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Performance of circular and square coils in electromagnetic–thermal non-destructive inspection

N. Tsopelas, N.J. Siakavellas*

Department of Mechanical Engineering & Aeronautics, University of Patras, 265 00 Patras, Greece

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Abstract

The performance of circular and square coils in electromagnetic–thermal non-destructive inspection of conductive plates is investigated numerically for various configurations. A coil is most effective when placed at an optimum distance from the plate, equal to 1/4 of the diameter for a circular coil or 1/4 of the side for a square coil. At this distance, the coils considered are equally efficient in detection of cracks. Substantial differences exist only when the coils are placed very close to the plate but then become less effective. For that case, the planar coils give better results. A coil with a section comparable in area with the inspected surface cannot inspect the whole surface effectively in a single inspection. The support of a smaller section coil is necessary in order to clarify the shape of the cracks that are not clear.

Keywords: Electromagnetics; Infrared thermography; Crack detection; Square coil; Planar coil

1. Introduction

Eddy-current non-destructive inspection is one of the most commonly used methods for the evaluation of conductive metal structures. An alternative method has been proposed that combines electromagnetic excitation and transient infrared thermography [1]. A coil is used to induce eddy currents inside the conducting material under inspection. The heat generated by the eddy currents creates temperature gradients and the resulting heat flow crosses the current flow. A crack with arbitrary orientation, will modify the heat flow either directly or indirectly and, consequently, the temperature distribution. By employing infrared thermography, it is then possible to visualize in 2D the temperature distribution over the surface of the tested work piece.

The effectiveness of the method when solenoid coils are employed has been investigated numerically in thin conductive plates [2]. It has been shown that the method is most effective when the mid-height center of the exciting coil is positioned above the plate at a distance equal to half the coil radius. The radius of the detection region depends on the heating time, the magnetic flux density, the coil radius and the crack orientation with respect to the heat flow. For the optimum configuration (with the coil placed at the optimum distance over an infinite plate) and typical parameter values, the radius of the detection region varies between 2.5 and 4 coil radii. In the case of a finite plate, the detection region is modified and extends beyond the corresponding one for the infinite plate, especially for the following cases: (a) when the cracks are near the plate corners, or near borders that do not allow heat diffusion; (b) when the shape of the plate is not symmetrical (e.g., rectangular) and the cracks are perpendicular to the longer side of the plate (i.e., perpendicular to the heat flow). By taking into consideration the above features, the plate surface may be divided properly into a few sub-regions, so that when the coil is placed successively above these regions, the whole surface is inspected effectively.

In contrast to the widely used circular coils, rectangular coils have been applied in eddy-current inspections of plates only lately [3–5]. In certain crack detection applications rectangular coils are considered superior to the circular ones because of their directional properties and their ability to create uniform eddy-current distributions.

*Corresponding author. Tel./fax: +30 2610 997 243.
E-mail address: siakavel@mech.upatras.gr (N.J. Siakavellas).

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On the other hand, planar coils show great promise in eddy-current NDT and offer attractive features for the detection of surface-breaking cracks in metals [6–9]. However, the fact that rectangular or planar coils exhibit some advantages in eddy-current NDT does not imply that these advantages are preserved in electromagnetic–thermal NDT, since in the latter method both current and heat conduction are employed for crack detection. Hence, it is interesting to investigate the effectiveness of different types of coils on electromagnetic–thermal NDT. In fact, since the shape of the coil section facing the inspected surface affects the eddy-current distribution on the plate, it is evident that the distribution of the heat power, generated by the eddy currents, is affected too. In turn, this will affect the temperature gradients developed within the plate and, consequently, crack detection.

In this paper, we extend our previous work on electromagnetic–thermal NDT and, besides the circular coils considered in [2], we consider here square coils as well as planar circular and planar square coils. The effectiveness of the method is examined in relation to the following fundamental parameters: (i) the coil distance from the plate, (ii) the shape of the coil section facing the plate (circular or square), and (iii) the type of the coil (flat or of finite height). Furthermore, we investigate whether it is possible to inspect effectively the whole surface of the plate in a single inspection, if the coil section facing the plate is comparable in area with the plate surface.

2. Theory

We assume that the material under inspection has the shape of a thin plate and lies in the x–y plane, while the exciting field is parallel to the z-axis, i.e. perpendicular to the faces of the plate. If a single current loop, parallel to the plate at a distance z is used for the excitation, the z-component of the magnetic flux density is given by the following expressions:

- For a circular current loop of radius R,

$$B_z(x,y,t) = \frac{\mu I(t)}{2\pi}\frac{1}{\sqrt{(R+r)^2+z^2}} \times \left[\frac{R^2-r^2-z^2}{(R-r)^2+z^2}E(m)+K(m)\right], \quad (1)$$

  where $r=\sqrt{x^2+y^2}$, $m=4Rr/[(R+r)^2+z^2]$ while $K(m)$ and $E(m)$ are complete elliptic integrals of the first and second kind, respectively [10]. In the present work, it is assumed that the current I flowing in the loop varies harmonically with time, i.e., $I(t)=I_0\sin(\omega t)$.
- For a rectangular current loop with dimensions $2a\times 2b$ (if we derive first the magnetic induction from a straight current element of length $2a$ or $2b$ and combine the results),

$$\begin{aligned} B_z(x,y,t) = {} & \frac{\mu I(t)}{4\pi}\frac{x+a}{(x+a)^2+z^2}\left[\frac{y+b}{\sqrt{(x+a)^2+(y+b)^2+z^2}} - \frac{y-b}{\sqrt{(x+a)^2+(y-b)^2+z^2}}\right] \\ & - \frac{\mu I(t)}{4\pi}\frac{x-a}{(x-a)^2+z^2}\left[\frac{y+b}{\sqrt{(x-a)^2+(y+b)^2+z^2}} - \frac{y-b}{\sqrt{(x-a)^2+(y-b)^2+z^2}}\right] \\ & + \frac{\mu I(t)}{4\pi}\frac{y+b}{(y+b)^2+z^2}\left[\frac{x+a}{\sqrt{(x+a)^2+(y+b)^2+z^2}} - \frac{x-a}{\sqrt{(x-a)^2+(y+b)^2+z^2}}\right] \\ & - \frac{\mu I(t)}{4\pi}\frac{y-b}{(y-b)^2+z^2}\left[\frac{x+a}{\sqrt{(x+a)^2+(y-b)^2+z^2}} - \frac{x-a}{\sqrt{(x-a)^2+(y-b)^2+z^2}}\right]. \end{aligned} \quad (2)$$

The corresponding expressions for a circular or square coil, which has N wire-turns, can be derived from Eq. (1) or (2) by superposition.

It is assumed that the frequency of variation of the current $I(t)$ and, consequently, of the exciting field is low, resulting to a penetration depth δ sufficiently greater than the plate thickness w. Hence, the density of the eddy current induced in the plate by the exciting field has two components, which may be expressed in terms of the stream function $u=u(x,y,t)$ as: $J_x=\partial u/\partial y$ and $J_y=-\partial u/\partial x$. This scalar quantity is a solution of the following equation [11]:

$$\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}=\sigma\frac{\partial B_{\text{tot}}}{\partial t}=\sigma\left(\frac{\partial B_z}{\partial t}+\frac{\partial B_s}{\partial t}\right), \quad (3)$$

where the total magnetic field inside the plate, B_{tot}, has been decomposed into the exciting field B_z (as given by Eq. (1) for a circular coil or Eq. (2) for a square coil (with $a=b$)), and the secondary magnetic field B_s due to the eddy currents. The latter is obtained from the Biot–Savart law, as an integral over the plate surface S:

$$B_s(x,y,t)=\frac{\mu w}{4\pi}\iint_S \frac{(x-x')\left(\partial u(x',y',t)/\partial x'\right)+(y-y')\left(\partial u(x',y',t)/\partial y'\right)}{\left[(x-x')^2+(y-y')^2\right]^{3/2}}\,\mathrm{d}x'\mathrm{d}y'. \quad (4)$$