MODEL DEVELOPMENT FOR BROADBAND SPIRAL-COIL EDDY-CURRENT PROBES

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Abstract. In this paper we demonstrate how the volume-integral algorithm of **VIC-3D©** can be applied to develop a computer code to design spiral-coil eddy-current probes for optimal broadband performance. This code will allow the designer to predict probe performance as a function of frequency, and is applied to model problems covering the frequency range of 10^7 to 10^{12} Hz.

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INTRODUCTION

Eddy-current measurements of conductivity spectra are needed to gauge the near-surface residual stress in surface-treated turbine engine components for life extension, where conductivity and stress are related via the piezoresistive effect. Broadband (0.1-100MHz) planar spiral-coil eddy-current probes are currently being developed using photolithography for the purpose of efficiently measuring the conductivity spectra for subsequent inversion to residual stress versus depth profiles. The key problem is that the probes do not perform well at high frequencies (>30 MHz) due to stray capacitive effects, which begin to dominate as the resonant frequency of the probe is approached. This parasitic effect is mainly due to capacitive coupling between adjacent traces of the coil, which makes it especially difficult to predict in terms of sensitivity. The objective of current research is to develop models to account for these problematic parasitic effects, and allow for probe optimization in the design stage, rather than through the tedious and inefficient trial-and-error approach. This will be done by enhancing the proprietary eddy-current volume-integral code, **VIC-3D©**.

AN ELECTRIC-DIPOLE MATHEMATICAL MODEL

The current version of **VIC-3D©** assumes that all applied current sources can be modeled as magnetic dipoles. This is reasonable because the currents are assumed to be solenoidal (zero divergence), and flow in parallel planes. Thus, the sources can be defined by a single magnetic dipole that is oriented normal to the planes. The field produced by these sources, then, are incident upon the anomalous region of the problem. This model works well for typical eddy-current problems, but allows only the computation of the inductance of the source. The solenoidal nature of the current precludes any possibility of computing the driving-point capacitance of the coil. In order to compute capacitance, and therefore the resonant frequency of the coil, we must relax the assumption of solenoidal current-flow, and assume that the excitation of the coil is an electric dipole.

We are going to apply volume-integral theory [1-2] to the metallic traces contained within the anomalous region shown in Figure 1. These traces are the 'anomaly' of the problem (much like a ferrite core in a conventional eddy-current probe), and the driving-point terminals form an electric dipole that will drive the coil.

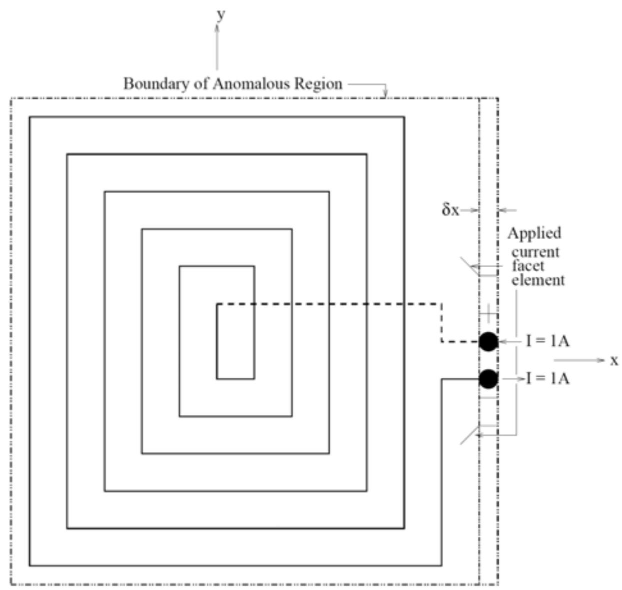

FIGURE 1. A printed-circuit rectangular-spiral coil lying within an 'anomalous region.' The electric dipole produced by the driving-point current excites the metallic traces of the coil. The convention in electric-circuit theory is that current enters the positive terminal of a passive load and leaves through the negative terminal.

TERMINAL CAPACITANCE OF A SIMPLE SQUARE COIL

Consider the 8 × 8 × 2 mm grid with 8 × 8 × 2 cells shown in Figure 2. The current enters cell 3, which makes it the positive terminal, and leaves cell 1, making it the negative terminal. Thus, cells 1 and 3 make up an electric dipole that will excite the remaining cells.

Figure 3 is a plot of the terminal capacitance as a function of the distance between the terminals, as deduced from the frequency of the zero-crossing of the broad resonance in the reactance functions. This result is reasonable, because we expect this capacitance to decrease with an increased separation of the terminals. In addition, this figure includes the capacitance of the 'naked terminals' as a function of the gap between the terminals. These capacitances are computed from the reactances (not shown) of the naked terminals at 10^8 Hz. The latter capacitances are smaller than the former since they include only the ramp functions of the terminal and not the tent functions that complete the terminal posts.

A TWO-LAYERED SPIRAL COIL

Figure 4 shows a two-layered spiral coil whose dimensions are 0.8 mm × 0.80 mm × 0.15 mm. The response through resonance is shown in Figure 5. Figure 6 shows the high-frequency response of the two-layered coil, in which two weaker resonances appear.

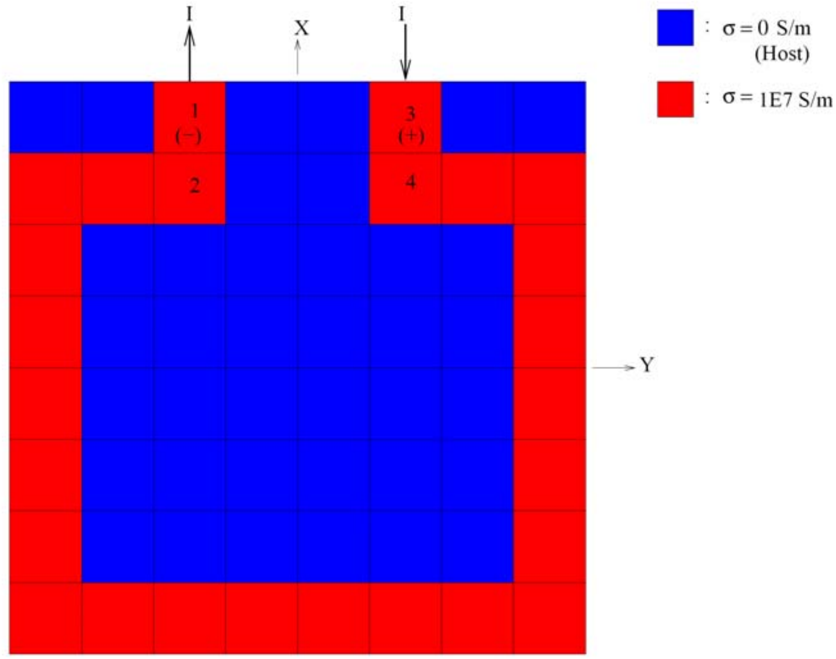

FIGURE 2. Illustrating a square coil on an 8 × 8 × 2 grid

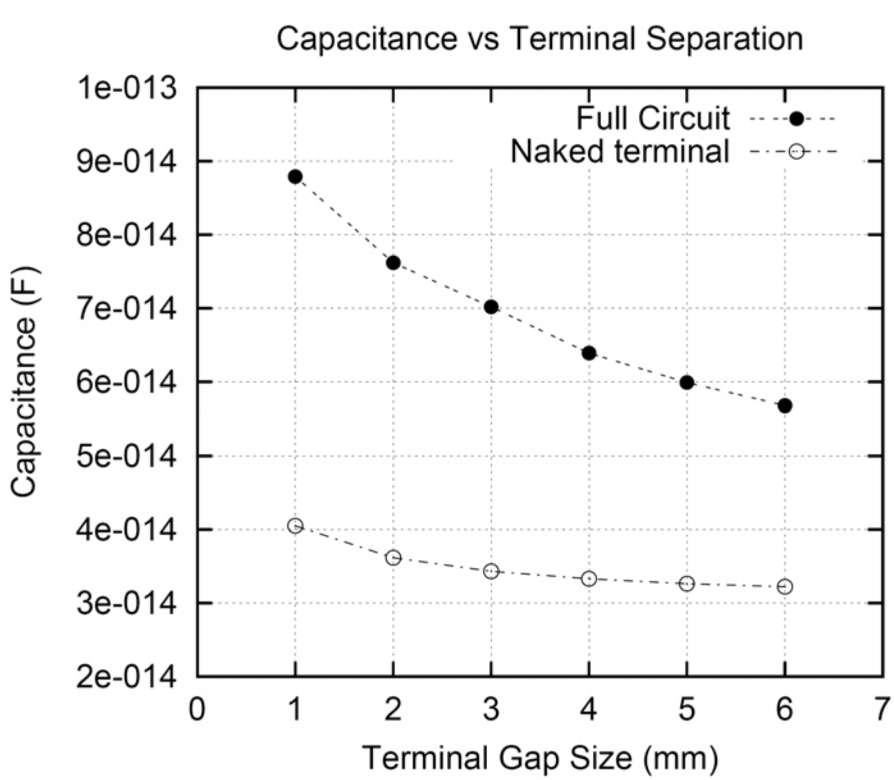

FIGURE 3. Showing the 'loaded' and 'naked' terminal capacitance as a function of the distance between the terminals.

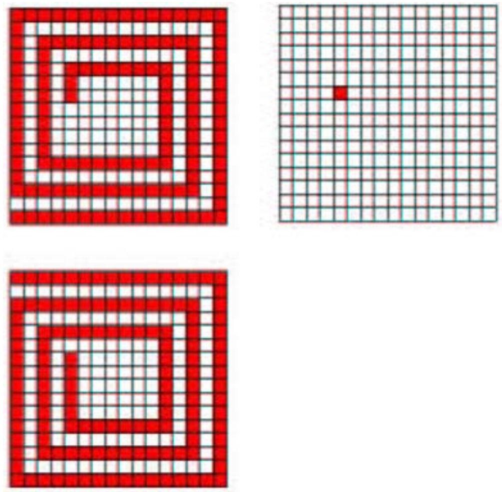

FIGURE 4. A two-layered spiral coil.

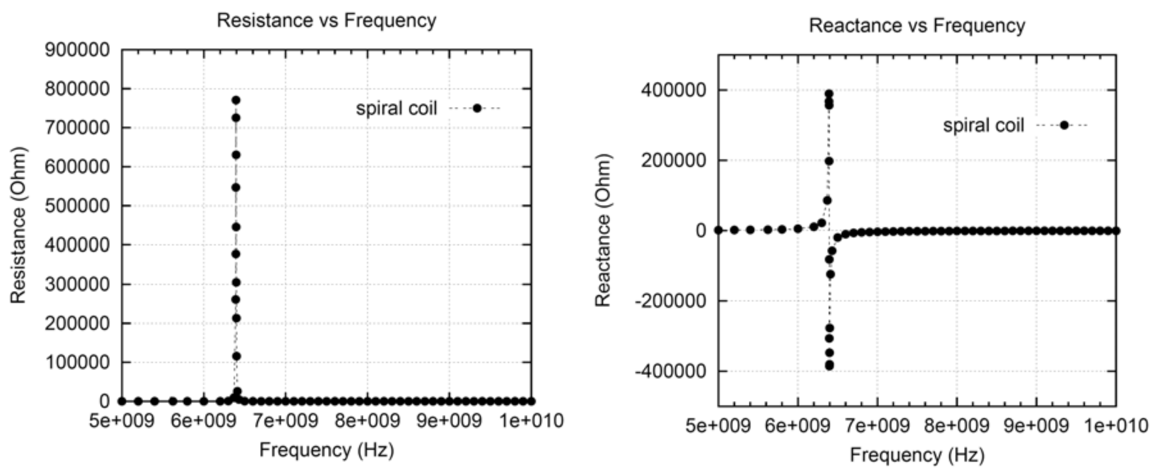

FIGURE 5. Results of the dipole model calculation of the two-layered spiral coil in freespace through resonance. Left: Resistance. Right: Reactance.

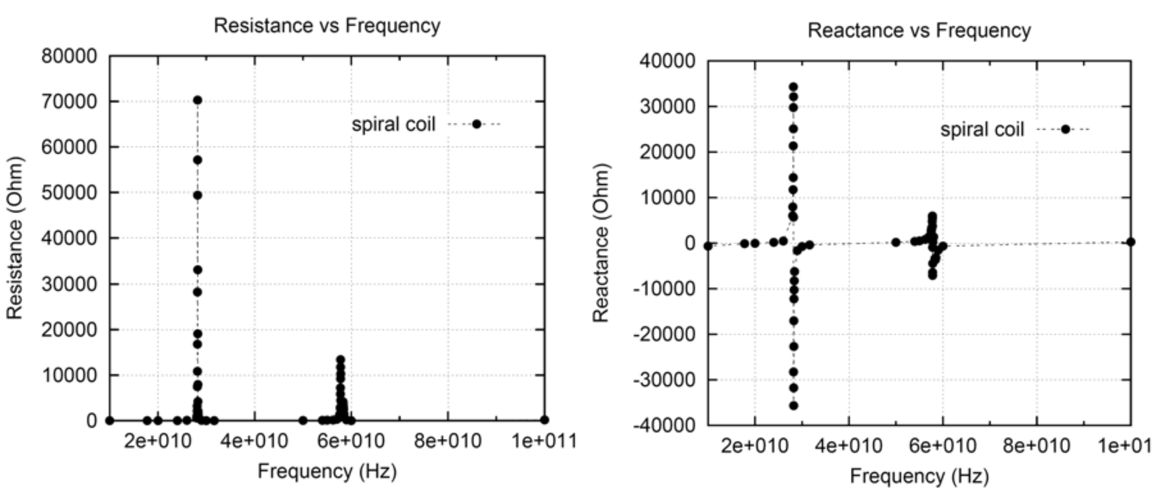

FIGURE 6. Results of the dipole model calculation of the two-layered spiral coil in freespace at higher frequencies; two weaker resonances appear. Left: Resistance. Right: Reactance.

A MODEL OF A THZ TRANSMITTER ON GaAs

The authors of [3] describe a high-efficiency transmitter structure for terahertz (THz) frequencies. The antenna consists of two 10 μm - wide metal lines deposited on semi-insulating GaAs, with a separation of 100 μm. Two metal tabs extend out from these lines toward each other. Figure 7 illustrates the structure. We have modeled this system by using a 16 × 16 × 2–grid (160 μm × 160 μm × 20 μm) placed on a 1mm thick plate having the nominal parameters for GaAs, σ = 100S/m and ε_{rel} = 10.9 [4]. The results of the impedance calculation are shown in Figure 8. The top portion of the figure shows the (negative) reactance function approaching zero with increasing frequency, which is typical of a series capacitor, while the bottom portion of the figure shows the reactance function passing through zero in the positive direction. This, of course, is typical of a series LC circuit at resonance. Note that the resistance function is small at the frequency of the reactance zero-crossing, further confirming a series resonance. At a still higher frequency, however, the reactance crosses back through zero in the negative direction, while the resistance reaches a (large) maximum value. This indicates that the structure is behaving as a parallel resonant circuit, in which a capacitor is in shunt with a series RL circuit. The shunt capacitance is small, and has no effect on the series resonance at the lower frequency. It is not necessary, of course, to think in terms of circuit elements in a computational electromagnetics problem of this kind, since we do not use the circuit model for computations, but it is interesting to observe a mathematical and physical consistency that lends confidence to our model calculation.

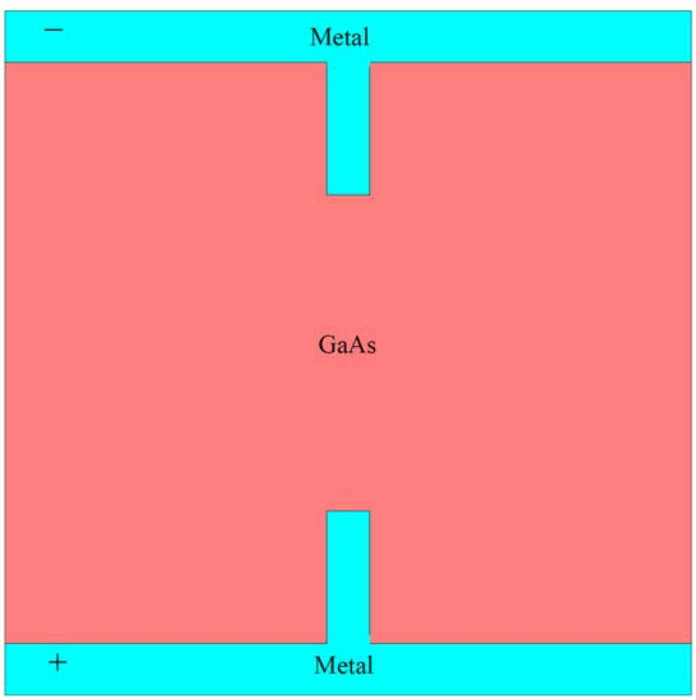

FIGURE 7. Sketch of a THz transmitter (after Figure 3 of [3]).

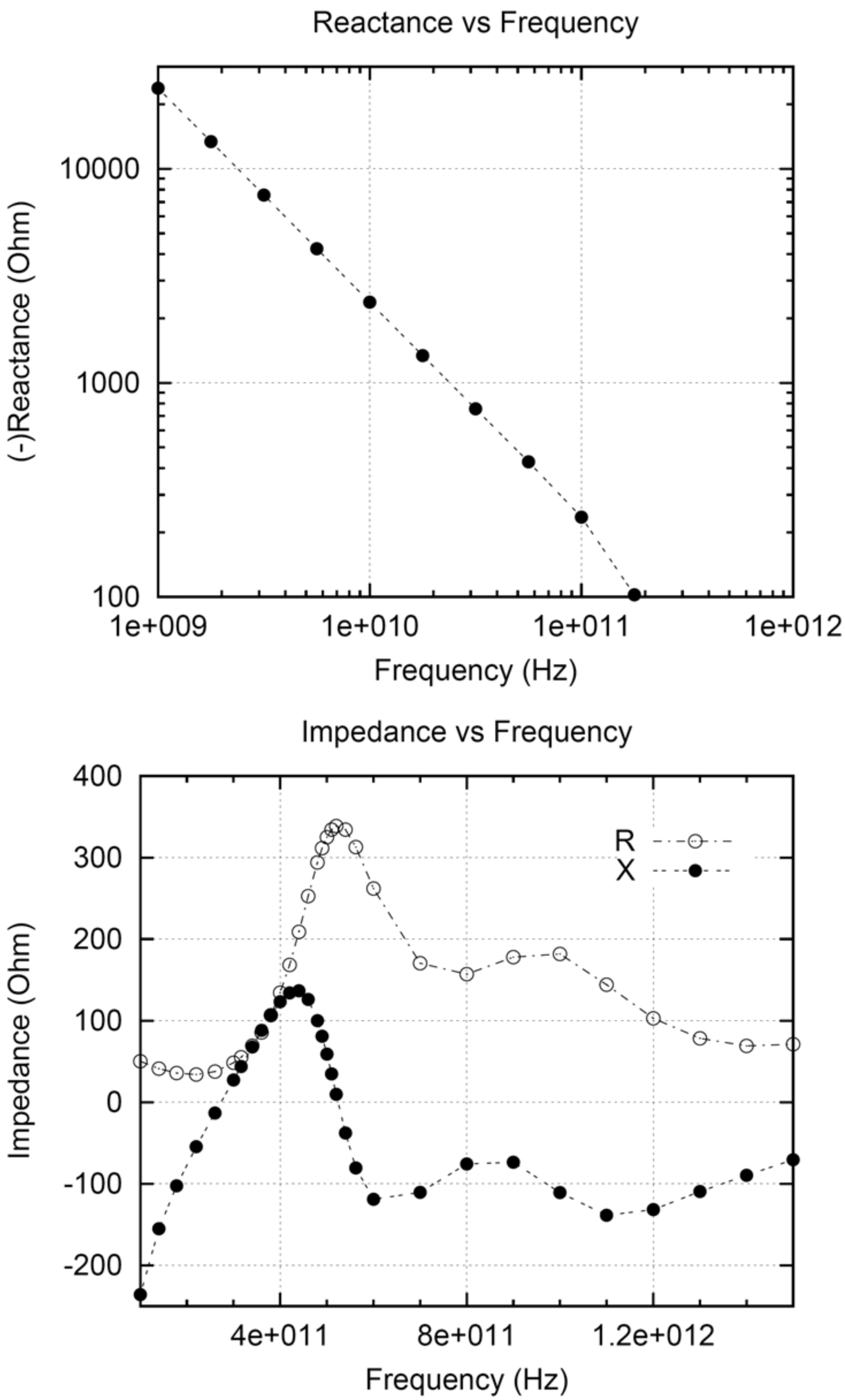

FIGURE 8. Results of the dipole-model calculation for the THz transmitter of Fig. 3 of [3]. Top: Low-Frequency Reactance. Bottom: High-Frequency Impedance.

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