

A LINEAR EDDY-CURRENT ARRAY  
DRIVEN BY A WHIP EXCITATION

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IDENTIFICATION OF THE PROBLEM

In eddy-current inspection, it is often desirable to use an array of sensors. An array can alleviate problems such as excessive scanning time and difficulties in positioning the sensors. Our "whip" excitation source, a single loop of wire carrying current, is used to excite a workpiece for an eight-sensor array of air-core, inductive, pancake coils. The whip is designed such that it produces an excitation similar to that produced by a single uni-directional wire carrying current. This design is accomplished by forming a loop of rectangular cross-section, placed tangentially to the surface of the test material. Figure 1 shows a conceptual drawing of the whip excitation. Due to its proximity to the test material, the closest side of the whip to the material has a much greater excitation effect than the current's return path.

A number of different types of sensors have been used with the whip excitation, all air core pancake coils. Small sensors can be made by hand winding a few turns of small gauge wire into a spiral. Larger sensors are best made on etched printed circuit board: the sensor geometry and uniformity are very easy to control. Small sensors provide higher resolution measurements, but they often are unable to provide a high-level signal. If the signal is excessively weak, noise factors, such as stray signal pickup from the wire leads, can cause poor results. The sensors are placed along the whip, between the whip and the sample. Our setup can handle eight sensors, each providing a signal to a separate channel in our amplifier system.

The array has been exercised on various samples in the laboratory, and some results are presented here. Though the whip array can theoretically be applied to a number of different material types and geometries, it works best for a flat plate made of a good conductor. Anisotropic materials are also good for the whip: the whip excites currents in a single direction, so the whip can be oriented in the direction of the conductivity of interest. Our data acquisition system consists of the sensor hardware, including the whip and associated sensors, and an eight-channel synchronous amplifier system, controlled by a PC computer. Some difficulties exist when using an array; for example, it often becomes necessary to adjust the data for phase, gain, noise, and drift differences in the sensors, as well as nonuniformity in the

exciting field. We describe the characteristics of the whip excitation in terms of frequency response and field uniformity, and we present our methods for dealing with the sensor variations mentioned above. Advantages are numerous; for example, using the eight-sensor array in our laboratory setup increased our effective scanning speed by approximately a factor of eight.

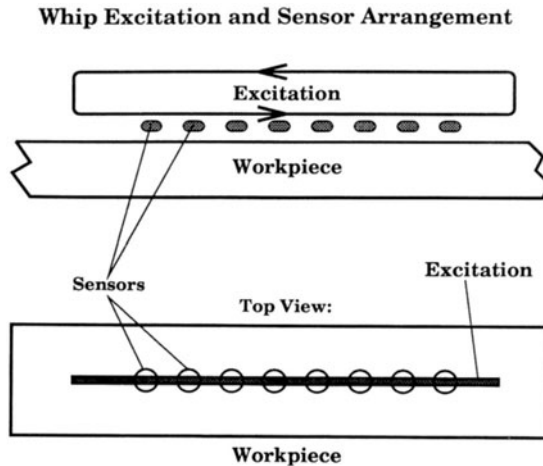


Figure 1. Conceptual drawing of the whip excitation.

#### ADVANTAGES AND DISADVANTAGES OF USING THE ARRAY

The whip array, presumably as with any array, speeds up measurements by providing multiple data points for each position in the scan sequence. An array with a large quantity of sensors might not require positioning at all: it might cover the entire region to be scanned. The whip excitation offers several additional advantages. One whip excitation can provide the excitation current for an essentially unlimited number of sensors -- the only limiting factors are the length of the whip and the size of the sensors. Sensors placed along the whip are oriented with axes normal to the surface of the test material. Thus, the background magnetic field is positive on one side of the whip and negative on the other side, so moving the sensor back and forth gives one the ability to "zero" the background signal, providing bridge-like results without the complexity of a bridge circuit. A conceptual drawing of the sensor positioned beneath the whip is shown in Figure 2.

Another advantage of the whip is that it is relatively simple to model on computer: it can be roughly approximated by a single line of current. A slightly better model takes into account the current return path. Assuming that the sensors are placed near the middle of the whip, and not near the ends, the portion of the whip normal to the test material (the "ends") can be ignored.

Finally, the directed current inherent in the whip can be utilized as an advantage under certain conditions. For example, cracks in isotropic

## Pancake Sensing Coil And Background Field

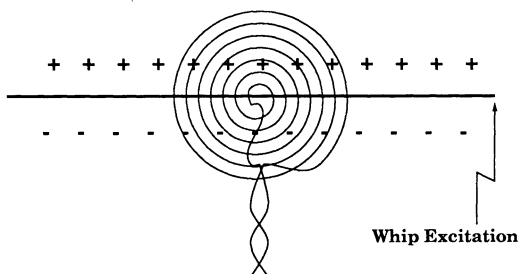


Figure 2. "Zeroing" the background field in a sensor excited by a whip.

materials can be most easily detected by orienting the excitation current in the planar direction normal to the direction of the cracks. In some cases, it may be known in advance which direction cracks will form, and in those cases, the whip would be an excellent way of exciting eddy currents for inspection. A stressed plate, for example, might tend to crack across the bending region, and the whip could be oriented to detect those cracks. In anisotropic media, the directional current induced by the whip can also be used. For example, it may be desirable to excite certain layers or directions in the current while essentially leaving the transverse-fiber direction alone.

Arrays, in general, have the disadvantage of placing more demand on the electronics. To process signals from multiple sensors, multiple amplifiers or multiplexing of signals is required. The whip also has a few specific disadvantages that may not be associated with other types of arrays. The various sensors in the array tend to have differing background offsets and phase-gain characteristics: correction for background, phase, and gain discrepancies between channels is therefore required. The whip excitation also tends to be large, and therefore has a relatively high inductance. High inductance affects the high-frequency measurements by introducing resonance at a relatively low frequency. High inductance also puts more demand on the frequency generator driving the excitation. The directional current inherent in the loop can be a disadvantage. Cracks in current direction are difficult to detect. As stated above, to most effectively detect cracks using the whip, the orientation of the cracks must be known ahead of time. Finally, the whip produces a non-uniform excitation field. The length of the whip must be chosen so that there is an acceptable variation along the portion occupied by sensors. The longer the whip, the more uniform the field becomes near the center. Long whips can cause edge effect problems since the inductance of the whip changes when part "hangs" over the edge of the sample.

### COMPUTER MODEL

To model the field from the whip excitation, we use a mathematical model based on Maxwell's equations. With the model, we compute the electromagnetic fields within graphite-epoxy and other materials [2]. Our model is derived from a matrix form of Maxwell's equations in the FFT domain ( $k$ -space) by performing a 2-dimensional FFT in the  $X$  and  $Y$  directions, in the plane of the material. It has been shown to be general enough to accommodate many

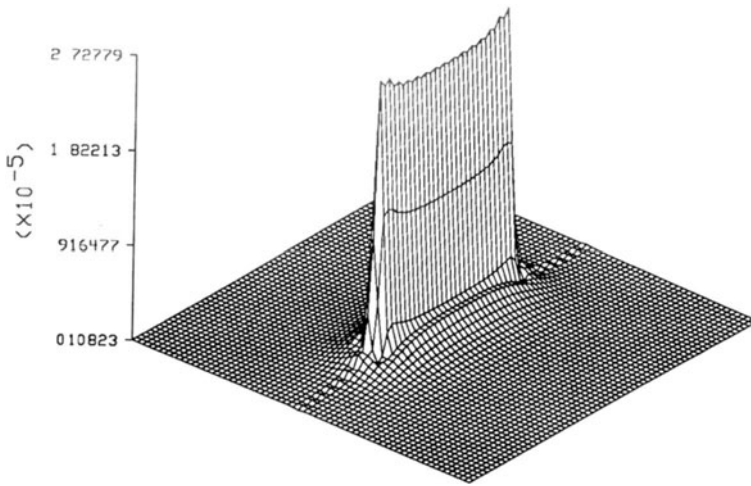


Figure 3. Model-calculated electric field in test material beneath whip.

different types of conductors and excitation geometries. The theory behind the model and its extension to ferromagnetic core probes is presented in [1]. We define the  $X$  and  $Y$  directions to lie in the plane of the slab of modeled material; the  $Z$  direction is normal to the surface. A number of model calculations were performed using various values for the whip geometry, distance from sample, and sensor (field point) spacing. The field was calculated at the  $Z$  value of the sensors, on a grid of points in  $X$  and  $Y$ .

One such computer model calculation is presented in Figure 3. Figure 3 shows, as a floating horizon three-dimensional plot, the electric field calculated by the model software. Near the center section, the electric field is fairly constant, meaning that the material is excited with approximately the same current for all sensors placed beneath that section of the whip. The electric field plot is proportional to the magnitude of the eddy-current induced in the material. Figure 3 also demonstrates that the field is very localized beneath the whip.

#### ACQUIRING DATA WITH THE WHIP ARRAY

Data points measured with the whip array can be acquired by "sweeping" the array across the test material and recording values at each stop. By "sweeping," we mean scan over the test material in a direction perpendicular to the whip orientation. At discrete intervals along the scan, readings are made from the sensors. In many cases, these data are not at a high enough resolution. The resolution can be increased by reducing the size of the sensor and packing more sensors into the same area or by "multi-scanning" the array. "Multi-scanning" the array is accomplished by sweeping the array as mentioned above, moving the array to a new position, and repeating the sweep. The process of moving the array and sweeping can be repeated to obtain data at the desired resolution. For example, one array of sensors that we actually used is shown in Figure 4, which is an array of eight sensors, arranged with a distance of 0.6 inches center-to-center. The eight sensors, when swept across the test material, cover an area of 4.8

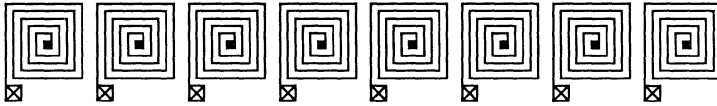


Figure 4. An array of eight sensors covering a 4.8 inch region.

#### Fine-Resolution Scanning with Widely-Spaced Sensors

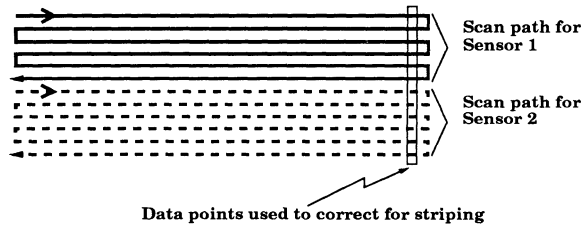


Figure 5. "Multi-scanning" concept: scan-translate-scan...

inches, with data points separated by 0.6 inches. If we wish to measure at 0.1 inch spacing, the array is first swept across the sample, recording values at each 0.1 inch stop. Then the entire whip/sensor assembly is moved over 0.1 inch, and the process is repeated. "Multi-scanning" is conceptualized in Figure 5. When the move/sweep process is repeated four more times (a total of six sweeps), the array covers roughly the same area as the single sweep, but in 0.1 inch increments rather than 0.6 inch increments. In this example, each sensor in the array is responsible for a "stripe" of data, six data points wide.

The multi-scan method allows one to make measurements at a finer spacing than the sensors in the array. This capability is particularly useful when it is not possible to pack the sensors close enough together: data can be acquired at a higher resolution than the sensor spacing. Also, "multi-scan" mode can be used to refine the measurement. After detecting a possible flaw area in "coarse" mode, the region of interest can then be re-scanned at a closer spacing.

One ill side-effect of using multiple sensors is that "striping" results from differences in sensor background signals and amplifier gain and phase performance. There are a number of reasons for signal differences between sensors:

- differing position of sensors relative to whip
- "stray" capacitance from placement of wires
- crosstalk
- non-uniform excitation field
- amplifier phase/gain characteristics
- differences sensor-to-sensor
- edge effects from non-infinite test setup.

A number of techniques can be used to deal with the above problems. The field from the excitation source can be made more uniform by increasing its length (at the expense of frequency response). Differences in excitation field might also be adjusted in software an amplitude difference. Crosstalk and stray pickup can be minimized by carefully routing and shielding the sensor wires, and the overall effect can be minimized by using sensors that provide a higher level signal. Sensors can be made more uniform by etching them on PC boards or otherwise creating sensors from a pattern. Edge effects can often be eliminated by correction in software.

## Correcting Data for Background Offset

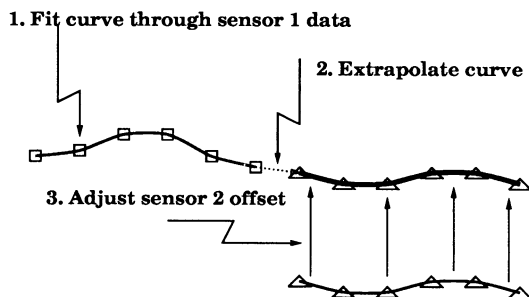


Figure 6. Correcting for offset differences in software.

It is possible to correct in software for striping caused by gain, phase, and offset differences. We have developed a straightforward technique. Firstly, the phase and gain characteristics of the individual channels of the amplifier are determined. The characteristics are determined by experiment. Secondly, the background signal is determined for each sensor in the array, relative to its neighbor. The background is determined by curve fitting and averaging, as illustrated in Figure 6. Finally, these characteristics are used in conversion software that calculates new data normalized to a constant gain, phase, and offset.

Figure 7 shows, as a grayscale image, data collected with an eight-sensor array and whip excitation, before correcting for "sensor striping" in software. Figure 8 shows the same data as Figure 7, after correcting for gain, phase, and offset differences between the different sensor channels. In the lower right corner of each image, there is an impact damage spot caused by hitting the sample with a hammer. Though the impact damage is visible in both figures, it is more pronounced in the processed data. Other features are also more apparent in the processed data, such as "tow" signals [3, 4] and fiber orientation. Note that the lower stripe, belonging to the sensor on the end of the array, did not perform well. This was probably due to a "loose wire" or other failure in that channel.

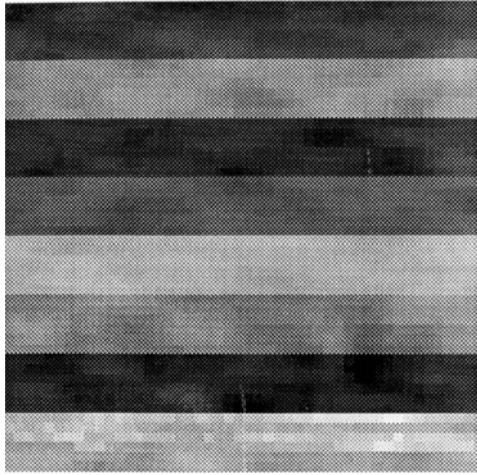


Figure 7. Graphite-epoxy material with ‘hammer bash’ in lower right corner, before correcting for sensor ‘striping.’

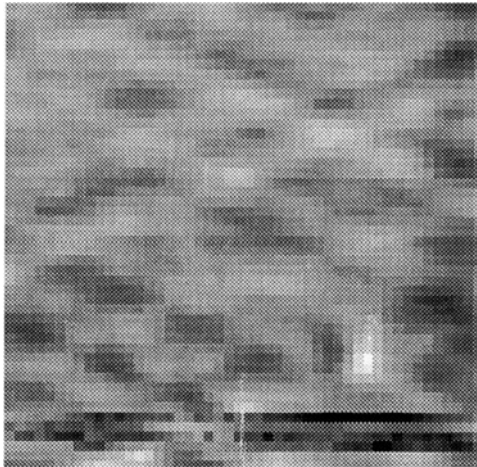


Figure 8. Graphite-epoxy material with ‘hammer bash’ in lower right corner, after correcting for sensor ‘striping’ in software.

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