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RESEARCH ARTICLE

On the working zone of a magnetometer-electromagnet measuring device when using opposing pole pieces with flat surfaces

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Abstract

Objectives. The work set out to develop an approach for assessing the working (local) zone in magnetometer-electromagnet measuring devices designed for controlling the magnetic properties of samples in which the homogeneity of the magnetic field should be observed in terms of constancy of the field strength or induction.

Methods. The coordinate characteristics of the field strength (induction) between pole components were experimentally obtained to identify the desired working zone (in the vicinity of the minimum of each of these characteristics), taking into account the distance b between the poles and their diameter D.

Results. Data on working zones between opposing flat poles are obtained for different values b and D. With increased ratios $b/D = 0.7–1.3$, the size of the working zone concentrated in the middle axial part of the interpolar area is estimated at a value not exceeding 25–30% of the distance b such that the characteristic longitudinal size of the sample does not exceed 5–10 mm. As D increases and b/D decreases, the working area increases. In particular, at $b/D \cong 0.5$, the size of the working area is estimated to be up to 90% and even 100% of the distance b.

Conclusions. A principled approach to the assessment of the working (axial) zone between opposing flat poles is demonstrated by obtaining and analyzing the necessary coordinate (significantly dependent on b and D) characteristics of the field strength (induction) between them.

Keywords: homogeneity of the magnetic field, magnetometer-electromagnet, strength, induction, flat pole pieces

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НАУЧНАЯ СТАТЬЯ

О рабочей зоне измерительного устройства при использовании в нем противостоящих полюсов с плоскими поверхностями

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Резюме

Цели. Цель работы – восполнить пробел, касающийся подхода к оценке рабочей (локальной) зоны в измерительных устройствах – магнитометрах-электромагнитах, предназначенных для контроля магнитных свойств образцов с обеспечением в данной зоне условия однородности магнитного поля: постоянства напряженности поля или индукции.

Методы. В основе методологии достижения поставленной цели – экспериментальное получение координатных характеристик напряженности (индукции) поля между полюсами и идентификация искомой рабочей зоны (в окрестности экстремума, фактически – минимума каждой из таких характеристик) с учетом расстояния b между полюсами и их диаметра D.

Результаты. Приведены экспериментально аргументированные данные о рабочих зонах между противостоящими плоскими полюсами для разных величин b и D. Так, при повышенных отношениях $b/D = 0.7–1.3$ размер рабочей зоны, сосредоточенной в срединной приосевой части межполюсной области, оценивается величиной, не превышающей 25–30% от расстояния b. Тогда характерный продольный размер образца со сравнительно малыми поперечными размерами (при размещении образца в такой зоне) не должен превышать 5–10 мм. С увеличением диаметра D и уменьшением отношения b/D рабочая зона увеличивается. В частности, при $b/D \cong 0.5$ размер рабочей зоны оценивается величиной до 90% и даже 100% от расстояния b.

Выводы. Показан и реализован принципиальный подход к оценке рабочей (приосевой) зоны между противостоящими плоскими полюсами посредством получения и анализа необходимых для этого координатных (экстремальных по виду, существенно зависимых от расстояния между полюсами и их диаметра) характеристик напряженности (индукции) поля между ними.

Ключевые слова: однородное магнитное поле, магнитометр-электромагнит, напряженность, индукция, плоские полюсные наконечники

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INTRODUCTION

Measuring devices based on ballistic magnetometers, whose key component is a solenoid, are widely used in science and technology for measuring various parameters, including those characterizing the magnetic properties of various samples and their materials. In order to create the necessary magnetic field in the working zone of which (i.e., the zone of a homogeneous magnetic field) the sample under study should be placed [1–6], an electromagnet is also used. The shape of the pole tips for creating the corresponding magnetic field between opposing magnetic poles is selected depending on the problem to be solved [7–15].

In order to create the necessary homogeneous magnetic field for studying magnetic properties of samples, the opposing surfaces of pole tips (truncated cone, cylindrical disks [9], etc.) should be flat and mutually parallel. Here the working zone (in which the required field homogeneity is observed, i.e., practically constancy of this or that value of the field strength *H*) is not the whole interpolar area, but only its median part depending on the distance *b* between the pole planes and their diameter *D*. Otherwise it may turn out that the results of measurements carried out in different parts of the studied object will be obtained under different conditions (by *H*), leading to incorrect results. Thus, the relevant issue of determining the working zone of such a measuring device is considered in the present article.

From the standpoint of the mentioned question, the main characteristic of the field between opposing magnetic poles (flat or differently reversed) is the coordinate characteristic of the field. This parameter, which is important both in the operation and creation of measuring devices of this type, is defined by the induction data *B* (or intensity $H = B/\mu_0$, where μ_0 is a magnetic constant) obtained in the interpolar area.

EXPERIMENTAL DATA, PROCESSING AND DISCUSSION

As follows from the above, a measuring device worthy of attention (a variant of a ballistic magnetometer) is an electromagnet employing opposing pole pieces whose surfaces, facing each other, are flat and mutually parallel. The sample under study should be placed between the disk-shaped pole pieces, as shown in Fig. 1, precisely in the working zone where the generated magnetic field is practically uniform. Meanwhile, in the interpolar area of such measuring device/magnetometer, the specified condition can be ensured only with a comparatively small distance *b* between the poles, and only in the central part of the area between them (as *b* increases, the field strength *H* decreases at the periphery and increases at the poles).

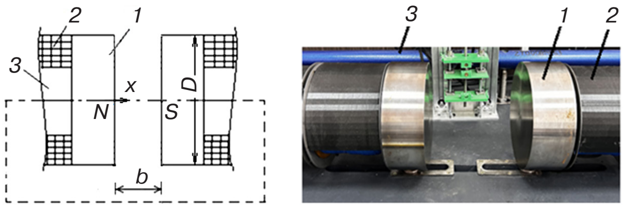

Fig. 1. Diagram and general view of a variant of the ballistic type magnetometer with pole tips-discs: (*1*) pole tip; (*2*) magnetizing coil; (*3*) magnet conductor. *N* and *S* are poles of the magnet, *x* is a direction of induction measurement

Figure 2 shows the coordinate characteristics of magnetic induction *B* obtained via a Hall sensor at a distance *x* from one of the poles along the interpolar axis [11]. For determining these characteristics, flat magnetic elements Nd–Fe–B with a diameter of *D* = 25 mm and a thickness of 10 mm were used. To determine characteristics analogous those depicted in Fig. 2, it is sufficient to experimentally obtain one of the symmetric branches of any of them [11]. The obtained values of *b* (increased compared to *D*) were *b* = 18–33 mm (*b*/*D* = 0.7–1.3).

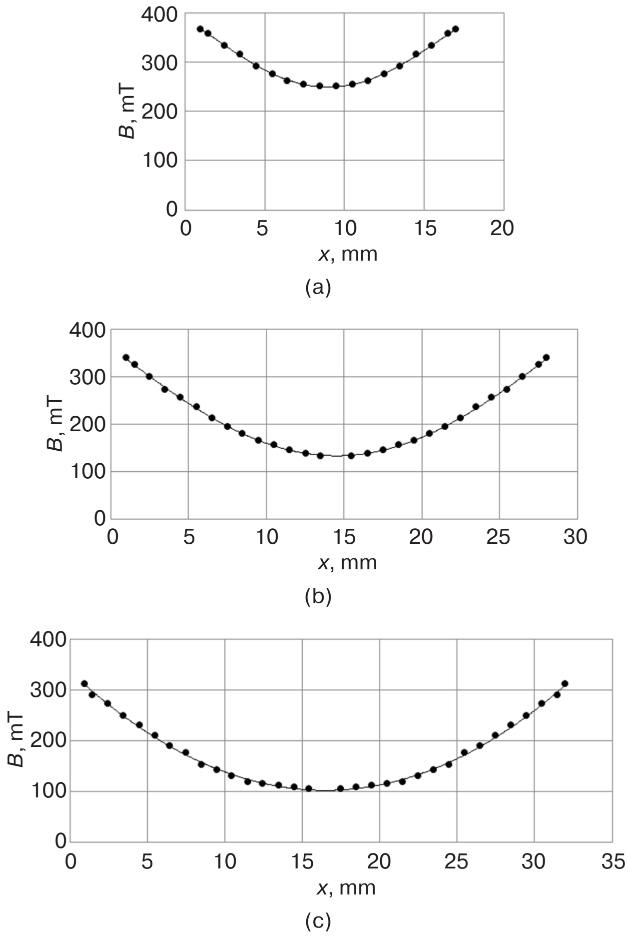

Fig. 2. Coordinate characteristics of magnetic field induction *B* between opposing poles with diameter *D* = 25 mm (for the near-axis part of the interpolar area) at different distances *b* between them: (a) 18 mm; (b) 29 mm; (c) 33 mm

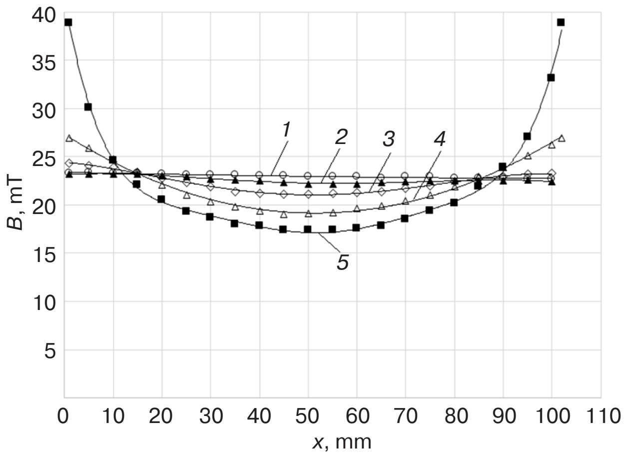

Fig. 3. Coordinate characteristics of induction *B* of the magnetic field between opposing poles with diameter *D* = 200 mm (for example, in the electromagnetic system according to Fig. 1) at the distance *b* = 102 mm between them:
1 (○) shows data for the near-axis part of the interpolar area; *2* (▲), *3* (◊), *4* (Δ), and *5* (■) shows data for the sections, which are 0.15*D*, 0.3*D*, 0.38*D*, and 0.45*D* away from the axis, respectively

According to the data given in Fig. 2, the working zone for the study of a particular sample is the median zone in the vicinity of the extremum (minimum) of the curve *B* from *x*; in terms of length, it can be estimated as no more than 25–30% of the value of *b*. For the researcher, this result means that the size of the sample under study when placed in such a zone should not exceed only 5–10 mm; moreover, this is true only for samples of relatively small transverse dimensions.

In order to achieve homogeneity of the field in it, the length of the working zone can be increased by increasing the diameter *D* of the poles (pole tips in the form of disks) and/or decreasing the distance *b* between them.

Figure 3 shows the coordinate characteristics of induction *B* between the poles with diameter *D* = 200 mm, which are remote from each other by distance *b* = 102 mm ($b/D \cong 0.5$). The corresponding dependencies are given both for the near-axis part of the interpolar area and for other parts of this area at different distances from the axis: 0.15*D*, 0.3*D*, 0.38*D*, and 0.45*D* (almost at the periphery).

In this case the working zone can be considered as practically the whole interpolar near-axis area; the transverse radius with respect to the axis is not more than 0.15*D*. Here the extent of the working zone, estimated by the value 90–100% of *b* (for the near-axis part of the interpolar area) may enable the docking of the ends of the studied sample with the pole surfaces, but only when studying samples of relatively small transverse dimensions.

At the same time, it should be borne in mind that increasing the diameter *D* of poles and decreasing the distance *b* between them, although solving the problem of creating the necessary working area (with the provision of practically homogeneous magnetic field), also limits the possibility of using such a working area for conducting studies of relatively oblong samples in it.

Due to the fact that the primary coordinate characteristic in such electromagnetic systems is characteristic in the axial direction of the interpolar area, where the induction force lines are not curved, the possibility of obtaining such characteristics by superposition may become relevant. It is only necessary to possess the corresponding coordinate characteristic of induction *B* from the side of one pole in the absence of an opposing magnetic pole having a mirror characteristic, which is conditionally located at a certain distance.

Figure 4 shows the coordinate characteristic of the field induction from the side of one magnetic pole of the indicated magnetic element [11]. It can be seen that as *x* moves away from the center of its pole surface, the field induction *B* monotonically decreases, obeying a dependence close to the exponential dependence [11].

Operating with this characteristic, including its "mirror reflection" symmetrical at a distance equal to this or that interpolar distance *b* (the size of the interpolar area), we can obtain the resulting induction characteristic by adding the corresponding induction values in the axis direction (here between the actual and fictitious poles) using superposition technique.

Figure 5 shows the results of such a method used to obtain the corresponding resulting (points □) coordinate characteristics of the induction *B* [11] for different values of the (fictitious) pole-to-pole distance *b*.

Figure 6 summarizes the actual data of induction *B*, obtained between the opposing (differently reversed)

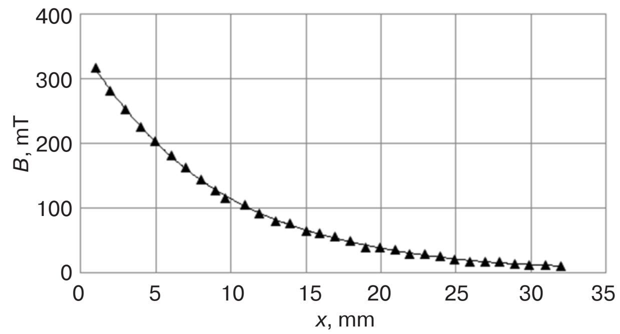

Fig. 4. Coordinate characteristic of the field induction *B* from the side of one pole of the magnetic element-disk at a distance from the center of the pole surface

magnetic poles, with the data of induction *B*, obtained by superposition.

The good agreement of the compared coordinate characteristics *B* (Fig. 6) testifies to the possibility of applying the superposition principle to this problem and obtaining a universal solution to the problem of obtaining the coordinate (i.e., near-axis) characteristics of the field induction in a system of two opposing poles with flat surfaces. Thus, it is possible to dispense with preliminary measurements of induction of a given magnetic system used in a measuring device by relying on the single coordinate characteristic obtained from the side of one magnetic pole. This confirms the possibility of practical use of the superposition principle in the creation of such systems.

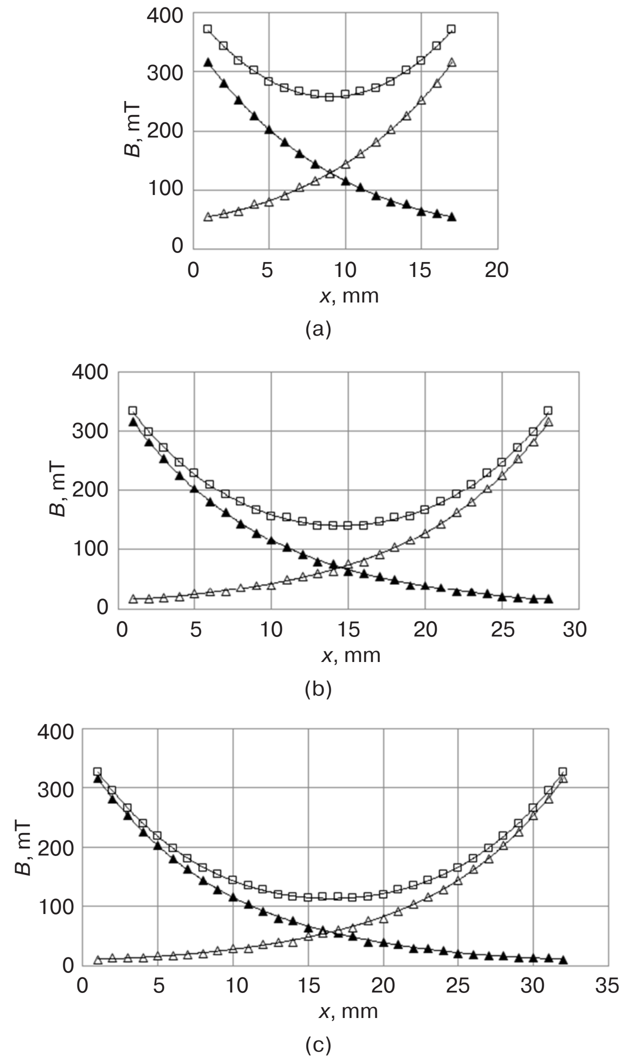

Fig. 5. Results of superposition of induction *B* (□) between the actual (data *B* are marked with the points ▲) and conditionally opposing at the distance *b* (data *B* are marked with the points Δ) magnetic poles of disk elements: (a) *b* = 18 mm; (b) *b* = 29 mm; (c) *b* = 33 mm

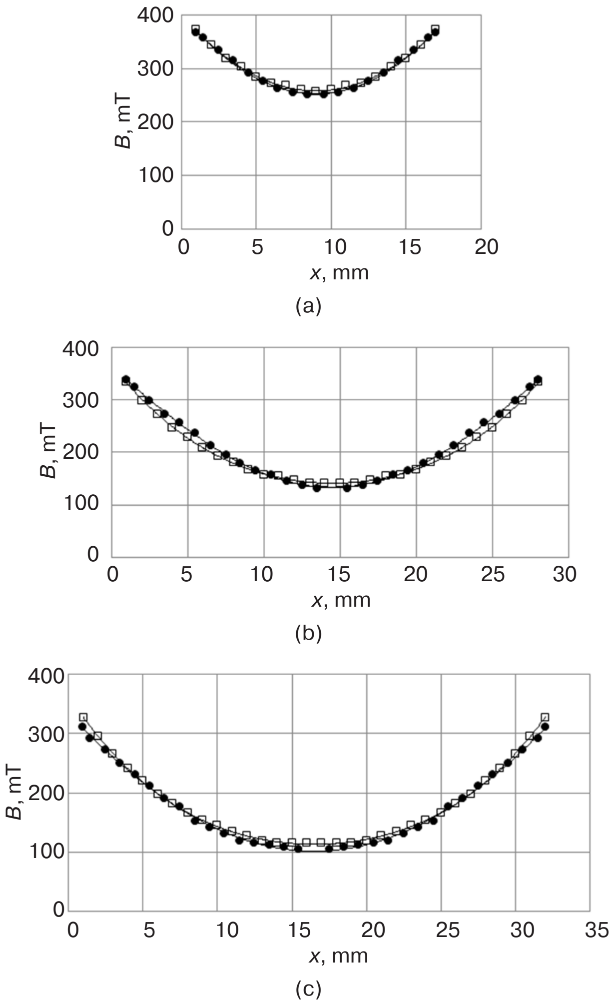

Fig. 6. Comparison of the actual coordinate characteristic of the induction data between two opposing poles separated by a distance *b* (points ● from Fig. 2) with the corresponding characteristic obtained by superposition of the induction data of each of these magnetic poles (points □ from Fig. 5): (a) *b* = 18 mm; (b) *b* = 29 mm; (c) *b* = 33 mm

CONCLUSIONS

Since different parts of a sample under study will be under different conditions (by *H* or *B*), the results of such measurements should be treated as not quite correct. The conducted study confirms the relevance of estimating the size of the working zone in which the values of field strength *H* or induction *B* are practically constant between the opposing flat poles in order to determine the reliability of determining the magnetic properties of samples placed in this zone.

Experimentally validated data on working zones when the opposing magnetic poles are in the form of flat disks are given for different distances *b* between pole planes and different diameters *D*. It is established that the size of the working zone will not exceed 25–30% of *b* at increased relative to *D* values of *b*. Thus, a sample placed in this zone for research should not exceed 5–10 mm and have a relatively small transverse dimension.

It is shown that the working area increases with increasing diameter *D* and decreasing distance *b*. In particular, at b = 102 mm and D = 200 mm (i.e., at $b/D \cong 0.5$), the size of the working zone is estimated by the value starting from 90% and up to 100% of *b* for the near-axial part of the interpolar area. This estimation applies to the permissible junction of the ends of the studied specimen with the pole surfaces, but only when studying specimens of relatively small transverse dimensions.

The possibility of estimating the working (near-axis) zone between the opposing planar magnetic poles by obtaining the necessary coordinate characteristics of the field induction (strength) between them by superposition (using the corresponding coordinate characteristics from the side of one of the magnetic poles) is confirmed.

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Authors' contributions

D.A. Sandulyak—methodology, data verification and analysis, writing and editing the text of the article.

M.N. Polismakova—conceptualization, conducting the research, writing and editing the text of the article.

D.A. Golovchenko—collecting and analyzing materials for the study, writing the original draft.

A.S. Kharin—conducting the research, collecting materials for the study.

A.V. Sandulyak—data verification, formal analysis, supervision.

A.A. Sandulyak—methodology, editing.

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