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A new dual driver planar eddy current probe with dynamically controlled induction pattern

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ABSTRACT

A new planar eddy current probe design is presented. This new concept is capable of dynamically modify the induced eddy currents pattern in accordance with the operational non-destructive testing parameters. The probe is composed by two orthogonally positioned driver traces and a set of sensing coils on each quadrant between the traces. Eddy currents result from the magnetic field contribution of the two driver traces and can be modified by changing the relative amplitude and phase of the currents flowing in the driver traces. Finite Element Modeling was used to simulate the eddy currents patterns and to predict the probe response to defects with different orientations. Experimental validation was carried using a prototype of the probe and artificial defects showing very good agreement with the Finite Element Modeling.

1. Introduction

Eddy Currents Testing (ECT) has been widely applied in the inspection and characterization of metallic parts. The method allows measuring properties such as conductivity and thickness and is particularly suited for the detection of imperfections located at the part surface [1]. Still, the estimation of such properties and the characterization of defects are normally difficult due to a complex relation between the testing results, the part characteristics and the unknown defect. To cope with this problem, researchers have used phenomenological approaches, based on electromagnetic models as in [2], and non-phenomenological methods, using statistic learning tools as in [3]. The successful application of both these approaches depends on the quantity and diversity of information that can be retrieved from the testing results.

One way to improve the useful information on each point of the tested part relies on applying multi-frequency (MF) techniques. In ECT, frequency has an important influence on the results since it determines the in-depth density of the induced eddy currents. One example of the application of a MF technique as described is reported in [4] where the conductivity profile of water jet peened parts were estimated from results at 8 different frequencies using a phenomenological approach. The depth of surface breaking defects was estimated in [5] from MF results using an empirical metric based in the evolution of the results of different frequencies. On a similar approach, other researchers have used Pulsed Eddy Current (PEC) techniques. In this case, the employed stimulus has a pulse waveform whose spectral composition is much richer. The authors of [6] investigated the influence of the pulse duty cycle while testing riveted aircraft lap joints with defects located at different depths. It was shown that the use of several duty cycle values allows gaining information at different depths. An empirical approach was used to identify the edges of a slot defect from time-domain features of PEC signals in [7]. The depth profile of slot defects was reconstructed using a linear model and PEC responses in [8].

In the previous examples, the use of different testing frequencies and its effect on the induced eddy currents was used to improve the information on the testing results. Another possibility relies on the use of probes that are designed to perform improved characterization. Eddy current array probes are often used to expand the tested area and improve testing speed as shown in [9]. Yet, the array elements allow exploring multiple measurements by multiplexing the coils used to generate and/or sense the magnetic field. This possibility was explored in [10] in a phenomenological approach to reconstruct defects on steam generator tubes of power plants. The same approach was verified to characterize surface breaking defects in [11]. The advantage of having multiple measurements was also

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explored to improve the quality of eddy current imaging results [12].

Other researchers proposed advanced eddy current probes with structures that allow inducing eddy currents whose alignment varies. These probes, often referred as having a rotating field (RoFEC probes [13]), are composed of at least two driver coils carrying phase-shifted sinusoidal currents and geometrically positioned to cause a rotation effect on the generated magnetic field. One possible implementation [14] to achieve the rotation effect uses two orthogonally wired driver coils and a circular pickup coil. The current flowing in the two driver coils were set to the same amplitude and a 90° phase shift. Results with machined defects showed that the angle between the defects and the probe has a direct influence on the pickup coil induced voltage phase, allowing the identification of the defect orientation. More details and the probe application on a ferromagnetic material can be found in [15]. Rotating fields have also been applied on the testing of tubes with one of the first approaches on this application described in [13]. Since then, several designs improved the initial concept by using additional driver coils as shown in [16,17]. In these designs, three driver coils are wired on axis rotated by 120°, and carry equal current amplitude but with a phase offset of 120°. As in a three-phase electrical machine, the magnetic field direction will rotate with a rate defined by the frequency of the driver coils current. Sensing of the resulting magnetic field is done by a pickup coil wired orthogonally to the three driver coils.

A planar probe able to dynamically change the induced eddy currents in agreement with the desired testing operating parameters is presented in this paper. This feature enables an improved characterization of the defect since multiple measurements with different induced currents patterns can be performed on each tested location and thus, more information can be retrieved to characterize the defect. The probe is composed by two driver elements and a set of sensing coils in a planar disposition and is partially inspired in a previous simpler design presented in [18]. The paper begins by describing the probe structure and principle of operation. Finite Element Modeling (FEM) was used to verify and highlight the changes on the induced eddy currents pattern resulting from different selection of the currents flowing in the two driver traces. Additional simulations were performed to verify the response of the probe when testing defects with different orientations and different induced current patterns. The validation of the simulated results using an experimental prototype and synthetic defects is reported before the discussion of some final conclusions.

2. Probe concept

The use of driver traces and sensing coils on a planar geometry was previously proposed in [18]. In this earlier probe, the primary magnetic field is generated by a driver trace placed in the middle of two sensing coils which act as a differential magnetic flux sensor. One of the limitations found in this original design was the inability to detect defects whose orientation was perpendicular to the sensitivity axis as reported in [19]. To overcome this limitation, an improved probe structure including additional driver and sensing elements was developed and patented [20]. The new probe structure features the ability to modify the induced eddy currents pattern by modifying the operational parameters during the test. The new probe is represented in Fig. 1 where four driver traces forming a cross in the middle of four sensing coils on each quadrant. It is also important to note that the sensing coils on the upper-right and lower-left quadrants are winded clock-wise while the other two coils are winded counter-clock-wise. The probe was named as IOnic+ derived from the original probe design and the fact that the crossed driver traces resemble the mathematical plus operator.

To simplify the electronics requirements to operate the probe, the driver traces are connected so that one same current flows in

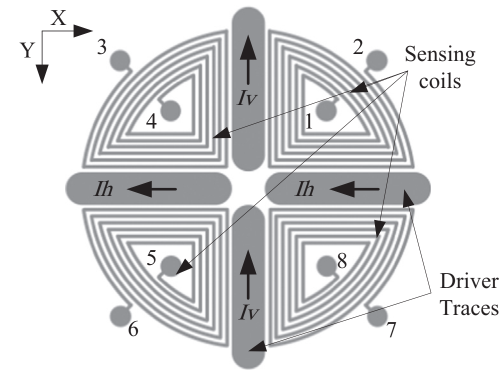

Fig. 1. Probe design. Driver traces and sensing coils representation in the probe layer.

the two horizontal driver traces (I_h) and another same current flows in the vertical ones (I_v). This allows driving the probe using two current generators instead the four required to drive each trace independently. The sensitive coils are wired in series so a single output voltage is required to be measured when a test is performed. This was done by ensuring connections between each pair of terminals 2–3, 4–5 and 6–7 and measuring the voltage difference between terminals 1 and 8, as depicted in Fig. 1.

Originally, the horizontal and the vertical driver traces were intended to be used completely separate, i.e., only one would be excited at a given time. This operation mode allows reproducing the behavior of the probe presented in [19] but included the possibility of changing the sensitivity axis in agreement with the activated pair of driver traces (verticals or horizontals). Fig. 2 shows the induced eddy currents pattern when the probe is positioned above a metallic part to be tested in these two situations. In Fig. 2(a), alternating current is flowing only in the vertical driver traces while in (b) current only flows in the horizontal driver traces. As shown, for the two cases, the induced currents flow underneath the activated driver trace (taking the opposite direction of the driver current) and describe a loop which closes in half-cylindrical trajectories bellow the sensing coils. Due to the way the sensing coils are wounded and its interconnections were set, as in the original probe, they act as a differential sensor. When the vertical driver traces are activated, the probe senses defects that affect the magnetic field symmetry between the left and right sensing coils. On the other hand, when activating the horizontal driver traces Fig. 2(b), the probe is able to detect the defects that unsettle the magnetic field symmetry between the upper and lower sensing coils. The electronic change on the activated driver traces allows avoiding the mechanical rotation which would be required using the original single trace, two coils probe design when testing for defects not following a specific direction, i.e., not aligned with the excitation trace.

In the new, four-quadrant probe, the two driver traces can be activated simultaneously with similar currents or having different amplitudes or phases. In the former case (the vertical driver traces carry a current with the same amplitude and phase of the horizontal ones) the eddy currents will have the pattern shown in the lighter arrows of Fig. 3(a). Near the driver traces, the induced eddy currents will take the opposite direction of the driver current. Remarkable differences can be noted in the way the eddy currents form closed loops in two distinct patterns. In the upper-right (first) and lower-left (third) quadrants, the magnetic field contribution from the two adjacent driver traces has the same direction. In this case, the eddy currents flow continuously from underneath one of the driver traces to the other forming a loop with similar form to the sensing coils windings. For the upper-left (second) and lower-right (fourth) quadrants, the magnetic field contributions of the two adjacent driver traces do not have the same direction. This forces eddy currents to join on the center of the