ARCHIVES OF ELECTRICAL ENGINEERING VOL. 65(1), pp. 133-140 (2016)

DOI 10.1515/aee-2016-0010

Tilt-shift eddy current probe impact on information value of response signal

VLADIMIR CHUDACIK, MILAN SMETANA

University of Zilina, Faculty of Electrical Engineering
Department of Electromagnetic and Biomedical Engineering
Univerzitna 1, 010 26 Zilina, Slovak Republic
tel. +421 41 513 5062
e-mail: vladimir.chudacik@fel.uniza.sk

(Received: 12.08.2015, revised: 12.01.2015)

Abstract: This article deals with the possibility for increasing of the informational value of a response signal using tilt-shift eddy current probe. Numerical simulations based on the FEM method using the OPERA 3D software as well as gained experimental results are presented. The simulated cracks are evaluated at the selected eddy current probe tilts and shifts with respect to conductive plate to obtain additional data needed for its evaluation and localization. Obtained simulation results are compared and discussed with the experimental results.

Key words: eddy current testing, eddy current probe, response signals, tilt-shift probe

1. Introduction

Usability and suitability of products may be limited by the presence of material defects and inhomogeneities arising from their use or incurred in the production. For optimal function of products is required to find these defects to avoid undesirable consequences. To an examination of material defects are often used the electromagnetic nondestructive testing (NDT) and nondestructive evaluation (NDE) methods. The main purpose of these methods is detection of a material inhomogeneities, defects and discontinuities, without mechanical damage of a tested object. Non-destructive evaluation extends this purpose. The maintenance in industry requires expect localization also characterization of a detected defect. The NDE has the ambition to classify and quantify defects that can be detected in various structures, [1, 2]. The main aim of non-destructive methods is to prevent a failure of the components, devices and equipment in industry, medicine, construction or household. The characteristics and advantages of non-destructive methods offer a possibility of periodic and thorough inspection of industry products, which ensures their safe, effective and long-term operation. Eddy current testing (ECT) method belongs to the non-destructive methods and can be applied to conductive materials [3-5].

The ECT is based on the phenomenon of electromagnetic induction. The common ECT method uses an alternate current to drive the probe. This coil generates appropriate electromagnetic (EM) field in its surrounding. The coil placed near to a conductive material cause the induction of eddy currents in this material. The induced eddy currents in the material flow as closed loops in a direction perpendicular to the primary EM field coil. The induced eddy currents subsequently generate secondary EM field. Secondary EM field counteracts the cause of its formation, interacts with primary EM field and causes the formation of the electromagnetic coupling, shown in Figure 1. Any change in the electromagnetic parameters of conductive material causes a change in the flow of induced eddy currents, which affects the resulting EM field and coil impedance, which is measurable, [4, 6-8].

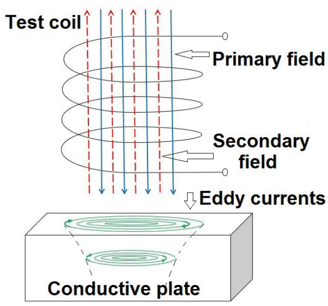

Fig. 1. Principle of the ECT method

The ECT method has several requirements that must be secure to properly measure such as suitable frequency, the geometry of the material and placing of the ECT probe, offset, electromagnetic properties, preventing unwanted movement of probe and vibrations. In this paper, the position and movement of the probe is evaluated. Tilting and shifting of the eddy current probe is investigating to increase the information content of the gained signals.

2. Numerical model and simulations results

The numerical model is created using the software OPERA 3D [9]. Numerical simulation of electromagnetic fields is based on the finite element method (FEM).

Fundamental factors, affecting the response signal in ECT, include: probe type, geometry, excitation waveform characteristics, electromagnetic properties of the inspected material etc. Further, frequency of the excitation signal is also very important.

Classical absolute probe is used for simulation model (Fig. 2a). The probe is placed in normal direction to the plate surface, with lift-off of h = 1 mm. Several tilt angles are set, separately: basic tilt angle of $\varphi = 0°$, next four scans are with the tilt angle of $\varphi_1 = 45°$ and $\varphi_2 = -45°$, in x-axis and in y-axis with maximal lift-off of h = 1 mm, shown in Figure 2b. The coil is driven by the harmonic current with the frequency of f = 10 kHz and the current density J = 2 A/mm^2.

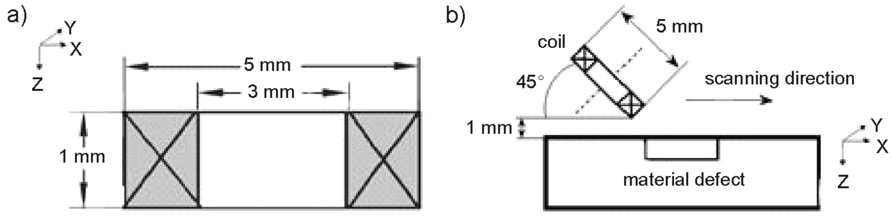

Fig. 2. A) geometry of the ECT probe, b) configuration with tilting positions

The conductive plate with a thickness of t = 10 mm has the electromagnetic parameters of the stainless steel SUS 316 L. The plate has the conductivity of σ = 1.35 MS/m and the relative permeability of μ_r = 1. The non-conductive defects having the rectangular shape with width of w = 0.2 mm, length of l = 10 mm and depths of d_c= [1, 3, 6, 9] mm are simulated in the middle of the conductive plate, separately. ECT inspection is realized as the one-dimensional scan, with defined number of points per line: 22. ECT probe`s response signal is acquired for five different configurations, separately. Then, for each defect, response signal database is created. Magnetic flux density individual spatial components are taken to compute the module of the response signal, as follows:

$$B_{\mathrm{mod}} = \sqrt{B_x^{\ 2} + B_y^{\ 2} + B_z^{\ 2}}. \tag{1}$$

ECT method is a comparative method giving the resulting signal ΔB_{mod}. This value is obtained according to Equation (2), where the B_{mod} represents plate with defect value and $B_{\mathrm{mod}}(0)$ represents defect free area value over the conductive plate:

$$\Delta B_{\mathrm{mod}} = B_{\mathrm{mod}} - B_{\mathrm{mod}}(0). \tag{2}$$

The main aim of the numerical model implementation is to evaluate the impact of the probe tilting and shifting, around the z-axis on a response signal. One dimensional scanning is performed over each crack along x-axis of the crack, relative to the crack centre. The data are acquired for every scanning line, creating 2D matrix of the scanned surface of the plate. All the data are processed and the appropriate maximum values are searched, to be used as evaluated data. The resulting signals are displayed in Figure 3, while the probe is oriented normally to the plate surface, φ = 0°. Inspected crack has the real edges in the range of $x \in < -5; 5 >$ along the x-axis. The resulting waveforms indicate maximum signal values at the position of $x_1 = -6$, $x_2 = 6$. These indications can be in correlation with the length of the crack, characterized by its edges.

Because the position of the detected peaks and the defect edges is only approximate, there's ambition to find another approach to be the detection more precise. It is known that the change of the probe tilting directly affects the response signal. Taking this fact into account, changing the tilt angle to value of φ = 45° in the scanning direction, giving one maximum and one minimum peaks. These peaks are not totally in coincidence with the peaks obtained using conventional normal orientation of the probe. Maximum peak value is at the same position, but with lower amplitude. Minimum peak value is located within the defect, see Figure 4.

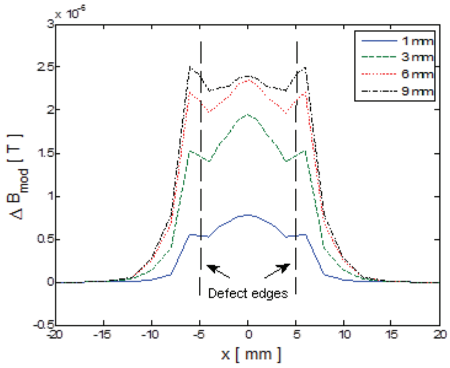

Fig. 3. Numerical simulation results: differential response signals using conventional ECT approach

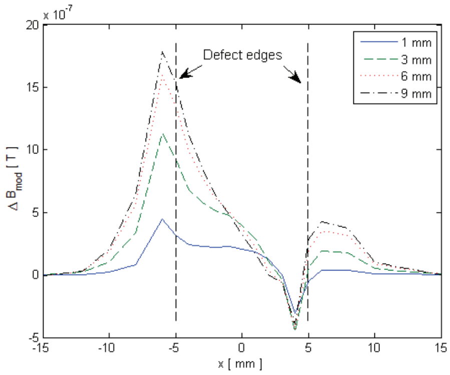

Fig. 4. Numerical simulation results: differential response signals using probe tilting in x-axis, $\varphi = 45°$ tilt

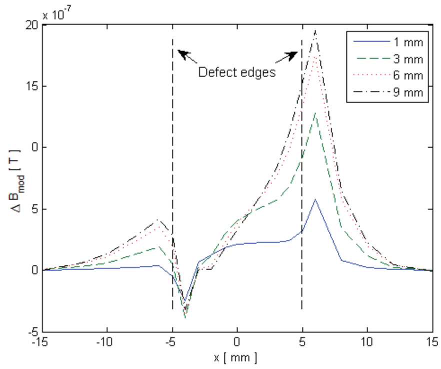

Fig. 5. Numerical simulation results: differential response signals using probe tilting, in x-axis, $\varphi = -45°$ tilt

The similar result is achieved by using mirroring angle with value of $\varphi = 45°$, see Figure 5. The distance of the simulated defect edges is equal to the distance of maximum peak and minimum peak but shifted in one direction. Also the distance of the peaks from the nearest simulated edge is the same. Using both the measurements and appropriate max/min peaks, it is possible to determine the position of the edge. The difference between these gives the value *a*, where value of *a*/2 specifies the distance of the real defect edge from another peak value, as shown in Figure 6. Thus, the first edge is identified at $x_1 = -5$ mm, by position of the maximum peak $x_{max} = -6$ mm. Further, minimum peak position gives value of $x_{min} = -4$ mm and second edge at position $x_2 = 5$ mm. The numerical simulations are performed for four different depths of the defect and their results can be analogically stated.

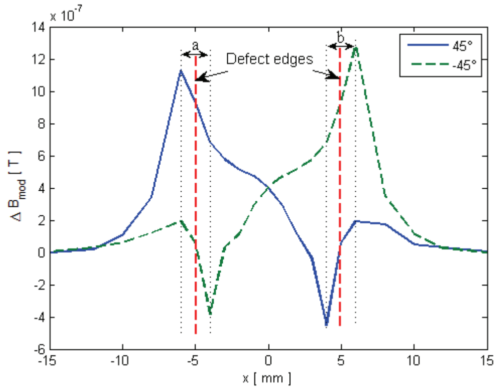

Fig. 6. Numerical simulation results: combination of differential response signals using probe tilting on 3 mm defect

In next section, shifting of the probe at the angles $\varphi_1 = 45°$ and $\varphi_2 = -45°$ in the y-axis is presented. This approach gives from one to three maximum peaks. Two maximum peaks have lower amplitude but directly determine a position of the defect edges, as shown in Figures 7, 8. Edges of the deeper defects can be clearly visible, but shallow defects are hard to identify. Optimal excitation frequency for given defect need to be find, from case to case. Moreover, it is possible to determine the value of *c*, equals to boundary peaks distance position and it is in correlation with the length of the defect, see Figure 9.

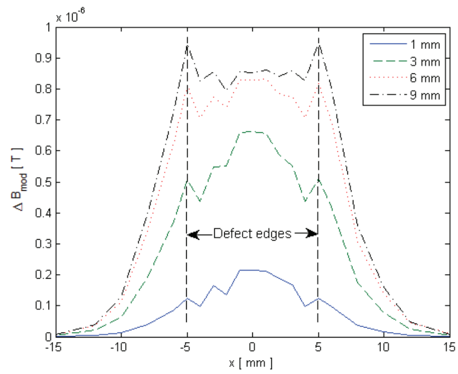

Fig. 7. Numerical simulation results: differential response signals using probe tilting in y-axis, $\varphi = 45°$ tilt

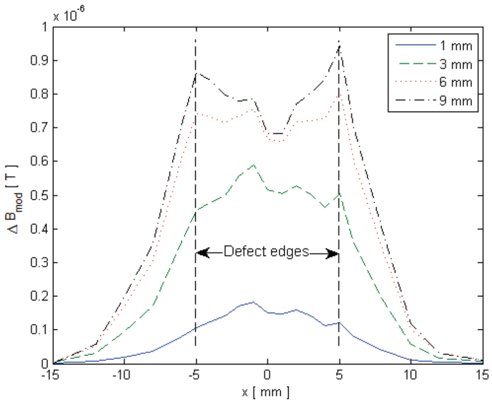

Fig. 8. Numerical simulation results: differential response signals using probe tilting in y-axis, $\varphi = -45°$ tilt

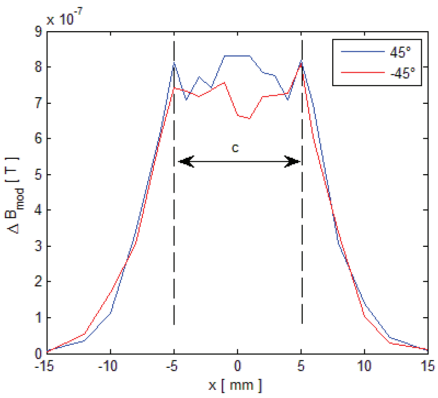

Fig. 9. Numerical simulation results: combination of differential response signals using probe tilting on 3 mm defect

3. Experimental results

The experimental measurements are carried out under the same conditions as used in the numerical simulations. The absolute ferrite-core probe KA2-1 (Rohmann GmbH) is driven by the harmonic voltage signal with an effective value of $U = 2$Vpp, within the frequency range of $f = <$ 10 kHz, 800 kHz $>$, shown in Figure 10. The measuring apparatus consists of: signal generator, 3-axis PC-controlled stage, ECT probe and lock-in amplifier.

Minimum ECT probe lift-off value is set to $l_0 = 1$ mm. The SUS316L plate specimen with a thickness of $h_1 = 10$ mm is inspected from the near-side. Defect depth of $h = 9$ mm and length of $l = 10$ mm is the same as in the simulations.

The experimental measurements obtained by presented configuration of the probe, in the range of B_{mod}, conform the simulation results shown in Figures 7 and 8. The simulation results coincide with the experimental ones in the range of imaginary part of Im{*Bz*}, shown in Figures 11 and 12. By scanning 1 sample corresponds to 1/7 mm. Tilt-shifted probe obtained results giving more precise results of the defect geometry, in comparison to the conventional scanning approach.

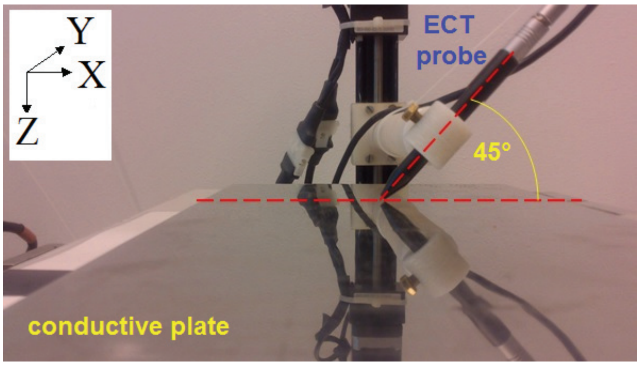

Fig. 10. Configuration of the ECT probe over the conductive specimen with defect

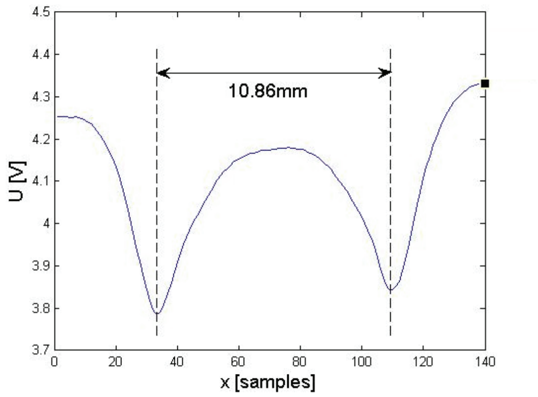

Fig. 11. Imaginary component of response signal – conventional scan

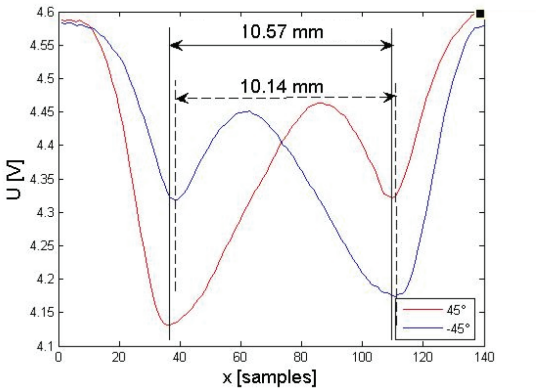

Fig. 12. Imaginary component of response signal – tilted probe scan

4. Conclusion

The article presented modification of the eddy current probe configuration, in the eddy current non-destructive inspection under harmonic excitation. An impact of tilting and shifting of the probe on response signals was investigated by numerical and experimental means. Obtained numerical simulation results give the potential for advanced edge detection using a tilt-shifted probe. It was possible to successfully identify searched defect edges using such approach. As could be seen from the experimental results, only the imaginary component of response signals can be taken into account, to give the appropriate information value signal. Quite good correlation between numerical and experimental signals was achieved for the imaginary component of gained signals. However, the experimental identification was only approached the simulations identification results. It is necessary to adjust the parameters of the probe. It can be concluded that it is necessary to design an advanced probe to achieve higher information content results, what is the next aim for future work.

References

[1] Garcia-Martin J., Gomez-Gil J.,Vayquez-Sanches E., *Non-Destructive Techniques Based on Eddy Current Testing*. Sensors 11(3): 2525-2565 (2011).

[2] Janousek L., Smetana M., Strapacova T. et al., *Advanced procedure for non-destructive diagnosis of real cracks from eddy current testing signals.* In ELEKTRO 2014: proceedings. [CD-ROM], Žilina: IEEE, p. 567-570 (2014).

[3] Rao B.P.C., *Practical eddy current testing*. Alpha Science International. Limited (2007).

[4] Dogaru T., Smith S.T., *Edge crack detection using a giant magneto-resistance based eddy current sensor*. Non-Destruct. Test. Eval. 16: 31-53 (2000).

[5] Janousek L., Smetana M., Capova K., *Enhancing information level in eddy-current non-destructive inspection*. International Journal of Applied Electromagnetics and Mechanics 33: 1149-1155 (2010).

[6] Carlstedt M., Porzig K., Ziolkowski M. et al., *Comparison of Lorentz Force Eddy Current Testing and Common Eddy Current Testing – Measurements and Simulations*. Electromagnetic Nondestructive evaluation (XVII), IOS Press 39: 218-225 (2014).

[7] Boltz E.S., Tiernan T.C., *New electromagnetic sensors for detection of subsurface cracking and corrosion.* Rev. Prog. Quant. Non-Destruct. Eval. 17: 1033-1038 (1998).

[8] Yuan S., Liang D., Shi L. et al., *Recent progress on distributed structural health monitoring research at NUAA.* Journal of Intelligent Material Systems and Structures 19: 373-386 (2008).

[9] Opera-3d Design Software, Cobham Technical Services, Vector Fields Simulation Software. [online][cit. 2015-10-26] < http://www.cobham.com/about-cobham/communications-and-con nectivity/about-us/antenna-systems/specialist-technical-services-and-software/products-and-services/design-simulation-software/opera/opera-3d.aspx