Mathematical Modeling and Magneto-Optical Visualization of the Electromagnetic Field in the Neighborhood of Defects in Conductive Materials*

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Abstract. In the article, based on the secondary sources method, a new mathematical model of a three-dimensional quasi-stationary electromagnetic field near massive conductors containing microscopic defects has been developed. To increase the computational efficiency of the modeling process, if it is necessary to take into account the ferromagnetic core of the inductor, a modification of the double-layer method of fictitious magnetic charges is proposed. The simulation results are compared with the experimental data obtained by the method of eddy current magneto-optical flaw detection on model defects.

Keywords: Method of Secondary Sources, Eddy Currents, Magneto-Optical Flaw Detection.

1 Introduction

Magneto-optical eddy current flaw detection [1-3] is one of the most effective methods for non-destructive testing of conductive non-ferromagnetic products. This method of flaw detection allows the monitoring and processing of results in an automatic mode, as well as obtaining detailed information about the structure of the defect. Microscopic defects have a significant electromagnetic response compared to defect-free samples, which allows them to be detected. The quality of control is influenced by the phase of registration of magnetic fields, the distribution of the three-dimensional magnetic field of the inductor, and the three-dimensional magnetic field of eddy currents that are induced by the inductor in the conducting sample, as well as many other factors.

In [4], the case of excitation of eddy currents in a test object using a normal flow inductor that does not contain a ferromagnetic core was studied in detail. With the correct choice of the initial phase of the inductor current and some other parameters, magneto-optical flaw detection allows obtaining a significantly contrasting image of the sample under study with a defect. However, there are defects, the specificity of the geometry of which leads to ineffective visualization using a normal flux inductor (for example, a round hole with a small diameter in comparison with the diameter of the inductor) - this is since the vector potential created by the normal flux inductor decreases significantly when approaching coil axes. Consequently, eddy currents in this area are insignificant. Such a distribution of eddy currents does not make a significant contribution to the magnetic field. Eddy currents of significant magnitude will, in this case, be induced in an area remote from the defect. Their magnetic field will be uninformative in terms of visualizing defects. This means that non-destructive testing with a normal flow inductor has significant application limitations. Thus, it becomes necessary to control the topology of the vector potential of the external magnetic field. For example, the concentration of vector potential in the area of interest. This can be implemented using a planar flux inductor [5], in which a magnetic flux distributed almost parallel to the plane of the test object is created. This is achieved by using a magnetic core that has corresponding geometry in the planar flux inductor.

However, the need to take into account the influence of the ferromagnetic core of the planar flux inductor significantly increases the complexity of the modeling process and the resource intensity of the computational problem. In this connection, an urgent problem arises of choosing the most efficient, in terms of using computing resources, the method for modeling the magnetic field created by the inductor. According to some characteristic features, such methods include the method of secondary sources, based on the concept of a double layer of fictitious magnetic charges. However, the classical implementation of this method has one significant drawback associated with the need to calculate the scalar magnetic potential [6-8].

The purpose of this article is to develop a new modification of the double layer method of fictitious magnetic charges, which makes it possible to avoid the procedure of calculating the scalar magnetic potential and to apply this method to model the problem of eddy current flaw detection.

2 The setting of the Modeling Problem

Fig.1 schematically shows the system “planar flux inductor – conducting sample”.

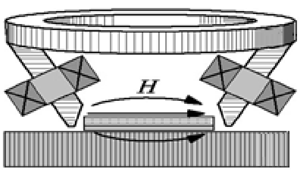

Fig. 1. Planar flux inductor and test object.

The hole in the center of the magnetic core is necessary only for reasons of magneto-optical visualization; for modeling, it is advisable to replace the “ring” magnetic core with a simpler shape. This will not affect the accuracy of the calculations, since the “ring” magnetic core is necessary to close the magnetic flux in a certain area, but the closure of the magnetic flux can also be ensured by replacing the magnetic core with an effective simplified form.

Here are the main parameters of the effective geometric shape of the inductor, which were taken for modeling purposes. The effective parallelepiped length is 70 mm, the width is 10 mm, the thickness is 11 mm, the tip length is 19.623 mm, the tip angle with XY plane is 15 degrees. The surface of the inductor and the discrete triangulation mesh are shown in Fig. 2.

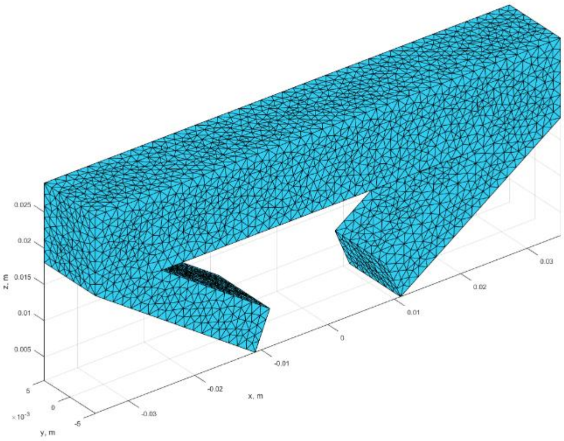

Fig. 2. Triangulation of the surface of the inductor magnetic core.

The test object, on the example of which the modeling was carried out, is three aluminum plates in the form of a parallelepiped with the following dimensions: the length (size that is transverse to the flux) is 14 mm, the width is 6 mm, and the thickness is 0.3 mm. The plates were placed parallel to each other with a gap of 40 and 20 μm, thus simulating two longitudinal slot defects. The inductor was excited by a time-periodic current at the frequency of 20 kHz.

3 Mathematical Formulation of the Problem

In this section, we present the mathematical model that allows you to fully describe the distribution of the electromagnetic field in the system "planar flux inductor – conducting sample".

The system of equations describing the distribution of secondary sources, which are a double layer of fictitious magnetic charges on the surface of the magnetic core of the inductor, can be expressed as:

$$\nu_i - \nu_k - \frac{\lambda}{2\pi}\left\{ \sum_{\substack{m=1\\ m\neq k}}^{N} \nu_m \int_{\Delta l_k^J} \boldsymbol{\tau}_{\mathbf{Q}} \int_{\Delta S_m} \mathbf{K}(P,Q)\, dS_P dl_Q + \sum_{\substack{m=1\\ m\neq i}}^{N} \nu_m \int_{\Delta l_k^U} \boldsymbol{\tau}_{\mathbf{Q}} \int_{\Delta S_m} \mathbf{K}(P,Q)\, dS_P dl_Q \right\} =$$

$$= 2\lambda \int_{\Delta l_k^J + \Delta l_k^U} \mathbf{B_0} \boldsymbol{\tau}_{\mathbf{Q}} dl_Q \,, \tag{1}$$

where ν is the density of fictitious magnetic double layer charges; $\boldsymbol{\tau}_{\mathbf{Q}}$ is vector tangent to the surface of the ferromagnet at the point $Q \in S$ (S is the surface of ferromagnet), $\mathbf{K}(P,Q) = \left[3(\mathbf{r_{PQ}}, \mathbf{n_P})\mathbf{r_{PQ}} - r_{PQ}^2 \mathbf{n_P}\right] / r_{PQ}^5$, $\lambda = (\mu - \mu_0)/(\mu + \mu_0)$, $k = 1, 2, ..., N$.

The system of equations (1) does not contain the scalar magnetic potential of free sources, and, therefore, can be directly applied to calculating the magnetic field in any multiply connected domains without introducing impenetrable partitions or solving an additional boundary value problem for finding the scalar magnetic potential.

After solving the system of equations (1) using the well-known formula for the induction of the magnetic field created by magnetic dipoles [9], the magnetic field can be calculated at any point in space.

4 Modeling Results and Comparison with Experimental Data

Fig. 3 shows the distribution of the normal component of the magnetic field strength generated near the considered sample.

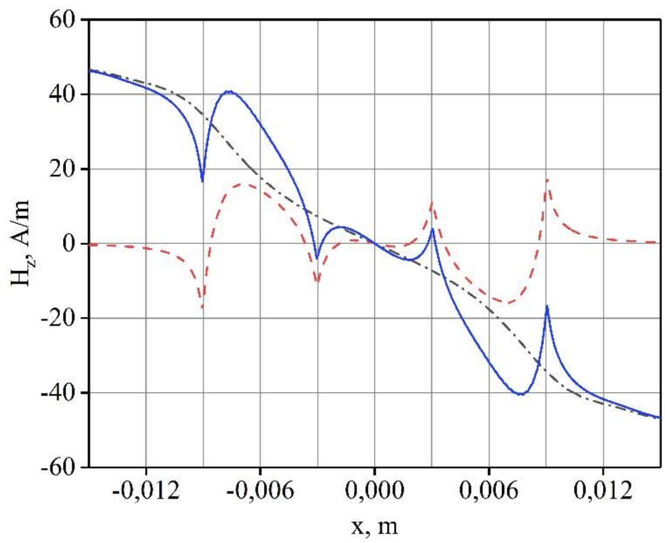

Fig. 3. The normal component of the magnetic field strength.

Fig. 3 shows the distribution of the normal component of the magnetic field strength created by the planar flux inductor (dash-dotted line), eddy currents (dashed line), and the total magnetic field of the entire system (solid line).

Fig. 4 shows a topogram of the normal component of the total magnetic field strength near the surface of the test object.

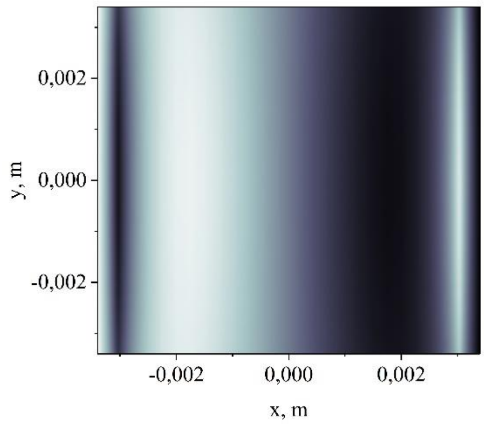

Fig. 4. Topogram of the magnetic field near the model test object obtained as a result of modeling.

Fig. 5 shows the experimental distribution of the normal component of the magnetic field near two extended-through defects with a thickness of 40 μm. This distribution was obtained by magneto-optical eddy current flaw detection at a frequency of 20 kHz using a planar flux inductor [10]. Comparison of model calculations (Fig. 4) and experimental visualization (Fig. 5) of the magnetic field distribution shows that a linear defect on both sides is surrounded by areas of the opposite color concerning the color of the defect itself. It is also seen that when passing from one defect to the second, a complete direction inversion of the normal component of the magnetic field occurs. Thus, the numerically obtained topogram of the resulting magnetic field shown in Fig. 4 is in qualitative agreement with the experimental data.

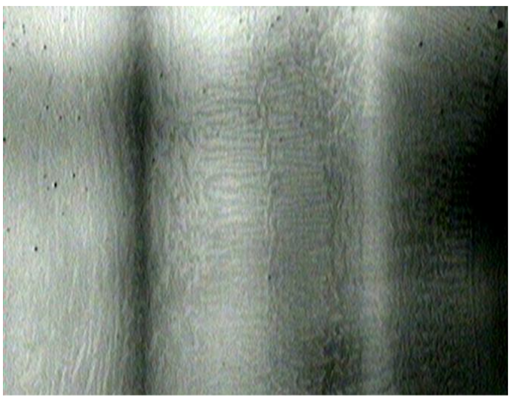

Fig. 5. Experimentally obtained the magneto-optical image of extended through defects when exciting eddy currents by a planar flux inductor.

Thus, the numerical model of the electromagnetic field of eddy currents is developed. Eddy currents are induced in a nonmagnetic conductor under the action of the field of free sources and magnetic core magnetized by the time-varying external magnetic field. From the results presented, it follows that the developed numerical model is in good agreement with the experimental data obtained by the method of eddy current magneto-optical flaw detection.

5 Conclusions

A new mathematical model of a spatially inhomogeneous magnetic field created by ferromagnetic bodies magnetized by a field of free sources is obtained. This model is based on a modified method of a double layer of fictitious magnetic charges. The proposed modification makes it possible to significantly simplify the modeling procedure since it eliminates the need to calculate the scalar magnetic potential. The simulation results are in good agreement with the experimental data obtained by eddy current magneto-optical flaw detection.

6 Acknowledgments

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