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Multilayer planar rectangular coils for eddy current testing: Design considerations

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ABSTRACT

Planar rectangular coils provide some interesting features different from those of pancake coils, such as good performance in conductivity measurement at high frequencies, high sensitivity to scratches and other shallow imperfections and the possibility of inspecting complex surfaces. The impedance of these coils has been modeled by different authors. A brief discussion of some analytical approaches in the literature is presented and calculations using the second-order vector potential approximation are introduced, aimed at the study of the influence of coil shape and size on the sensitivity to electrical conductivity of the substrate. Three cases were modeled, (A) coil in free space—inductance L_0 as a function of number of turns (n) and width of the spiral conductive lanes (c) for different coil inner shape factor (rr_i); (B) coil on a conductive substrate (Zircaloy-4)—impedance change, ΔZ, as a function of $f \cdots \sigma$, the product of the test frequency (f) and the substrate electrical conductivity (σ) for different rr_i and (C) coil sensitivity to small changes in $\sigma(\Delta\sigma)$.

$L_0 = L_0(c, n)$ increased as expected with n and/or coil area and decreased with shape factor. Normalized ΔZ depends strongly on inner rr_i, the curves (or surfaces) for smaller values of rr_i enclosing those for larger values. Another shape factor, the outer shape factor (rr_o), was introduced. Strong dependence of the sensitivity to $\Delta\sigma$ on n was observed, as well as the existence of an optimal theoretical frequency. Because the sensitivity to surface conditions also increases with coil size, it could be established that for conductivity assessment it is better to use coils with the smallest n and c, compatible with the particular application, and that the resolving power for this type of measurements is not greatly affected by the shape factor.

1. Introduction

Planar coils exhibit some interesting features, such as good performance in conductivity measurement at high frequencies, high sensitivity to scratches and other shallow imperfections [1], the possibility of inspecting complex surfaces if an adequate mounting is supplied [2] and the fact that any number of identical planar coils can be made with the printed-circuit technique. Planar rectangular coils were first used at our laboratory in an inspection for edge cracks in cooperation with an NDT crew from abroad. The main advantage of those rectangular planar coils was their power to eliminate (or at least minimise) the well-known edge-effect, i.e., the characteristic bridge unbalance signal which is produced when the sensor approaches the edge of the conductive test piece [1].

Rectangular planar coils have additional advantages, such as improved packing when tiled into arrays and simpler artwork [3]. The use of planar coils for NDT has been reported in the literature in Refs. [4–13], among others. Yamada et al. describe the construction of a special rectangular planar coil system for eddy current testing and the use of this system for crack detection in flat components and in the inspection for discontinuities in the circuit traces of printed circuits. Many other authors have also constructed planar inductors and studied their properties. Planar coils have been used for the assessment of electrical and magnetic properties of materials and for the evaluation of thin resistive or magnetic layers on components.

The use of theoretical models for eddy current testing, which can be applied to signal modeling via the input of practical test parameters, is very useful and instructive, in particular for the optimization of coil design. This line has been explored for some time, starting with the papers by Cheng [14] and Dodd and Deeds [15], who base their calculations on the vector potential **A**. Another approach is that given in [2,16] based on the second-order vector potential (SOVP) formalism. The authors have

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explored modeling with the SOVP method as developed by Theodulidis and Kriezis in [17]. In previous papers [16,18,19], theoretical expressions for the inductance (L_0) and the impedance (Z) of planar rectangular coils were derived and used to model the characteristics and performance of the real coils made in our laboratory for a semiinfinite conductor [16] and for a plate conductor [18]. Eddy current distribution in semiinfinite and finite conductive specimens were calculated in [19] using the results in [16,18].

The SOVP approximation used in the above-mentioned papers and in this one is classical, in that the solution domain is not truncated and the final analytical solutions are thus functions of infinite integrals on the x and y coordinates. The planar coil in the present problem is parallel to the semiinfinite substrate that extends to infinity in the $z<0$, x and y regions, with z normal to both substrate and coil. Other approximations also give solutions to the Maxwell equations describing the eddy current problems modeled here. These methods can be numerical, such as FEM, analytical or quasi-analytical. A discussion of the methods to model eddy current problems which are currently used, or have once been used, is presented in the Introduction to [20]. Among the analytical or semianalytical methods (i.e., which give closed-form solutions for fields and coil impedance) much effort was devoted to those with eigenfunction expansion solutions, such as the truncated region eigenfunction expansion (TREE) method. Very important contributions to the TREE method are presented by Theodoulidis et al. in [20–24].

The TREE method uses variable separation techniques to give analytical expressions for the electromagnetic (EM) fields in the different regions, as does the classical method. But unlike this approach, the TREE solution domain is truncated with the adequate border conditions, limiting the range of a particular coordinates which otherwise would have been infinite. The solution for that coordinate is thus an infinite series, the terms of which are the eigenfunction expansion solutions to the differential equations describing the problem in each truncated region. The series is then truncated and only a finite number of terms are taken. Some advantages of series solutions vs. integral solutions mentioned in the literature are:

(a) more efficient numerical implementation, the truncation errors can be easily controlled by increasing the number of terms considered or by taking a bigger domain [22]. This increased efficiency is particularly important when the solution has to be calculated in many points, e.g., in flaw modeling in the volume integral method or in the simulation of current distribution.
(b) the main advantage of the truncated domain method is that, through an adequate selection of the discrete eigenvalues and the corresponding eigenfunctions, the field continuity conditions can be simultaneously satisfied in 2-coordinate interfaces and mixed border conditions in 1-coordinate. Thus, the number of problems which can be treated analytically increases, as illustrated in papers [21–24] and in [20].

Originally, we used the classical approach in our modeling of the planar rectangular coils, constructed infinite integral solutions and wrote the corresponding codes. Since only semiinfinite homogeneous conductive media (without any edges, cuts or inhomogeneities) have been modeled so far, there was no need for testing faster series solutions. Besides, the number of points calculated in the analysis presented here is not so time-consuming as to prompt the need for the efficiency of the TREE method.

The probes made with the rectangular coils constructed in [1] and modeled in [16,18] and [19] satisfied the criteria that probe-sensitive area be less than 2.25 cm^2 and its impedance lie in the range (5–200) Ω, i.e., the normal input impedance of commercial e.t. equipment. The coils were made with the usual technique for the construction of printed circuits, i.e., they consist of rectangular spiral copper traces on a fibre glass substrate. These copper traces may lie on one or both faces of the substrate and there may be one or more spirals per face. A thin layer of epoxy resin protects the copper traces. Because great repeatability in coil production was especially sought for, once the design was achieved, coil construction was made at a printed-circuit manufacturing company. The supplier introduced further constraints, mainly on the width of the circuit traces (c) and the gap (s) between them: none could be smaller than 200 μm and were actually calculated in mils (8 mils). Moreover, because circuit traces must be straight lines if good repeatability was required, no planar circular coils could be made, and thus only rectangular or square coils were available for the experiments. Fig. 1 illustrates what the coils look like. For the simulations in the present paper, however, variable c values in the range one-eighth to twice the supplier's value and a fixed s of one-half the supplier's value were selected. All the values used in the simulations are listed in Table 1.

The directional properties of the rectangular coils depending largely on the shape factor and the size of the coil, in the present work, the expressions in [16] are applied to the study of the performance of flat rectangular coils when construction parameters are changed. These results are therefore a tool for coil design for particular applications. The design variables considered in the simulations presented in this paper are thus the number of turns in the coil (n), the width (c) and the shape factors (rr_i, inner shape factor and rr_o, outer shape factor, defined, respectively, as the ratio of the sides of the innermost loop and the ratio of the sides of the outermost loop), while the thickness (t_c) of the copper lanes making the turns, the gap between the copper lanes (s), the thickness of the substrate of the printed circuit (t_s) are fixed parameters. Variables and parameters are defined in Fig. 1. For the study of the impedance (Z) and its variation ΔZ, material and test parameters, namely magnetic permeability (μ), electrical

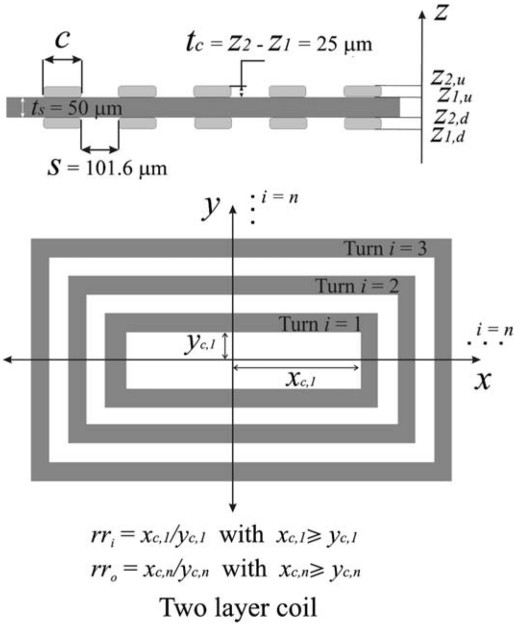

Fig. 1. Features of the modeled coils.