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RECENT TRENDS AND DEVELOPMENTS IN EDDY CURRENT NON-DESTRUCTIVE EVALUATION

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Abstract: *The paper analyses developments and summarizes recent trends in eddy current non-destructive evaluation. Basic principle of the method is explained and its possible applications in non-invasive evaluation of conductive materials are summarized. Main aspects connected with application of the method in practice are discussed in details together with actual issues of research and developments. Authors' group activities in this field are presented on the basis of the reported current state-of-the-art.*

Key words: *non-destructive evaluation, eddy currents, instruments, excitation, probes, magnetic sensors, inversion*

Introduction

Many structures require periodical inspection to keep safety and reliability of various processes. Non-destructive testing (NDT) methods are utilized for this purpose because of leaving an inspected structure undamaged in its original state.

System health monitoring and condition based maintenance are of high interest nowadays. Accordingly, not only reliable detection but also precise evaluation of inspected parameters should be considered. Thus, many efforts have recently been put on enhancing non-destructive evaluation (NDE) methods to accomplish their challenging missions.

Different physical principles are utilised for the non-destructive inspection of materials. One of the most employed conventional electromagnetic methods is eddy current non-destructive testing (ECT). It originates from the electromagnetic induction phenomena and its principle underlies in the interaction of induced eddy currents with structure of an examined body. The ECT possesses several beneficial advantages. Therefore it has been widely applied for fast primary inspection in many industrial fields. However, in contrast to the simplicity of the method, recent trends in NDE open several challenging issues.

The paper summarizes recent trends and developments in eddy current non-destructive evaluation. The authors' group has been involved in R&D activities in this field for several years. Their experiences and achievements are presented on the basis of the reported state-of-the-art.

At first, the principle of the method is briefly explained according to the macroscopic Maxwell's electromagnetic field theory. Possibilities of ECT utilization in different applications are then specified. As the method is especially employed in defectoscopy, the paper is particularly devoted to this application. The last paragraph brings overview of numerical modelling of ECT inspection.

The second section focuses on eddy current excitation and sensing. Harmonic excitation as well as newly applied pulsed one are considered. Special attention is put on ECT sensors that represent the most important part of inspection apparatuses.

Signal evaluation is concerned in the third section. Manual and automatic approaches are explained. New possible application area of ECT are then summarized followed by the conclusion.

1 Eddy-current non-destructive testing

1.1 Principle of the method

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]-[3].

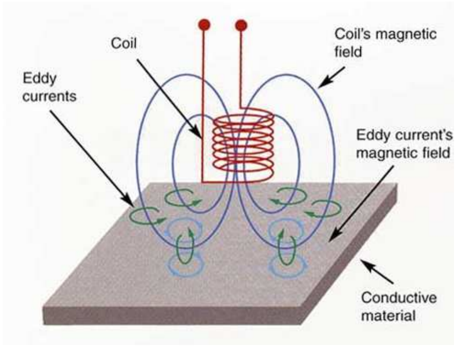


Fig.1: Principle of ECT

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:

$$\nabla \times \mathbf{H}_p = \mathbf{J}_{ex}, \tag{1}$$

where $\mathbf{H}_p$ [A.m^{-1}] denotes the primary magnetic field intensity vector and $\mathbf{J}_{ex}$ [A.m^{-2}] is the exciting current density vector.
Electromotive force is induced in a conductive object which is in proximity of the coil according to the Faraday's law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}_p}{\partial t}, \tag{2}$$

where $\mathbf{E}$ [V.m^{-1}] is the electromotive force vector and $\mathbf{B}_p$ [T] is the primary magnetic flux density vector, while $\mathbf{B}_p = \mu\mathbf{H}_p$, μ [H.m^{-1}] is the magnetic permeability.
Eddy-currents flow in the conductive object according to the Ohm's law:

$$\mathbf{J}_{ed} = \gamma\mathbf{E}, \tag{3}$$

where $\mathbf{J}_{ed}$ [A.m^{-2}] is the eddy current density vector, γ [S.m^{-1}]is the electric conductivity, and their vector lines must be closed due to:

$$\nabla \cdot \mathbf{J}_{ed} = 0. \tag{4}$$

A secondary electromagnetic field $\mathbf{H}_{ed}$ generated by the eddy-currents:

$$\nabla \times \mathbf{H}_{ed} = \mathbf{J}_{ed}, \tag{5}$$

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 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 driving, the coupling is influenced by the following significant 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).

It should be noted that the ECT is the relative method, not the absolute one, and gained signals have to be compared with reference ones. It results in evaluation of perturbations of the resulting electromagnetic field.

1.2 Applications of the method and its properties

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 listed in the previous subsection. The ECT is therefore applied especially 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 conductive products (dimensions, etc.),
- detection and evaluation of discontinuities (defects) in conductive materials, etc.

The principle of the ECT has been known for several decades. However, rising employment of the ECT in different technical applications imposes new challenging appeals on R&D activities.

Nowadays, the most wide spread application area of the ECT is the detection and possible evaluation of different discontinuities in conductive materials, so called defectoscopy. Remaining part of the paper is therefore devoted to this domain.

Presence of a defect in a conductive material causes a local change of the material electromagnetic parameters. As the eddy current vector lines must be encircled (4), the presence of a defect changes the eddy current density distribution. The principle is shown in Fig. 2.

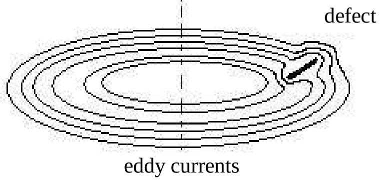


Fig.2: Principle of a crack detection using ECT

The change in eddy current density distribution influences the resulting electromagnetic field. The perturbation electromagnetic field therefore occurs comparing to the no-crack situation and this perturbation field can be sensed and further evaluated. As it was already mentioned, ECT is the relative method and the perturbation signal is obtained by subtracting of the crack signal and no-crack signal. The perturbation signal carries quantitative information about an inspected defect.

The ECT posses several benefits:

- high sensitivity for surface breaking defects,
- high inspection speed,
- contact-less inspection,
- versatility,

especially comparing to the ultrasonic testing (UT), one of the most utilized NDT techniques. These advantages determine continuously enlarging application area of ECT mainly in nuclear, petrochemical and aviation industries [4]-[6].

On the other hand, also disadvantages of the method should be mentioned. ECT signals are integral values and they do not carry explicit information about crack dimensions. It means that the inverse problem is ill-posed. Therefore, evaluating the depth of a defect from the ECT signals is quite difficult [7]. In addition, the skin-effect concentrates induced currents on the surface of a tested material. Eddy current density decays almost exponentially into material depth and thus increasing depth of a surface breaking defect causes raising uncertainty of the depth evaluation because of the ECT signal saturation.

1.3 Analysis of the method

Computational analyses are economically much more effective as well as time saving than trial experimental investigations. Basic model of the ECT for analysis is shown in Fig. 3. The region Ω_1 is an ambient environment, Ω_2 denotes an inspected conductive object and Ω_3 represents an ECT probe.

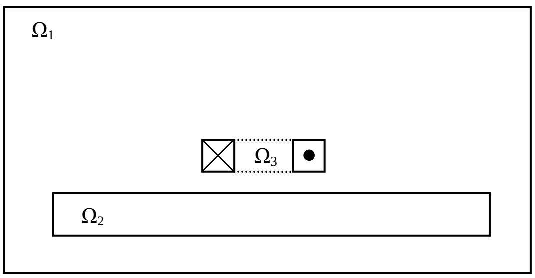


Fig.3: Model of ECT

ECT can be analyzed based on the electromagnetic field theory or the electric circuit one. The later approach substitutes an ECT probe and a conductive object by an air transformer equivalent circuit and changes of parameters of the equivalent circuit are evaluated [1]. However, this approach is only approximate and coincidence of predicted signals with measured ones is quite low. For this reason the electromagnetic field theory is more preferable for the analysis.

The set of partial differential electromagnetic field equations can be solved analytically or numerically. Analytical approach can deal only with very simple linear geometrical problems [8]-[10]. However, predicted ECT signals correspond well with reality.

Modern computational resources make it already possible to extensively utilize numerical methods for electromagnetic calculations. The numerical methods are based on distretization of a considered volume and on approximation of solutions. Nowadays, the numerical methods are quite matured and they are used to predict ECT signals in great extend. Three methods are mainly employed for the purpose: the finite element method, the boundary element method and the finite difference method [11], [12].

The ECT problem can be considered as the quasi-stationary one and the displacement currents can be neglected. Usually, the electrodynamics potentials, i.e. the magnetic vector potential **A** [T.m] and the electric scalar potential φ [V] are solved. The set of partial differential equations for the model shown in Fig. 3 using the potentials under the harmonic excitation with phasor representation is as follows:

- for Ω_1: $$\nabla^2 \dot{\mathbf{A}} = 0\,, \tag{6}$$
- for Ω_2: $$\nabla^2 \dot{\mathbf{A}} - \mathrm{j}\omega\mu\sigma\dot{\mathbf{A}} - \mu\sigma\nabla\dot{\varphi} = 0\,, \tag{7}$$ $$\nabla \cdot \sigma\left(-\nabla\dot{\varphi} - \mathrm{j}\omega\dot{\mathbf{A}}\right) = 0\,, \tag{8}$$
- for Ω_3: $$\nabla^2 \dot{\mathbf{A}} = -\mu\dot{\mathbf{J}}_{ex}\,, \tag{9}$$

where j is the complex unit, ω [rad.s^{-1}] is the angular frequency and σ [Ω.m] is the resistivity and the dot over the potentials denotes that they are complex quantities.

A detecting coil is not modelled as a specific region as it has the same electromagnetic properties as the air. The phasor of induced voltage in the detecting coil is calculated after analysis of the electromagnetic field based on:

$$\dot{U}_i = -\mathrm{j}\omega\int_{\mathbf{S}} \dot{\mathbf{B}} \cdot \mathrm{d}\mathbf{S} = -\mathrm{j}\omega\oint_{\mathbf{l}} \dot{\mathbf{A}} \cdot \mathrm{d}\mathbf{l}\,, \tag{10}$$

where **S** [m^2] is the vector of the detecting coil active area and **l** [m] is the boundary line of **S**.

Current computer hardware and software means enable to numerically simulate quite complicated problems even non-linear with fine enough discretization, and to gain results within relatively short time. Mainly the finite element method is used for the calculations.

2 EDDY-CURRENT NON-DESTRUCTIVE INSTRUMENTIATION

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

- ECT instruments,
- ECT probes,
- positioning systems and manipulators.

2.1 ECT instruments

ECT instruments supply exciting coils of ECT probes, sense the ECT signals, process and display them. The instruments have been developed for several decades and their functionality is already matured. At first, analogue technique has been employed for the purpose. The instrument consists of a source and the Maxwell bridge to detect signals. The signals are then pre-amplified, filtered and processed. Nowadays, the digital technology is replacing the analogue one.

The harmonic currents are mostly utilized to drive exciting coil(s). Usually, several frequencies are employed for the inspection. The exciting signals under different frequencies are superimposed or multiplexed. The multi-frequency excitation is especially used to distinguish between useful signals and background noises. Sensed signals are processed based on the symbolic-complex theory. Real and imaginary parts of the signals are then displayed in time history or in the complex plane.

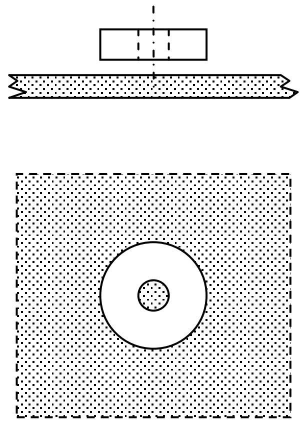
The authors' group in cooperation with Japanese research institute IIU Corp. proposed a novel approach for harmonic ECT excitation. Phase-shifted exciting currents drive several exciting coils at the same time. The purpose is to suppress eddy current density on the surface of an inspected material and to change its distribution along material depth. By using the proposed approach deeper surface breaking cracks in massive structures can be not only detected but also evaluated. More information can be found in [13].

Nowadays, a pulsed excitation of eddy currents (PEC) is of high interest. It is a new technique that has been particularly developed and devised for sub-surface crack inspection and evaluation. Several research groups as well as the authors' group are intensively working in this field [14], [15]. PEC testing applies a broad band pulse and analyzes the transient voltage response, which can yield a signal with a frequency content from DC to 100 kHz or higher. Because the penetration depth of eddy currents depends on excitation frequency, thus PEC testing allows more volumetric inspection and fetches more information. Gained signals can be analyzed in the time domain or in the frequency domain.
The PEC technique is still in its early stage and thus many challenging issues like adjusting of a driving pulse, possibilities of signal evaluation, etc. are frequently discussed.

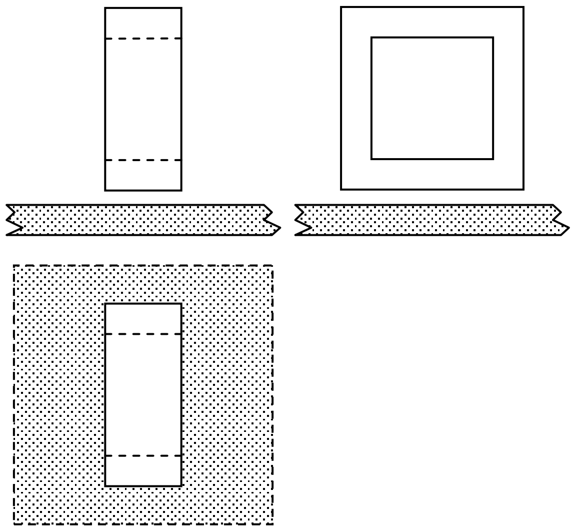
2.2 ECT probes

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.

Features of ECT probes depend on number, shape, configuration, orientation, dimensions and connections of coils as well as on parameters of a magnetic circuit.
Due to simplicity of analysis, synthesis, construction and production usually coils of a circular shape (Fig. 4a) or a rectangular shape (Fig. 4b) are used to build up the probes. They can be oriented normally (Fig. 4a) or tangentially (Fig. 4b) regarding the surface of a tested body. The shape and the orientation of exciting coil(s) determine distribution of the eddy current density vector in a tested body. Even the electromagnetic coupling between an exciting coil and a tested object is weaker when the coil is oriented tangentially, the eddy currents are less attenuated along the object's depth comparing to the normal orientation [16]. However, an ECT probe with a tangentially oriented exciting coil has the directional properties.



a) normally oriented circular coil



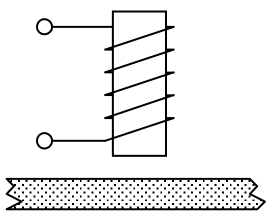
b) tangentially oriented rectangular coil

Fig.4 Basic shapes and orientations of coils

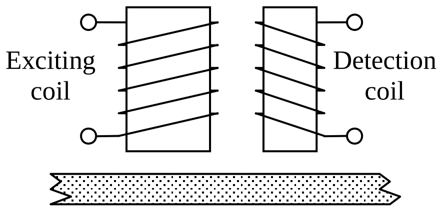
There are two basic configurations of the probes concerning the connection between the excitation circuit and the detection one:

- self inductance probes,
- mutual inductance probes.

In case of the self inductance probes, the driving and the detection coil(s) are identical and impedance of the coil(s) is evaluated. In the later case, the exciting and the detection coils are separated and induced voltage in the detection coil(s) is evaluated. Examples of both ECT probe configurations are shown in Fig. 5.



a) self inductance probe



b) mutual inductance probe

Fig.5 Basic types of ECT probes

According to the number and connection between detection coils they can work in:

- absolute mode, when an ECT probe consists of only one detection coil,
- differential mode, when an ECT probe consists of two detection coils and they are connected magnetically opposite,
- additive mode, when an ECT probe consists of two detection coils and they are connected in series,
- mixed mode, when an ECT consists of more than two detection coils.

The differential connection of detecting coils, shown in Fig. 6, is mostly utilized especially because of wobbling noise compensation.

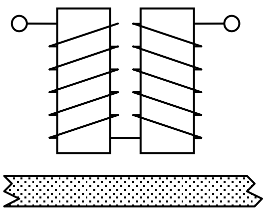


Fig.6 Differential connection of detection coils

Optimal ECT probe should assure [17]:

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

Exciting coil(s) of ECT probe should thus induce eddy currents with high density and such distribution that eddy current lines are significantly perturbed when a detect is in presence. The detection circuit should assure that maximum of the perturbation field is sensed.

The detected signal is a complex variable depending on many parameters. The one that is of interest is a local change of the material electromagnetic parameters. Other parameters such as:

- distance between a probe and the surface of an inspected body, so called lift-off,
- inclination of the probe,
- geometrical arrangement and dimensions of the inspected body,
- construction inhomogeneities of the inspected body (for example welds),
- surface treatment of the inspected body,
- presence of near conductive objects, etc.,

can negatively influence the sensed signals. However, those influences can be suppressed by an appropriate design of a probe and its optimization [18], [19].

ECT probes are usually made with the air core. However, ferromagnetic materials are also used for the design to make the core or a shielding of coils [20].

Magnetic sensors are employed to sense low intensity perturbation electromagnetic field in ECT [21]. Figure 7 gives an overview of sensitivity level of various magnetic sensors [22].

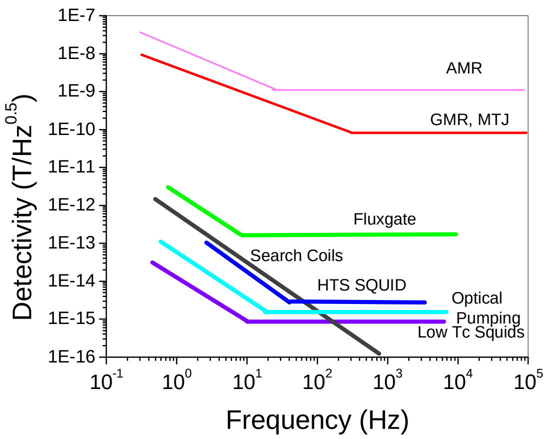


Fig.7 Sensitivity of magnetic sensors [22]

Fluxgate, Anisotropic Magnetoresistive (AMR), Giant Magnetoresistive (GMR) and Spin-Dependent Tunnelling (SDT) sensors are mainly used in ECT.

The most common fluxgate sensor consists of two coils wrapped around the high permeability ferromagnetic core. Magnetic induction of the core is changed by the presence of an external magnetic field. A driving signal is applied to one of the coils and the measured signal is taken from the second one. Changes in core permeability affect the measured signal as its amplitude variations.

AMR sensors usually consist of four ferromagnetic resistor stripes connected in Whetstone bridge. Changes of magnetic resistance due to applied magnetic field can be up to 3%. AMR sensors offer small size and noise sensitivity.

GMR sensors use the phenomenon of large magnetic field dependent changes in resistance in thin ferromagnetic/nonmagnetic metallic multilayer structures. Comparing to small changes of resistance in AMR, GMR material can achieve about 10% - 20% changes in resistance. The resistance of two thin ferromagnetic layers separated by a thin nonmagnetic conducting layer can be altered by changing the moments of the ferromagnetic layers from parallel to anti-parallel. Layers with parallel magnetic moments will have less scattering at the interfaces, longer mean free paths, and lower resistance. Layers with anti-parallel magnetic moments will have more scattering at the interfaces, shorter mean free paths, and higher resistance.

SDT structures are very similar to those of GMR. The difference is that an extremely thin insulating layer is used instead of the conductive interlayer separating the two magnetic layers. The conduction is due to quantum tunnelling through the insulator. Changes in resistance of 10% to 40% have been observed in SDT structures.

Many ECT probes have been developed over past decades reflecting special demands of particular applications. Probe design and development is still of high interest because, as it has been already mentioned, the area of ECT utilization is gradually wide-spreading.

The authors' group developed a new probe based on the principle of phase-shifted excitation briefly introduced in section 2.1 [13]. Configuration of the probe is shown in Fig. 8.

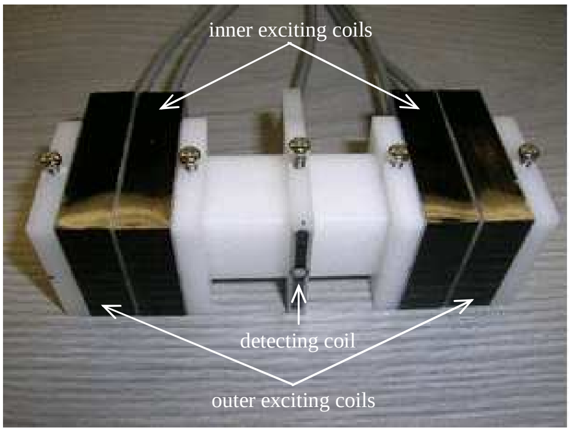


Fig.8 Configuration of a new probe

The probe is of mutual induction type and consists of four coaxial exciting coils and one detecting coil. The inner exciting coils and the outer ones are connected in series, respectively. The two groups of the exciting coils are driven by two harmonic currents with a same frequency but different phases. Proper adjustment of the excitation circuit allows to change exponential profile of the eddy current density distribution under the detecting coil in such a way that zero density is obtained on the surface of a tested material. The probe is designed for inspection of deeper surface breaking defects in thicker structures. Numerical investigations as well as experimental verifications revealed that the probe can be used for evaluation of surface breaking cracks with a depth up to 25 mm. In contrast, an ECT probe with standard excitation can be employed only up to a depth of 10 mm under same conditions.

3 EDDY-CURRENT NON-DESTRUCTIVE EVALUATION

3.1 Evaluation of crack dimensions

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, because the inverse problem is ill-posed.

Commercial NDT systems provide raw data with limited or absent capability of interpreting quantitatively the data. They can detect an anomaly but they are usually unable to find its shape and dimensions [12]. Typically, commercial systems rely on calibrated curves measured on pre-fabricated etalons and on the skills of an operator.

The maximum value of sensed ECT signal and especially the signal phase in this point depend mainly on a crack depth. Thus, a crack depth can be roughly estimated from this phase information when it is compared with signals of known artificial defects. However, there is an intention to turn this „art" into a quantitative science.

The progress in powerful computers has allowed developing of automated procedures to make decisions. Two approaches are utilized for automatic evaluation procedures in general:

- deterministic,
- stochastic [12], [23], [24].

Usually, one dimensional signal gained by scanning just above an indicated crack along its length is taken as an input to the evaluation procedure. Mostly, three variables of the defect are estimated, its depth, length and position of its centre, while a profile, a width and the electromagnetic parameters of the defect are adjusted in advance.

The deterministic methods are the model based. They work according on difference minimization between measured and simulated signals. The process is iterative and therefore large number of forward simulations is required. Databases of pre-computed signals [23] as well as parallel computing on supercomputers [25] can help to shorten the evaluation time.

The stochastic approaches simulate the mapping between eddy currents signals and defect profiles based on many known datasets. So called evolution algorithms, for example neural networks, genetic algorithms, are utilized for the inversion [26], [27].

Satisfactory results are reported by several groups for evaluation of artificial slits [24]. Even very small cracks with dimensions in a range of tenths of millimetres can be detected with high probability and their dimensions can be quite precisely evaluated. Good results are also reported for evaluation of several close parallel artificial slits [28]. However, evaluation of real cracks, especially stress corrosion cracking (SCC) remains still very difficult [7]. It has been found out that a numerical model of an SCC is quite different from the one of an artificial slit. SCC is partially conductive and thus the width of a crack also strongly influences the sensed signal [29]. It means that another two variables, i.e. width and conductivity of a cracked region, should be taken into account for the reconstruction. The ill-posedness of the inverse problem is therefore increased [30]. Many efforts are devoted to develop reliable techniques for SCC evaluation. Proper numerical modelling of SCC cracks [29] and approaches to increase information level contained in signals are mainly concerned [31].

A unique idea for enhancing sizing ability in eddy-current non-destructive testing has been proposed by the authors' group in cooperation with the Japanese research institute IIU Corp. [31], [32]. A detected crack is inspected using two different ECT probes driven at the same exciting frequency but producing different eddy current distributions. The crack signals obtained with the two probes are linearly superposed and a unique value of the ratio of superposition is extracted from the mixed signals. Numerical investigations and experimental verification revealed that the value provides clear indications of the crack's depth. In addition, the depth of a notch five times as deep as the standard depth of penetration was well evaluated using the method.

3.2 *Evaluation of crack type*

There are two major crack types appearing in structural components of various processes, the fatigue crack (FC) and the stress corrosion one (SCC). The mechanisms of the initiation and the propagation are different for the two types of crack. Therefore, the crack evaluation depends on its type. So far, destructive testing has been performed to examine whether a detected crack is FC or SCC. However, time-consuming destructive testing leads to a huge financial burden. If it is possible to distinguish between FC and SCC non-destructively, it significantly shortens the time necessary for the evaluation and provides therefore large economical advantages.

A novel inspection procedure has been proposed for non-destructive evaluation of a crack type [33]. The principle comes out from a fact that the nature and the process of cracking are different for FC and SCC. Thus, they show different physical features. FCs are narrow and the cracked region is not conductive while SCC zone is wider and partially conductive. This makes significant difference in their electromagnetic properties.

A mutual induction probe with the directional properties is utilized for the inspection. Two C-scans are made over a cracked region, one with perpendicular orientation of the eddy currents concerning a crack and the second one with their parallel orientation. Numerical simulations as well as experimental verifications clearly showed that by comparing maximum values of the two signals gained for the two scans it is possible to evaluate whether a detected crack is of fatigue type or stress corrosion one.

4 CONCLUSION

The paper summarized recent trends and developments in eddy current non-destructive evaluation. At first, the principle of eddy current non-destructive testing was explained. Accordingly, possible applications of the method in real inspection were listed. Eddy current instrumentation was discussed in the next section, while eddy current probes were mainly concerned. Potential of eddy currents in evaluation of crack dimensions and crack type was the analyzed.

Application area of eddy current non-destructive evaluation is still wide-spreading. Therefore, there are still many challenging appeals that need to be concerned. The current R&D activities can be according to actual problems and practical experiences summarized as follows:

- 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.

Authors’ group actively works in the above mentioned areas. Their achievements were explained on the basis of the reported state-of-the art.

5 REFERENCES

[1] Sun, Y.: An introduction to electromagnetic nondestructive testing, published in Proceedings of the ISEM’97 conference, 1998. pp. 145-152.

[2] Auld, A.B., Moulder, J.C.: Review of advances in quantitative eddy current nondestructive evaluation, published in Journal of Nondestructive Evaluation, Vol. 18, 1999, pp. 3-36.

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

[4] Takeda, T. et al.: Inspection techniques for primary pressurized water cooler tubes in the high temperature engineering test reactor, published in Nuclear Engineering and Design, Vol. 217, 2002, pp. 153-166.

[5] Kim, D., Udpa, L., Udpa, S.: Remote field eddy current testing for detection of stress corrosion cracks in gas transmission pipelines, published in Materials Letters, Vol. 58, 2004, pp. 2102-2104.

[6] Burkhardt, G.L. et al.: NDE of aging aircraft structure using orthogonal-axis eddy current probes, published in Review of Progress in Quantitative Nondestructive Evaluation, Vol. 16, 1997, pp. 1021-1027.

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

[8] Dodd, C.V., Cheng, C.C., Deeds, W.E.: Induction coils coaxial with an arbitrary number of cylindrical conductors, published in Journal of Applied Physics, Vol. 45, No. 2, 1974, pp. 638-647.

[9] Theodoulidis, T.P., Tsiboukis, T.D.: Analytical solutions in eddy current testing of layered metals with continuous conductivity profiles, published in IEEE Transactions on Magnetics, Vol. 31, 1995, pp. 2254-2259.

[10] Theodoulidis, T.P., Kriezis, E.E.: Impedance evaluation of rectangular coils for eddy current testing of planar media, published in NDT&E International, Vol. 35, 2002, pp. 407-414.

[11] Ida, N.: Numerical modeling for electromagnetic non-destructive evaluation, Chapman & Hall, London, 1995.

[12] Rubinacci, G., Tamburino, A., Ventre, S.: Fast numerical techniques for electromagnetic nondestructive evaluation, published in Nondestructive Testing and Evaluation, Vol. 24, 2009, pp. 165-194.

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

[14] Li, Y., Tian, G.Y., Simm, A.: Fast analytical modelling for pulsed eddy current evaluation, published in NDT&E International, Vol. 41, 2008, pp. 477-483.

[15] Smetana, M., Strapačová, T., Janoušek, L.: Pulsed excitation in eddy current non-destructive testing of conductive materials, published in proceedings of the TRANSCOM conference, Žilina, 2009.

[16] Hoshikawa, H., Koyama, K.: Eddy current distribution using parameters normalized by standard depth of penetration, published in Review of Progress in

Quantitative Nondestructive Evaluation, Vol. 18, 1999, pp. 515-521.
[17] Chen, Z., Miya, K.: A new approach for optimal design of eddy current testing probes, published in Journal of Nondestructive Evaluation, Vol. 17, 1998, pp. 105-116.
[18] Ramirez, J.A., Freeman, E.M.: Shape optimization of electromagnetic devices including eddy-currents, published in IEEE Transactions on Magnetics, Vol. 31, 1995, pp. 1948-1951.
[19] Thollon, F., Burais, N.: Geometrical optimization of sensors for eddy currents non destructive testing and evaluation, published in IEEE Transactions on Magnetics, Vol. 31, 1995, pp. 2026-2031.
[20] Morozov, M., Novotny, P.: Evaluation of eddy current probes based on local field excitation, published in NDT&E International, Vol. 35, 2002, pp. 147-153.
[21] Čápová, K., Čáp, I., Janoušek, L., Smetana, M.: Recent trends in electromagnetic non-destructive sensing, published in Advances in Electrical and Electronic Engineering, Vol. 7, 2008, pp. 322-325.
[22] http://qdev.boulder.nist.gov/817.03/whatwedo/magsensors/Roadmap.doc, June 18, 2009.
[23] Chen, Z., Yusa, N., Miya, K.: Some advances in numerical analysis techniques for quantitative electromagnetic nondestructive evaluation, published in Nondestructive testing and evaluation, Vol. 24, 2009, pp. 69-102.
[24] Yusa, N.: Development of computational inversion techniques to size cracks from eddy current signals, published in Nondestructive testing and evaluation, Vol. 24, 2009, pp. 39-52.
[25] Yusa, N. et al.: Large-scale parallel computation for the reconstruction of natural stress corrosion cracks from eddy current testing signals, published in NDT&E International, Vol.36, 2003, pp. 449-459.
[26] Rao, B.P.C: An artificial neural network for eddy current testing of austenitic stainless steel welds, published in NDT&E International, Vol.35, 2002, pp. 393-398.
[27] Koyama, K. et al.: Fundamental study of flaw estimation in eddy current testing using genetic algorithm, published on CD from the 16th World Conference on NDT, 2004.
[28] Rebican, M., Chen, Z., Yusa, N., Janošek, L., Miya, K.: Shape reconstruction of multiple cracks from ECT signals by means of a stochastic method, published in IEEE Transactions on Magnetics, Vol. 42, 2006, pp. 1079-1082.
[29] Yusa, N., Kenzo, M.: Discussion on the equivalent conductivity and resistance of stress corrosion ccks in eddy current simulations, published in NDT&E International, Vol. 42, 2009, pp. 9-15.
[30] Yusa, N., Huang, H., Miya, K.: Numerical evaluation of the ill-posedness of eddy current problems to size real cracks, published in NDT&E International, Vol. 40, 2007, pp. 185-191.
[31] Janoušek, L., Yusa, N., Miya, K.: Utilization of two-directional AC current distribution for enhancing sizing ability of electromagnetic nondestructive testing methods, published in NDT&E International, Vol. 39, 2006, pp. 542-546.
[32] Janoušek, L., Čápová, K., Yusa, N., Miya, K.: Multi-probe inspection for enhancing sizing ability in eddy-current non-destructive testing, published in IEEE Transactions on Magnetics, Vol. 44, 2008, pp. 1618-1621.
[33] Chen, Z., Janoušek, L., Yusa, N., Miya, K.: A non-destructive strategy for the distinction of natural fatigue and stress corrosion cracks based on signals from eddy current testing, published in Journal of Pressure Vessel Technology, Vol. 129, 2007, pp. 719-728.

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