# ADVANCES IN EDDY-CURRENT NON-DESTRUCTIVE EVALUATION

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**Summary** The paper presents a general overview of recent developments in the eddy-current non-destructive evaluation. Basic principle of the eddy-current non-destructive testing is explained and possible applications of the method in non-invasive evaluation of conductive materials are summarized. Actual issues of research and development in this field are discussed. A novel method for depth evaluation of a detected crack using eddy-current testing signals is proposed.

## 1. INTRODUCTION

Non-destructive evaluation (NDE) of materials is defined as a group of activities aiming to the investigation and the characterization of materials as well as structures without their mechanical damage. Different physical principles and phenomena are utilised for the NDE of materials. One of the electromagnetic methods, originating from the principle of electromagnetic induction, is an eddy current non-destructive testing (ECT) of conductive materials. Increasing trends of utilization of the method in practical inspections, especially in the last period, impose gradually raising demands on research and development (R&D) in this field.

The paper summarizes recent advances in eddy-current non-destructive evaluation. After the principle of the method is explained, possibilities of its utilization in different applications are listed. Actual issues of R&D activities in this field are summarized and discussed. A novel approach in the eddy-current non-destructive evaluation is proposed and the presented results prove its effectiveness in depth evaluation of a detected defect.

## 2. PRINCIPLE OF ECT

The principle of the ECT, shown in Fig. 1, underlies in the interaction of induced eddy currents with a structure of an examined body [1], [2].

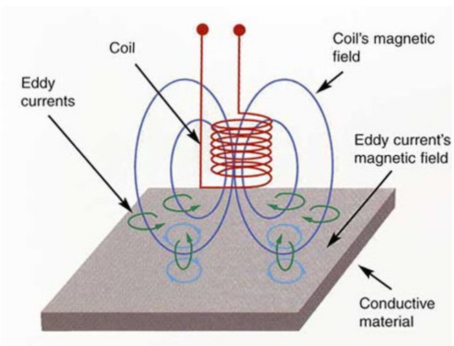


*Fig. 1 Principle of ECT*

A primary alternating exciting electromagnetic field is generated in the vicinity of a coil driven by an alternating current. Electromotive force is induced in a conductive object which is in proximity of the coil and eddy-currents flow there according to the electromotive force. A secondary electromagnetic field generated by the eddy-currents counterworks to the primary exciting electromagnetic field. 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 field.

The resulting electromagnetic field of the coil and the conductive object depends on geometrical parameters of the system as well as on the electromagnetic parameters of the conductive object. For the given excitation, i.e. configuration, dimensions and orientation of the coil(s) and its feeding, the coupling is influenced by the following important parameters:

- position of the coil with respect to the object,
- geometrical configuration of the object,
- dimensions of the object, mainly its thickness,
- the electromagnetic parameters of the object (conductivity, permeability),
- nature of the object (homogeneity, linearity, anisotropy).

Utilization of the ECT in practical applications depends on a possibility to detect fluctuations in the resulting electromagnetic field due to changes in the important parameters. The ECT is therefore applied in:

- thickness measurements of conductive materials,
- thickness measurements of non-conductive coatings on conductive materials,
- measurements of the electromagnetic parameters (conductivity, permeability) of conductive materials,
- verification of conductive material treatment,
- verification of selected parameters of products (dimensions, etc.),
- detection and evaluation of discontinuities (defects) in conductive materials, etc.

Rising employment of the ECT in different technical applications imposes new challenging appeals on R&D activities.

## 3. ACTUAL ISSUES OF R&D ACTIVITIES

The principle of the ECT has been known for several decades. Nowadays, the most wide spread application area of the ECT is the detection and possible evaluation of different discontinuities in conductive materials.

The hardware and the software means of the ECT can be divided into following groups:

- ECT instruments,
- ECT probes,
- evaluation of measured signals,
- positioning systems and manipulators.

ECT instruments supply exciting coils of the probes and sense the ECT signals. Frequently, several superimposed harmonic exciting signals are used to drive the eddy currents. It helps to gain information about a defect under several frequencies at the same time. Moreover, better separation between the useful signals and background noises can be obtained. Nowadays, the R&D activities are increasingly focused on a pulse excitation [3]. Its advantage comparing to the conventional harmonic excitation is in a wide frequency spectrum response obtained with one exciting impulse [4].

ECT probes are one of the most important elements in the non-destructive testing, because they transfer information between an ECT instrument and a conductive object through the induction coupling. Usually, inductance coils are utilized to build ECT probes. However, magnetic sensors are employed in sensing low intensity fields [5].

Features of ECT probes depend on number, shape, configuration, orientation, dimensions and connections of coils as well as on parameters of a magnetic circuit. Optimal ECT probe should assure [6]:

- high sensitivity to expected defects,
- high probability of detection of expected defects,
- possibility to distinguish parameters (location, dimensions, etc.) of expected defects.

Many types of ECT probes have been developed reflecting special demands of particular applications [7]-[9]. ECT probes with ferromagnetic cores are sometimes utilized for precise localization of the electromagnetic field [10]. However, the non-linearity of the cores brings another unknown into the evaluation.

Sensed signal is the integral value. Its phase depends mainly on a crack depth. Thus, a crack depth can be roughly estimated from the signal phase information. Solving of inverse problems represents more sophisticated approach in crack evaluation. Selected parameters of defects (depth, length, position, profile, etc.) are reconstructed based on the measured signals. Two approaches are utilized for the purpose [11]:

- deterministic,
- stochastic.

Usually, two variables of a defect are estimated, its depth and length, while a profile, a width and electromagnetic parameters of a defect are adjusted in advance.

A difference between measured and simulated signals is minimized in the deterministic methods [12]. The process is iterative and therefore large number of forward simulations is required. Databases of pre-computed signals [13] as well as parallel computing on supercomputers [14] can help to shorten the evaluation time.

The stochastic methods utilize so called evolution algorithms, for example neural networks, genetic algorithms, for the inversion [15], [16].

At present, it is possible to detect even very small artificial or fatigue crack and quite precisely estimate its depth in homogeneous or non-homogeneous structures [17]. Current research activities are mainly focused on the following areas:

- design, development and optimisation of ECT probes to satisfy severe demands of non-destructive inspection of structures with real defects,
- reliable detection and localization of unknown and in most cases invisible defects with variable orientation, parameters, profile and structure,
- precise estimation of main parameters of a defect, especially its length and depth,
- new possibilities of practical applications of the ECT.

The issues listed above are closely related to each other and they are determined by actual problems and practical experiences.

## 4. NOVEL EVALUATION METHOD

ECT signals are integral values and they do not carry explicit information about the crack dimensions. Therefore, evaluating the depth of a defect from the ECT signals is quite difficult [18]. In addition, the skin-effect concentrates induced currents on the surface of a tested material which means that obtaining information about the depth is essentially difficult.

This section proposes a novel method for a crack depth evaluation from the ECT signals.

A new probe [19] shown in Fig. 2 is used for the inspection. The probe consists of four rectangular exciting coils and a circular detecting coil placed in the centre between the exciting coils. The exciting coils are oriented tangentially regarding the surface of a tested sample and the pick-up coil has the normal orientation. The inner exciting coils and the outer ones are connected in series, respectively.

A detected crack is inspected twice. At first, only the inner exciting coils of the probe are driven and only the outer exciting coils are driven during the second inspection. Different distances of the inner and the outer exciting coils from the detecting coil assure a different profile of the eddy current density along the material depth under the detecting coil.

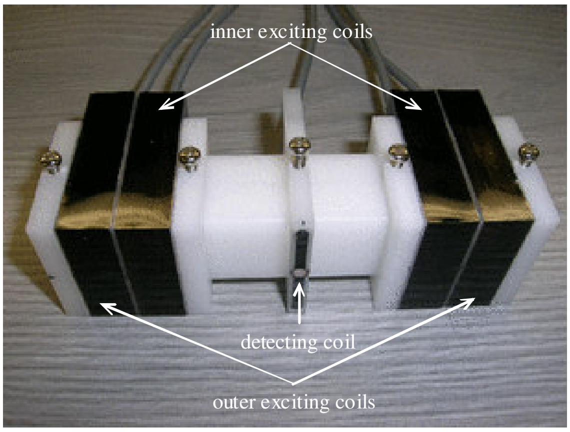


*Fig. 2 Picture of a new probe*

The probe scan right over the crack along its length; the windings of the exciting coils are perpendicular to the crack length. The two sensed signals of a same crack gained during two inspections are linearly superimposed according to the following relations:

$$\begin{aligned}\mathrm{Re} &= C_1 \cdot \mathrm{Re}_1 - C_2 \cdot \mathrm{Re}_2 \\ \mathrm{Im} &= C_1 \cdot \mathrm{Im}_1 - C_2 \cdot \mathrm{Im}_2\end{aligned}, \qquad (1)$$

where $\mathrm{Re}_1$, $\mathrm{Re}_2$ are the real parts of two complex signals; $\mathrm{Im}_1$, $\mathrm{Im}_2$ are the imaginary parts of two complex signals; and $C_1$, $C_2$ are real positive numbers defining a ratio of the superposition:

$$\alpha = C_1 / C_2 \ , \qquad (2)$$

where max $(C_1, C_2) = 1.0$. The phase of the resulting superimposed complex crack signal $\varphi$ corresponding to the maximum absolute value is evaluated with respect to the value of the ratio. The phase is given by the following equation:

$$\varphi = \arctan \frac{\mathrm{Im}_\mathrm{m}}{\mathrm{Re}_\mathrm{m}} \ , \qquad (3)$$

where $\mathrm{Re}_\mathrm{m}$ and $\mathrm{Im}_\mathrm{m}$ are the real and the imaginary parts of the superimposed crack signal corresponding to the maximum absolute value of the signal.

A plate specimen made of the stainless steel SUS316L is inspected to evaluate effectiveness of the proposed method. The electromagnetic characteristics of the material include conductivity of $\sigma$ = 1.4 MS/m and relative permeability of $\mu_r = 1$. The thickness of the specimen is $d = 25$ mm. Non-conductive surface braking notches of the rectangular shape with a length of $l_c = 40$ mm, a width of $w_c = 0.5$ mm and depths of $d_c$ = 10, 12, 15, 20 mm model the cracks. The frequency of 10 kHz is adopted in the inspection.

Figure 3 illustrates dependences of the superimposed crack signal phase change on the ratio of superposition for four cracks. It can be observed that the phase of the superimposed signal changes with increasing the ratio of superposition, while this change depends on the crack depth. Thus, a unique feature value of the ratio of superposition can be extracted from the dependence gained for one crack. It is a value of the ratio where the crack signal rotates in a half angle of its overall rotation.

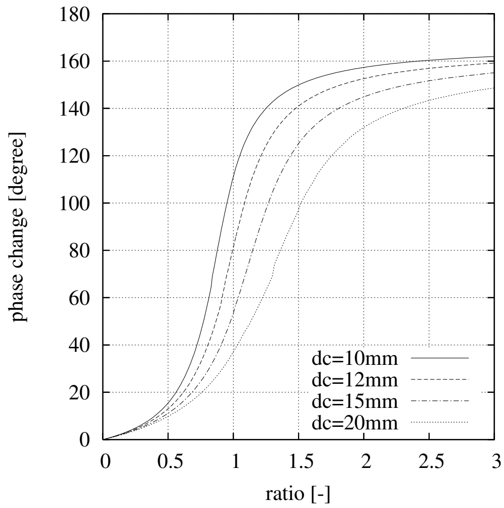


*Fig. 3 Dependences of the superimposed crack signal phase change on the ratio of superposition for the cracks with depths of dc = 10, 12, 15 and 20 mm*

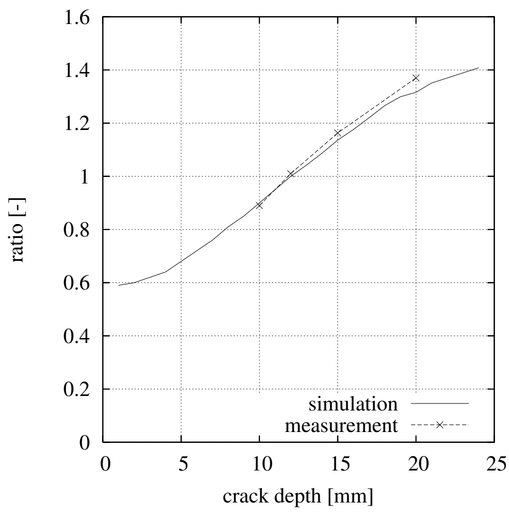


*Fig. 4 Dependences of the feature value of the ratio of superposition on the crack depth*

The dependences of the feature value of the ratio of superposition on the crack depth gained from numerical as well as experimental signals are shown in Fig. 4. The numerical results are plotted for a wide range of the crack depth, from 0% to 100% of the material thickness $d = 25$ mm, to highlight advantages of the proposed method. As it can be seen, there is a unique dependence between the feature value of the ratio of superposition and the crack depth. It means that the depth of an inspected defect can be determined from the dependence based on the feature value of the ratio obtained from measured signals according to the steps described above. Moreover, the numerically gained dependence is almost linear within the investigated range and thus, the depth of surface breaking defects that are much deeper than the standard depth of penetration ($\delta = 4.25$ mm in this case) can be unambiguously evaluated using the method.

## 4. CONCLUSION

The paper dealt with recent advances in eddy-current non-destructive evaluation. Principle of the method was explained in the beginning in order to demonstrate variety of possible applications. Recent research and development activities in this field were summarized. Novel method for non-destructive evaluation of a crack depth using eddy-current testing signals was proposed. The numerical and the experimental results proved the effectiveness of the method even for surface braking cracks that are much deeper than the standard depth of penetration.

**Acknowledgement**

This work has been supported by the grant VEGA No. 1/0308/08 of the Slovak Ministry of Education.

## REFERENCES

[1] Sun, Y.: *An introduction to electromagnetic nondestructive testing*. Proceedings of the ISEM'97 conference, IOS Press, 1998. pp. 145-152.

[2] Janoušek, L., Marek, T., Gombárska, D.: *Eddy current non-destructive evaluation of conductive materials*. Communications, No.1, 2006, pp. 29-33.

[3] Sophian, A. et al.: *Design of a pulsed eddy current sensor for detection of defects in aircraft lap-joints*. Sensors and Actuators, Vol.101/2002, pp. 92-98.

[4] Tsuboi, H., Seshima, N: *Transient eddy current analysis of pulsed eddy current testing by finite element method*. IEEE Transactions on Magnetics, Vol.40/2004, pp. 1330-1333.

[5] Uesaka, M. et al.: *Eddy-current testing by flexible microloop magnetic sensor array*. IEEE Transactions on Magnetics, Vol.34/1998, pp. 2287-2297.

[6] Chen, Z., Miya, K.: *A new approach for optimal design of eddy current testing probes*. Journal of Nondestructive Evaluation, Vol. 17/1998, pp. 105-116.

[7] Kurokawa, M., Miyauchi, R., Enami, K.: *New eddy current probe for NDE of steam generator tubes*. Electromagnetic Non destructive Evaluation, Vol.3/1999, pp. 57-64.

[8] Huang, H. et al.: *Design of an eddy-current array probe for crack sizing in steam generator tubes*. NDT&E International, Vol.36/2003, pp. 515-522.

[9] Janoušek, L., Čápová, K, Yusa, N., Miya, K.: *Advanced probe with array of pick-up coils for improved crack evaluation in eddy-current non-destructive testing*. Proceeding of abstracts from The 12th International Workshop on Electromagnetic Nondestructive Evaluation ENDE 2007, Cardiff – UK, June 19–21, 2007, pp. 33.

[10] Morozov, M., Novotny, P.: *Evaluation of eddy current probes based on local field excitation.* NDT&E International, Vol.35/2002, pp. 147-153.

[11] Cardelli, E. et al.: *New perspectives in non-destructive electromagnetic diagnosis.* International Compumag Society Newsletter, Vol.11/2004, pp. 7-21.

[12] Chen, Z. et al.: *Inversion techniques for eddy current NDE using optimization strategies and a rapid 3D forward simulator*. International Journal of Applied Electromagnetics and Mechanics, Vol.20/2004, pp. 179-187.

[13] Chen, Z. et al.: *Reconstruction of crack shapes using a newly developed ECT probe*. Electromagnetic Nondestructive Evaluation, Vol.2/1998, pp. 225-232.

[14] Yusa, N. et al.: *Large-scale parallel computation for the reconstruction of natural stress corrosion cracks from eddy current testing signals*. NDT&E International, Vol.36/2003, pp. 449-459.

[15] Rao, B.P.C: *An artificial neural network for eddy current testing of austenitic stainless steel welds*. NDT&E International, Vol.35/2002, pp. 393-398.

[16] Koyama, K. et al.: *Fundamental study of flaw estimation in eddy current testing using genetic algorithm.* On CD from the 16th World Conference on NDT, 2004.

[17] Yusa, N. et al.: *Application of eddy current inversion technique to the sizing of defects in Inconel welds with rough surfaces*. Nuclear Engineering and Design, Vol.235/2005, pp. 1469-1480.

[18] Yusa, N. et al.: *Caution when applying eddy current inversion to stress corrosion cracking.* Nuclear Engineering and Design, Vol.236/2006, pp. 211-221.

[19] Janoušek, L. et al.: *Excitation with phase-shifted fields - enhancing evaluation of deep cracks in eddy-current testing*. NDT&E International, Vol.38/2005, pp. 508-515.