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CALCULATION OF THREE-DIMENSIONAL FIELDS IN TASKS OF DEFECTOSCOPY

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Summary: The mathematical models of magnetic field, which allow to determine. leakage field of defects considering of a presenting the researched domain ferromagnetic cores of the magnetically sensitive element are considered in article. The models allow to execute numeral calculation of an electromagnetic field in cores created by both the field of a defect, and the field excitation. The calculation allows to receive datas for the rational arrangement of ferromagnetic cores, and also to determine the transformation function of the magnetically sensitive element.

Key words: magnetic field, field of defect, defectoscopy.

INTRODUCTION

In defectoscopy the solution of field tasks of calculation of leakage field of defects, forming of a field in cores of magnetic systems etc. is the basic condition of creation of highly effective inspection systems. The task of calculation of a magnetostaticfield can be divided into three stages. At the first stage the mathematical formulation of a problem based on the Maxwell's equation is developed and reduced to getting the integral or differential equations for a considered boundary problem. At the second stage the simplifications and assumptions in distribution of fields and sources in considered domains are entered. The third stage is devoted to getting of numerical results.

According to the modern publications devoted to problems of the numeral solution of magnetostatics tasks, three methods are the most common: finite difference method (FDM), finite element method (FEM) and integral equation method (IEM).

In FDM the problem is initially formulated as differential equations in partial derivatives [Demirchan K.S., Chechyrin V.L., 1986; Il’in V.P., 1985; Marchyk G.I., 1980; Samarskiy A.A., 1971]. In the researched domain a quantity of discrete points associated with the set — grid, and functions of continuous argument associated with functions, determined on a grid. For each mesh point differential difference equation associated with differential is written approximately, which consideration of boundary conditions, make system of the algebraic equations.

The theory FEM for the solution of the elliptic equations is expound in works [Zenkevich O., Morgan K., 1986; Sil'vester P. Ferrari R., 1986; Streng G. Fix J., 1977; Norri D., de Friz J., 1981]. This method is reduced to research of global function representing the considered phenomenon in all points of analyzed domain. The whole domain is divided into final adjacent subareas (final elements), the sought global function is drawing in parts on each of these elements.

The main drawback of FEM and FDM is the necessity to limit the calculated domain which leads to more calculation errors. The error of results of calculation by these methods can be determined by realization of repeated calculation with increased number of elements.

Recently IEM based on the theory of the potential of surface or volumetric distribution of field sources has been used widely [Grinberg G.A., 1962; Aleksandrov G.A., Fillipov E.S., 1983; Tozoni O.V., 1975]. Transition from differential equations of the electromagnetic field to integral equations is done by the Green function. Characteristic in IEM is the existence of the large variety of the integrated equations, differed on properties of solution and of the forms of writting. Therefore the search of economic mathematical models and constructions of effective computing algorithms of the solution of the integrated equations is rather urgent. The analysis of the references on IEM shows, that its using is most expedient to calculation of three-dimensional fields.

OBJECTS AND PROBLEMS

The magnetic field in homogeneous anisotropic environment is created by distribution of direct currents with density $\vec{\delta}$, located in domain V_i, limited surface S. The vector of inductance $\vec{B}$ and the field vector $\vec{H}$ submit to the equations

$$\mathrm{rot}\vec{H} = \vec{\delta} \tag{1}$$

$$\mathrm{div}\vec{B} = 0 \tag{2}$$

in domain V_i and to the equations

$$\mathrm{rot}\vec{H} = 0 \tag{3}$$

$$\mathrm{div}\vec{B} = 0 \tag{4}$$

in unlimited domain V_e, which is external in relation to V_i. Choosing the Cartesian system of coordinates, where datum lines x, y, z are parallel to the main lines of tensor of absolute permeability $\tilde{\mu}_a = \mu_0 \mu_{ij}$, and let $\tilde{\mu}_a$ a diagonal tensor of relative permeability, and μ_x, μ_y, μ_z to be its diagonal components (other components are equal to zero). Then

$$\vec{B} = \vec{i}\,\mu_0 \mu_x H_x + \vec{j}\,\mu_0 \mu_y H_y + \vec{k}\,\mu_0 \mu_z H_z\,. \tag{5}$$

Put vector potential by means of a correlation $\vec{B} = \mathrm{rot}\vec{A}$. Granting that $\vec{H} = \dfrac{\vec{B}}{\tilde{\mu}_a}$ is from (1) and we get the equation relative to $\vec{A}$

$$\mathrm{rot}\frac{1}{\tilde{\mu}_a}\mathrm{rot}\vec{A} = \mu_0\vec{\delta}\ . \qquad (6)$$

Having entered new expression for vector potential $\vec{A}_1 = \tilde{\mu}\vec{A}$, assume $\mathrm{div}\vec{A}_1 = 0$. (That the given condition can be really executed as it is established below). Then, after replacement variables $x = \sqrt{\mu_x}\, x_1$, $y = \sqrt{\mu_y}\, y_1$, $z = \sqrt{\mu_z}\, z_1$, the equation (6) can be written down as one vector Poisson's equation

$$\frac{\partial^2 \vec{A}_1}{\partial x_1^2} + \frac{\partial^2 \vec{A}_1}{\partial y_1^2} + \frac{\partial^2 \vec{A}_1}{\partial z_1^2} = -\mu_0\mu_x\mu_y\mu_z\vec{\delta}\ . \qquad (7)$$

The solution of the given equation can be written down as

$$\vec{A}_{1q} = \mu_0\mu_x\mu_y\mu_z\frac{1}{4\pi}\int_{V_{1q}}\vec{\delta}_{1q}\frac{dV_{1q}}{R_1}\ . \qquad (8)$$

Passing to original coordinates x, y, z and function $\vec{A}$, we receive for it the following expression

$$\vec{A}_q = \mu_0\sqrt{\mu_x\mu_y\mu_z}\frac{1}{4\pi\tilde{\mu}}\int_{V_i}\vec{\delta}_p\frac{dV_p}{R_a}\ , \qquad (9)$$

where:

$$R_a = \sqrt{\frac{\left(x_q - x_p\right)^2}{\mu_x} + \frac{\left(y_q - y_p\right)^2}{\mu_y} + \frac{\left(z_q - z_p\right)^2}{\mu_z}}\ . \qquad (10)$$

Granting that $\vec{A}_1 = \tilde{\mu}\vec{A}$, it is easy to notice, that a condition $\mathrm{div}\vec{A}_1 = 0$, with the help of which (6) received (7) is carried out, if

$$\mathrm{div}_q\int_{V_i}\vec{\delta}_p\frac{dV_p}{R_a} = 0\ . \qquad (11)$$

If $\mathrm{div}\,\vec{\delta} = \sqrt{a^2 + b^2}$ in volume V_i, that follows from the equation (1), then the equality (11) will be identity at anyone differentiable function, put on a place R_a^{-1} [Tamm I.E., 1976]. Thus, the formula (9) really gives the solution of the equation (6), through which vectors $\vec{B}$ and $\vec{H}$ can be evaluated in equations (1) — (4). In particular for the field vector $\vec{H} = \dfrac{\mathrm{rot}\vec{A}}{\tilde{\mu}_a}$ we receive the formula

$$\vec{H}_q = \frac{1}{4\pi\sqrt{\mu_x\mu_y\mu_z}} \int\limits_{V_i} \frac{\left[\vec{\delta}_p, \ \vec{r}\right]}{R_a^3} dV_p \, , \tag{12}$$

where: $\vec{r} = \vec{i}\left(x_q - x_p\right) + \vec{j}\left(y_q - y_p\right) + \vec{k}\left(z_q - z_p\right)$; and the function R_a is determined by the formula (10). For a linear current with force I in the closed circuit *l* the formula (12) becomes

$$\vec{H}_q = \frac{1}{4\pi\sqrt{\mu_x\mu_y\mu_z}} \oint\limits_{l} \frac{\left[d\vec{l}_p, \ \vec{r}\right]}{R_a^3} dV_p \, . \tag{13}$$

This formula evaluates the Biot-Savart-Laplace law for homogeneous anisotropic environment.

There is the formula similar to (9) that will be used in construction of the integral equations:

$$\vec{A}_q = \mu_0\sqrt{\mu_x\mu_y\mu_z}\,\frac{1}{4\pi\tilde{\mu}} \oint\limits_{S} \vec{i}_p \frac{dS_p}{R_a} dV_p \, , \tag{14}$$

where $\vec{i}_p$ is density of superficial currents.

The exceptional vector potential also needs the scalar potential for calculation of a magnetic field in piecewise homogeneous anisotropic environment. The differential equation for it, is got out from the equations (3) and (4):

$$\mu_x \frac{\partial^2\varphi}{\partial x^2} + \mu_y \frac{\partial^2\varphi}{\partial y^2} + \mu_z \frac{\partial^2\varphi}{\partial z^2} = 0 \, . \tag{15}$$

The fundamental solution of the given equation is the function R_a^{-1}, where R_a is determined by the formula (10). Considering, that in some domain of anisotropic environment V the volumetric magnetic charges with density ρ are located, doing the same as at a formula construction (9), it is possible to find:

$$\varphi_q = \frac{1}{4\pi\sqrt{\mu_x\mu_y\mu_z}} \int\limits_{V} \rho_p \frac{dV_p}{R_a}$$

— and the similar expression for potential of a simple layer of charges distributed on a surface S:

$$\varphi_q = \frac{1}{4\pi\sqrt{\mu_x\mu_y\mu_z}} \oint\limits_{S} \sigma_p \frac{dS_p}{R_a} \tag{16}$$

Nothing, that potential (16) satisfies equation (15) everywhere outside of S.

Considering nowadays the technique of the construction of the integral equations, we use the following model problem. The constant currents with given density $\vec{\sigma}_0$ are located in unlimited domain V_e of anisotropic environment with diagonal tensor of magnetic permeability $\tilde{\mu}_{ae} = \mu_0\tilde{\mu}_e$ (fig. 1).

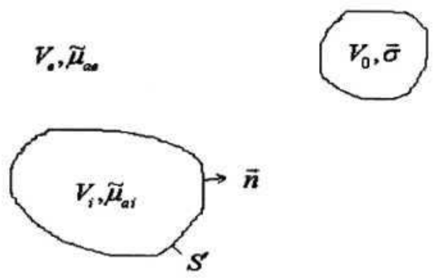

Fig.1.

The internal limited domain V_i is also filled with anisotropic environment with the diagonal tensor of magnetic permeability $\tilde{\mu}_{ai} = \mu_0 \tilde{\mu}_i$ ($\tilde{\mu}_i \neq \tilde{\mu}_e$). The constant currents are located in domain $V_0 \in V_e$. The vectors $\vec{H}_i$, $\vec{H}_e$ of a secondary field caused by secondary sources S, should submit to the equations: $\vec{H}_e$ — equation (1) in domain V_0 and equation (3) in domain $V_e - V_0$; a vector $\vec{H}_i$ — equation (3) in domain V_i. The vector $\vec{B}$ should satisfy with the equation (2) in all space, excluding S.

On environment interface the conditions of a continuity tangential components of making complete field vectors should be carried out: $\vec{H}'_i = \vec{H}_i + \vec{H}_{0i}$, $\vec{H}'_e = \vec{H}_e + \vec{H}_{0e}$. The vector $\vec{H}_{0i}$ of a field of the given currents is determined only in domain V_i on conditions that all space is filled of homogeneous anisotropic environment with tensor $\tilde{\mu}_{ai}$, similarly the vector $\vec{H}_{0e}$ is determined only in domain V_e on conditions that all space is filled of homogeneous anisotropic environment with tensor $\tilde{\mu}_{ae}$. According to the given representation of an external field, tangential components of vectors of a secondary field should submit to a boundary condition

$$\left[\vec{n}, \vec{H}_e - \vec{H}_i\right] = \left[\vec{n}, \vec{H}_{0i} - \vec{H}_{0e}\right]. \tag{17}$$

Besides on a surface S the normal components of the induction of a complete field $\vec{B}'_i$, $\vec{B}'_e$ should be continuous. It will give one more boundary condition

$$\left(\vec{n}, \tilde{\mu}_e \vec{H}_e - \tilde{\mu}_i \vec{H}_i\right) = \left(\vec{n}, \tilde{\mu}_i \vec{H}_{0i} - \tilde{\mu}_e \vec{H}_{0e}\right). \tag{18}$$

To construction of the integral equations in the given task it is necessary to apply the domain separated method, according to which the domains V_i, V_e, the special representations for field vectors $\vec{H}_i$, $\vec{H}_e$ should used. In domain V_e a sought vector we shall present as $\vec{H} = \mathrm{rot}\vec{A}_e$, where $\vec{A}_e$ we shall determine by the formula (14). In result

$$\vec{H}_{iq} = \frac{1}{4\pi m_e} \oint_S \frac{\left[i_p,\ r_e\right]}{R_{ae}^3} dS_p, \tag{19}$$

where: $m_e = \sqrt{\mu_x \mu_y \mu_z}$; R_{ae} is determined by the formula (10) at $\mu_x = \mu_{xe}$, $\mu_y = \mu_{ye}$, $\mu_z = \mu_{ze}$, $x = x_e$, $y = y_e$, $z = z_e$.

In domain V_i vector $\vec{H}_i$ is determined as gradient of potential (16):

$$\vec{H}_{iq} = \frac{1}{4\pi\tilde{\mu}_i m_i} \oint_S \sigma_p \frac{\vec{r}}{R_{ai}^3} dS_p , \tag{20}$$

where: $m_i = \sqrt{\mu_x \mu_y \mu_z}$; R_{ai} is determined by the formula (10) at $\mu_x = \mu_{xei}$, $\mu_y = \mu_{yi}$, $\mu_z = \mu_{zi}$, $x = x_i$, $y = y_i$, $z = z_i$.

In expressions (19), (20) vectors $\vec{H}_i$, $\vec{H}_e$ are determined outside of S. To use boundary conditions (17), (18), it is necessary to find limiting value of expressions $\left[\vec{n},\vec{H}_e\right]$, $\left[\vec{n},\vec{H}_i\right]$, $\left(\vec{n},\tilde{\mu}_e \vec{H}_e\right)$, $\left(\vec{n},\tilde{\mu}_i \vec{H}_i\right)$ on a surface S. Considering that the point q is normal to a surface S in domain V_e (outside of S). According to it S as a Lyapinov surface [4], we shall take up expression

$$\left[\vec{n}_q,\vec{H}_{eq}\right] = \frac{1}{4\pi m_e} \oint_S \frac{\left[\vec{n}_q\left[\vec{i}_p, \ \vec{r}_e\right]\right]}{R_{ae}^3} dS_p . \tag{21}$$

Using the formula $\left[\vec{a}\left[\vec{b},\vec{c}\right]\right] = \vec{b}(\vec{a},\vec{c}) - \vec{c}(\vec{a},\vec{b})$, where $\vec{a},\vec{b},\vec{c}$ are an arbitrary vectors, reduce (21) to assume:

$$\left[\vec{n}_q,\vec{H}_{eq}\right] = \frac{1}{4\pi m_e} \oint_S \vec{i}_p \frac{\left(\vec{n}_q,\vec{r}_e\right)}{R_{ae}^3} dS_p - \frac{1}{4\pi m_e} \oint_S \vec{r}_e \frac{\left(\vec{n}_q,\vec{i}_p\right)}{R_{ae}^3} dS_p . \tag{22}$$

In this expression at $q \in S$ the second part is improper integral, that is possible to show with the help of the theory of potential [Gunter N.M., 1953]. In the first part we shall make replacement of variables: $x_1 = \frac{x_e}{\sqrt{\mu_{xe}}}$, $y_1 = \frac{y_e}{\sqrt{\mu_{ye}}}$, $z_1 = \frac{z_e}{\sqrt{\mu_{ze}}}$, with the result that it looks like

$$\frac{1}{4\pi} \oint_{S_1} \vec{i}_{1p} \frac{\left(\vec{n}_{1q},\vec{R}_1\right)}{R_1^3} dS_{p1} ,$$

where: index "1" indicate on using coordinates x_1, y_1, z_1; and $R_1 = \sqrt{\left(x_{1q} - x_{1p}\right)^2 + \left(y_{1q} - y_{1p}\right)^2 + \left(z_{1q} - z_{1p}\right)^2}$. This expression is normal derivative of potential of a simple layer with density $\vec{i}_{1p}$. Its limiting value on S is known [Gunter N.M., 1953]:

$$\frac{1}{4\pi}\oint_{S_1}\vec{i}_{1p}\frac{\left(\vec{n}_{1q},\vec{R}_1\right)}{R_1^3}dS_{p1}\Bigg|_{q\to S_1}=\frac{\vec{i}_{1q}}{2}+\frac{1}{4\pi}\oint_{S_1}\vec{i}_{1p}\frac{\left(\vec{n}_{1q},\vec{R}_1\right)}{R_1^3}dS_p\,. \quad (23)$$

Coming back to variables x_e, y_e, z_e and substituting the received expressions in (22), we shall receive, that on S:

$$\left[\vec{n}_q,\vec{H}_{eq}\right]=\frac{\vec{i}_{1q}}{2}+\frac{1}{4\pi m_e}\oint_S\frac{\left[\vec{n}_q\left[\vec{i}_p,\ \ \vec{r}_e\right]\right]}{R_{ae}^3}dS_p\,. \quad (24)$$

The limit of expression $\left[\vec{n},\vec{H}_i\right]$ on a surface S, where the vector $\vec{H}_i$ is submitted by the formula (20), is singular integral existing as the principal value [Mixlin S.G., 1977]. In result, substituting the received expressions for $\left[\vec{n},\vec{H}_i\right]$, $\left[\vec{n},\vec{H}_e\right]$ in boundary conditions (17), we receive first of the sought integral equations:

$$\vec{i}_q+\frac{1}{2\pi m_e}\oint_S\frac{\left[\vec{n}_q\left[\vec{i}_p,\ \ \vec{r}_e\right]\right]}{R_{ae}^3}dS_p-\frac{1}{2\pi\tilde{\mu}_e m_i}\oint_S\sigma_p\frac{\left[\vec{n}_q,\vec{r}_e\right]}{R_{ai}^3}dS_p=2\left[\vec{n}_q,\vec{H}_{0iq}-\vec{H}_{0eq}\right] \quad (25)$$

For construction of the second integral equation it is necessary to calculate limiting value on S with the expression $\left(\vec{n},\tilde{\mu}_i\vec{H}_i\right)$, where $\vec{H}_i$ is determined by the formula (20). Doing the same as at a formula construction (23), we shall receive, that on S

$$\left(\vec{n},\tilde{\mu}_i\vec{H}_i\right)=-\frac{\sigma_p}{2}+\frac{1}{4\pi m_i}\oint_S\sigma_p\frac{\left(\vec{n}_q,\vec{r}_i\right)}{R_{ai}^3}dS_p\,. \quad (26)$$

The limit of expression $\left(\vec{n},\tilde{\mu}_e\vec{H}_e\right)$ on a surface S, where the vector $\vec{H}_e$ is submitted by the formula (19), is singular integral. In result, substituting $\left(\vec{n},\tilde{\mu}_i\vec{H}_i\right)$ and (24) in boundary conditions (18), we receive second of the sought integral equations:

$$\sigma_p+\frac{1}{2\pi m_i}\oint_S\sigma_p\left[\frac{\left(\vec{n}_q,\vec{r}_i\right)}{R_{ai}^3}-k_1\right]dS_p+\frac{1}{2\pi m_e}\oint_S\frac{\left(\vec{n}_q\,\tilde{\mu}_i\left[\vec{i}_p,\ \ \vec{r}_e\right]\right)}{R_{ae}^3}dS_p=2\left(\vec{n}_q,\tilde{\mu}_i\vec{H}_{0i}-\tilde{\mu}_e\vec{H}_{0e}\right). \quad (27)$$

The equations (25), (27) form sought system of integral equations are for the solution of the following model problem. The constant k_1 is added to a nucleus of first integral that is equivalent to execution of a condition

$$\oint_S\sigma_p\,dS_p=0\,, \quad (28)$$

which is necessary for unique system solution (25), (27).

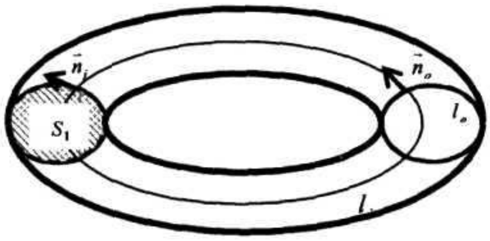

Fig. 2.

If the sources of an external field are located in area V_i, the sought system of the equations can be constructed on the same way. In area V_i tensity of a secondary field is determined as $\vec{H} = \dfrac{\mathrm{rot}\vec{A}}{\tilde{\mu}_a}$, where:

$$\vec{A}_i = \frac{1}{4\pi\tilde{\mu}_{ae} m_i} \oint_S \vec{i}_p \frac{dS_p}{R_{ai}}$$

There is this area V_e $\vec{H}_e = -\nabla\varphi_e$, where:

$$\varphi_e = \frac{1}{4\pi m_e} \oint_S \sigma_p \frac{dS_p}{R_{ae}}$$

The formulas for defined values $\left[\vec{n},\vec{H}_i\right]$ and $\left(\vec{n},\tilde{\mu}_e \vec{H}_e\right)$ on S are

$$\left[\vec{n},\vec{H}_i\right] = -\frac{i_q}{2} + \frac{1}{4\pi m_i} \oint_S \frac{\left[\vec{n}_q\left[\vec{i}_p, \quad \vec{r}_i\right]\right]}{R_{ai}^3} dS_p \tag{29}$$

$$\left(\vec{n},\tilde{\mu}_{ae} \vec{H}_e\right) = -\frac{\sigma_p}{2} + \frac{1}{4\pi m_e} \oint_S \sigma_p \frac{\left(\vec{n}_q,\vec{r}_e\right)}{R_{ae}^3} dS_p \tag{30}$$

After substitution of expressions for $\vec{H}_0$, $\vec{H}_e$ in boundary conditions (17), (18) and using the correlations (29), (30) the following system of the equations similar on structure to system (25), (27) will turn out:

$$\vec{i}_q + \frac{1}{2\pi m_i} \oint_S \frac{\left[\vec{n}_q\left[\vec{i}_p, \quad \vec{r}_i\right]\right]}{R_{ai}^3} dS_p + \frac{1}{2\pi\tilde{\mu}_{ae} m_e} \oint_S \sigma_p \frac{\left[\vec{n}_q,\vec{r}_e\right]}{R_{ae}^3} dS_p = 2 \quad \left[\vec{n}_q,\vec{H}_{0i}-\vec{H}_{0e}\right] \tag{31}$$

$$\sigma_p + \frac{1}{2\pi m_e} \oint_S \sigma_p \frac{\left(\vec{n}_q,\vec{r}_e\right)}{R_{ae}^3} dS_p + \frac{1}{2\pi\tilde{\mu}_{ai} m_e} \oint_S \frac{\left(\vec{n}_q\left[\vec{i}_p, \quad \vec{r}_i\right]\right)}{R_{ai}^3} dS_p = 2\left(\vec{n}_q,\vec{H}_{0i}-\vec{H}_{0e}\right) \tag{32}$$

This system has the unique solution, if area V_i is one connected system. The integrated operator rather σ in the second equation does not need updating, as the integrated equation of an external Neumann's problem has the unique solution. If the area V_i is biconnected and limited by surface of a toroidal type, it is necessary to use an additional condition as

$$\oint_{l_e} \left(\vec{i}, \vec{n}_e\right) dl = 0,$$

where: l_e is closed circuit laying on the external part of S; $\vec{n}_e$ is the unit vector of normal to l_e, laying in a flatness, which is tangent to S (fig. 2). The given condition provides equality to zero of circulation of a vector $\vec{H}_e$ on any circuit covering the surface S. After multiplication on $k_1\vec{n}_e$ it should be added to the equation (31), that will supply the unique system solution of (31), (32).

CONCLUSIONS

The offered technique of construction of the integrated equations allows to calculated leakage fields of defect considering of a presenting the researched domain ferromagnetic cores of the magnetically sensitive element. As the cores deform a field of defect and they are sources of an electromagnetic field, so exact definition of size of a field of defect necessary for the subsequent definition of the size of defect, needs the joint solution of system of the equations describing as a field of the core, as a field of defect on a surface of test object.

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РАСЧЕТ ТРЕХМЕРНЫХ МАГНИТНЫХ ПОЛЕЙ В ЗАДАЧАХ ДЕФЕКТОСКОПИИ

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Аннотация: В статье рассматриваются математические модели поля, которые позволяют определять поле рассеяния дефекта с учетом нахождения в расчетной области ферромагнитных сердечников магниточувствительных элементов. Модели позволяют выполнять численное вычисление электромагнитного поля в элементах, созданных как областью дефекта, так и полем возбуждением. Вычисления позволяют получать данные для рационального использования ферромагнитных сердечников, а также для определения передаточной функции магниточувствительных элементов.

Ключевые слова: магнитное поле, область дефекта, дефектоскопия.