system.

To demonstrate that photoinductive measurements of a probe's field intensity can be used for calibration, it is important to correlate PI measurements of a probe with corresponding flaw signals. Such a comparison of eddy-current flaw signals and PI measurements is shown in Fig. 4. The eddy current probes used for this comparison are commercially available 2 MHz probes; eddy current flaw measurements were taken on a 3-mm long EDM notch in titanium. Peak signals from these measurements were normalized and then plotted against each other to show the correlation between PI and flaw signals more explicitly. These results are shown in Fig. 5. Within the estimated imprecision of the measurements, the results are consistent with a linear transfer function. Further studies of the correlation between PI measurements and flaw signals are underway.

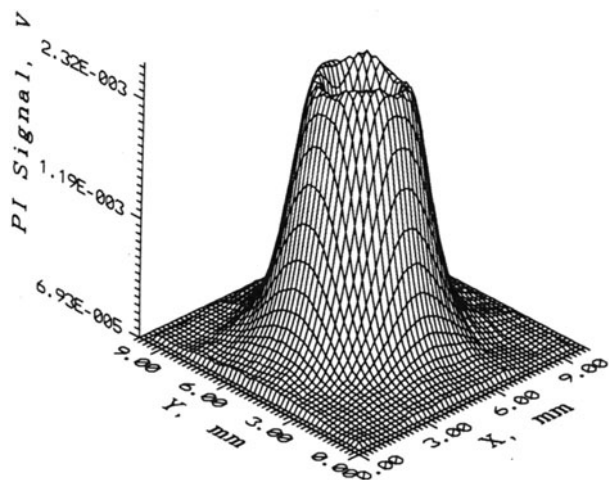


Fig. 2. Example of a complete field map of a 100-kHz commercial eddy current probe.

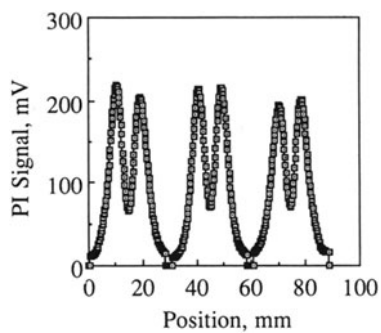


Fig. 3. PI scans of three 100-kHz eddy-current probes.

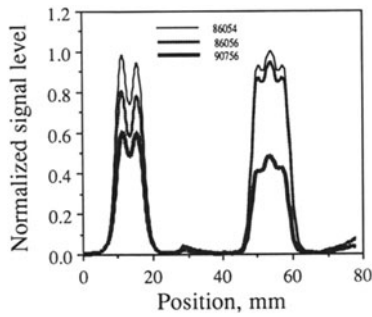


Fig. 4. Comparison of PI measurements on three nominally identical probes with eddy-current flaw scans using the same probes. Eddy-current results were obtained using an EDM notch in titanium.

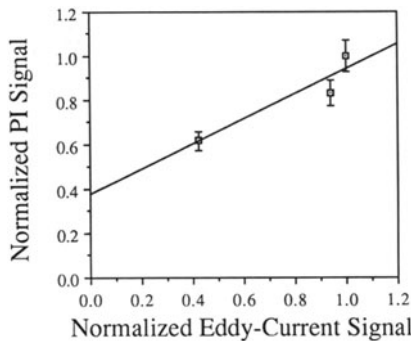


Fig. 5. Correlation of normalized peak eddy-current flaw signal with normalized peak PI signal taken from measurements shown in Fig. 4. The straight line in the figure is a least-squares fit to the data.

CONCLUSIONS

We have examined three different approaches to calibrate eddy current probes using the photoinductive technique. The first approach we considered was a theoretical inversion scheme in which the PI signal yields the approximate free space electromagnetic field intensity and distribution. This approach is difficult to implement owing to the lack of an exact PI inversion method that could be linked with a forward eddy current theory applicable to all probes. The second approach considered was a case by case method in which each eddy current probe would be scanned over a flaw standard one time to establish the transfer function for this probe. Subsequent routine calibrations would then only require a PI scan. Although this method has no fundamental obstacles to implementation, we judged it to be cumbersome owing to the requirement that both eddy current and PI measurements must be made for the initial calibration of each probe. Furthermore, this method would still rely on artifact standards to some extent. The third approach we considered was to use an empirical model to predict the eddy current signal from a given PI measurement. This method is the most attractive because it is simple to implement and yet it provides the flexibility to handle a wide range of probe designs as well as different materials and flaws. Work is continuing on the second and third approaches.

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