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ADVANCED PROBES FOR ELECTROMAGNETIC NON-DESTRUCTIVE TESTING

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ABSTRACT

The paper deals with the problems of sensing parts for material electromagnetic non-destructive testing (eNDT) with emphasize on eddy current testing (ECT). Various modifications of ECT sensing are compared and discussed from the desired detected signal characteristics point of view. The two new designed ECT probe systems are described here. The first one is dedicated for deeper cracks detection and the second one has been proposed for pipe inspection on the principle of remote field ECT method. In addition to the optimization of usual probe coils arrangements for the given tasks, the new magnetic sensors as e.g. giant magneto-resistance (GMR) are presented. The advanced ECT sensors are characterized by their sensitivity, frequency range and sensor dimensions.

1. INTRODUCTION

Non-destructive electromagnetic testing (eNDT) is an effective methodology for diagnostics in many technical and scientific applications. The requirements of new effective eNDT tools are connected with the wide and still increasing demands of high quality and reliability standards in industrial production and also with developments of other technical and scientific areas, e.g. medicine, geology, civil and environmental engineering, etc.

Various NDT techniques form a wide group of rather different tools, which are based on different physical phenomena and they are characterized by different and specific performance and application fields. From the application point of view the eNDT is used in many areas - from the inspection of metallic pipes to the aeronautical maintenance and from the localization of liquids in subsoil to the thoracic imaging for clinical diagnostics.

One of the most popular eNDT methods is the eddy current testing (ECT) and evaluation. The principle of ECT can be briefly described by the following way. Eddy current coil fed by alternating sinusoidal current (AC), of frequencies in the range 50 Hz to 10 MHz, generates primary magnetic field according to the Ampere´s law. This primary magnetic field induces eddy currents in the tested conductive material object according to the Faraday´s law. Then eddy currents generate secondary magnetic field in the opposite direction in. agreement with the Lenz´s law. Following from these processes the coil impedance changes in the case of material changes, e.g. in the presence of imperfections - defects in the material object. The impedance change is measured, analyzed and correlated with the defect dimensions. The locus of impedance change formed during the movement of an eddy current probe coil over a test material having defect is called an eddy current signal. Its amplitude provides information about the defect size and its phase angle with respect to lift-off gives information about the defect location or depth, Fig.1.

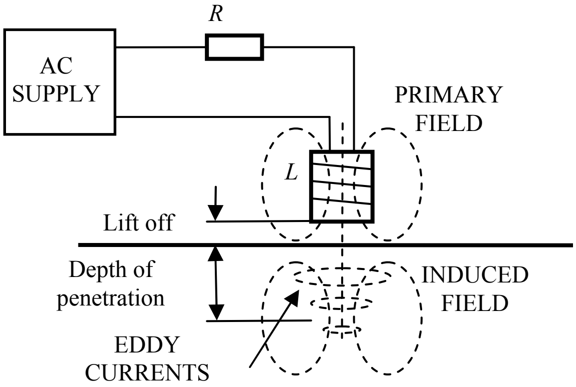

Fig. 1. Eddy current testing set – up.

Eddy current density in material is not uniform into material depth direction. It is the greatest on the surface and decreases monotonously with depth (skin effect) according to the relation of standard depth of penetration which decreases with increasing frequency, conductivity and permeability. It means that for measuring thickness of thin surfaces very high frequencies are to be used and on the contrary for detection of sub-surface buried defects and for testing highly conductive (magnetic) thick materials low frequencies are to be employed.

Usually the driving current is kept constant (few hundreds of mA) and the impedance changes occurred due to perturbation of eddy currents at defect regions are to be measured. Since these changes are very small (μΩ), high precision AC bridge is used. The bridge imbalance is correlated with the defect or material characteristic responsible.

The ECT instrument consists usually of an oscillator (for exciting frequency), constant AC supply, AC (Maxwell) bridge circuit, amplifier and screen (to display the changes in a 2D graph or as a vector). In modern systems there a personal computer with the necessary hardware (plug-in card) and software is used for the measurements, adjustment, data storage, analysis and management. The ECT is the mostly used technique for detecting fatigue cracks and corrosion in conductive materials. The cost of using technology is low and it is possible to monitor subsurface defects and defects under insulating coatings without touching the surface specimen. One of the most important parts of ECT device is the sensing part called probe which is created obviously by probe coils or other sensors.

Because safety-critical systems depend on early detection of fatigue cracks to avoid major failures, there is an increasing need for eddy current probes that can reliably detect very small defects. Also there are increasing demands for probes that can detect deeply buried defects to avoid disassembling structures. There are also many other applications where ECT is successfully used, e.g. material thickness measurements, coating thickness measurements and conductivity measurements for the material identification, heat damage detection, case depth determination or heat treatment monitoring. According to the application areas the measuring set-up is designed a realized.

2. ECT PROBES ARRANGEMENTS

As it was mentioned above the appropriate selection of probe coil is very important in ECT in order to get the right (desired) information from it. ECT probes usually combine an excitation coil that induces eddy currents in a specimen and a detection element that identifies the perturbation of the eddy currents caused by cracks or other defects The most common probes used in ECT are surface or pancake probes (with the axis normal to the surface) which are chosen for inspection of plates and bolt-holes either as a single element or an array, in both absolute and differential modes. The encircling probes are used for inspection of rods, bars and tubes with outside access and the Bobbin probes for pre- and in- service inspection of heat exchanger, steam generator, condenser and others with inside access, Fig. 2, [1]. These three types can also operate in the send–receive mode with the separate coils for sending and receiving of signal and also in absolute or differential mode.

The absolute EC probe consists of a single sensing coil for signal excitation and reception. It is determined for detection of cracks as well as for gradual changes. But absolute probes are also sensitive to lift-off, probe tilt, temperature changes, etc.

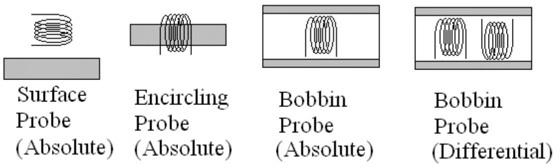

Fig. 2. Configurations of ECT probes.

Differential probes have two sensing coils wound in opposite direction and investigating two different regions of the material. These probes are good for high sensitivity detection of small defects and they are more immune to changes in temperature and probe wobble.

There are many factors which influence eddy current response from a probe. Successful assessment of flaws relies on holding the others constant, or somehow eliminating their effect on the results. The main factors are material conductivity, permeability, frequency, geometry and the lift-off.

As for the material conductivity is seen the greater the conductivity the greater the flow of eddy currents on the surface. From the conductivity measurements we can get the information about the material composition, heat treatment and work hardening, etc.

For the non-ferrous metals the permeability is the same as of the “free space”, the relative permeability is equal to one, and for the ferrous metals it has values several hundreds or more. Permeability is varying strongly within the metal part due to localized stresses, heating effects, etc.

Frequency greatly affects the eddy current response but it can be controlled without problems. Geometrical features such as curvature, edges, grooves, etc. affect the eddy current response. The used techniques must recognize this, e.g. in testing an edge for cracks the probe will normally be moved along parallel to the edge so that small changes may be easily seen. Where the material thickness is less than the effective depth of penetration this will also affect the eddy current response.

As for the proximity or lift-off the closer a probe coil is to the surface the greater will be the effect on that coil. It means that the lift-off signal arises as the probe is moved on and off the surface and the sensitivity will be reduced as the coil product spacing increases.

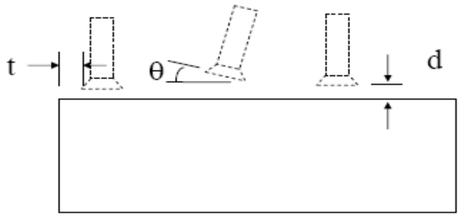

Fig. 3. Positions of ECT probes by object testing.

Fig. 3 shows various positions of the probe above the tested object according to changes of liftoff, tilt and geometry of edge effects.

3. ADVANCED ECT PROBES

Eddy current testing probes usually combine an excitation coil that induces eddy currents in a specimen and a detection element that identifies the perturbation of the currents by cracks or other defects.

3.1. The New ECT Probe for Deeper Defects

In order to detect deeper defects in material object it is necessary to propose the advanced coils configuration and following data processing, as it was realized and described in [3], [4], [5]. The key idea is to inspect a crack using various distributions of alternating currents owing inside an inspected body to gather relevant information about the depth of a defect.

The novel ECT probe for non-destructive inspection of near-side deep cracks in thick conductive structures is shown in Fig. 4.

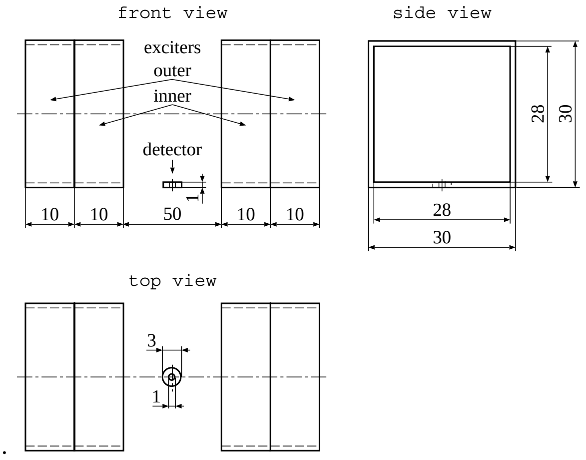

Fig.4. Arrangement and dimensions of the novel eddy current testing probe

The probe consists of four coaxial rectangular tangential exciting coils divided into two detached sets separated by a space of 50 mm. The inner exciting coils and the outer ones of the sets are connected in series, respectively, and they are driven independently by phase-shifted currents of 180°. The signal is picked-up by a normal circular coil placed in centre between the two sets of the exciting coils.

A plate specimen shown in Fig. 5 is inspected in this study. It is made of stainless steel SUS316L which is frequently used as a base material for design of structural components in nuclear power plants; ECT is employed for non-destructive inspection of those components. Thickness of the specimen is 25 mm and electromagnetic characteristics of the material are: conductivity of $\sigma = 1.4$ MS/m and relative permeability of $\mu_r = 1$.

An electro-discharge machined (EDM) notch – crack with a length of 40 mm, a width of 0.5 mm is introduced into near-side of the specimen, Fig. 5.

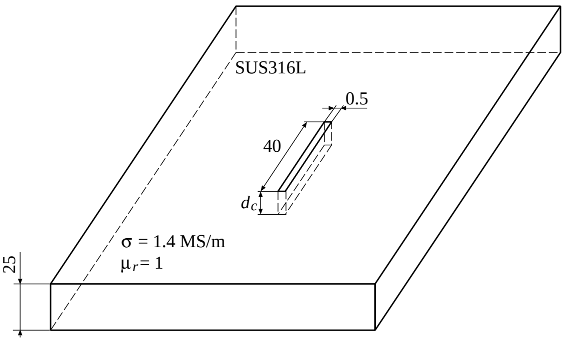

Fig. 5. Test-piece

A depth of the notch is changed from 0 to 100% of the material thickness.

A three dimensional finite element code is used to calculate distribution of the magnetic vector potential and of eddy currents in a considered volume. The voltage induced in the pick-up coil is then calculated.

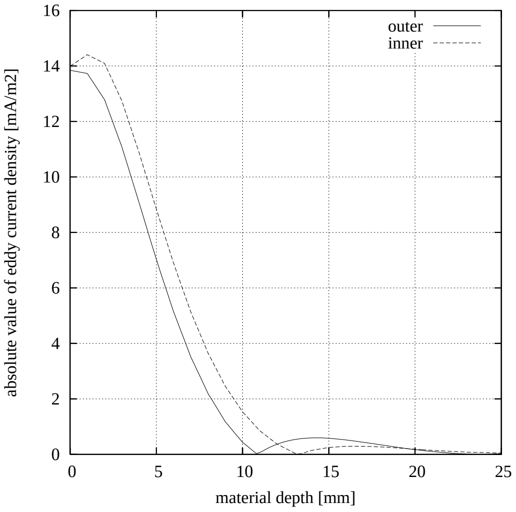

Fig.6. Dependence of absolute value of eddy current density on material depth for the outer exciting coils and for the inner exciting coils, respectively

Distance between the exciting coil and the pick-up coil influences the distribution of eddy current density under the pick-up coil. The situation is shown in Fig. 3 for two cases: 1) only outer exciting coils of the novel probe are driven; 2) only inner exciting coils of the novel probe are driven. As it can be seen, there is a difference between the characteristics due to different positions of the exciting coils concerning a position of the pick-up coil. Those differences can be also observed in the calculated crack signals; only one

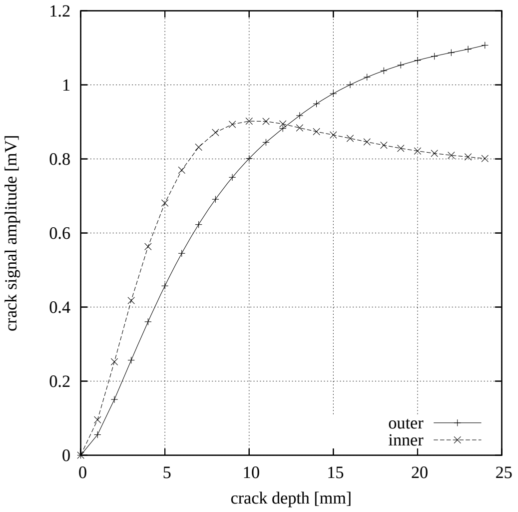

Fig. 7. Dependence of the crack signal amplitude on the crack depth gained with the novel probe when only outer exciting coils or the inner exciting coils are driven

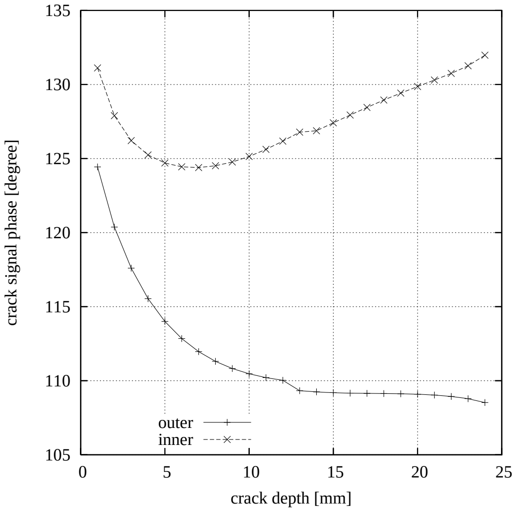

Fig. 8. Dependence of the crack signal phase on the crack depth gained with the novel probe when only outer exciting coils or the inner exciting coils are driven

pair of the exciting coils, i.e. a pair of the inner coils or a pair of the outer coils, is utilized to drive eddy currents, Fig. 7, 8.

When the inner and the outer exciting coils of the two sets are driven at the same time independently from each other by phase-shifted currents of 180 , the distribution of eddy current density under the pick-up coil depends on a ratio of densities of those exciting currents. It means that the distribution of eddy current density can be changed by changing the ratio. An example the pick-up coil along the material depth is plotted for the ratio of the inner and the outer exciting currents densities of $J_i / J_o = 6.4/10$. As it can be seen,

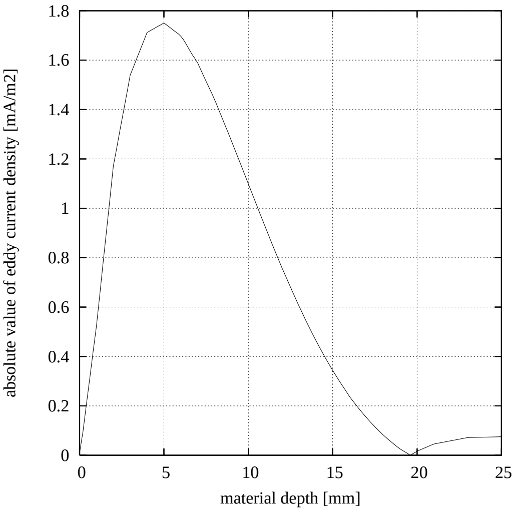

Fig. 9. Dependence of absolute value of eddy current density on material depth, the inner and the outer exciting coils are driven at the same time with currents shifted by 180°, the ratio of exciting currents is Ji/Jo = 6.4/10

by a proper adjustment of the exciting currents densities it is even possible to suppress eddy current density on the surface of material to zero.

It has been found out that the distribution of eddy current density along material depth under the pick-up coil influences amplitude, phase as well as shape of a crack signal. Therefore, by changing the ratio it is possible to rotate the crack signal and to vary its amplitude.

Next the influence of the eddy current distribution on the crack signal is investigated.

Five signals of the crack with a depth of $d_c = 10$ mm for five different values of the ratio J_i/J_o plotted in the complex plane are shown in Fig. 7. It is evident that the crack signal rotates clockwise with increasing of the ratio while its amplitude decreases up to a certain value of the ratio and then increases again. This dependence can be more clearly observed in Fig. 8. Although the ratio was changed in a wider range, the dependences of the crack signal amplitude and its phase on the ratio are shown just up to $J_i/J_o = 3$ as this range is sufficient to explore considered changes in the crack signal.

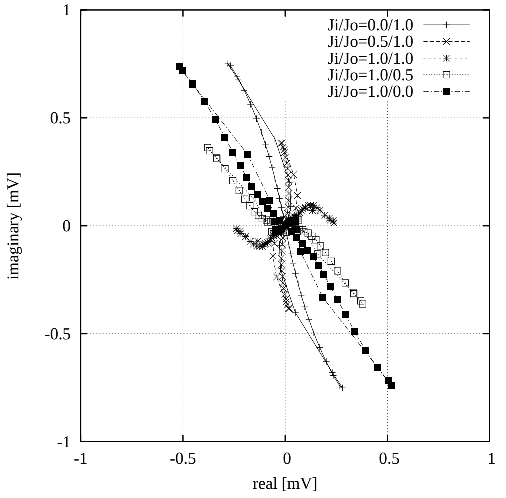

Fig. 10. Signals of the crack with a depth of dc = 10 mm for different values of the ratio Ji/Jo

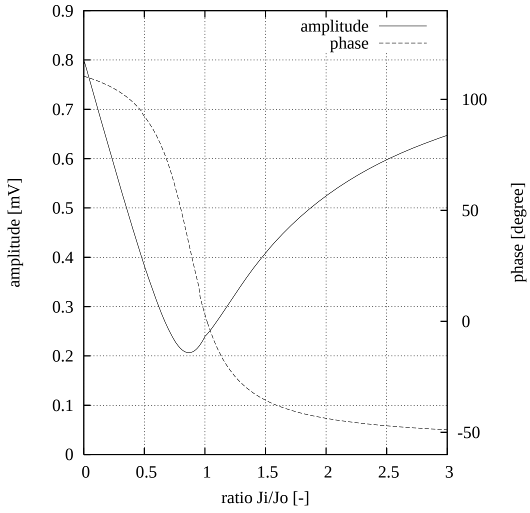

Fig. 11. Dependences of the crack signal amplitude and its phase on the ratio J_i/J_o for the crack with a depth of d_c = 10 mm

Similar dependences for the crack with depths of 5, 10, 15 and 20 mm are shown in Fig. 9, 10. The amplitudes are plotted in unite values referred to a maximum amplitude of the signal for whole range of the ratio and for each depth of the crack. The change of the crack signal phase is referred to a value of the phase when only outer coils are driven ($J_i/J_o = 0$). It can be seen that depth of the crack determines a value of the ratio when the crack signal amplitude reaches its minimum (Fig. 9). Rotation of the crack signal with increasing value of the ratio also depends on the crack depth (Fig. 10). Thus, two features can be extracted from these characteristics for the crack with a certain depth: 1) value of the ratio when amplitude of the crack signal reaches its minimum; 2) value of the ratio when the crack signal rotates of an angle defined as a half value of the total crack signal rotation.

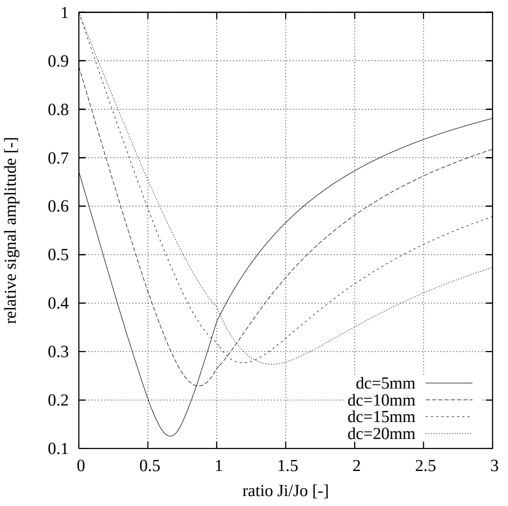

Fig. 12. Dependences of the crack signal relative amplitude on the ratio J_i/J_o for the crack with depths of d_c = 5, 10, 15 and 20 mm

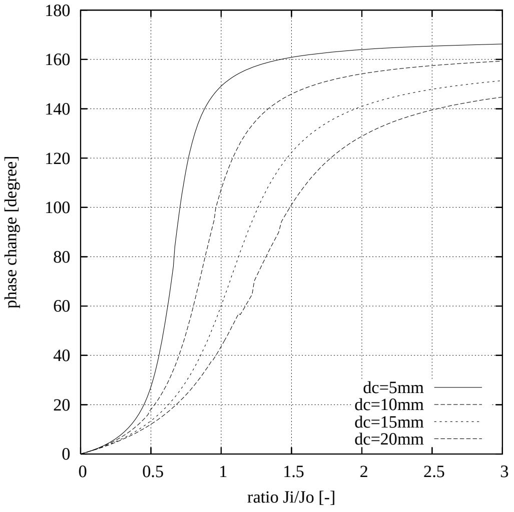

Fig. 13. Dependences of the crack signal phase change on the ratio J_i/J_o for the crack with depths of d_c = 5, 10, 15 and 20 mm

Dependences of the ratio Ji/Jo on the crack depth for the two extracted features are shown in Fig. 14. As it can be seen, the dependences for both the extracted features are nearly the same and they are almost linear. It can be concluded that for each depth of the crack there is a unique value of the ratio where the crack signal amplitude reaches a minimum value and the signal rotates in a defined angle. Therefore, when a detected crack is inspected using the novel probe with different adjustments of the ratio, it is possible to find a value of the ratio for the two extracted features and thus to directly estimate a depth of the crack.

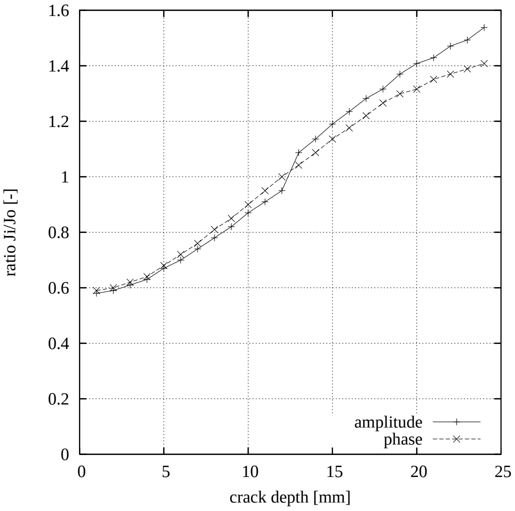

Fig. 14. Dependences of the ratio J_i/J_o on the crack depth d_c for the two extracted features

A novel eddy current testing probe utilizing phase-shifted excitation was used to drive eddy currents of various distributions controlled by changing the ratio of the exciting currents densities. It was shown that amplitude and phase of the crack signal depend on the distribution of eddy currents and thus on the ratio. Signals of considered crack were calculated for wide range of the ratio by means of numerical simulations. Two features were extracted from the obtained complex crack signal characteristics; first one for the signal amplitude and the second one for the signal phase. It has been proved that the extracted features can be very helpful in direct estimation of a crack depth.

3.2. The New RFECT Probe for Pipe Investigation

The optimization and creation of a new probe modification is connected with the used ECT technique. The principle of remote field eddy current testing (RFECT) method and the new coils probe development used in the remote field eddy current testing devoted to the inspection of pipes have been realized and described , [2], [6].

The RFECT probes are usually made of the bobbin coils positioned coaxially inside the tube. The distance between the exciting and the pick-up coil is approximately 2-3 times a tube diameter. The usual configuration of the RFECT probe contains two exciting coils positioned on both sides of the pick-up coil. Differential connection of two closely positioned pick-up coils is frequently employed for reduction of the wobbling noise.

The RFECT reliably works when the probe is positioned inside the tube. However, not all the tubes are accessible from their inside. When the exciting coil encircles the outer surface of a tube it is not possible to gain the remote field effect with conventional configurations of the RFECT probe even the distance between the exciting and the pickup coils is quite large. Design of a new probe dedicated for the remote field eddy current testing of a magnetic tube from its outer surface is presented here.

The paper considers the inspection of a magnetic tube with an outer diameter of 500 mm and a wall thickness of 10 mm, [9]. The tube is accessible only from its outer surface. It has been reported that the standard configurations of the RFECT probe do not allow remote field inspection from outside a tube. Thus, the main goal is to design a new probe able to work properly in the given configuration.

There are many variable parameters concerning the design of a probe, i.e. arrangement of coils and their dimensions, distance between the coils, inspection frequency, etc. Numerical simulations were carried out to find out proper arrangement and dimensions of the new probe. The finite element method was used for the purpose.

Preliminary results clearly indicated that complex arrangement of coils, e.g. double excitation, does not bring any advantage in reaching the remote field effect from outside the tube. Thus, simple configuration with one exciting coil and one pick-up coil has been chosen. Both the coils are of the bobbin type and encircle the tube from the outside.

A proper shield must be used for gaining the remote field effect from outside the tube. Several configurations and materials of the shield have been studied. Preliminary numerical results illustrated that complex shield does not bring reasonable results for sake of the remote field effect. Therefore, one monolithic shield covering both the coils has been chosen for further investigations.

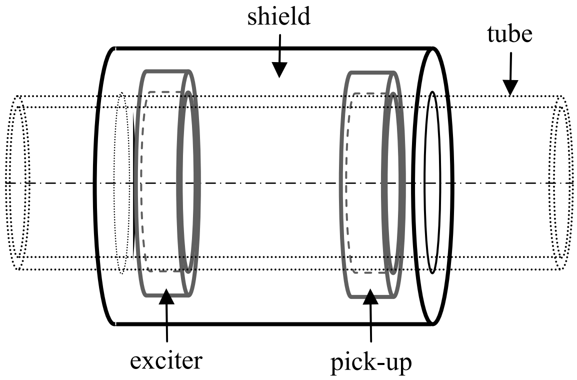

Fig. 15. Layout of the new RFECT probe

Layout of the new RFECT probe is shown in Fig. 15. It should be noted that the dimensions of the coils (width, height) have been set in advance as they do not influence the required behavior of the probe. The increasing distance between the coils as well as the increasing exciting frequency reduce the amplitude of the pick-up signal. Thus, it is preferable to adjust both the parameters as low as possible to obtain a higher level of the detected signal. However, certain limitations have to be taken into account. Dimensions and material of the shield are adjusted along with the other parameters.

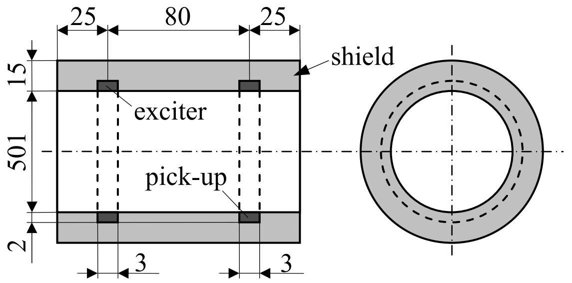

Fig. 16. Configuration and dimensions of the new RFECT probe

Configuration and dimensions of the new RFECT probe are given in Fig. 16. Note that the drawing is not proportional. The shield is made of the Cobalt. Its electromagnetic properties are: conductivity of $\sigma = 16$ MS/m and relative permeability of $\mu_r = 68$. Exciting frequency is set to a value of 300 Hz.

Whole circumferential wall thinning of variable depth and of variable width is used to model the inner (ID) and the outer defects (OD) in the tube. The tube is numerically inspected with the proposed probe. Figure 17 displays Lissajous plot of the crack signals for the ID and the OD cracks with a depth of 20% of the tube wall thickness and a width of 5 mm.

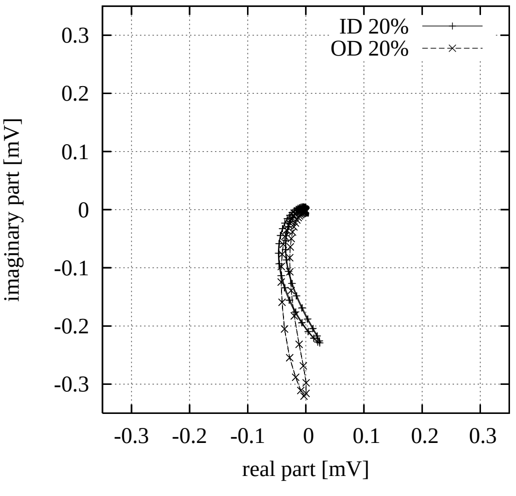

Fig.17. Lissajous plot of the crack signals for the ID and the OD cracks with a depth of 20% of the wall thickness and a width of 5 mm

It can be seen that the signals of ID and OD cracks are close to each other. The depth of the ID and the OD cracks is varied from 0 to 100% of the tube wall thickness. The width of the crack is set to 20 mm in this case. Figure 18 shows the crack signal amplitude as well as its phase as a dependence on the crack depth. It can be observed that the ID signals are as clear as the OD ones that confirm correctness of the proposal.

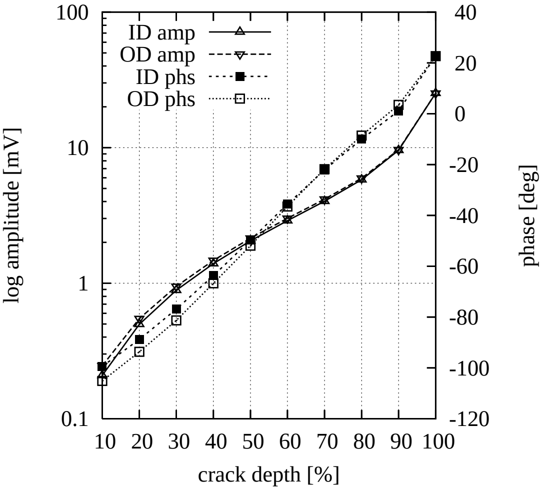

Fig.18. Dependence of the crack signal amplitude and its phase on the crack depth, crack width is 20 mm

The shield is the key point of the new probe. The remote field effect is gained despite the tube is inspected from its outside. Moreover, shorter distance between the coils can be adjusted. Although, the tube has outer diameter of 500 mm, the distance between the coils is only 80 mm.

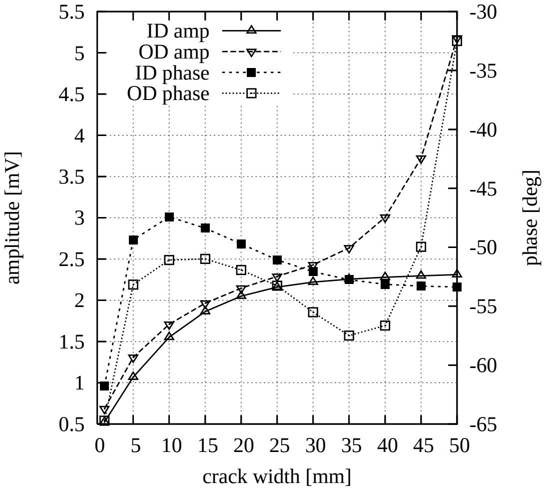

Fig. 19 Dependence of the signal on the crack width for the ID and the OD cracks of 50% in depth

Figure 19 displays how the signal depends on the crack width. The ID and the OD cracks of 50% in depth are considered. Since the distance between the coils is quite short, it can be observed that when the crack is wider than 40 mm, the difference between the signals of the ID and the OD cracks starts to become significant.

It was also found that the magnetic shield helps to achieve the remote field effect when the coils are located outside the tube. Moreover, the shield allows shortening the distance between the exciting coil and the pick-up coil and thus to increase level of the pick-up signal.

3.3. The Solid-state Magnetic Sensors for ECT

But except of coils and their various arrangements the ECT detection elements can be also superconducting quantum interference (SQUID) detectors, or solid-state magnetic sensors, such as Hall Effect, fluxgate or magneto-resistance (AMR or GMR) and spin-dependent-tunneling (SDT) sensors.

The use of low-field solid-state magnetic sensors represents a significant advance over more traditional inductive probes in use today, [7]. Two key attributes will open opportunities for increased use of eddy current probes: sensor constant sensitivity over a wide range of frequencies and development of smaller sensors.

Probes that detect eddy current fields using inductive coils have less sensitivity at low frequencies. Unfortunately, this is where the device would have to operate to detect deep flaws. Small sensing coils which are required to detect small defects also have low sensitivity. In contrast, small, high-sensitivity thin film sensors can locally measure a magnetic field over an area comparable to the size of the sensor itself /tens of micrometers/. Limitation of conventional eddy current probes is the difficulty of detecting small cracks originating at the edges of a specimen. This defect is the most common type encountered in practice. An example is the cracks that appear around the fastener or rivet holes in aircraft multilayer structures. Most inductive coil probes are sensitive to both the edge and the cracks initiating from or near the edge. The edge creates a large signal that obscures the small signal from the crack. GMR and SDT magnetic sensors can be oriented to eliminate the edge signal. With this orientation the presence of the edge enhances the signal from the crack.

To achieve high resolution for detecting small surface and near-surface defects it is necessary to reduce the dimensions of the excitation coil. The minimum length of a detectable crack is roughly equal to the mean radius of the coil. There have been developed and tested probes incorporating small, flat, pancake coils or planar excitation coils deposited on the sensor substrate.

Recent development of thin film magnetic technology has resulted in films exhibiting a large change in resistance with magnetic field. This phenomenon is called giant magneto-resistance to distinguish it from conventional anisotropic magneto-resistance (AMR). Whereas AMR resistors exhibit a change of resistance of up to 3%, various GMR materials achieve about a 10% - 20% change in resistance.

GMR films have two or more soft magnetic layers of iron, nickel and cobalt alloys separated by a nonmagnetic conductive layer such as copper. Because of spin-dependent scattering of conduction electrons, the resistance has maximum value when the magnetic moments of the layers are anti-parallel and minimum when they are parallel, [7].

The main components of an eddy current probe for non-destructive testing are pancake-type coil and an AC bridge of GMR or SDT sensors. Arrangement of coil and GMR sensor for eddy current detection of defects in conductors is shown in the Fig. 20, [7]. When measuring the sensing axis, it must be kept the GMR probe coplanar with the surface of specimen. The excitation field on the coil axis, being perpendicular to the sensing axis of the GMR, has no effect on the sensor. In this way, the detected field, which is the result of the perturbation of the eddy current flow paths caused by the crack, is separated from the excitation field.

Eddy current induced in the surface of a defect-free specimen are circular because of the circular symmetry of the field produced by the coil.

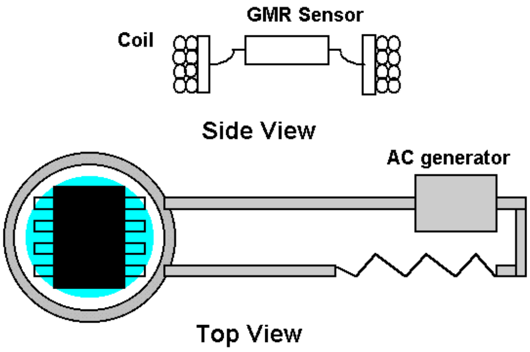

Fig. 20. Setup of ECT with GMR sensor.

The tangential component of the field created by the eddy currents is zero at the location of the sensor. In presence of defects, the eddy currents are no longer symmetrical and the probe provides a measure of the perturbed eddy currents caused by underlying flaws. The size of the coil is related to the resolution necessary to detect the defects. For large defects and for deep defects, large coils surrounding the sensors are required. Small coils located close to the specimen are necessary to resolve small defects.

Eddy currents shield the interior of the conducting material with the skin depth related to the conductivity and the frequency. By changing the frequency it is possible to probe differing depths of the material. GMR sensors with their wide frequency response, from DC to the MHz range, are well suited to this application. The small size of the sensing element increases the resolution of defect location while the detector is raster-scanned over the surface.

More rapid scans can be performed using an array of detectors, [8].

Within the recent development there were built the optimized EC probe prototypes to detect and map different types of defects encountered in practice. They are evaluated probe performance on calibrated slots of different lengths, widths, and heights machined into the top surface, bottom surface, or edges of specimen. The results are combined with the results obtained on a specimen that contained real cracks artificially grown around a hole. Finally, they demonstrated magnetic profile imaging by scanning a given object using a high-resolution probe, [8].

EC probes were tested on surface cracks longer than the excitation coil diameter. Quality of the maps produced when scanning this type of defect depends on the relative orientation of the sensitive axis of the GMR sensing elements with respect to the crack orientation. Short surface cracks can also be reliably detected using small excitation coils. The unidirectional sensitivity of GMR sensors enables the detection of cracks at and perpendicular to the edge of a specimen. This discrimination is possible because the sensitive axis of the sensor can be oriented parallel to the edge. Consequently, the output signal of the sensor is caused only by the crack.

4. CONCLUSION

The main characteristics of ECT probes were described and compared in the paper. The two new probe arrangements for both the deeper defects detection and the RFECT outer probe optimization proposed and realized by authors were presented and discussed.

According to the various requirements on the detected signals and to the used ECT techniques the applications of usual and selected advanced probe devices were discussed and mutually compared. As for the last ECT sensing trends the emphasis was put mainly on the solid state GMR sensors and their properties such as the constant sensitivity in a wide frequency range, their small size and the possibility of low magnetic fields measurement.

5. ACKNOWLEDGEMENT

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