Surface Eddy Current Probes: Excitation Systems of the Optimal Electromagnetic Field (Review)

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Abstract

Development of technical tools with improved metrological and operational characteristics is the actual problem of the eddy current testing. Ensuring the optimal distribution of the electromagnetic excitation field in the testing zone carries out confident detection of the defects and determination of their geometrical parameters by means of eddy current testing. The purpose of the work was to conduct an analysis of scientific and technical information in the field of eddy current testing to study of the use of electromagnetic excitation fields with a priori specified properties, as well as to generalize and systematize the accumulated experience and approaches to conduct theoretical research in this direction.

A review of publications in the field of non-destructive electromagnetic testing devoted to the improvement of the excitation systems of eddy current flaw probes was carried out. The authors considered approaches in which a uniform distribution of the electromagnetic field on the control object surface was achieved by linear and non-linear optimal synthesis of excitation systems, provided the immobility of the probe relative to the testing object. Analysis of eddy current probe designs with a homogeneous excitation field created by circular, rectangular tangential and normal coils, as well as by creating a rotational excitation field was carried out. The authors studied designs of the excitation coils of probes with fields of complex configuration characterized by the original fractal geometry which can increase the probability of identifying defects that were not amenable to detection by classical probes.

Studies that suggested the formation of optimal configuration fields in a given area using magnetic cores, field concentrators made of conductive materials and specially shaped screens were analyzed. The authors studied approaches to the implementation of the optimal synthesis of excitation systems of probes with uniform sensitivity in the testing zone using surrogate optimization for cases of moving testing objects taking into account the speed effect.

The experience, as well as the results of theoretical studies devoted to the problem of designing eddy current probes with uniform sensitivity in the testing zone due to the uniform density distribution of the induced currents flowing in the object were generalized and systematized. As a result, the classification of probes on a number of features that characterize the excitation systems was proposed.

Keywords: eddy current probe, optimal electromagnetic excitation field, uniform eddy current density distribution, uniform sensitivity.

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Накладные вихретоковые преобразователи: системы возбуждения оптимального электромагнитного поля (обзор)

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Актуальной задачей вихретокового контроля является разработка технических средств с улучшенными метрологическими и эксплуатационными характеристиками. Уверенное обнаружение дефектов и определение их геометрических параметров средствами вихретокового контроля осуществляется при обеспечении оптимального распределения электромагнитного поля возбуждения в зоне контроля. Цель работы заключалась в проведении анализа научно-технической информации в области вихретокового контроля для изучения сведений об использовании электромагнитных полей возбуждения с априори заданными свойствами, а также обобщения, систематизации накопленного опыта и подходов к проведению теоретических исследований в данном направлении.

Проведён обзор публикаций в области неразрушающего электромагнитного контроля, посвящённых совершенствованию систем возбуждения преобразователей вихретоковых дефектоскопов. Рассмотрены подходы, в которых однородное распределение электромагнитного поля на поверхности объекта контроля достигается линейным и нелинейным оптимальным синтезом систем возбуждения при условии неподвижности преобразователя относительно объекта контроля. Проведён анализ конструкций вихретоковых преобразователей с однородным полем возбуждения, созданным круговыми, прямоугольными тангенциальными и нормальными катушками, а также за счёт создания вращательного поля возбуждения. Изучались конструкции катушек возбуждения преобразователей с полями сложной конфигурации, характеризующиеся оригинальной фрактальной геометрией, которые позволяют увеличить вероятность выявления дефектов, не поддающихся обнаружению классическими преобразователями.

Также проанализированы исследования, в которых предлагается формирование полей оптимальной конфигурации в заданной зоне с применением магнитопроводов, концентраторов поля из проводящих материалов и экранов специальной формы. Изучались подходы к реализации оптимального синтеза систем возбуждения преобразователей с равномерной чувствительностью в зоне контроля с использованием суррогатной оптимизации для случаев движущихся объектов контроля с учётом эффекта скорости.

Обобщён и систематизирован опыт, а также результаты теоретических исследований, посвящённых проблеме проектирования вихретоковых преобразователей с равномерной чувствительностью в зоне контроля, обусловленной однородным распределением плотности индуцированных токов, протекающих в объекте. Предложена классификация преобразователей по ряду признаков, характеризующих их системы возбуждения.

Ключевые слова: вихретоковый преобразователь, оптимальное электромагнитное поле возбуждения, однородное распределение плотности вихревых токов, равномерная чувствительность.

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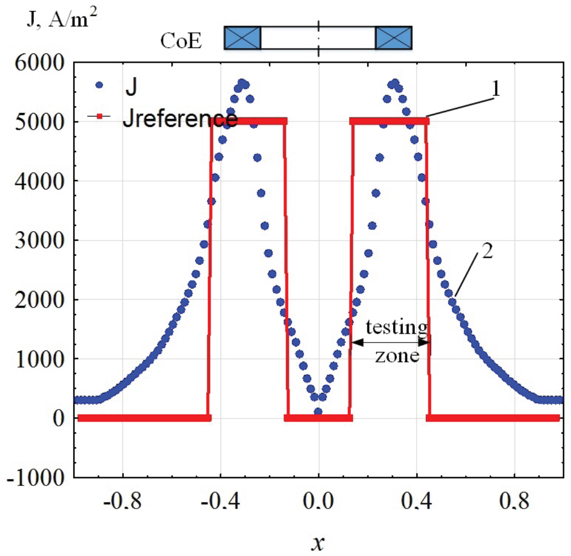
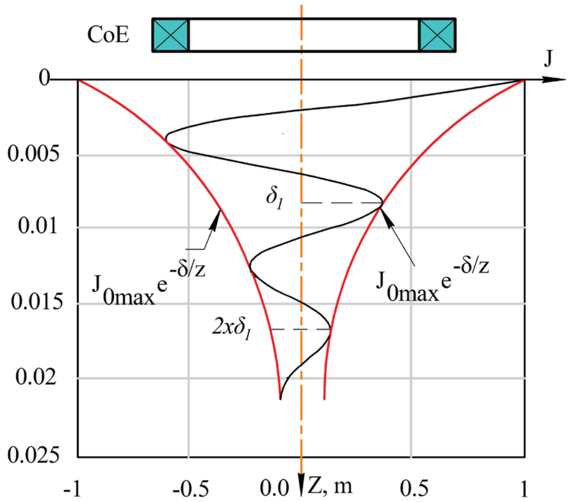
Introduction

The problem of detecting defects by the eddy current method is quite complex. A comprehensive solution of the problem involves not only the detection, but also the determination of the defects shape, allowable geometric dimensions, and possible local structural deviations of the material. Using of the eddy current probes (ECP) with improved metrological and operational characteristics can solve this problem. The classical design of ECP [1] has typically an uneven sensitivity (Figure 1*a*) due to the inhomogeneous distribution of the eddy current density (ECD) which impedes the ability to effectively solve the problem of flaw detection and defectometry. The ECD distribution in the testing object (TO) volume depends on a combination of parameters, for example, the shape, geometrical and electrophysical characteristics of the TO, the mutual position of the excitation system (ES) relative to the TO, etc. It is the inhomogeneous ECD distribution limits the sensitivity of the surface eddy current probe (SECP) to the testing defects, and accordingly, a priori determines the mutual position of the ES relative to the controlled surface. Moreover, this disadvantage manifests itself even more in the case when TO and the ECP move relative to each other, since in this case the transfer current additionally affects the distribution of the ECD, which manifests itself in the so-called speed effect. In order to reliably detect the defects and determine their geometrical parameters by eddy current testing, it is important to ensure the optimal electromagnetic field (EMF) of excitation in the testing zone (Figure 1*a*).

As optimal field, we understand such a field that has a priori given configuration, providing uniform or close to it sensitivity. For example, the U-shaped form of the EMF tension distribution, which is localized and maximally concentrated in the testing zone and has a zero value outside it. Possible options for generating a field are its given distribution both on the surface of the TO and at a certain depth of the TO (Figure 1*b*).



a



b

Figure 1 – The eddy current density distribution of a circular non-coaxial eddy current probe on the surface (*a*) and in depth (*b*) of the testing object: 1 – desired uniform distribution; 2 – characteristic distribution of the classic design

The purpose of the work was to analyze scientific and technical information in the field of eddy current testing to study the use of excitation EMF with a priori specified properties, as well as to generalize, systematize the experience and approaches to conducting theoretical research in this direction.

The solution of the problem

The developed fundamentals of the synthesis theory [2–9] allow implementing new technical solutions in constructions that positively affect the field of excitation of ECP. Different works with various objectives realized the idea of purposefully changing the probing properties of the generated EMF.

So, the solution of the problem of reducing the interaction zone of the ECP field with the product and reducing the magnetic fluxes of scattering [10] increased the noise immunity and selectivity. The creation of an EMF with a predetermined distribution topology improved the selectivity and sensitivity of ECP [1–9, 11–30]. Moreover, the improvement of both parts of the ECP, namely, the ES and the field detector, allowed achieving the desired results.

Summarizing the study of the problem of the formation of the optimal excitation EMF, the authors proposed the variant of the ECP classification by this attribute (Figure 2). Firstly, authors dwelled on the problem of creating the EMF with specified properties for the case of the static TO. The case of generating a uniform EMF distribution is of particular note. The specified properties of EMF that changed in accordance with predetermined dependences are most often obtained in two ways. The first one is the creation of an uneven distribution of the excitation current in the ECP generator coil [2–4]. The second one is the using the specific geometry of the excitation winding of the ECP [8, 12–13].

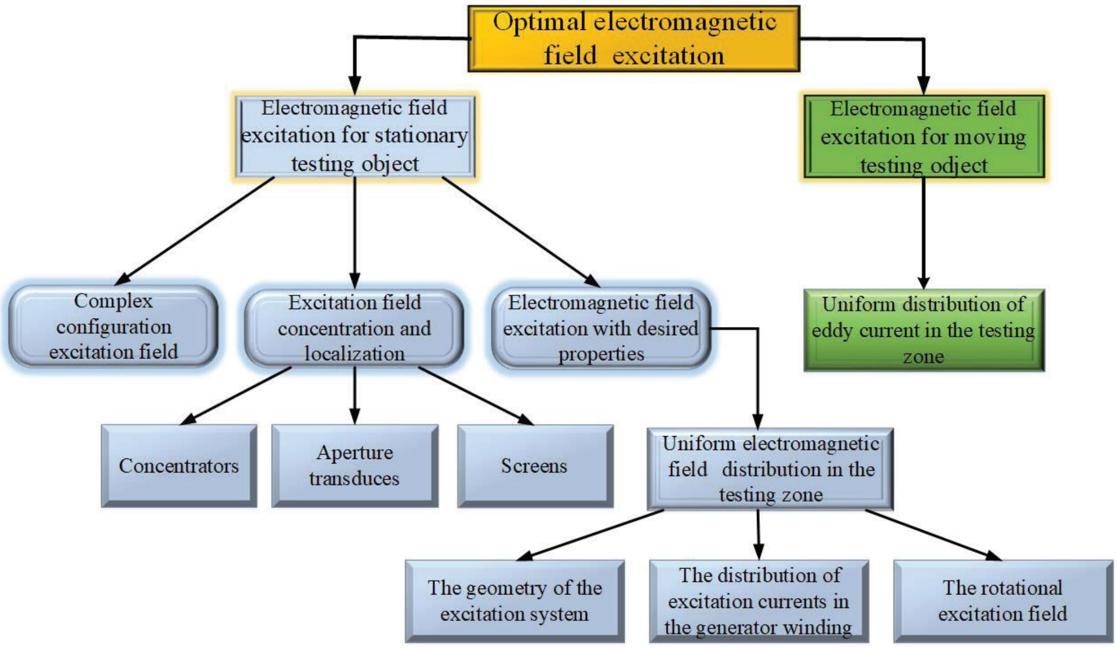


Figure 2 – A generalized classification scheme for eddy current probe with an optimal electromagnetic excitation field

The works [2–4, 8–28] studied this problem. The development of modern computer technology, new opportunities for using more advanced mathematical apparatus and software contribute to the intensification of the efforts of researchers in this direction.

Therefore, in [2–4] the main idea was the obtaining the desired field structure in the control zone by means of linear ECP synthesis. The works considered the problem of synthesizing the ECP excitation fields with given output characteristics from the spatial coordinates of the local inhomogeneities of the controlled products. The resulting structure of the plane-parallel EMF implemented the invariance of the probe output signal to the spatial position of the local defect. After determining the structure of the EMF, the problem of synthesizing the sectional windings of ECP was carried out, realizing the necessary distribution of the field in the control zone. The resulting multisectional ES had $N = 8$ excitation windings with a normalized distance between the windings. The winding connection scheme, namely counter-coordinated inclusion of sections along the field and the number of turns W of each winding was determined. Experimental and theoretical data showed the possibility of practical implementation of a complex configuration of the excitation field, when its intensity increases with distance from the source. However, such a distribution can only be created in a limited area, beyond which the field decreases, approaching zero. The disadvantage of linear synthesis [3, 4] is the receiving the real values of the current density in the coil sections, which greatly complicates the practical implementation of the ECP, as well as the need to preset the number of sections, the distance between them and their geometrical dimensions. The synthesis issue remains unresolved when the required field structure is achieved by the ECP parameters nonlinearly included in the formula for calculating the excitation field.

In [5], the authors proposed a solution to the problem of nonlinear optimal synthesis, namely, determining the location of the windings of the sections of the excitation coils (CoE) in space and their geometrical dimensions at a fixed density of the excitation current in the generator coil. Several options were considered. The first option – in accordance with the well-known EMF intensity distribution function, the radii of the sections of the generator coil were determined, providing such a distribution with fixed *z*-coordinates of the sections and magnetomotive forces (MMF) (Figure 3*a*). The second option involved determining the *z*-coordinates of the sections at fixed radii and MMF (Figure 3*b*). To search for the extremum of a nonlinear optimization problem, an algorithm that is suitable for multidimensional "ravine" objective functions was applied.

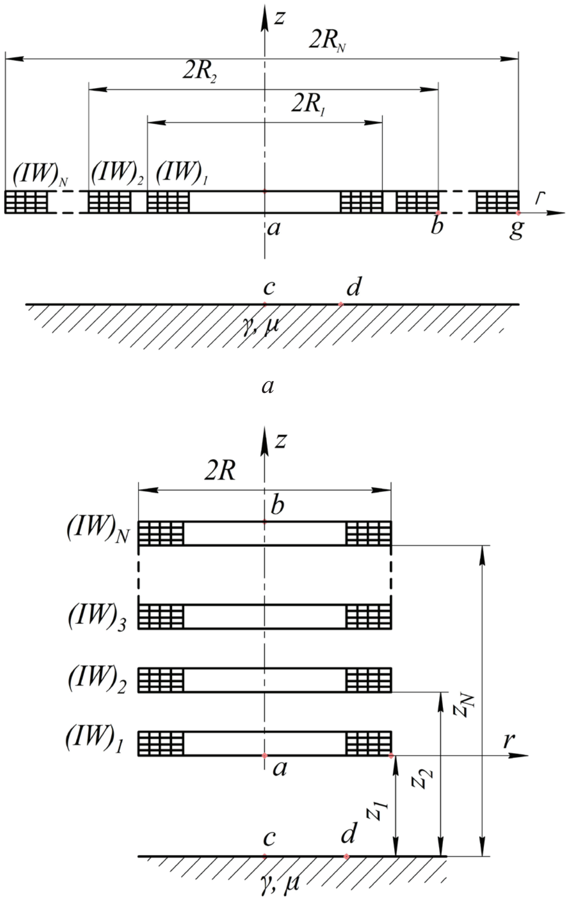


Figure 3 – Nonlinear synthesis of eddy current probe coil: *a* – z_i, $(Iw)_i$ = const, R_i – var, i = 1, ..., N; *b* – R_i, $(Iw)_i$ = const, z_i – var, i = 1, ..., N

The considered approaches [2–5] are parametric optimization methods and the problem of choosing the structure of the ES ECP, i. e. number of sections in the generator coil is still unresolved. The reason for this is the subjective difficulties in choosing a structure, which can lead to an unsuccessful version in the sense of reproducing a given distribution or to an excessively complex structure. It is impossible to correct the error of the choice of structure by means of parametric optimization.

One of the ways to overcome these difficulties was proposed in [6], namely, the method of structurally parametric synthesis of the source of excitation EMF. The purpose of the synthesis of such magnetic ECP system, along with the search for the optimal values of the section parameters, is to obtain the simplest ES design, which ensures a given distribution of the excitation field in space. The paper considers the probing field of the ECP without taking into account the TO reaction. Structural synthesis is performed by the stochastic optimization method, namely, using the genetic algorithm. The obtained values of the average relative deviations indicate a significant improvement in the quality of the generated field of the synthesized magnetic system compared to the results of [4]. A significant simplification of the ES structure in terms of the number of sections and a decrease in its length was achieved, and the number of turns in the sections was reduced by two orders of magnitude at the same current values. That is, a higher accuracy of reproducing a given field distribution was achieved, and at the same time, technical indicators of the system design was significantly improved.

A large number of scientific reports are devoted to various designs of ECP with a uniform field of excitation created by rectangular, tangential or other types of coils and, as a result, to the problems of increasing sensitivity to detection of defects [13–23, 30]. It is assumed that a uniform configuration of the EMF intensity in the control zone is generated and the corresponding excitation of the uniform distribution of the ECD in a static TO is caused by it.

In particular, in [14], several such configurational structures of unidirectional exciting and measuring coils were analyzed, as well as varieties of ECP designs that create rotational eddy currents (REC). A tangential rectangular

CoE with an alternating current source generates a magnetic field inducing eddy current (EC) on the surface of the test sample (Figure 4*a*). EC flows in straight lines perpendicular to the magnetic field (Figure 4*b*). The following structures of similar ES are considered: a tangential rectangular CoE and a circular measuring one (Figure 5*a*); both coils are tangential and rectangular (Figure 5*b*); a system of tangential coils, one of which is exciting and two are measuring (Figure 5*c*); a tangential rectangular CoE and a detector, which is a magnetoresistive GMR sensor (Figure 5*d*); a rectangular CoE and two semicircular flat detector coils (Figure 5*e*).

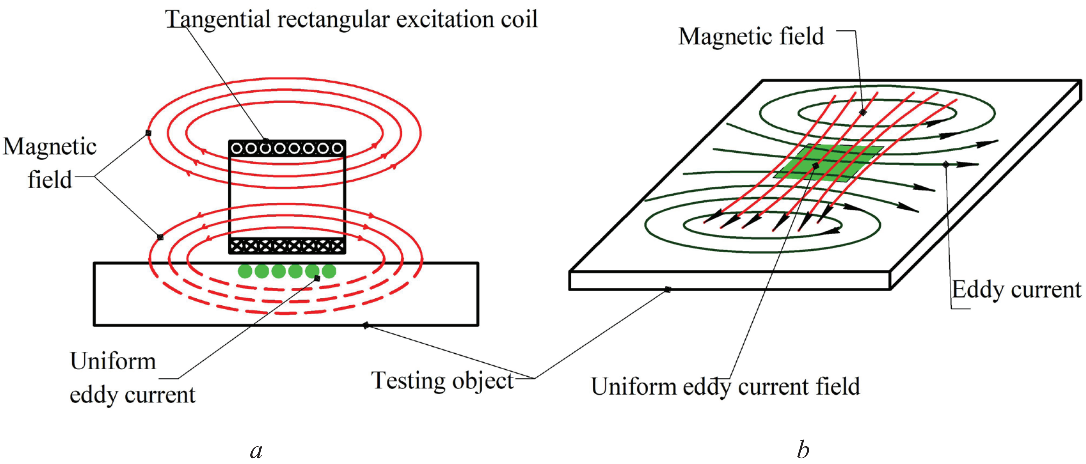


Figure 4 – The principle of generating a uniform eddy current density [14]: *a* – circulation of the magnetic field of the coil and the eddy current created by it; *b* – excitation zone of a uniform eddy current on the surface

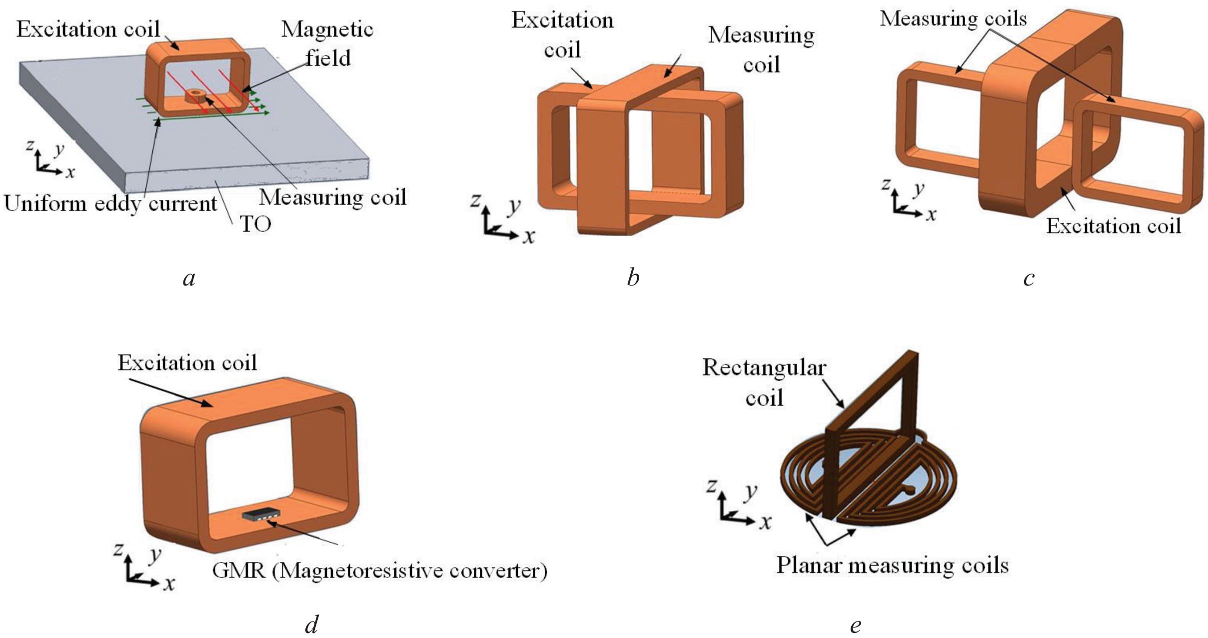


Figure 5 – Structures of the unidirectional exciting and measuring coils [14]

All presented designs create EC in only one direction. In addition, the paper did not address the choice of the ratio of the geometrical dimensions of CoE, which allow adjusting the width of the testing zone. The implementation of a uniform EMF distribution with the help of a rectangular CoE was considered in [23], namely, its location when the winding faces the TO surface (Figure 6).

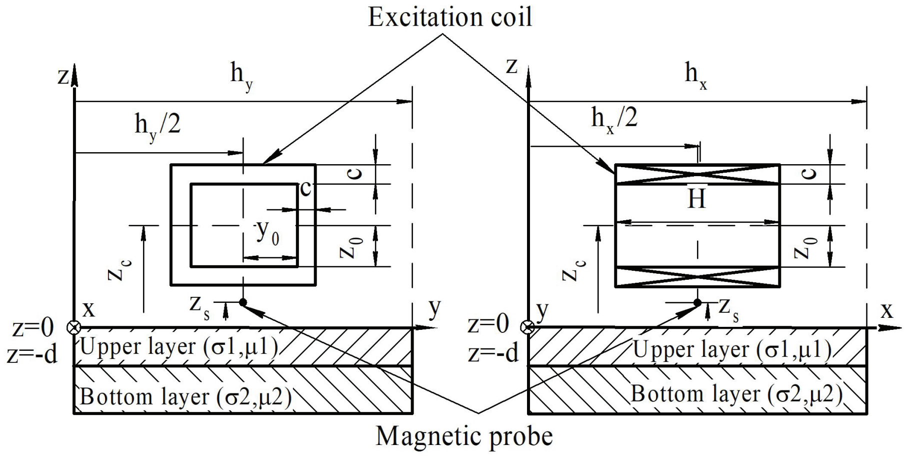


Figure 6 – The configuration of the eddy current probe located above the conductive testing object [23]: *a* – view in the *x*-direction; *b* – view in the *y*-direction

The uniformity of the EC and EMF configurations was investigated by modelling using the ETREE (Extended Truncated Region Eigenfunction Expansion) method. The calculated distribution of ECD on the plate surface and the EMF components above the plate surface are shown in Figures 7, 8 respectively.

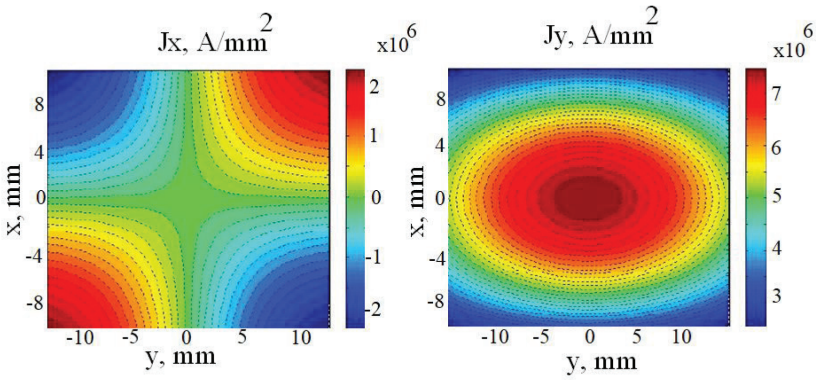


Figure 7 – The calculated eddy current density on the plate surface [23]: *a* – *x*-component; *b* – *y*-component

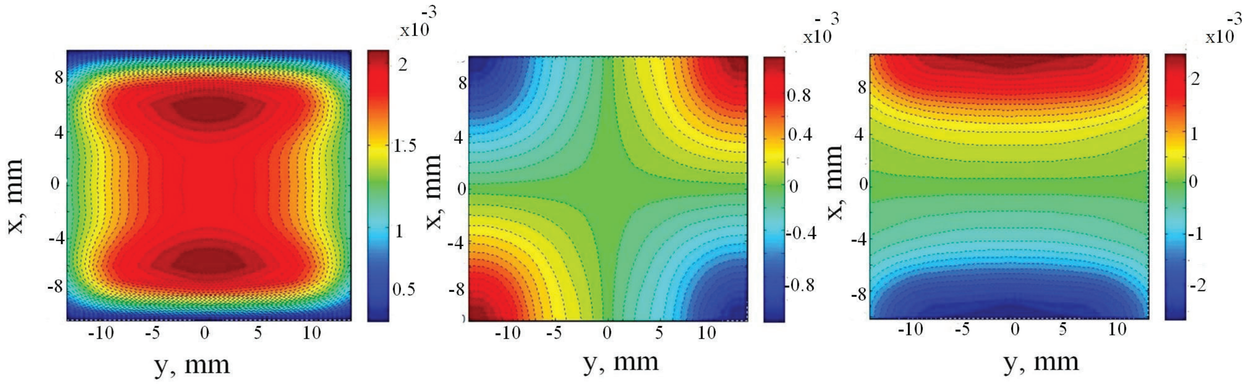


Figure 8 – The calculated values of the components of the electromagnetic field above the investigated surface [23]: *a* – B_x; *b* – B_y; *c* – B_z

The resulting degree of homogeneity is 20 ppm for EC and 5.9 ppm for induction of EMF. This indicates that in the control zone the EC on the plate surface and the total EMF above the upper surface of the plate are homogeneous, and this contributes to a highly sensitive detection of defects. But such a high degree of uniformity of both the field and the EC is provided only in the zone of small geometrical dimensions (2×2) mm.

In [13] the formation of a uniform distribution of the EC within the sensor testing zone was studied by determining the profile of the external radius of the CoE to obtain a uniform sensitivity in the scanning area. The resulting design of the sensor allows inducing a given distribution of the ECD inside the conductive cylinder (Figure 9).

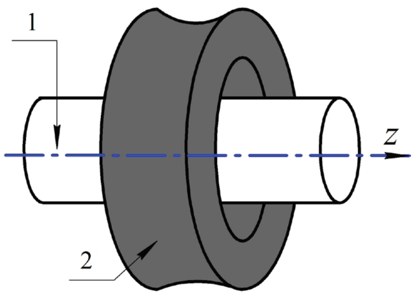


Figure 9 – Sensor design [13]: 1 – cylindrical sample under investigation; 2 – excitation coil

The design problem was solved by minimizing the deviation quadratic function between the desired and calculated values of the vector potential at the control points inside the study area:

$$F(p) = \frac{1}{2} \cdot \sum_{k=1}^{K} \left| A^{e}\left(r_k, z_k\right) - A^{d}\left(r_k, z_k\right) \right|^2 .$$

The Newton optimization algorithm was used to minimize the objective functional. The problem of increasing the sensitivity to defects regardless of their orientation due to the creation of a rotational field of excitation is discussed in [12, 14, 24, 25]. One of these types of ECP with a uniform field is the creation of a variant with REC, for the generation of which two currents are used in the ES with a phase difference of 90°. For example, a Hoshi rotary sensor has two tangential rectangular CoE1 and CoE2 and one flat circular measuring coil (Figure 10) [14].

The proposed sensor can detect defects regardless of their direction on the surface of the investigated TO.

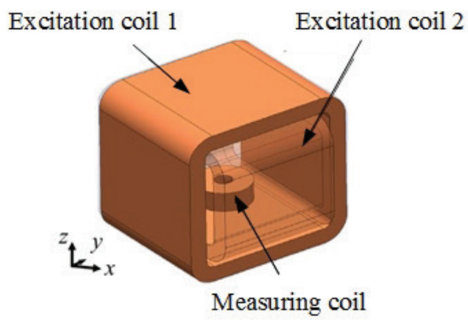


Figure 10 – Hoshi Rotary Sensor [14]

To develop the idea a double rotational sensor was proposed in [14], which has four tangential rectangular CoEs and four-pole quarter-circular detector coils (Figure 11), operating on the same principle. Using current and phase control, it is possible to identify defects as reliably as possible without changing the position of the ECP.

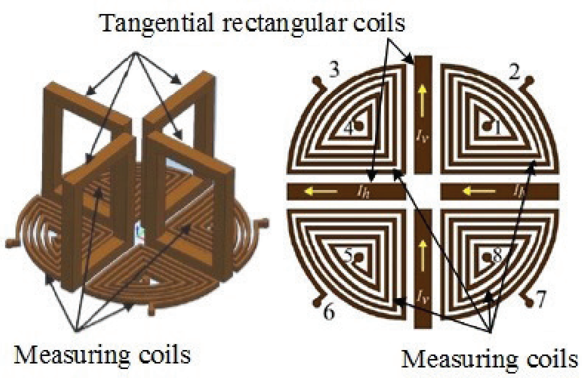


Figure 11 – Double rotary sensor [14]

The work [12] considered a variant of generating a rotational field of excitation, implemented by a system of orthogonal coils. First, an optimized ECD distribution was calculated, which provides uniform sensitivity to defects regardless of their spatial orientation, and then a coil design with an uneven winding density was created (Figure 12).

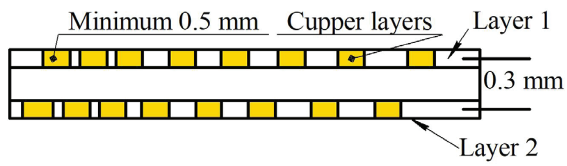


Figure 12 – The design of the rotary sensor multilayer coil [12]

Each coil consists of at least two layers. To obtain a higher degree of distribution continuity than in the case of a single-layer coil, in the 2-layer case, the copper layer of one of the coils was displaced, closing the air gaps. A feature of the optimized coil design is that the resulting field of excitation is more uniform in the region of the detector array in comparison with a conventional coil. The distribution of coil excitation currents was optimized using the polynomial approximation method.

As in previous considered works, a rotational-type ECP was proposed in article [25]. To obtain a uniform distribution of the ECD in the zone of the measuring coil by means of numerical analysis, the optimal CoE sizes were calculated (Figure 13).

The obtained zone of uniform distribution of ECD is quite large (Figure 14), therefore, the detection of defects by such an ECP is more efficient.

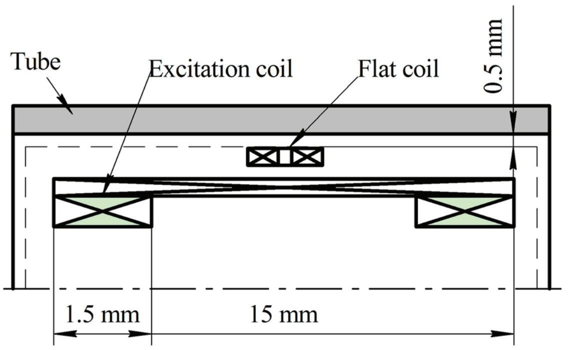


Figure 13 – The design of the rotary sensor [25]

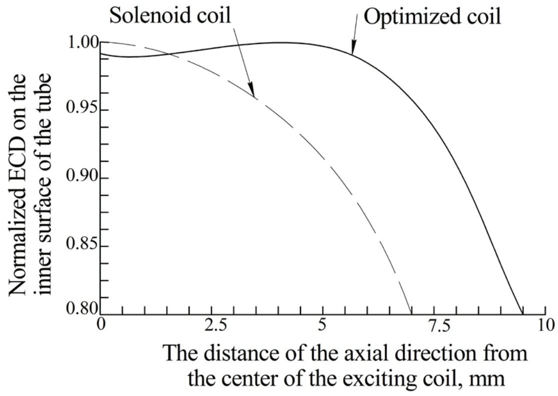


Figure 14 – The topography created by a uniform distribution of the eddy current density in a testing zone [25]

The intensity of the generated ECs affects the ability to detect a defect. In the study [10], with the aim of increasing it, the design of the ECP containing two pairs of coils with the same dimensions and opposite winding directions was proposed (Figure 15*a*).

In the area under the coil (Figure 15*c*), the ECs merge and form homogeneous ECs with an intensity of almost two times greater than from a single coil.

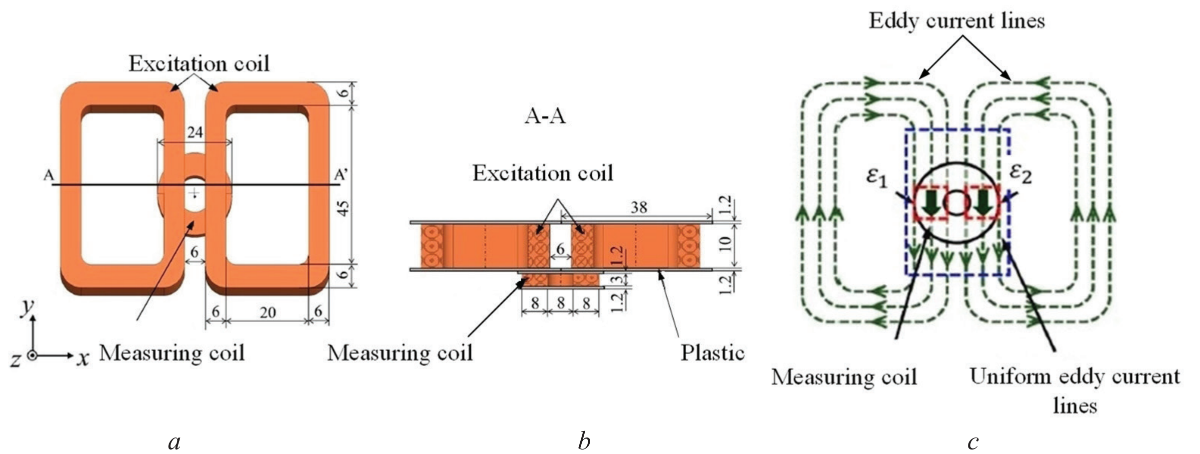


Figure 15 – Sensor design [10]: *a* – general view; *b* – section A-A; *c* – the eddy currents flow diagram (the zone with uniform eddy currents is indicated by a rectangle)

The middle part of the sensor is the most sensitive zone for detecting defects. The characteristics of both coils should be the same to achieve the best effect. When analyzing by the finite element method, it was found that the ECD dependence generated using a conventional non-doubled homogeneous sensor has only one amplitude peak, whereas a sensor with two rectangular coils has three maxima (Figure 16).

Moreover, the maximum amplitude of the ECD is approximately 1.9 times greater than other peaks. In addition, this maximum is 1.8 times greater in comparison with a conventional sensor. Moreover, the effective distribution of ECs has a large area, so the detection area is three times wider than that of a conventional sensor (Figure 16).

The disadvantage of such ETP, as well as for previous designs (Figure 5), is the formation of unidirectional EC, which requires a change in its orientation in space to identify defects with an unknown a priori orientation.

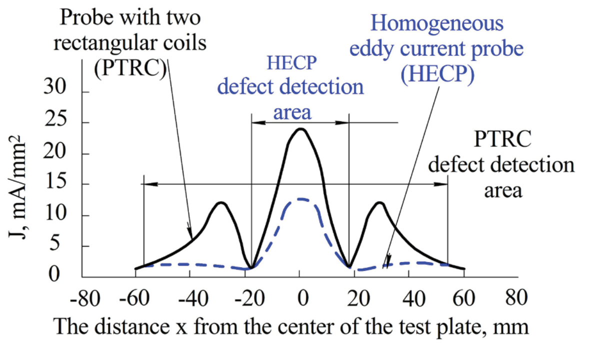


Figure 16 – The eddy current density distribution on the surface of the testing object [10]

The use of ETP with a predetermined EMF topography when detecting defects of complex shape and limited sizes, the control of which reveals the influence of the edge of the object on the ECP signals is relevant. In [8, 9] it is precisely such cases that were considered. In [8] the CoE optimization problem, which creates an almost uniform and tangential field on the surface of TO was solved by solving a multi-parameter multi-purpose optimization problem. The Monte Carlo method optimized a flat coil with several parameters varying: the number of turns, the core gap of the coil, the width of the copper strip of the printed conductor, the size of the air gaps, the length and width of the coil (Figure 17).

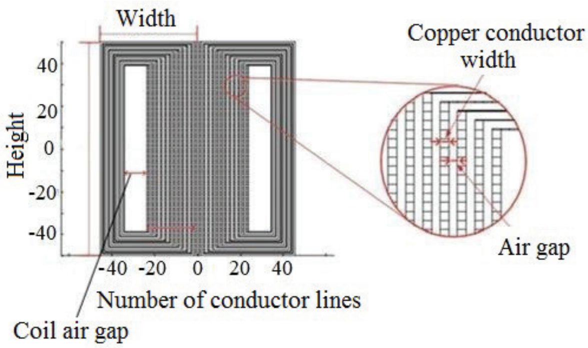


Figure 17 – The configuration of the excitation coil [8]

The work [9] considered the similar problem as in [8], which the genetic algorithm with non-dominant sorting (NSGAII) can solve. A modified NSGAII algorithm optimizes a flat coil, where the gaps between the turns are variables. For optimization objective functions f_1 and f_2 are set, which are respectively minimized and maximized. The first objective function is the standard deviation of the obtained ECD from a given uniform distribution, and, accordingly, the lower this value, the better the uniformity of the currents. The rate of induced EC is a measure of its intensity. Therefore, the larger this value, the better the ability to detect defects. There is no single solution that satisfies both conditions. Therefore, a number of non-dominant solutions are found. Solution A has large values of f_1 and f_2, which corresponds to unsatisfactory uniformity and a high value of the ECD (Figure 18). Solution B, on the contrary, has high uniformity and a low ECD value. Solution C is a compromise between the degree of homogeneity of the ECD and its values in the control area.

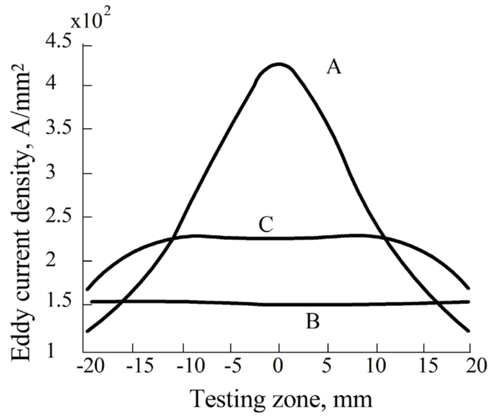


Figure 18 – Distribution of induced eddy currents [9]

For comparison, Figure 19 shows the images of coils with uniform gaps between the conductors with the same currents flowing in them and the optimized one with uneven gaps. The position of the lines of conductors for a conventional coil (Figure 19*a*) is uniform, whereas for an optimized coil, the lines of conductors are few in the center and more densely located at the edges. ECs induced by an optimized coil are more homogeneous than a conventional coil with uniform gaps between the conductors (Figure 19*b*).

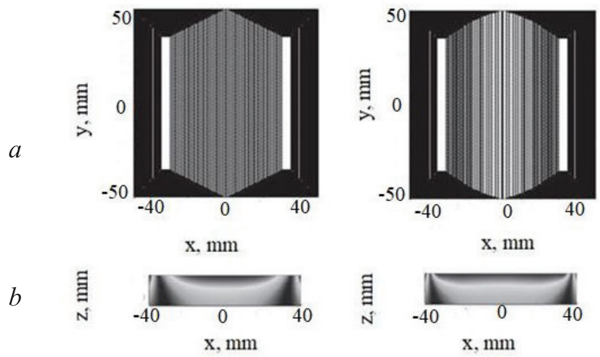


Figure 19 – Unidirectional eddy current probe with uniform eddy current density [9]: *a* – coil designs with uniform and uneven spacing between conductors; *b* – eddy current distribution

The works [26–28] are devoted to study of such drawback of ECP as the exponential attenuation of EC in depth in the sample under study and, accordingly, the application of various measures to eliminate this drawback. The main idea of these works is to suppress EC at the surface of the TO and implement deeper penetration of EC into the thickness of the material. This idea is realized by a combination of several coils, which are powered by an excitation current with different amplitudes and phases, which allows obtaining the desired effect [26]. The obtained results show that the radius of the coil and its height have a strong influence on the attenuation of the EC along the TO depth, when its thickness is several times greater than the standard depth of penetration of the EMF. As a disadvantage of this work, it is possible to note that the synthesis problem was not solved, but was only investigated by sorting a diverse combination of design parameters of the CoE and its height above the TO, and, accordingly, their effect on the attenuation of the EC along the depth of the investigated TO.

The authors analyzed the ECP excitation systems that generate fields of complex configuration at the next stage. A rather interesting study was published in [29]. In order to increase the sensitivity, it was proposed to use a fractal CoE, in particular, in the form of a Koch curve (Figure 20). Such system generates EC in the investigated TO, the topography of which is due to the multiradii of the winding. This design of the CoE increases the probability of detecting defects that cannot be detected using an ECP with a circular CoE, namely those whose length is much less than the radius of the CoE.

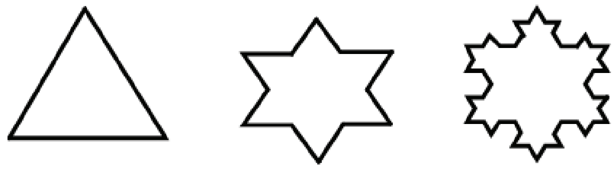
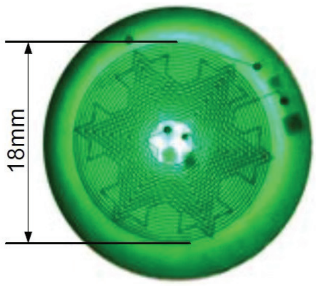


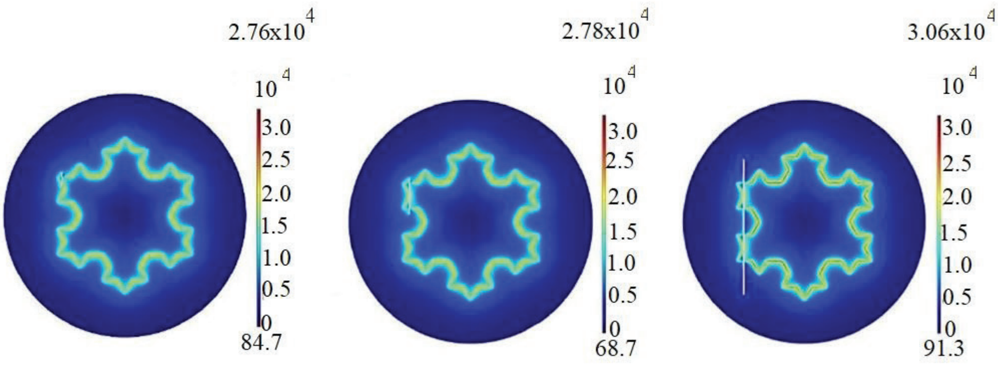
Figure 20 – The geometry of the excitation coil in the form of the first three shapes of the Koch curve [29]

The proposed sensor has a CoE with fractal geometry and measuring coils made by printing on a fourlayer printed circuit board (Figure 21*a*). The ECD diagrams on the surface of the test sample depending on the size of the defect were studied. The diagrams in Figure 21*b* show that the obtained ECD is approximately the same both for small and large sizes of defects, since multi-radii of ECs increase the probability of interaction between ECs and a defect.

We also investigated the obtained maximum values of the magnetic flux density depending on the location of defects on the TO with orientation at different angles (Figure 22). Despite the advantages of such planar ECP, the problem of creating a uniform distribution of ECD remains unresolved.



a



b

Figure 21 – Design and eddy current density distribution with fractal geometry of the excitation coil [29]: *a* – sensor design; *b* – eddy current density distribution

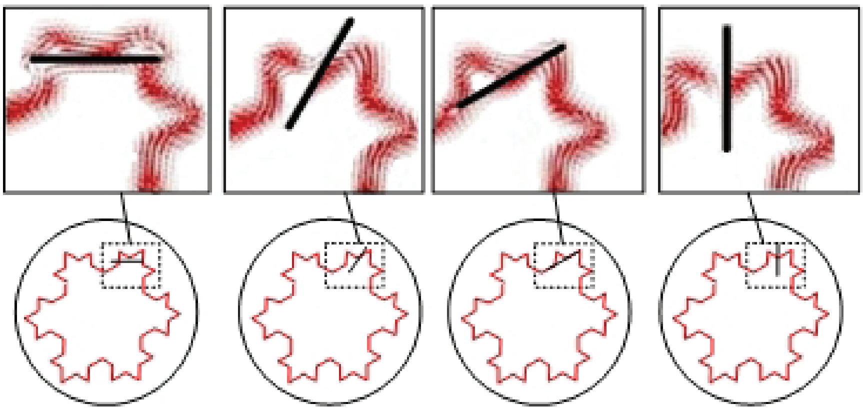


Figure 22 – Eddy current configuration according to defects location [29]

A different approach to the formation of the EMF of the optimal configuration in a given zone was used in [11, 14], where magnetic cores, field concentrators made of conductive materials, and screens of a special shape with and without "masks" are used. For example, a sensor with magnetization device was proposed in [14]. The sensor has an electromagnet with U-shaped core and a combination of a tangential rectangular detector coil for measuring the magnetic flux density *Bx* and a flat rectangular coil for measuring the magnetic flux density *Bz* (Figure 23).

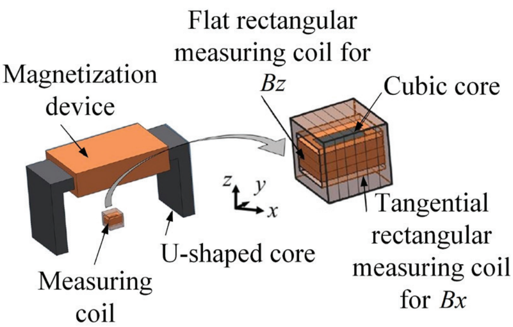


Figure 23 – The structure of the sensor with unidirectional eddy current [14]: *a* – general view; *b* – field detector

Sensors of this type [11, 14] are effective in detecting defects in TO of complex shape and limited sizes, in monitoring which, the effect of the edge of the object on the signals of the ECP is especially felt. For screened ECPs, when shielding elements are placed on the ends of the feedthrough probes, in addition to the positive effect, a negative one also arises, such as an increase in field inhomogeneity in the control zone. The use of "masked" ECP leads, along with an increase in locality, to a decrease in the sensitivity of ECP. Within these designs, it is much more difficult to realize the uniformity of the EMF distribution in the control zone. In addition, the presence of metal structural elements of the ECP is undesirable in conditions of elevated temperature.

The above studies are devoted to the synthesis of ECPs with a given configuration of the probing field in the control zone, but they considered stationary TOs. As a result of the analysis, it was found that there is almost complete lack of information about solving the problem of creating a SECP with uniform sensitivity for moving TOs, which requires taking into account transfer currents during synthesis. In this direction a number of studies concerning circular SECP was carried out. So, in article [31] an optimal synthesis of ES probes with uniform sensitivity in the control zone using the socalled surrogate optimization was performed. Its use is due to the need to reduce the required computing resources in the synthesis and allows getting a solution search in real time [32]. At the same time, this approach requires the preliminary creation of probes metamodels using the theory of experimental design and the theory of artificial neural networks. The computerized design of the experiment is used to generate nodal points evenly spaced in the search hyperspace [33], while the neural network committee-cascade approximator is used for constructing a multidimensional response surface [31, 34].

The authors of [34] developed the theoretical foundations of the optimal surrogate parametric synthesis of moving circular non-coaxial SECPs with uniform sensitivity, having a planar ES structure. For the synthesis of ECP a metaheuristic hybrid algorithm of global optimization by a swarm of particles with the evolutionary formation of a swarm composition is used, which is effective for finding an extremum of multidimensional "ravine" target functions [35–37].

Conclusion

The paper analyzes the scientific and technical information in the field of eddy current testing for the use of eddy current probes with excitation electromagnetic field with a priori specified properties. The experience of theoretical research in this direction was generalized and systematized.

The works in which linear or nonlinear synthesis is used to achieve a uniform distribution of the electromagnetic field on the surface of the test sample for a stationary eddy current probe were considered. The eddy-current probe designs with a uniform field of excitation created by circular, rectangular tangential and normal coils, as well as through the use of a rotational field of excitation, were analyzed. The designs of excitation coils of probes with fractal geometry were considered. These designs make it possible to increase the probability of detecting defects that cannot be detected using classical eddy current probes. It is shown that similar studies for moving eddy-current probes are only in the initial stage. They are aimed at the realization of circular anaxial eddy current probes with excitation systems of a planar structure.

Thus, an analysis of scientific research on the design of eddy current probes with an a priori specified configuration of the excitation electro-magnetic field established that the issue of the synthesis of circular non-coaxial eddy-current probes with volumetric and mixed structures of excitation systems taking into account the speed effect remains unresolved. In addition, eddy-current probes of frame types, both normal and tangential, which are used to control moving testing object, require detailed studies.

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