FERRITE CORE EDDY CURRENT PROBE MODEL: DESCRIPTION AND VERIFICATION

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INTRODUCTION

A model of eddy current probes with ferrite cores has been developed. The model is applicable to axisymmetric cores in the vicinity of a conducting half-space (the work piece). The model is based on modern methods of computational electromagnetics, and is intended to provide a systematic and rational basis for the design and characterization of probe coils. Eddy current responses of four probes on an aluminum workpiece were predicted by the model and compared with experimentally measured responses.

MODEL DERIVATION

Initially in deriving the model, the ferrite core was replaced by an equivalent controlled source of Amperian currents, which, together with the true current in the exciting coil, comprise the total source of the electromagnetic field. The field is expressed as an integral over the regions occupied by the source currents, i.e., the core and coil. The integrand is a vector function of two arguments: one the source point occupied by the currents, the other the field point at which the electromagnetic field is to be evaluated.

The amperian source current density is directly related to the magnetization of the ferrite core, but this current density is not known a priori because it depends on the value of the field at the source point. Hence, the equation for the unknown Amperian source current density is an equation whose unknown appears both outside and inside an integral operator. This integral equation is reduced to an algebraic system by the method
of moments\textsuperscript{1}, and is then solved using a linear equation solver. In applying the method of moments, piecewise constant functions were used both for expansion of the unknown field variables and for testing. Having the Amperian and true currents, the electromagnetic field can be computed at any point of space, including within the workpiece, by straightforward integration. In addition, the driving-point impedance of the coil and core can be computed as a function of frequency at any lift-off.

The results of such model-computed impedances are presented below and also compared with measured values. The derivation of the integral equation and other analytical matters are discussed in the second reference\textsuperscript{2}.

Fig. 1. Schematics of the four probes used to test the model.
RESULTS OF SOME MODEL CALCULATIONS

The model was applied to the four probes shown in Figure 1. All of these coil-core combinations are axisymmetric, with the axis shown as a dashed line.

The first combination consisted of a coil wound around a bobbin, with the ferrite core absent, whereas the second consisted of the same coil wound around a hollow cylinder. The final two combinations consisted of the same coil wound around a cup core, the only difference between the two being the position
of the lip of the bobbin; in cup core (A) the lip is in ("lip in"), whereas in (B) the lip is out ("lip out"). In all of these combinations, the workpiece, which is not shown, is at the top of the figure.

Figure 2 shows the \( \mathbf{B} \)-field within the cylinder when the workpiece was absent (the coil-core combination is then said to be "in air"). Figures 3 and 4 show the \( \mathbf{B} \)-field within the two cup cores when they also were in air. In all of these figures \( \mathbf{B} \) had the correct variation from cell-to-cell; within each cell, of course, it was constant, because of the use of piecewise constant expansion functions in the method of moments.

When the coil-core combination was "in air" the quadrature component of the time-harmonic fields vanished. Hence, the field lines drawn in these figures are for the real part only. Had the field been sketched when the coil-core combination was in the vicinity of the workpiece, it would have been necessary to show both the real and quadrature components.

To verify the correctness of the \( \mathbf{B} \)-field variation, an estimate of the divergence of \( \mathbf{B} \) was computed using finite differences. At each of the points at which this was done, the divergence was close to zero, at least within the tolerance established using piecewise constant expansion functions.

The driving point impedances of the coil-core combinations also were computed as functions of frequency when the workpiece was present. Lift-off was zero for all combinations except the coil, alone, for which the lift-off was approximately 0.022". The results are shown in Figures 5 – 8. In all cases the frequency response showed the correct behavior of a coupled system in which all bases are in the "secondary" (the workpiece).

EXPERIMENTAL VERIFICATION

Experimental Procedure

Eddy current responses from the four probes shown in Figure 1 were measured with a Hewlett Packard Model 4192A LF Impedance Analyzer. The impedance and phase angle values were measured at five frequencies from 10 KHz through 1 MHz. The measurements were made for each probe, both with the probe in air and on the workpiece. The resistance and reactance (in-phase and quadrature components) were calculated for each data point.

Experimental Results

The resistance vs reactance curves for the four probes on the workpiece are shown in Figures 5 through 8 where they are labeled "Experimental".
Fig. 3. Sketch of B-field in cup core (lip in), in air.

Fig. 4. Sketch of B-field in cup core (lip out), in air.
Discussion

The predicted values of the reactive component were within 10% of the measured values for all four probes at all frequencies except for the Cup Core-lip in configuration where the predicted value was about 12% greater than the measured value.

The predicted resistance values were within in 8% of the measured values at lower frequencies. However, above 100 KHz there was an increasing separation with frequency between the predicted and measured values. These differences between the values predicted by the model and the experimental values were attributed to the fact that the model was "lossless"; i.e. it did not take into account losses in the coil or ferrite cores.

MODIFICATION OF THE MODEL

Because the model was "lossless" it was necessary to determine the coil losses and the core losses and to add these values to the resistance values predicted by the model. The differences between the predicted values and measured values were within experimental error at 100 KHz and below, so the predicted values were modified only at 500 KHz and 1 MHz.

Determination of Coil Losses

The differences between the DC resistance of the coil alone (air core) and the measured resistance of the coil in air at 500 KHz and 1 MHz were taken to be the coil losses at those frequencies. When these experimentally determined coil losses were added to the predicted values on the workpiece, the resulting values (modified predicted values) were within 4% of the measured values. (See Figure 5.) Prior to modification, the predicted values at 500 KHz and 1 MHz were 58% and 74% less than the measured values.

Determination of Core Losses

Resistance due to hysteresis in the cores was estimated using data supplied by the manufacturer and were also calculated using the experimental data. The resistance values so obtained were added along with the coil losses to the resistance values predicted by the model. The resulting modified predicted values are shown in Figures 6, 7 and 8.

Experimental Determination of Core Losses. The core plus coil losses were found by subtracting the DC resistance of the coil from the resistance values measured at 500 KHz and 1 MHz for each probe in air. These values were added to the values predicted for the probes on the workpiece. The resulting values
Fig. 5. Resistance vs. reactance curves for air core probe on the workpiece.

Fig. 6. Resistance vs. reactance curves for the cylindrical core probe on the workpiece.
Fig. 7. Resistance vs. reactance curves for the cup core (lip in) probe on the workpiece.

Fig. 8. Resistance vs. reactance curves for the cup core (lip out) probe on the workpiece.
were within 5% of the measured values for the cup core. The modified predicted resistance values for the cylinder were within 20% of the experimental values. The unmodified predicted resistance values were 50% and 25% of the measured values at 500 KHz and 1 MHz, respectively.

Theoretical Determination of Core Losses. The values for the effective resistances due to core losses were computed from the expression

\[ R = \frac{\omega L}{Q} \]  

where the numerator is the inductive reactance as computed from the lossless model, and the denominator is an effective "Q" that was determined from the manufacturer’s data. Q is rarely known with great precision, perhaps ± 20%.

To obtain the modified predicted losses, the computed resistances, along with the experimentally determined coil losses were added to the predicted values. These modified predicted values were within 15% of the measured values at both frequencies for the cup cores and within 20% for the cylinder. At 500 KHz the modified predicted value for the cylinder was almost identical to the measured values.

CONCLUSION

The losses in the coil and the core, rather than the "reflected secondary resistance" of the workpiece, dominate the driving point resistance, especially at higher frequencies. When the model predicted resistance values were modified by these core and coil losses, the results agreed very closely with the experimental values, thus validating the model.

REFERENCES


DISCUSSION

F. Muennemann (Stanford): Did you try to compare the field shapes that you predicted?

H.A. Sabbagh: We have no mechanism for measuring field shapes. It wasn't until I came here that I found that you folks were working with Southwest in measuring fields with their Hall probe.
F. Muennemann: Another method would be to introduce some perturbing element, like a hole.

H.A. Sabbagh: That's right. We haven't done that, but you are quite right. Although I'm pretty satisfied that some model computations of the current induced in the work piece would permit us to estimate the field, we don't really have an experimental verification.