THE REMOTE FIELD EFFECT AND ITS INTERPRETATION

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INTRODUCTION

The Remote Field Effect (RFE) and the testing method based on it have attracted considerable attention from the research community. The need to explain the apparent discrepancies between the effect and the known electromagnetic field behavior is the reason for this attention.

The RFE is an effect observed in remote regions of the magnetic field of a circular coil. In testing magnetic and nonmagnetic conducting materials, the field due to a coil at relatively large distances behaves differently than at short range. For example, the field on the outer surface of a tubular material is equal or larger than on the inner surface. This leads to similar or larger sensitivity to discontinuities on the outer surface and thus the value of the method.

Two basic explanations of the RFE have been proposed. One assumes a wave propagating from the inside of the material to the outside and then back again [1]. The second is based on simple induction effects [2]. The two explanations are substantially different. If the first explanation were correct, a new phenomenon could be associated with the effect. With the second, one simply looks at very low level induced fields due to the coil.

Models based on the propagation effect, assume that the coil induces eddy currents in the tested material. These currents diffuse to the outer surface of the material and propagate along it in a kind of guided mode afforded by the outer surface of the material. Then, these currents diffuse back into the material to create a signal which has equal (or greater) sensitivity to outside defects. This explanation disregards the fact that at such low frequencies the propagation effects are negligible and it does not explain the fact that the sensitivity to internal defects (those that are not close to either surface) is equally large. Also, if this were the correct explanation, an infinitely thick tube (outer surface at infinity or very large) will produce a negligible signal due to a defect close to the inner surface. The diffusion out and then in again will effectively reduce the signal to zero. Obviously, the propagation effect cannot be considered at zero frequency yet, the flux density of a coil at zero frequency is practically the same as that at nonzero frequencies.

This paper attempts to show that the Far Field Effect is nothing more than the induction due to a coil at large distances. As such, it is properly called a Weak Field Effect and obeys the standard diffusion equation everywhere in space. As an induction phenomena, it exists regardless of the material in which the induced fields exist. It will be shown that the same phenomena occurs in free space and is simply the induction due to a circular coil. The effect is larger in conducting and ferromagnetic materials.

GENERAL

It is normally assumed that the phenomenon involved in the RFE only occurs in tubular samples. However, if the method does not depend on the geometry or the material in the geometry, then it should apply to any cylindrical geometry. For example, a circular coil over a flat sample is a cylindrical geometry and the same effect can be observed.

In order to create a condition identical to that of the RFE, it is sufficient to show that in the region of interest, the magnitude of the flux density on the outer surface of a material is equal or larger than on the inner surface. For a very large diameter tube (effectively an infinite thickness tube) it is sufficient to show that at a larger diameter, the flux density is larger than at a smaller diameter inside the material.

Perhaps the most convincing argument for the diffusion model is the fact that all calculations performed to date [3-5] were done with steady state sinusoidal finite element programs. These programs exclude any propagation effects by assuming an instantaneous induced field everywhere in space. The reason the far field effect is observed is the fact that a solution to the exact field equation at low frequencies is found. An analytic calculation to the coil in air for example, is usually carried out as a dipole approximation which does not exhibit the same field distribution as a regular coil [6]. As mentioned above, the same effect is observed at zero frequencies.

The results in this work were obtained through the numerical solution to the following equation:

$$\nu\left(\frac{\partial^2 A}{\partial r^2} + \frac{1}{r}\frac{\partial A}{\partial r} + \frac{\partial^2 A}{\partial z^2} - \frac{A}{r^2}\right) = - J_s + j\omega\sigma A \tag{1}$$

This is the pre-Maxwellian form of the magnetic field equations in terms of the magnetic vector potential A (displacement currents are neglected). It is written in the cylindrical coordinates system with z coinciding with the tube's axis.

From the magnetic vector potential the flux densities and induced voltages are calculated directly [6].

Velocity effects are calculated through a modified form of Eq. (1):

$$\nu\left(\frac{\partial^2 A}{\partial r^2} + \frac{1}{r}\frac{\partial A}{\partial r} + \frac{\partial^2 A}{\partial z^2} - \frac{A}{r^2}\right) = - J_s + j\omega\sigma A + \sigma v\frac{\partial A}{\partial z} \tag{2}$$

where v is the velocity of the coils in the z direction (along the tube's axis).

The last term on the right hand side is the induced current density through motion [7].

RESULTS

The geometry used to obtain the results presented in this paper is shown in Fig. 1 (including dimensions). It consists of a tube and a coil inside it. The second coil, usually used in testing is only used for pick-up. It does not affect the field distribution. Either a standard coil or a small surface coil may be used for pick-up. The difference is in the component of the field the coil is sensing. With a standard coil, the tangential component is sensed while with a surface coil, the component normal to the surface is sensed. For the calculations in free space, the tube is assumed to have the properties of free space. The flux densities (normal and tangential to the tube) are calculated outside the inner and outer surfaces of the tube and compared.

Figure 2 shows the results calculated for a coil in air, where the normal and tangential flux densities are calculated at the two radii shown by the two dotted lines in Fig. 1a. The flux density for either component is larger at the larger radius, beyond a cross over point. This crossover point, which happens to be at about one coil diameter for the normal component of the flux density, depends on the location at which the flux density is calculated and the radius of the coil. The larger the radius, the further away the crossover point is but has nothing to do with the outer radius of the tube. This result indicates that for maximum sensitivity, the location of the pickup coil must be adjusted according to the radius at which the defect is located.

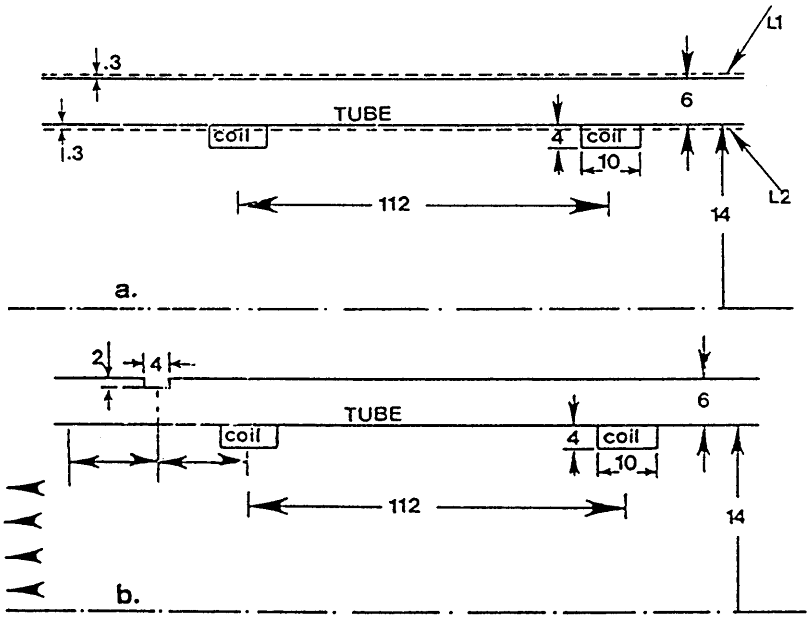

Figure 1. Geometry modeled. Dimensions are in mm. The two dotted lines show where comparisons are made. In 1b, the coils are moving to the left.

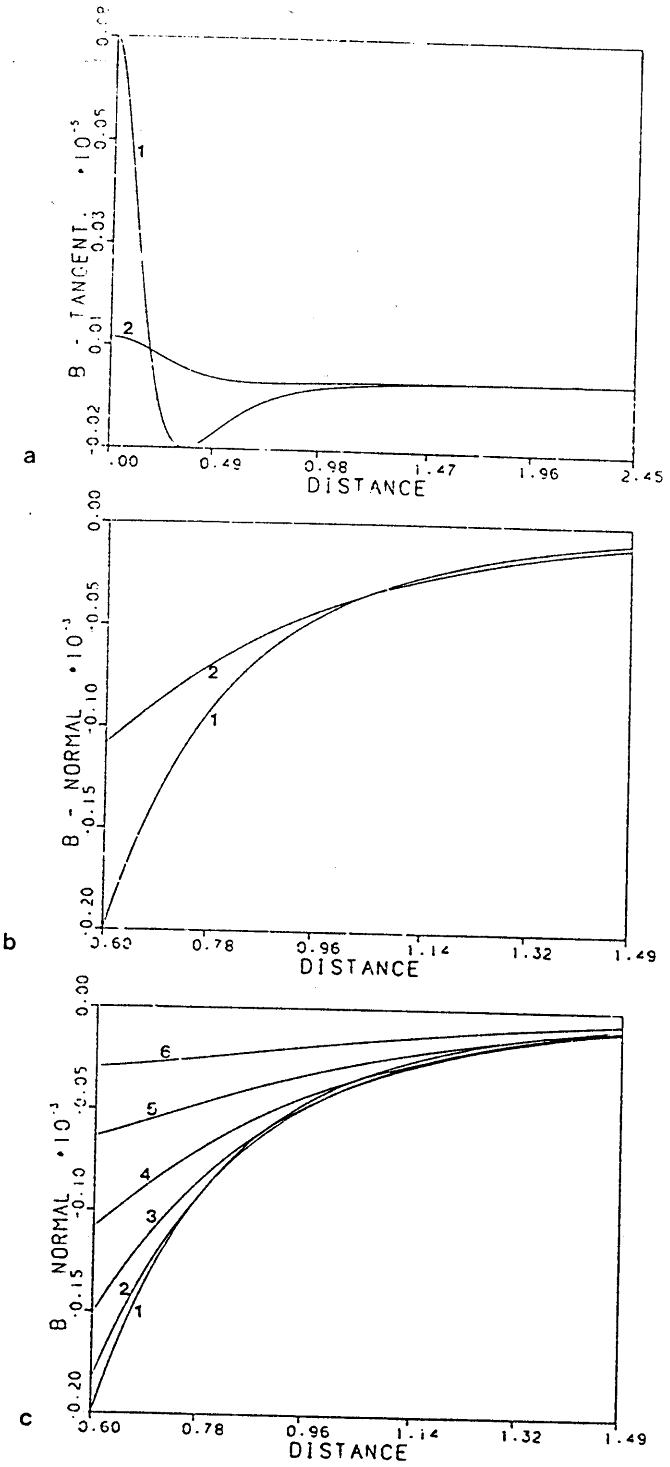

Figure 2. Flux density for coil in air. a. Tangential component of the flux density, b. Normal component of flux density, c. Normal component at six locations: $r_1>r_2>r_3>r_4>r_5>r_6$.

Figure 3 shows the same basic effect except that now the coil is inside a conducting, magnetic tube ($_r$-50). Figure 4 repeats the same results for a nonmagnetic tube. Other than the fact that the crossover points are more distinct, the three figures are essentially the same. This clearly indicates that the effect is universal and only has to do with the field produced by a coil, not with any new or unique electromagnetic effect.

Figure 5 shows the effect of velocity on the signal obtained. Fig. 5a shows the signal due to the axisymmetric slot in Fig. 1b at zero velocity. Fig. 5b shows the same signal at a velocity of 10 m/sec. In addition to a shift in the peak of the signal, there is a change of two orders of magnitude in the amplitude. Both of these must be taken into account when testing.

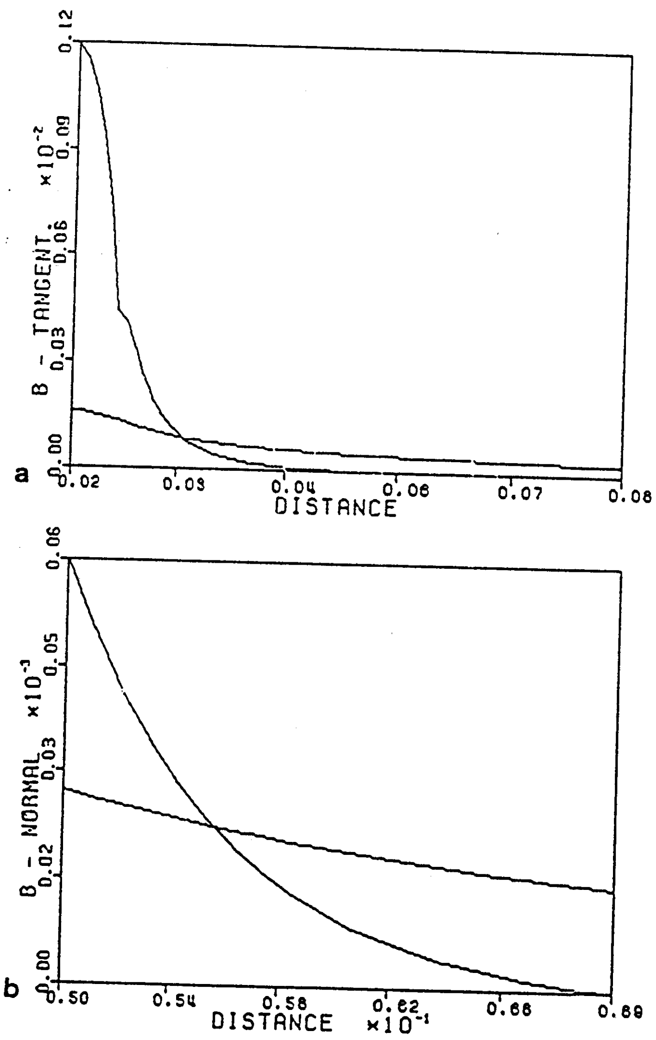

Figure 3. Flux density for a ferromagnetic tube ($_r$-50). a. Tangential component of flux density, b. Normal component of flux density.

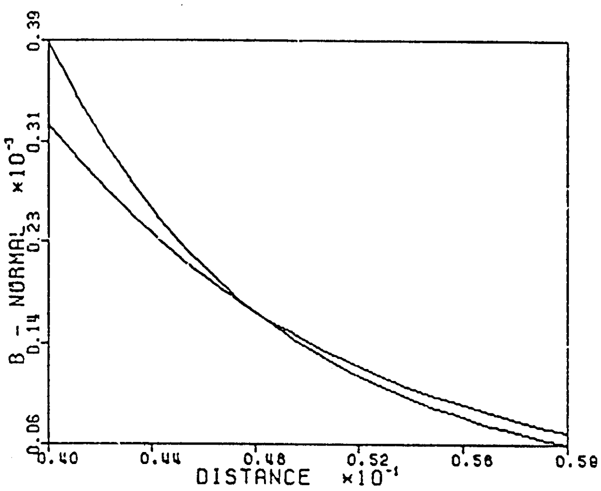

Figure 4. Normal component of flux density for coil in nonmagnetic tube.

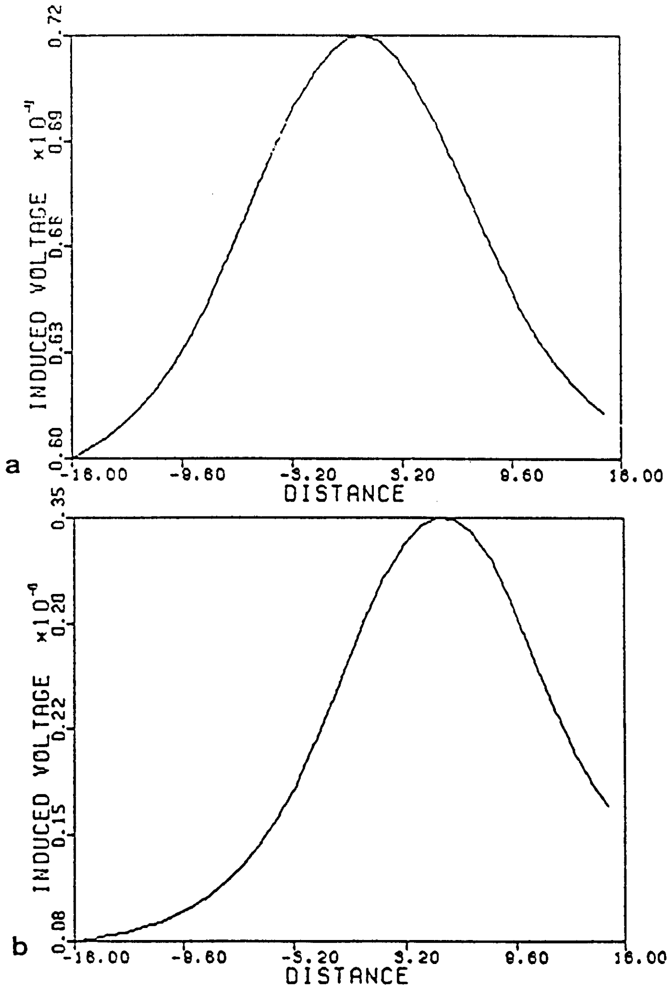

Figure 5. Induced voltage in pick-up coil. a. At zero velocity, b. At 10 m/sec.

CONCLUSIONS

The results in this paper clearly show the Weak Field Effect to be a diffusion or induction process, regardless of the material in which the fields are induced. The explanation of eddy currents diffusing to the surface of tubular samples is unsatisfactory since the same effect can be observed in free space. The fact that the effect is an induction effect makes it a variation on the standard eddy current test without the need for a special model. Any accurate eddy current model is a good model for this effect.

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