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Models of Magnetic Driver Interaction with Ferromagnetic Surface and Geometric Data Computing for Clamping Force Localization Patches

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***Abstract*— This paper deals with the main features of electromagnetic interaction between the mobile robot's (MR) electromagnetic driver and ferromagnetic surface. In particular, the problems of clamping force calculation are discussed for robotic applications. The main attention is paid to computing of geometrical parameters of clamping forces localization patches by proposed combination-generation method. Efficiency of the method is checked by computer simulation and shown for one arc of localization patch's contour. Obtained results show rather high accuracy of this processing and its ability to be used in a functional structure of an experimental setup for fast Hall sensors' data stream computing at clamping force calculation by computerized tools.**

***Keywords*— clamping device, mobile robot, clamping force, simulation, control system, finite elements, data processing.**

I. Introduction

Complicated industrial complexes are widely used in modern industrial conditions, which fully or partially equipped with the objects of robotics [1,2]. Thus, industrial robots are successfully used in machine building for metalworking and assembly of prefabricated constructions. Such systems allow not only to significantly increase the productivity of the given technological operations, but also to reduce the risks to human health and life under hazardous conditions [3-5]. This is especially true for execution of works related to the release of aggressive and toxic substances indoors and outdoors or in conditions of increased danger (radiation, elevated temperature, high-altitude works) [6-9]. To accomplish such tasks, the most successful solution is the use of mobile robots (MRs), equipped with technological tools and means of vertical movement in the form of appropriate movers.

In the domestic production the need for MRs which are able to move safely along the sloping and vertical surfaces is actual in the following areas: shipbuilding and ship repair, oil and gas refining and transportation, the agrarian sector [3,4,6-9]. Cleaning, cutting, welding, polishing, painting and inspection of large areas, as well as installation of individual elements and fire extinguishing on vessels, bridge supports, tanks and large diameter pipelines, elevators are the main tasks that can be successfully performed by such MRs. It should be noted that the majority of working surfaces in the above-mentioned applications have a ferromagnetic nature, therefore magnetic or magnetically operated clamping devices (CDs) and propulsion systems are used in such MRs' structures, which are able to provide better control of adhesion with the working surface and high speed of movement with electromagnets and permanent magnets [3-7], unlike pneumatic [2] or vacuum [9] CDs.

Magnetic and magnetically operated CDs are widely used not only in the tasks of robotics. It is difficult to do without them when carrying out black metals lifting-transport operations, assembly of prefabricated designs, machining in the constructions of magnetic tables and magnetic suspension apparatus. So, CDs can be used in almost all types of machining in single, serial and mass production [10,11]. At present, it is difficult to find an industrial enterprise where magnetic and electromagnetic plates, chucks, lifting devices, demagnetizers, etc., isn't used. However, the common problem in such systems is the complexity of determining the clamping force (CF), created by magnetic CD, and actually there are no developed systems for its control. Therefore, the widespread implementation of advanced technological devices using the energy of the magnetic field in the industry requires essential improvement of these devices and makes particularly relevant works about its research and optimization [10].

So, **the main aim of the work** is comparative analysis of applied tasks of magnet's driver and ferromagnetic surfaces interaction in context of computing of geometrical parameters of clamping forces localization patches by using of considered models of their interaction with proposed combined method for different applications in robotics, industry and services.

II. Analysis of the Main Models of CD's Interaction with Ferromagnetic Surface and CF Calculation

For the above applications, different types of CDs are used [3-8,10,11], in particular:

- magnetic based on permanent magnets;

- magnetically operated on the basis of electromagnets (direct and alternating current supply);
- composite, which are built on the principle of permanent magnets with electromagnets combinations or magnetic assemblies, e.g. Halbach assemblies.

Structurally, CDs can be in different ways mounted in the designs of robots, machine tools and grippers: stationary and fixedly with a fixed air gap or with several angular/linear degrees of freedom (then, most often, the gap varies during the operation) – in relation to the working ferromagnetic surface (FS) [12-15]. However, there are situations in operation conditions when the air gap between the CD and the FS can be changed in an unpredictable manner. For example, in shipbuilding and ship repair we can observe the conditions of local uncertainty in the area of the pressed magnet to the working FS: varying thickness, the presence of significant pollution, excrescences, holes or damages, high welds. Despite the fact that the surface of the ship hull is globally determined (there are drawings, the main dimensions can be measured), the local uncertainties of the ferromagnetic and non-ferromagnetic nature have a decisive effect on the distribution of magnetic induction on the working FS and the efficiency of the magnetic field energy use to create the appropriate value of the CFs within its localization [16].

Next, consider the basic existing methods of CF calculating for CDs to determine the most suitable for use in conditions of local uncertainty of the working FS and the need to control the created force.

A. *Energy Approach*

This approach is to determine the permeance of the gap between the surface of the magnet and the FS at different configurations of this gap and the probable paths of the magnetic flux portions. By this method, the dependence of the electromagnetic force (created by the CD) on the gap is a reversed power function with an index equal to 2 [17,18], so even a slight increase in the gap results in a significant reduction in the value of the CF. In general clamping force F can be defined considering the energy balance at the electromagnet anchor motion and air gap changing without taking into consideration dissipation flows, constant value of magnetomotive force IW and unsaturated magnetic system as

$$F = -\frac{(IW)^2}{2} \cdot \frac{dG}{d\delta}, \qquad (1)$$

where G – the gap's magnetic permeance taken for the current anchor position, δ – air gap thickness.

Another case of the use of the energy approach to determining the clamping force applies to the magnetic systems that operate at constant flux linkage. Then without taking into account dissipation flows

$$F = -\frac{1}{4} \cdot \frac{\Phi_{\delta m}^2}{G^2} \frac{dG}{d\delta}, \qquad (2)$$

where $\Phi_{\delta m}$ – maximum value of magnetic flux in the gap [18].

Equations (1) and (2) show that such approach assumes the constancy of magnetomotive force or the flux linkage. Therefore, in case of the necessity of the CF control or the local uncertainty of the FS, it is not suitable for further consideration.

B. *Sources Interaction Method (Coulomb Approach)*

This approach is to determine the interaction of field carriers – superficial and volume magnetic charges and magnetic dipoles. So, it is necessary to use the means of field theory, by which one of the spatial characteristics of the field distribution (magnetic dipoles or conditional magnetic charges) can be determined [19,20].

To implement this method, various techniques and approaches are used. In particular, the well-described and mathematically uncomplicated is the use of mirror images method, according to which a field of the charge located next to a well-conducting surface (FS in our case) can be found. In this case, the influence of the whole conducting surface (the effect of the charges induced on it) is replaced by the field of the mirror image of the given charge with a reversed sign [21]. A calculation scheme, a mathematical model, a methodology and an example of determining the basic parameters of a magnetic field for a walking MR with separate CDs are given in [5]. In the calculation process the authors calculate the normal and tangential components of the CF, as well as the main vector and the main moment acting on the clamping magnet [22]. The limitation of this approach lies in the fact that it is well suited for defining the CF of CD based on permanent magnets. When describing a permanent magnet, its magnetization remains (is) the same over its entire surface (for the rectangular magnet in [5]) in accordance with the adopted CM's model. While for an electromagnet the density of "magnetic charges" is a function of the coordinates of the pole face, which is determined by the solution of the field problem. However, the general method of finding images for any problem in the case of several boundary surfaces has not been developed, but in some examples [23] the method of successive approximations gives the correct results.

C. *Approach Based on Artificial Intelligence Means*

Neuro-fuzzy observers of CF, which is created by electromagnetic MR's CD, are proposed in [24,25] and for another applications – in [26-28]. According to the data on the supplying voltage and spatial position of the electromagnet, which are measured experimentally, the authors sufficiently accurately determine the CF value. Such approach can be found in applications for CDs based on a permanent magnet, as well as for combined CDs. However, the disadvantage of this method is that for each CD it is necessary to carry out a series of measurements to form the training and test samples of the proposed hybrid observers before putting MR into operation. In addition, such a technique does not take into account the peculiarities of the electromagnetic interaction of the CD with a FS in the presence of local uncertainties of the ferromagnetic nature (holes, damages, weld seams, structural elements, etc.).

At the same time, the authors select the phenomenological basis for the functioning of the MR's magnetically operated wheel mover, that consists in the CF formation of the electromagnetic CD by means of the magnetic interaction (i.e. by means of a magnetic field) of the FS's elements with the magnet's poles. Obviously that the main factors of this interaction can be fully taken into account at computing the CDs and the value of the required guaranteed value of their strengths, if we take as a basis the Laplace equation and the method partly outlined in [5].

III. Combination-Generation Algorithm for Computing of Geometrical Parameters of Clamping Forces Localization Patches

In [5] authors propose an idea of clamping force automatic control and monitoring system based on Hall sensors' measurements in the feedback. In this case, the Hall sensors measure the current values of magnetic induction on the clamping surface of the CD, by which the CF value can be indirectly determined. The informating-controlling system must process a big data stream with at least 5 sensors to estimate the dimensions of the patch (area) of the created CF localization (Fig. 1, a) and CF's value. In this case the sizes of the patch refer to the points of its breakdown into elementary area parts – the finite elements (FEs) – both for the area of the patch, and its contour. Based on practical experience, for a patch (created by one MR's CD) a partition at one coordinate must be applied up to 100÷200 points. Therefore, when considering a two-dimensional problem an array of patch's FEs will consist of 10,000 to 40,000 cells. But for solving of a field task it is required to create a square matrix of equations coefficients which may have already an order from 10^8 to 10^{10}. Such number of data items must be formed just for one of the patch's geometric parameters set (for all linear or angular parameters up to 10). The amount of data that needs to be processed at this stage is substantially expanded due to the availability of several CDs (depending on the MR's design) and the speed of the MR's movement. The last factor reduces the time of processing continuous data stream from sensors at computing CF and requires the development of fast and reliable algorithms to determine the main geometric parameters of the patch and the created strength value [29].

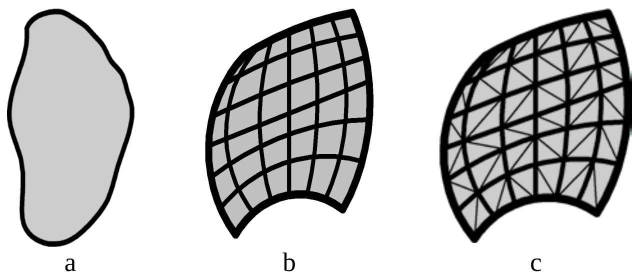


Fig. 1. An arbitrary form of the CF localization patch (a), the breakdown of the patch by arches (b), and an illustration of the formed FE after splitting (c).

The key tool for determining the clamping strengths by the method of sources interaction is the algorithm for calculating the main geometric parameters of the FS's parts – patches, on which the CF is directly created (the places of CF localization). Due to the existing local uncertainties of the working surface (ferromagnetic and non-ferromagnetic), the main area of CF creation may have an irregular shape (while neglecting the leakage flux with less than 5% of the main flow of the CD). So, the contour of this region can have some complex or arbitrary shape (Fig. 1, a), and therefore it is important to get its geometric parameters with high accuracy.

The active CF value is determined after solving the Poisson equation by finding the integral sum of the forces created by each individual FE of the FS [30]. To do this, it is necessary to split the formed patch into the grid of FEs by tracing separate lines or arcs (Fig. 1, b). Such approach is also used in problems of approximation of complex spatial surfaces, including the ship's hull [31,32]. The points of intersection of these lines will be nodal points for the elementary pieces of the patch area, on which elementary clamping strength are created.

The uniform grid of FE consisting of equilateral triangles is established as optimal in the theory of numerical methods [33,34]. But, it is not possible to satisfy such a requirement for a complex surface with variable curvature. Therefore, the criterion of the quality of the approximation should be the minimum deviation of the internal angles of triangular FEs (Fig. 1, c) from the canonical value of 60° with a minimal spread of their areas. These conditions can be formulated as

$$K = \left[\min \varphi_i\right] \cap \left[S_{\min} \le S \le S_{\max}\right], i = 1..3, \quad (3)$$

where φ_i – internal angles of triangular FE; S – FE's area; $S_{\min}$, $S_{\max}$ – restrictions on the spread of the FEs areas. Then the optimal grid will be the FEs grid, each element of which is formed by the maximum K criterion condition within the given sample of node points. Thus, the possibility of optimizing the FEs grid is due to the presence of a sufficiently wide sample. However, traditional combinational or generational approaches impose significant limitations in this sense [31]. The first of them practically does not allow for any variations. And the second, being a locally deterministic procedure, does not guarantee the convergence of the grid to a given region on a complicated surface.

Therefore, a synthetic approach is proposed, the essence of which is the design of an isoparametric lattice covering the whole region on which an excess amount of points that belong to a given surface is formed using spline approximation. The triangular FEs (are optimal in the sense of the formulated criterion K) are formed on this set of points. Such algorithm is a globally deterministic procedure that performs local optimization of grid parameters of the FEs, and can be implemented as software.

Thus, the proposed in [5,24] approach for computing CD based on the Laplace equation can be described in several stages of determining the basic patches' geometric parameters. Each stage, in turn, consists of certain actions, some of which are separate applied geometric problems that can be used as a fully prepared mathematical apparatus for solving problems related to the field theory when processing continuous streams of input data of sufficiently large dimension. So, it is expedient to carry out the statement of the essence of such processing in the form of an algorithm that is convenient for next modeling.

Stage 1. Specification of the source data for the patch's configuration. It is first necessary to specify the contour of the working FS on which the calculations are made to compute the CDs and created CFs. For this, the number of arcs M (in the general case, of different curvatures) constituting the contour of the boundary of the patch (not less than 2, M is an integer) is given. Then give the coordinates ($X_{ip,j}$, $Y_{ip,j}$) of initial point of the next arc, coinciding with the coordinates of the end point of the previous arc ($X_{ep,j\text{-}1}$,$Y_{ep,j\text{-}1}$), where j – arc number of the arbitrary number of arcs *M*. After that by specifying the curvature radii of the arcs $R_{c,j}$ we introduce the restriction: $R_{c,j}$ must be at least half the length l_j of the segment of the straight line connecting the beginning and end of the arc. If $R_{c,j} = 0{,}5l_j$ is specified then the arc will be a semicircle; if $R_{c,j} > 100l_j$ then the arc becomes a straight line segment. Moreover, the positive value $R_{c,j}$ indicates that when passing this arc (motion from the initial to the end point) the point of the center of curvature is situated on the right. So, the negative value of $R_{c,j}$ indicates that when passing this arc (motion from the initial to the end point) the point of the center of the curvature is situated on the left.

Stage 2. Coordinates calculation of the arcs' centers of curvature, sector angles, directions of the chord and the normal of the corresponding arcs. We calculate the coordinates ($X_{cc,j}$,$Y_{cc,j}$) of the arcs' centers of curvature and the sector angles γ_j corresponding to each of them by using Fig. 2, which shows the coordinate plane with one arc as a separate part of the entire contour. Main designations at Fig. 2 are *IP* – initial point, *EP* – end point, *CC* – center of circle, *CP* – central point of the arc's chord, α – angle of the arc chord inclination to the vertical, β – angle of the arc chord inclination to the horizontal.

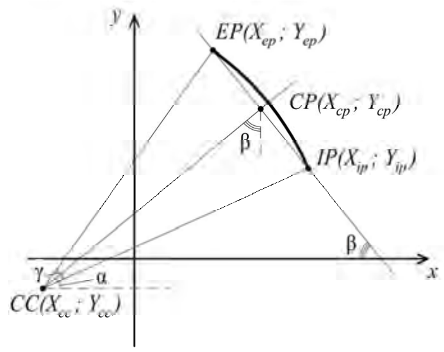


Fig. 2. Scheme for determining the main geometric parameters of the created by CD CF localization patches (for the first quadrant of the coordinate plane)

Initially, the coordinates of the point *CP* (X_{cp}; Y_{cp}) are calculated as the half-sum of each corresponding coordinate [35]. Half of the $\widehat{IPEP}$ arc chord length is obtained from the formula for determining the length of the segment denoted by l_c. Then the height of an isosceles triangle h_c formed by a chord and two radii R_c drawn from the common center of curvature of the arc to its ends *IP* and *EP*, it is also the bisector of the sector angle γ

$$h_c = \sqrt{R_c^2 - l_c^2}\ , \tag{4}$$

$$\gamma = 2\mathrm{arctg}\left(l_c / h_c\right). \tag{5}$$

The angle of the $\widehat{IPEP}$ arc chord inclination to the horizontal and it is the angle of inclination of the bisector of the sector angle γ to the vertical

$$\beta = \mathrm{arctg}\left|\frac{Y_{ep} - Y_{ip}}{X_{ep} - X_{ip}}\right| = \mathrm{arctg}\left|\frac{\Delta Y_{ipep}}{\Delta X_{ipep}}\right|. \tag{6}$$

Similarly, the angle of inclination of the arc chord to the vertical, and for the bisector of the sector angle γ – to the horizontal

$$\alpha = \mathrm{arctg}\left|\frac{X_{ep} - X_{ip}}{Y_{ep} - Y_{ip}}\right| = \mathrm{arctg}\left|\frac{\Delta X_{ipep}}{\Delta Y_{ipep}}\right|. \tag{7}$$

Note here that the determination of the angles α and β from (6) and (7) is valid in the case of the location of the arc in the first quadrant (Fig. 2). Features of the calculation for the other cases are making some changes in the determination of the direction of the normal and the chord of the any arc, which are taking into account by the following equations for α_{rez} and β_{rez}

$$\beta_{rez} = \begin{cases} \beta, \text{ if } \Delta X_{ipep} > 0 \cap \Delta Y_{ipep} > 0 \\ \pi - \beta, \text{ if } \Delta X_{ipep} < 0 \cap \Delta Y_{ipep} > 0 \\ -\pi + \beta, \text{ if } \Delta X_{ipep} < 0 \cap \Delta Y_{ipep} < 0 \\ -\beta, \text{ if } \Delta X_{ipep} > 0 \cap \Delta Y_{ipep} < 0 \end{cases}, \tag{8}$$

$$\alpha_{rez} = \begin{cases} \alpha, \text{ if } \Delta X_{cccp} > 0 \cap \Delta Y_{cccp} > 0 \\ \pi - \alpha, \text{ if } \Delta X_{cccp} < 0 \cap \Delta Y_{cccp} > 0 \\ -\pi + \alpha, \text{ if } \Delta X_{cccp} < 0 \cap \Delta Y_{cccp} < 0 \\ -\alpha, \text{ if } \Delta X_{cccp} > 0 \cap \Delta Y_{cccp} < 0 \end{cases}, \tag{9}$$

where $\Delta X_{cccp} = X_{cp} - X_{cc}$, $\Delta Y_{cccp} = Y_{cp} - Y_{cc}$ (according to Fig. 2). Analogous equations determine the angles α_{ip} and α_{ep} – the directions from the point of the center of arc's curvature to the initial and end points, respectively.

Further the coordinates of the point *CC* are determined taking into account the position of the arc on the coordinate plane and its curvature:

$$\text{if } R_c < 0 \Rightarrow \\ \Rightarrow X_{cc} = X_{cp} - h_c \sin\beta_{rez};\ Y_{cc} = Y_{cp} + h_c \cos\beta_{rez}, \tag{10}$$

$$\text{if } R_c > 0 \Rightarrow \\ \Rightarrow X_{cc} = X_{cp} + h_c \sin\beta_{rez};\ Y_{cc} = Y_{cp} - h_c \cos\beta_{rez}. \tag{11}$$

The lengths of each of the arcs l_j [35] and the total length of the contour $L = \Sigma l_j$ are calculated at the end of the second stage.

Stage 3.Calculation of the parameters of finite elements. The number of elementary sections m_j, into which each arc is divided, is set so that the $\Delta l_j = l_j/m_j \approx \Sigma l_j/\Sigma m_j = L/M$ ratio is approximately maintained. Then the sector angles for each elementary arc $\Delta\gamma_j = \gamma_j/m_j$ and the corresponding lengths of the elementary arc FEs as $\Delta l_j = l_j/m_j$ are calculated. So, chord length of elementary arc

$$\Delta l_{ch,j} = 2R_c \sin \Delta\gamma_j / 2. \tag{12}$$

Next, we calculate the angles of the direction of the normal $\overrightarrow{n_{j,i}}$ to the elementary arc at the midpoint $\alpha_{j,i}$ and the slope angles of the elementary arc chord to the X-axis $\beta_{j,i}$ in a similar manner, as in (6) – (9). Then the coordinates of the node points ($x_{j,i}$, $y_{j,i}$) of the partition of the j-th arc into FEs and collocation points ($\xi_{j,i}$, $\eta_{j,i}$) are calculated as

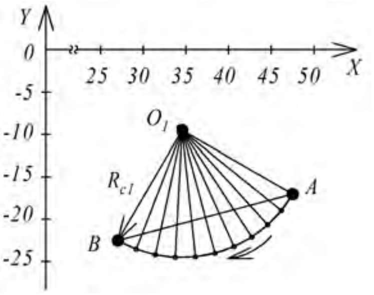
$$\begin{aligned} &\text{if } R_c < 0 \Rightarrow \begin{cases} x_{j,i} = x_{cc,j} + \left|R_{c,j}\right| \cos\left(\alpha_{ip,j} + i\Delta\gamma_j\right) \\ y_{j,i} = y_{cc,j} + \left|R_{c,j}\right| \sin\left(\alpha_{ip,j} + i\Delta\gamma_j\right) \end{cases} \\ &\text{if } R_c > 0 \Rightarrow \begin{cases} x_{j,i} = x_{cc,j} + \left|R_{c,j}\right| \cos\left(\alpha_{ip,j} - i\Delta\gamma_j\right) \\ y_{j,i} = y_{cc,j} + \left|R_{c,j}\right| \sin\left(\alpha_{ip,j} - i\Delta\gamma_j\right) \end{cases} \end{aligned}, \quad (13)$$

$$\begin{cases} \xi_{j,i} = x_{cc,j} + \left|R_{c,j}\right| \cos\alpha_{j,i} \\ \eta_{j,i} = y_{cc,j} + \left|R_{c,j}\right| \sin\alpha_{j,i} \end{cases}. \quad (14)$$

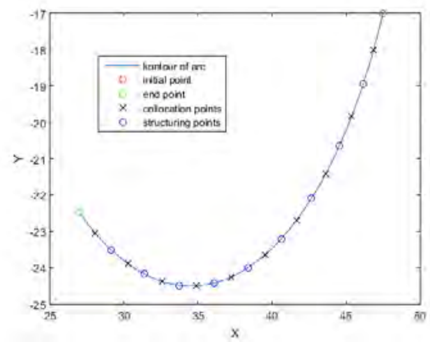
In addition, at the end of the geometric calculations, the relation $\Sigma l_{j,i}/\Sigma m_j = L/M$ is checked, which shows the accuracy of determining the arc length of the elementary part by the actual angle $\Delta\gamma_j$ and the radius of curvature R_c.

IV. Modeling the Main Stages of the Algorithm and Checking the Accuracy of the Received Results

The developed in Section III algorithm was translated into program code and modeled for the given values of the initial and end points of the arc, the radius of its curvature and the number of the partitions. Fig. 3, a shows the given curve and its partitions, which obtained by a computer program for designing drawings. Moreover, A(47.500000;-17.009619) – initial point (the beginning of the arc); B(27.009619;-22.500000) – end point (end of arc); R_1 = 15.000000 (R_1 > 0 – the center of curvature is on the right when passing the arc from the initial to the end point). The simulation results of the proposed approach application are presented in Fig. 3, b.



a



b

Fig. 3. Checking the proposed approach to determining the basic geometric parameters of one arc of the CF localization patch: a – a given arc, b – the results of computer simulation.

Fig. 3 shows good performance of the algorithm for solving the assigned tasks and its suitability for CF computing and control by embedded tools. The accuracy analysis of the one arc individual geometric parameters determination of the CF localization patch shows the high correspondence of the obtained results with the given values. For example, the given value of the parameter α is -1,30899693899575, and it turned out that the calculations -1,30899694088797; for α_{ip} -0,523598775598299 and -0,523598780767938; for $\beta_{1,1}$ -2,17293491873294 and -2,17293492357484 respectively (the worst cases of the obtained results are indicated). So, the computing error is less than 10^{-5} per cent.

V. Conclusions

The main features of electromagnetic interaction between the clamping electromagnetic driver and FS interaction are considered for robotic, industry and services applications. The main attention is paid to **c**omputing of geometrical parameters of CF localization patches by proposed combination-generation method as finite element method better modification.

Simulation results of computing of CF localization patches geometrical parameters by proposed combined method evidently show its high accuracy, which proves the adequacy of the developed algorithm for computing the main geometrical parameters of force localization patches. So, the method can be successfully used for practical implementation of the sensors system based on Hall transducers' data stream computing at CFs calculation [5]. However, developed in [5] CF control system strongly requires data stream processing from the sensors for indirect CF determination by field theory means. So, proposed in present paper method is practically applicable for integration equations solving in sources interaction method and another applications though some refinements in the way of computational complexity reduction yet may be accomplished.

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