Ladislav JANOUŠEK
University of Žilina

Effect of exciting system configuration on eddy currents distribution in non-destructive evaluation of materials

***Abstract**. The paper focuses on eddy currents distribution in conductive materials under non-destructive inspection. Effect of various parameters of an exciting system on the distribution is studied by numerical means. A circular coil is utilized to drive eddy currents in a conductive plate under harmonic excitation. Diameter of the coil is varied together with the clearance between the coil and the plate surface. Attenuation of the eddy current density along the plate thickness is studied and the results are analyzed.*

Streszczenie.** Tematem artykułu jest badanie rozpływu prądów wirowych w środowisku przewodzącym. Autor poprzez symulacje numeryczne określa wpływ różnych parametrów systemów wzbudzania na rozpływ prądów wirowych. Cewka kołowa stanowi wzbudnik, zaś obiektem na który oddziałuje jest czworokątny wycinek płaskiej powierzchni.. Przedmiotem badań jest oszacowanie stopnia tłumienia prądów wirowych w zależności od grubości rozpatrywanego materiału. **(Wpływ parametrów układu wzbudzania na rozpływ prądów wirowych w środowisku przewodzącym)

Keywords: non-destructive evaluation, eddy currents attenuation, exciting system, conductive materials
Słowa kluczowe: badania nieniszczące, tłumienie prądów wirowych, materiały przewodzące.

Introduction

Eddy current testing (ECT) is one of the most common electromagnetic methods employed in non-destructive evaluation of conductive materials. The principle of ECT underlies in the interaction of induced eddy currents with a structure of an examined conductive body based on the electromagnetic induction phenomena. A primary alternating exciting electromagnetic field is generated in the vicinity of a coil driven by a time-varying current according to the Ampere's law. Electromotive force is induced in a conductive object which is in proximity of the coil according to the Faraday's law. Eddy-currents flow in the conductive object according to the Ohm's law and their vector lines must be closed. A secondary electromagnetic field generated by the eddy-currents counterworks to the primary exciting electromagnetic field according to the Lenz's theorem. The induction coupling therefore exists between the coil and the conductive object. It can be simply considered as an interaction between the primary and the secondary electromagnetic fields. The method is widely applied in various fields accounting for measurements of material thickness, proximity measurements, corrosion evaluation, sorting of materials based on the electromagnetic properties. However, the most wide spread area of its application in present is the detection and possible evaluation of discontinuities [1].

ECT probes are one of the most important elements in the non-destructive evaluation, because they transfer information between an ECT instrument and a conductive object through the induction coupling. Optimal ECT probe should assure high sensitivity to expected defects, high probability of detection of expected defects and their classification possibility (location, dimensions, etc.) [2]. Many ECT probes have been developed over past decades reflecting special demands of particular applications [1]-[4]. R&D activities focusing on new excitation techniques and signals' interpretation have allowed to wide spread application possibilities of the method [5]-[7]. Probe design and development is thus still of very high interest to obtain good performance of inspection.

Eddy currents distribution in an inspected material significantly determines basic features of the probe such as sensitivity, penetration and resolution. According to the electromagnetic field theory, the distribution of eddy currents in a material depends mainly on a testing frequency and the electromagnetic parameters of a material. However, under real conditions there are much more variables with substantial influence on this distribution such as shape of coils, their dimensions, configuration of inspection, material thickness, clearance between coil/s and a material surface (lift-off), etc.

The author has already invented a novel exciting system providing enhanced resolution of deeper surface breaking defects [4]. The system consists of four detached rectangular coils. The coils are of same dimensions and they are oriented tangentially regarding the surface of an inspected material. A new ECT probe was developed employing the exciting system. The numerical and experimental results proved excellent performance of the probe concerning the depth resolution of a detected deep surface breaking defect. However, the probe has two particular drawbacks that limit its application. It has directional properties and it is quite bulky.

Current research activities are focused on development of an improved exciting system. It is based on circular coils oriented normally to a surface of an inspected material to overcome drawbacks listed above. In order to employ an idea presented in [4] it is very indispensable to have a good knowledge of a coil dimensions influence on the eddy current distribution. Parametric numerical analyses are therefore carried out in this paper. The purpose is to find out combination of two circular exciting coils that provide similar distribution of eddy currents on a material surface; however, they provide slightly different attenuation of the eddy current density along the material depth.

Numerical investigations

Numerical calculations using the finite element method are carried out to investigate influences of certain parameters on eddy currents distribution.

A plate conductive specimen is modelled in this study to explore attenuation of eddy currents along its depth. The plate thickness is adjusted to 30 mm. The electromagnetic parameters of the plate are set to the following values: $\sigma = 1.35 \cdot 10^{6}$ S$\cdot$m^{-1} and $\mu_r = 1$, that correspond to a material SUS316L frequently used for structural components in petrochemical and nuclear industries.

An exciting coil of the circular shape is employed to drive eddy currents in the plate. Axis of the coil is oriented normally regarding the plate's surface. This type of exciting coil in the given orientation is commonly utilized in a variety of applications. An ECT probe with such exciting coil does not account for the directional properties. Cross-section of the coil winding is kept constant for all the calculations, in concrete 1 x 1 mm^2, because preliminary investigations showed that these dimensions have only minor impact on the eddy current attenuation along the material depth. Outer radius of the coil r_c is varied to investigate its influence on the attenuation. It is gradually adjusted to the following values r_c = 2,3,4,5,6,7,8,9,10,12,15,20 mm. Clearance between the coil and the plate surface, hereinafter referred as the lift-off, is sequentially tuned to lf = 0.5,1,2,3,4,5,6,7,8,9,10,12,14,16,18,20 mm. The coil is driven with the harmonic current while the current density is kept constant at a value of 1 A•mm^{-2} and the frequency is adjusted to 10 kHz. The standard depth of penetration for the given parameters equals to δ = 4.33 mm. The ratio between the material thickness and the standard depth of penetration is thus almost 7.

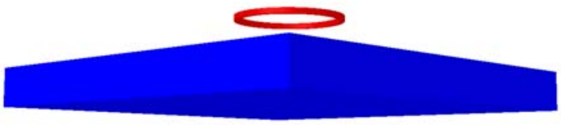

Fig.1. Layout of the model

A very fine model of the system, shown in Fig.1, is built up based on the finite tetrahedral elements. Only ¼ of the system is considered employing appropriate boundary conditions. The mesh consists of approximately 4 million elements. Particular results of numerical simulations are summarized in the following section.

Results and discussions

Two parameters of the exciting system, i.e. the coil radius r_c and the lift-off lf are varied to investigate influences of these parameters on the eddy current attenuation along the material depth. Important findings are reported and discussed here.

The distribution of eddy current density vector in the material is stored after successful execution of each simulation. The results are then processed in such a way that only one dependence of the eddy current density absolute value on the material depth for each case is used for the evaluation. The dependence is taken along the material depth direction under a surface point where the eddy current density has the maximum value.

The dependences of the eddy current density absolute value on the material depth for the coil with a radius of r_c = 2 mm and for several values of the lift-off are shown in Fig.2. Note that the vertical axis is in logarithmic scale. Attenuation of eddy currents along the material depth has the exponential character. However, it can be observed that the results gained for different values of the lift-off show diverse behaviour. The same dependences but in relative values are shown in Fig.3 in order to highlight contrast between the curves. Each dependence of the eddy current density absolute value on the material depth is normalized by its maximum value. It can be seen that the eddy current attenuation strongly depends not only on the standard depth of penetration, i.e. the frequency, the conductivity and the permeability, but also on the lift-off. Larger clearance between the coil and the plate surface provides eddy current distribution with less attenuation along the material depth.

Similar dependences in relative values for the coil with a radius of r_c = 5 mm and of r_c = 20 mm are shown in Figs. 4 and 5, respectively. The presented results clearly show that the impact of lift-off on the eddy current attenuation along the material depth decreases for the coil with larger diameters.

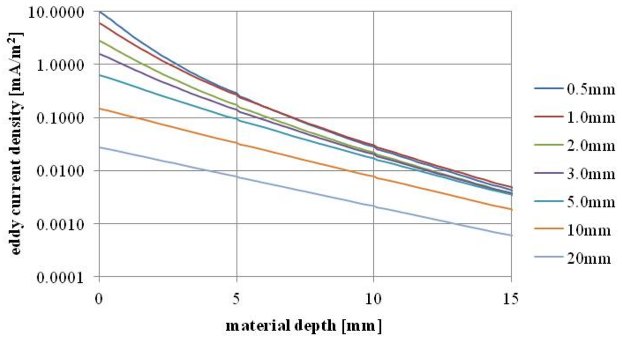

Fig.2. Dependences of eddy current density in absolute values on the material depth for different adjustments of lift-off, r_c = 2 mm

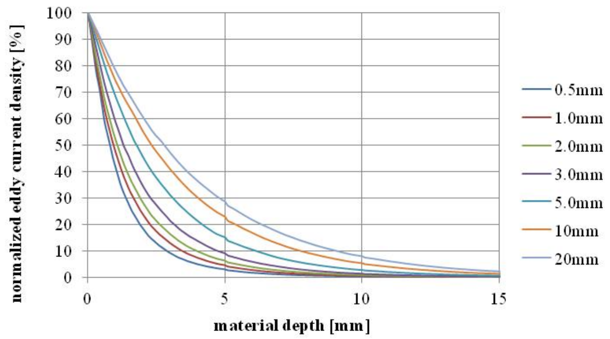

Fig.3. Dependences of eddy current density in relative values on the material depth for different adjustments of lift-off, r_c = 2 mm

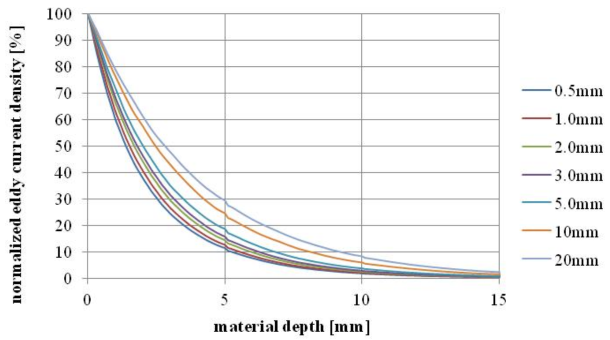

Fig.4. Dependences of eddy current density in relative values on the material depth for different adjustments of lift-off, r_c = 5 mm

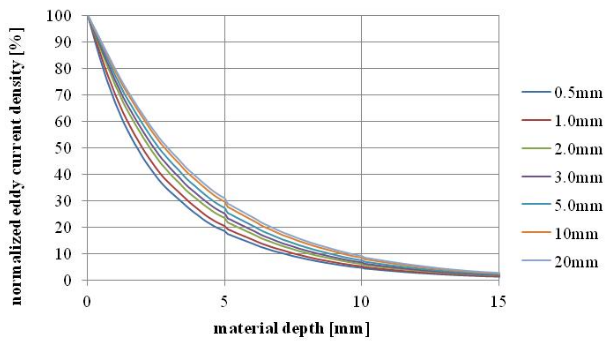

Fig.5. Dependences of eddy current density in relative values on the material depth for different adjustments of lift-off, r_c = 20 mm

A specific value of the distance from material surface along its depth, denoted hereinafter as the penetration depth, is calculated for all the evaluated distributions of the eddy current density. It is the value where the eddy current density falls to 36.79% of its surface value. The penetration depth is then plotted as a dependence on the coil radius r_c and the lift-off *lf* as well. Figure 6 shows the calculated dependence. As it can be seen, by proper adjustment of the exciting system parameters the penetration depth can be increased several times comparing to a case when only small coil is placed with a small lift-off over a material. However, this effect depends on frequency or more specifically on the ratio of the material thickness and the standard depth of penetration.

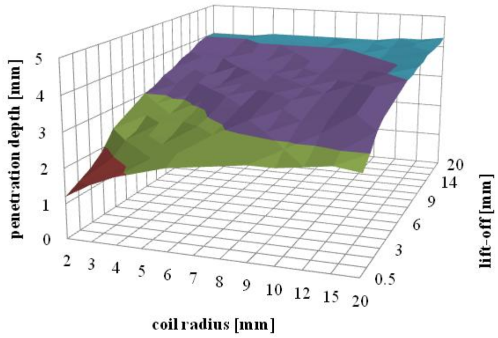

Fig.6. Penetration depth as function of coil radius and lift-off

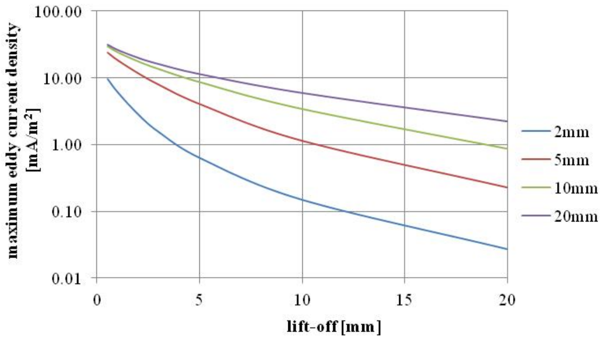

Fig.7. Dependences of maximum eddy current density in absolute values on the lift-off for the coil with various radiuses

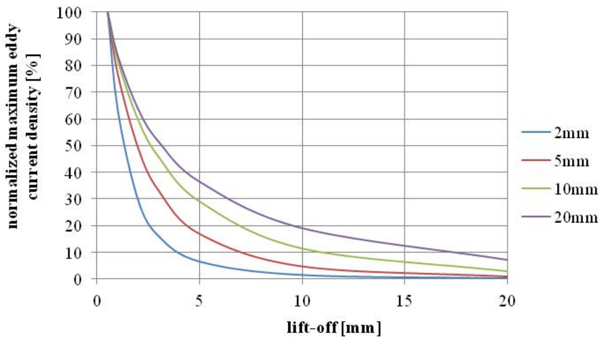

Fig.8. Dependences of maximum eddy current density in relative values on the lift-off for the coil with various radiuses

It should be noted that the maximum value of eddy current density decreases with enlarging the lift-off as it is shown in Fig.7. However, the coil radius has the opposite impact. With enlarging the coil radius the maximum value of eddy current density increases. The same dependences but in relative values are shown in Fig.8. It is clear from the presented results that the lift-off change has smaller influence on the maximum value of eddy current density when a coil with larger radius is employed.

Conclusion

The paper concerned on the attenuation of eddy currents along material depth in non-destructive inspection. Influences of selected parameters of eddy current exciting system on the attenuation were studied by numerical means. A conductive plate specimen having the electromagnetic parameters of SUS316L and a thickness of 30 mm was used for the study. Circular exciting coil positioned normally regarding the plate surface drove eddy currents. The coil was fed by the harmonic current with a frequency of 10 kHz. Two parameters of the exciting system, specifically the coil radius and the lift-off were altered. Distribution of eddy current density was evaluated for various adjustments of the parameters. The results clearly demonstrated that the coil radius and the lift-off as well have strong impact on the eddy current attenuation along material depth even the material thickness is several times larger than the standard depth of penetration. Further studies will focus on design of a unique exciting system composed of two coils having different dimensions and lift-offs. It is expected that such exciting system would provide enhanced resolution of deeper surface breaking defects in thick conductive materials.

Acknowledgements

This work was supported by the Slovak Research and Development Agency under the contracts No. APVV-0349-10 and APVV-0194-07. This work was also supported by grant of the Slovak Grant Agency VEGA, project No. 1/0765/11.

REFERENCES

[1] Janoušek L., Čápová K., Gombárska D., Smetana M., Progress in eddy-current non-destructive evaluation of conductive materials, *Acta Technica CSAV*, 55 (2010), 13-28.

[2] Chen Z., Miya K., A new approach for optimal design of eddy current testing probes, *Journal of Nondestructive Evaluation*, 17 (1998), 105-116.

[3] Thollon F., Burais N., Geometrical optimization of sensors for eddy currents non destructive testing and evaluation, *IEEE Transactions on Magnetics*, 31 (1995), 2026-2031.

[4] Janoušek L., Chen Z., Yusa N., Miya K., Excitation with phase shifted fields – enhancing evaluation of deep cracks in eddy-current testing, *NDT&E International*, 38 (2005), 508-515.

[5] Smetana M., Strapáčová T., Pulsed eddy currents as a new approach in non-destructive evaluation of conductive materials, *Proc. of TRANSCOM*, 2009, Žilina – Slovak Republic, 63-66.

[6] Janoušek, L., Smetana M., Alman M., Interactions of partially conductive cracks with eddy currents in non-destructive evaluation, *Przegląd Elektrotechniczny*, 87 (2011), 59-61.

[7] Gombárska D., Smetana M., Wavelet based signal analysis of pulsed eddy current signals, *Przegląd Elektrotechniczny*, 87 (2011), 37-39.

Authors: *doc. Ing. Ladislav Janoušek, PhD., Department of Electromagnetic and Biomedical Engineering, Faculty of Electrical Engineering, University of Žilina, Univerzitná 1, 010 26 Žilina, Slovak Republic, E-mail: janousek@fel.uniza.sk*