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RESEARCH ARTICLE

Expanding the capabilities of new magnetometers of ponderomotive and magnetic-rheological types with hemispherical poles

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Abstract
Objectives. The work sets out to explain the expanded capabilities of new magnetometers by conducting appropriate studies. In order to determine the magnetic susceptibility of small-volume objects, ponderomotive and magnetic-rheological magnetometers with hemispherical pole pieces are used to create the magnetic field required for a limited working zone.
Methods. The research is carried out using an original method, which includes finding the coordinate characteristic of the induction of the field B through direct step-by-step measurements by the Hall sensor in the interpolar space along the line of action of the ponderomotive force to provide a basis for obtaining the coordinate characteristic of the gradient.
Results. In magnetometers using hemispherical poles of increased diameter D: 157 and 184 mm, mutually disconnected from one or another by the distance b, the desired key dependencies of magnetic induction B were experimentally obtained (with a step-by-step distance x from the center of symmetry of the interpolar space along the line of action of the ponderomotive force) to provide the dependence of the gradient grad$B = dB/dx$. The characteristic inflection of each of the curves B from x and corresponding individual extremum of the following curves dB/dx from x, in the vicinity of which the values of dB/dx are practically stable, meets the requirement of determining the dislocation of the executive (working) zone such that the inhomogeneity of the field is almost constant.
Conclusions. Coordinates of executive zone dislocation are obtained from established and generalized dependencies B from x and dB/dx from x. To calculate these coordinates, which depend on D and b but do not depend on the magnetizing force of the winding, the corresponding analytical (phenomenological) expressions of power and logarithmic form are obtained. The possibility of using these expressions to identify the executive zone of magnetometers without resorting to additional series of experiments is shown. The expediency of using hemispherical pole pieces of increased diameter is also demonstrated. On this basis, the length of the executive zone can be increased to conduct studies with samples of a wider range of sizes.

Keywords: ponderomotive principle, magnetometer, magnetic susceptibility of the sample, executive zone, coordinate characteristics of induction and gradient, power dependence, logarithmic dependence

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НАУЧНАЯ СТАТЬЯ

Расширение возможностей новых магнитометров пондеромоторного и магнитно-реологического типов с полюсами-полусферами

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Резюме

Цели. Для определения магнитной восприимчивости малообъемных объектов применяются магнитометры пондеромоторного и магнитно-реологического типов с полюсами-полусферами, позволяющими создавать требуемое для лимитированной рабочей зоны магнитное поле. Цель работы – проведением соответствующих исследований показать, что возможности новых созданных магнитометров могут быть расширены.

Методы. Исследование проводится согласно оригинальному методу, включающему получение координатной характеристики индукции поля B (посредством прямых пошаговых измерений датчиком Холла) в межполюсном пространстве по линии действия пондеромоторной силы с последующим нахождением координатной характеристики градиента.

Результаты. В магнитометрах с применением полюсов-полусфер повышенного диаметра D: 157 и 184 мм, взаимно разобщаемых на то или иное расстояние b, экспериментально получены ключевые зависимости магнитной индукции B при пошаговом удалении x от центра симметрии межполюсной области по линии действия пондеромоторной силы, а по ним – зависимости градиента grad$B$ = dB/dx. Характерный перегиб каждой из кривых зависимостей B от x и индивидуальный экстремум последовавших из них кривых зависимостей dB/dx от x, в окрестности которого значения dB/dx практически одинаковы, отвечает требованию выбора дислокации исполнительной (рабочей) зоны, где неоднородность поля практически постоянна.

Выводы. По установленным и обобщенным зависимостям B от x и dB/dx от x найдены координаты дислокации исполнительной зоны. Для вычисления этих координат, зависящих от величин D и b и не зависящих от намагничивающей силы обмотки, получены аналитические (феноменологические) выражения степенного и логарифмического вида. Показана возможность использования этих выражений для идентификации исполнительной зоны магнитометров, не прибегая к проведению дополнительных серий экспериментов. Показана целесообразность применения полюсов-полусфер повышенного диаметра, что позволяет увеличить протяженность исполнительной зоны и проводить исследования с образцами более широкого спектра размеров.

Ключевые слова: пондеромоторный принцип, магнитометр, магнитная восприимчивость образца, исполнительная зона, координатные характеристики индукции и градиента, степенная связь, логарифмическая связь

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INTRODUCTION

In various areas of science and technology, it is necessary to obtain data on the magnetic properties of dispersed materials, in particular, composites, powders, suspensions [1–13]. This issue becomes particularly relevant when a relatively small volume of the material under study is available, for example, small samples of ferroimpurities isolated from technological bulk and liquid media for laboratory purposes.

In this regard, it is highly important to have appropriate means of monitoring the magnetic properties of small-volume samples, for which magnetometers based on the ponderomotive principle are generally preferable [14–25]. A contemporary direction in the creation of means for controlling the magnetic characteristics—in particular, in terms of their magnetic susceptibility—of small-sized bodies when using this kind of magnetometer, including small-volume dispersed samples and their individual particles involves the use of pole tip-hemispheres [26–32] (Fig. 1). Such a solution can be used to obtain the necessary working zone, i.e., the zone of stable (along a certain coordinate, generally according to the action of the ponderomotive force) inhomogeneity in terms of gradient and/or magnetic force factor without the difficulties that usually arise in such cases. An indication of the dislocation of this zone is shown in Fig. 1 in the form of a thickening on the *x*-axis as the axis along which the sample under study is suspended or the particle under study is forced to move in the liquid.

To identify this zone in the interpole region of the magnetometer, it is necessary to obtain the coordinate characteristics of the intensity H (or induction B) of the created inhomogeneous magnetic field [26–32]. Since the relative magnetic permeability of the air medium in the interpole region is close to unity, the values of H and B are related by means of a constant: $H = B/\mu_0$, where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant.

At the same time, the condition for the presence within the working zone of the created inhomogeneous field of some stable (practically constant) value—for example, the gradient of intensity grad$H$ (or the

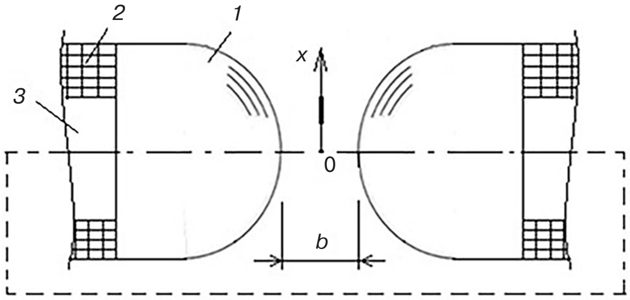


Fig. 1. On the application of pole tips-hemispheres (*1*) in the electromagnetic system with winding (*2*) on the magnetocoupler (*3*) in magnetometers based on the ponderomotive principle

gradient of induction grad$B$)—is unambiguous. The values of the field intensity H (induction B) within such a zone, in particular, in the direction x in which the ponderomotive force F (Fig. 1), measured in the magnetometer, acts, must conform to a linear relationship. Only in this case, the corresponding differentiation of such dependence—i.e., the transition to the desired relation dH/dx or dB/dx—will demonstrate the constancy (here, stability along the x coordinate) of the parameter of interest $dH/dx \cong \text{grad}H = \text{const}$ or $dB/dx \cong \text{grad}B = \text{const}$.

At the same time, already well-proven magnetometers suitable for realization of these methods comprise poles–hemispheres of comparatively small diameter D = 100 mm and 135 mm [26, 27, 29–32]. This somewhat limits the necessary executive zone considering its dislocation and extent in the objectively somewhat constricted interpole space.

The capabilities of such magnetometers can be extended by using poles–hemispheres of larger diameter D. Of course, this requires a set of studies for obtaining the coordinate (along the x-direction of the ponderomotive, i.e., magnetic, force) characteristics of induction B (intensity H), gradient grad$B \cong dB/dx$ (grad$H \cong dH/dx$), force factor Bgrad$B$ (Hgrad$H$) and consequential generalized analytical dependencies, which are necessary for operative prediction and control of the location of the desired working zone (i.e., the zone of relatively stable field inhomogeneity). At the same time, it is important to establish to what extent such dependencies agree with the previously established dependencies obtained in [26–32] for poles–hemispheres of a smaller diameter.

RESULTS AND DISCUSSION

It was mentioned earlier that the key characteristic for identifying the executive zone of magnetometers of the stipulated ponderomotive principle based on the manifestation of the ponderomotive (i.e., magnetic force) is the coordinate characteristic of the induction B (intensity H) of the magnetic field between the poles, represented here by poles–hemispheres.

As in [26–32], step-by-step values of B along the chosen direction x (Fig. 1) were measured using a milliteslameter fitted with a Hall sensor placed on a coordinate table. The direction x of the sensor movement, which should lie in the plane of symmetry of the area between the pole tips-hemispheres, can be selected by the experimenter by moving the sensor in one of the variants of such direction most convenient for making measurements. Here, specific values of x correspond to the distance from the centerline of the poles to the current location of the sensor. In Fig. 1 this direction is shown upwards; however, in the real design it was more convenient to move in the direction perpendicular to the drawing, i.e., towards oneself.

The experiments were performed alternately using two pairs of pole tips-hemispheres with diameters of D = 157 mm and of D = 184 mm, mutually removed by one or another distance b: for D = 157 mm—from b = 9.5 mm to b = 24 mm; for D = 184 mm—from b = 6.5 mm to b = 28 mm. The magnetizing force $I\omega$ of the winding of the electromagnetic system (Fig. 1) was varied by the value of the supply current I in the range $I\omega$ = 3000–22500 A. In this case, the number of winding coils ω = 3000.

The results of step-by-step measurements of the magnetic induction B in the accepted direction x (Fig. 1) between the poles–hemispheres with the diameter D = 157 mm are shown in Fig. 2 (points) for different values of $I\omega$ and b. This allowed us to obtain the corresponding coordinate characteristics (lines) of B and $dB/dx \cong \mathrm{grad}B$. For this purpose, the experimental data B (Fig. 2, points) were subjected to approximation (Fig. 2, lines) by a fourth degree polynomial using the *Advanced Grapher*[1] software environment.

When their inflection is traced as described in [26–32], the rather meandering appearance of the coordinate characteristics B from x in Fig. 2 indicates the possibility of artificial linear (simplified) approximation of the dependencies of induction B on the x coordinate precisely in the vicinity of the inflection point of each of these dependencies. So, here (i.e., where the section of the curve B from x can be linearly approximated), the gradient of induction $\mathrm{grad}B = dB/dx$ is an almost constant value.

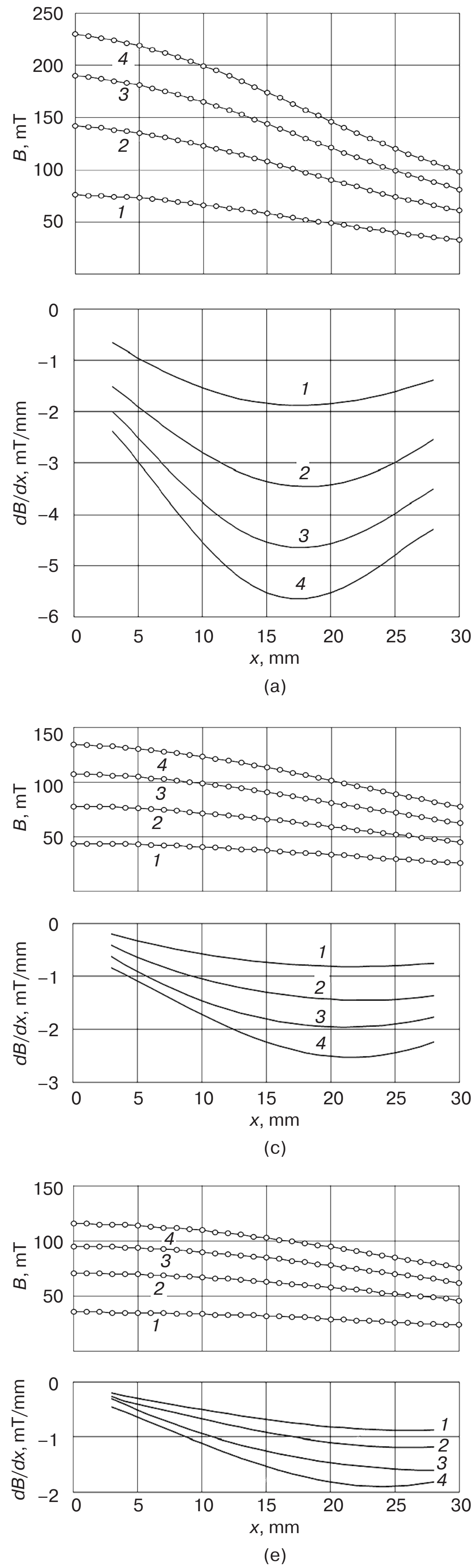
This can be verified in the extreme form of the gradient coordinate characteristics (Fig. 2) according to the very close values of the gradient (bounded area) in the vicinity of the extremum.

From the obtained coordinate characteristics of the gradient (Fig. 2) directly follows the information about the coordinate (abscissa) of the extremum of each of these characteristics, i.e., the value $x = x_{extr}$ (Table 1), and thus on the coordinate of the dislocation of the corresponding executive, namely, the working zone between the poles–hemispheres with diameter D = 157 mm.

[1] https://www.alentum.com/agrapher/. Accessed May 12, 2025.

Table 1. Coordinates of the extremum x_{extr} (dislocation of the stable gradient zone) between poles–hemispheres with the diameter D = 157 mm at different values of magnetizing force $I\omega$ of the winding and different distances b between poles–hemispheres

$I\omega$, A	x_{extr}, mm					
	b = 9.5 mm	b = 13 mm	b = 15.5 mm	b = 18 mm	b = 21 mm	b = 24 mm
3000	17.60	22.26	21.90	22.34	22.17	27.70
6000	18.15	20.86	22.73	22.41	26.21	26.01
12000	17.50	20.54	21.17	22.76	29.49	27.46
22500	17.65	19.58	21.61	22.75	24.12	26.58
Average	**17.73**	**20.81**	**21.85**	**22.57**	**25.5**	**26.94**



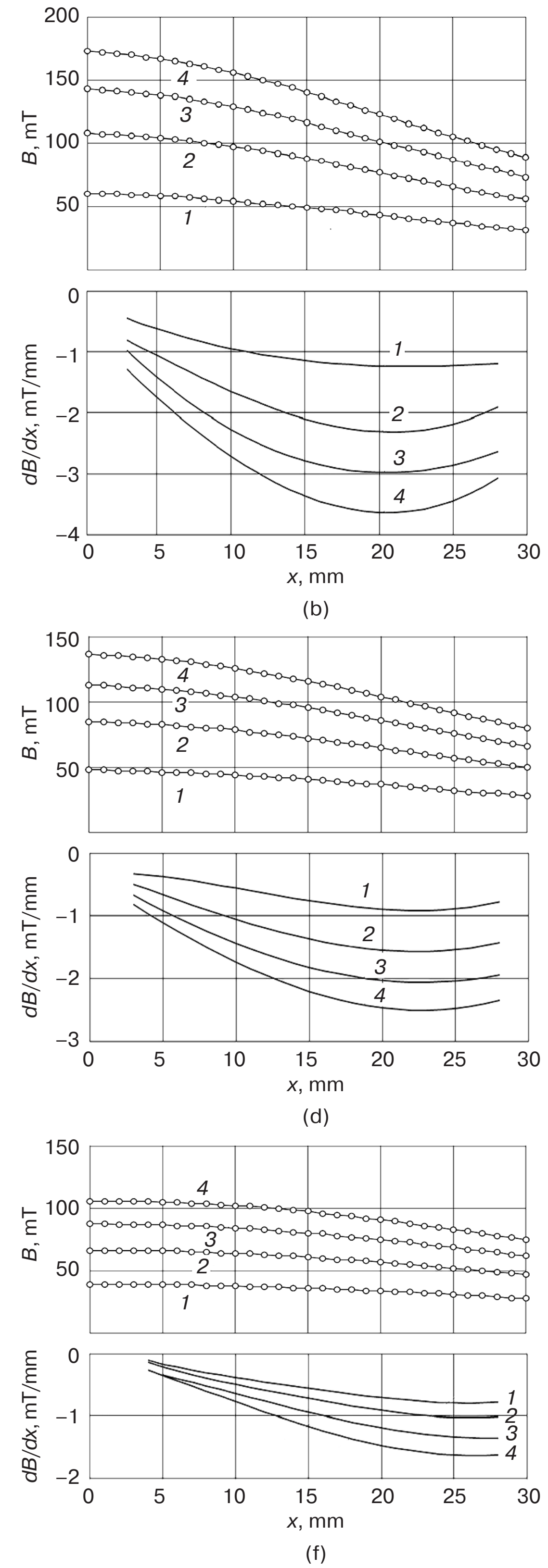


Fig. 2. Coordinate characteristics of induction and field gradient between poles–hemispheres of the diameter D = 157 mm at their mutual distance b: (a) 9.5 mm; (b) 13 mm; (c) 15.5 mm; (d) 18 mm; (e) 21 mm; (f) 24 mm; for the values of the magnetizing force $I\omega$: (*1*) 3000 A, (*2*) 6000 A, (*3*) 12000 A, (*4*) 22500 A

The obtained data x_{extr} indicate an important fact noted earlier: despite the different values of the magnetizing force $I\omega$ of the winding of the electromagnetic system of the magnetometer, the values of the coordinates of the extrema of the field induction gradient characteristics (Fig. 2) at the same value of b (i.e., the coordinates of the dislocation of the working zones) are very close to each other.

This fact, already found earlier for poles–hemispheres of smaller diameter [26–32], is all the more relevant if we present the ordinates of the initial characteristics available in Fig. 2 in relative quantities, namely, as the ratio of the current (by x) values of the induction B to the individual "starting" value of the induction B_0 obtained at $x = 0$, i.e., to B/B_0, for the corresponding value of the magnetizing force $I\omega$.

Figure 3 shows as an example such characteristics obtained from the data borrowed from Fig. 2a. It can be seen that irrespective of the value $I\omega$ the data B/B_0 are generalized by a single dependence; here, in contrast to Fig. 2a, the point designations have been intentionally changed with a corresponding inflection of this dependence. This also indicates a single dislocation of the working zones at the same mutual distance b of the poles–hemispheres. The dependencies of B/B_0 on x for other values of b are equally revealing (Fig. 4).

The above arguments are methodologically important for the experimenter: when performing experiments to determine the effect of field magnitude on the magnetic susceptibility of a sample, its dislocation between the poles should not be changed.

The extent of the zone (along the x coordinate) of almost constant values of the grad$B$ parameter, i.e., the extent of the working zone of the magnetometer, is indicated by the data of Figs. 2–4, namely, those parts of the dependencies of induction B and relative induction B/B_0 on x that are amenable to linear approximation (areas in the vicinity of the inflection point of such dependencies).

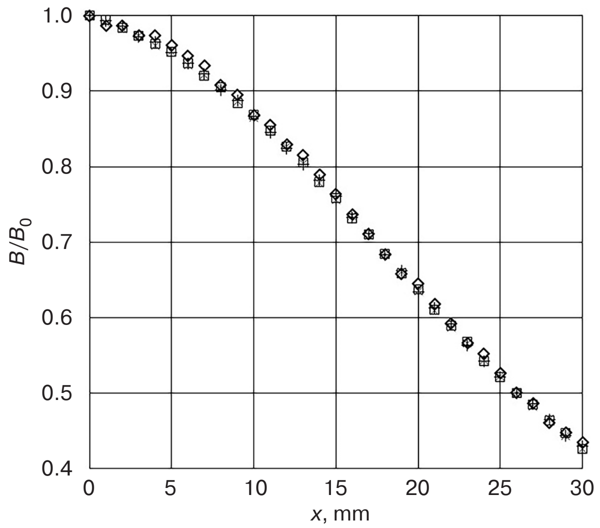


Fig. 3. Generalized (from the data on Fig. 2a) coordinate characteristics of the induction B in relative values B/B_0, b = 9.5 mm, for values of the magnetizing force $I\omega$: ◊ 3000 A, + 6000 A, □ 12000 A, × 22500 A

The extent of the working zone of the magnetometer is even more clearly indicated by the coordinate characteristics of the parameter grad$B$ (Fig. 2): this zone is localized in the vicinity of the extremum of one or another dependence of the parameter dB/dx = grad$B$ on x.

The obtained data (Table 1) on the coordinate x_{extr} of the dislocation of the working zone of the magnetometer

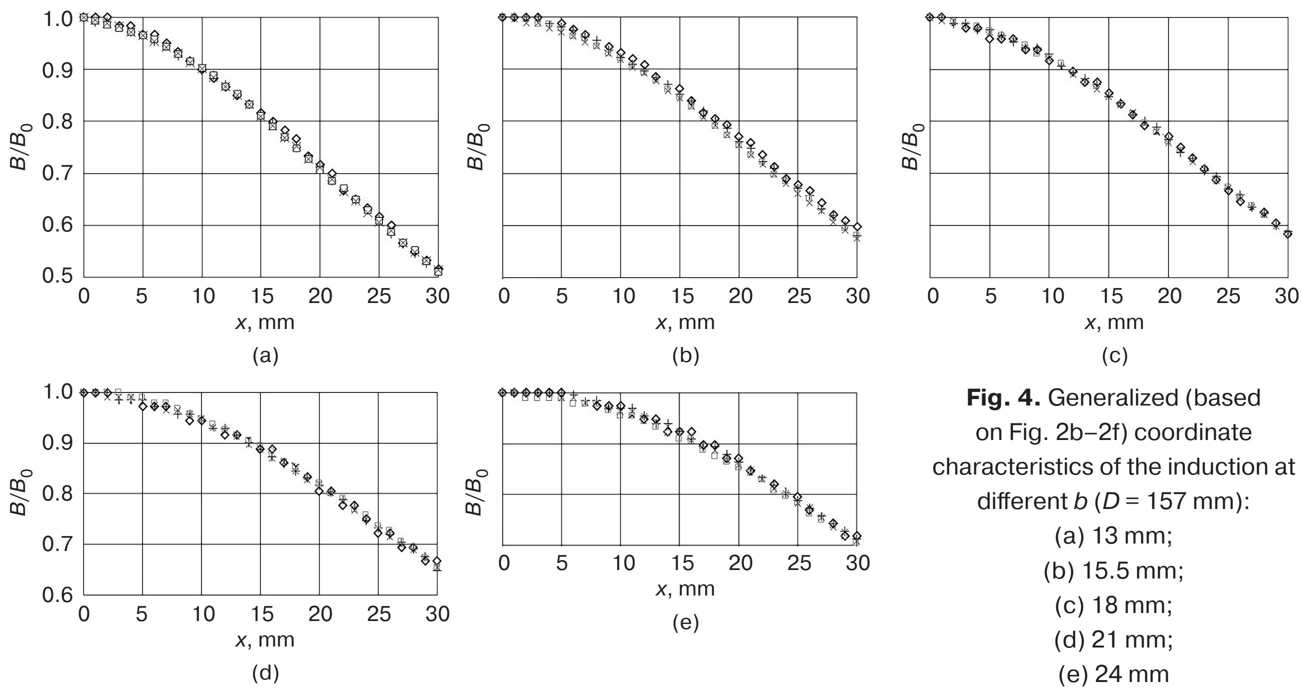


Fig. 4. Generalized (based on Fig. 2b–2f) coordinate characteristics of the induction at different b (D = 157 mm):
(a) 13 mm;
(b) 15.5 mm;
(c) 18 mm;
(d) 21 mm;
(e) 24 mm

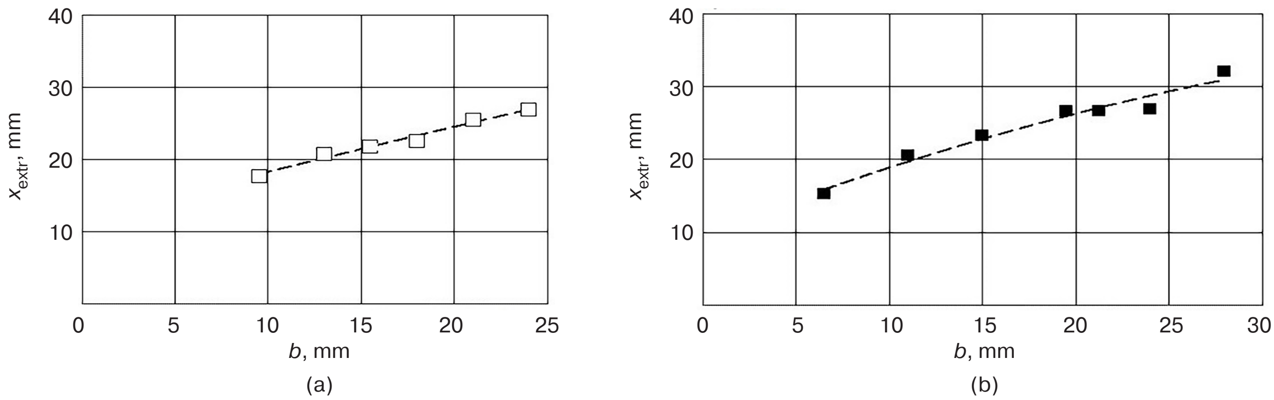


Fig. 5. Dependence of the dislocation coordinate of the working area of the magnetometer on the distance between its poles–hemispheres with the diameters D = 157 mm (a) and D = 184 mm (b)

depending on the mutual distance b of the poles-hemispheres with the diameter D = 157 mm are shown in Fig. 5a (points □). Figure 5b (points ■) shows similar data obtained using poles–hemispheres with the diameter D = 184 mm. Information similar to that previously shown in Figs. 2–4 and Table 1 for D = 184 mm is shown in Figs. 6, 7 and in the Table 2.

It is important to note that if the data obtained for both pairs of poles–hemispheres (Table 1, Table 2, Fig. 5), i.e., for D = 157 mm and D = 184 mm, are presented in a more universal, dimensionless form, namely, as x_{extr}/D on b/D (Fig. 8), the expected (similar to [31]) result follows—they are generalized by a single dependence.

The representation of these data in semi–logarithmic coordinates (Fig. 8b) shows the possibility of their quasi-linearization in these coordinates in the investigated range b/D = 0.035 … 0.153 with obtaining the calculation formula of the logarithmic form:

$$\frac{x_{extr}}{D} = A \ln \frac{b/D}{k} \quad (1)$$

at values of phenomenological parameters A = 0.061 and k = 0.0096.

The possibility of quasi-linearization of the same data is also observed in logarithmic coordinates (Fig. 8c) by obtaining an alternative calculation formula of the degree type:

$$\frac{x_{extr}}{D} = G\left(\frac{b}{D}\right)^z \quad (2)$$

at the values of the phenomenological parameters G = 0.43 and z = 0.48.

It is interesting to compare the found expressions (1) and (2) with the corresponding expressions obtained earlier for poles–hemispheres of smaller diameter: D = 100 mm and D = 135 mm [31]. It is important to note that, remaining functionally similar, the compared expressions differ slightly only in the values of the phenomenological parameters A, k, G and z: A = 0.061 instead of A = 0.063, k = 0.0096 instead of k = 0.0095, G = 0.43 instead of G = 0.45, z = 0.48 instead of z = 0.5.

Table 2. Coordinates of the extremum x_{extr} between poles–hemispheres of the diameter D = 184 mm at different values of the magnetizing force $I\omega$ of the winding and different distances b between poles–hemispheres

$I\omega$, A	x_{extr}, mm						
	b = 6.5 mm	b = 11 mm	b = 15 mm	b = 19.5 mm	b = 21.2 mm	b = 24 mm	b = 28 mm
3000	15.65	20.75	23.71	–	26.3	25.58	32.20
6000	15.59	20.67	23.44	26.77	26.965	28.2	32.17
12000	14.89	20.55	22.97	26.71	27.25	28.025	32.32
22500	14.81	20.27	22.81	–	25.85	25.66	31.86
Average	**15.24**	**20.56**	**23.23**	**26.74**	**26.59**	**26.87**	**32.14**

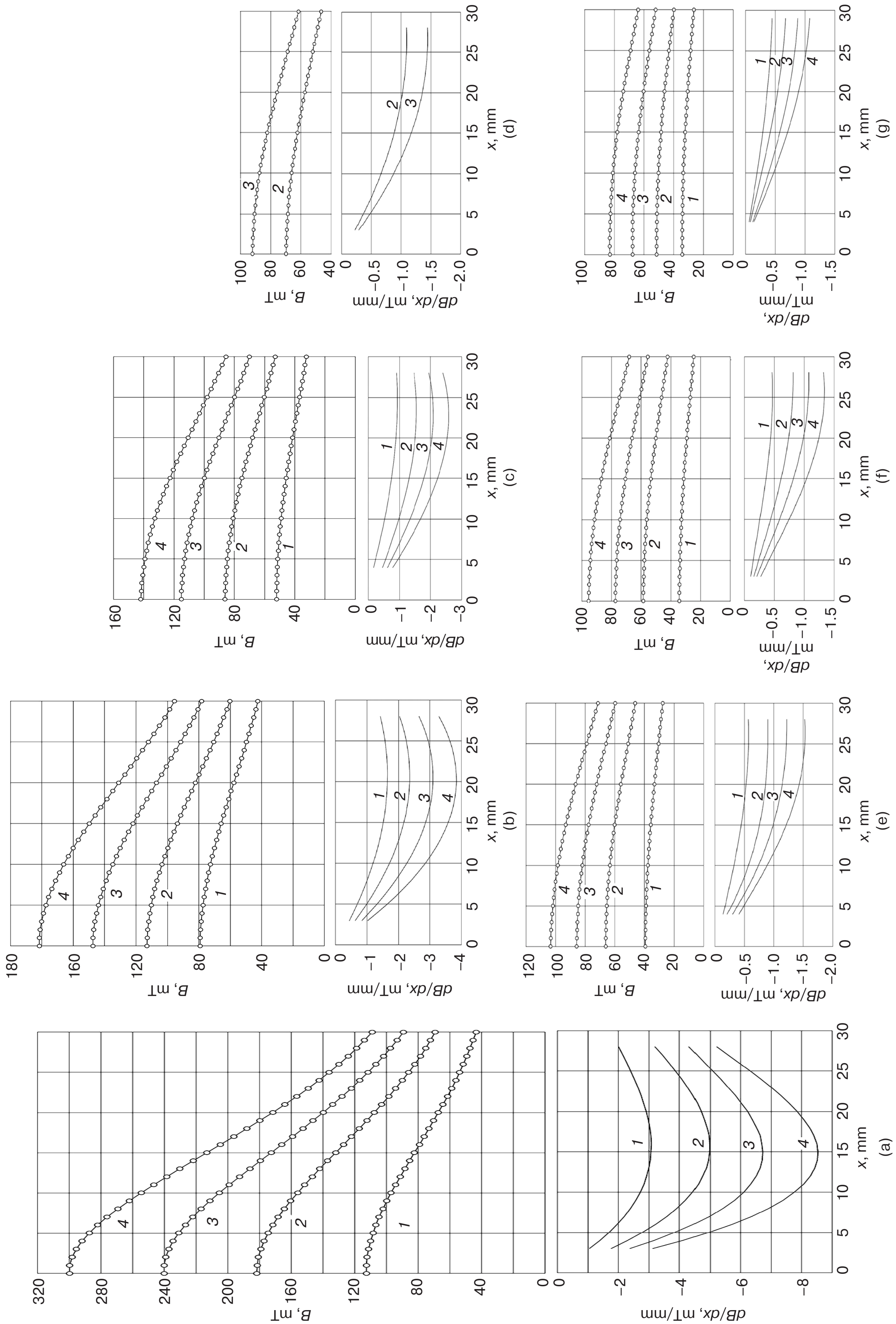


Fig. 6. Coordinate characteristics of induction and field gradient between poles–hemispheres of the diameter D = 184 mm at their mutual distance b:
(a) 6.5 mm; (b) 11 mm; (c) 15 mm; (d) 19.5 mm; (e) 21.2 mm; (f) 24 mm; (g) 28 mm; for the values of magnetizing force $I\omega$: (*1*) 3000 A, (*2*) 6000 A, (*3*) 12000 A, (*4*) 22500 A

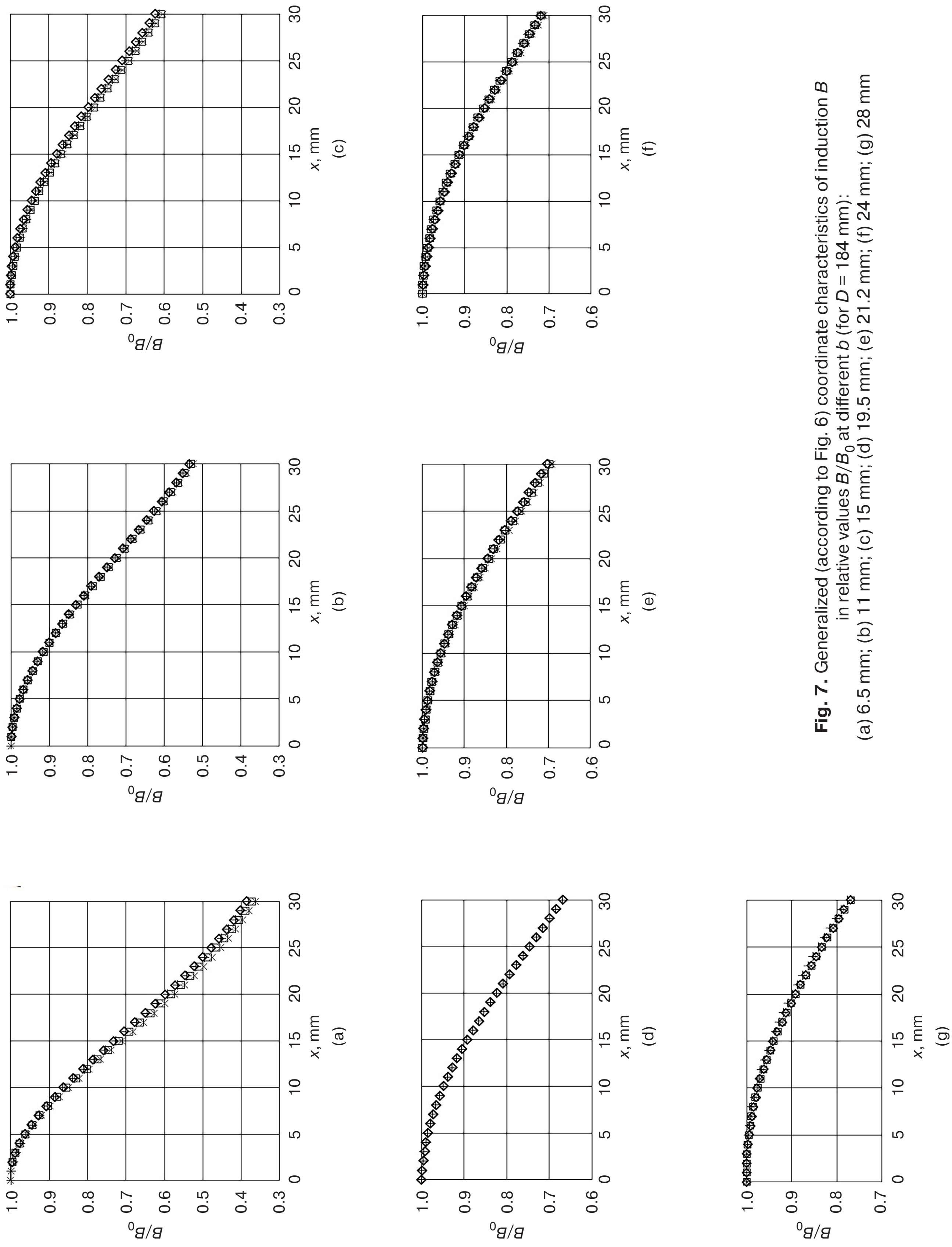


Fig. 7. Generalized (according to Fig. 6) coordinate characteristics of induction B in relative values B/B_0 at different b (for D = 184 mm): (a) 6.5 mm; (b) 11 mm; (c) 15 mm; (d) 19.5 mm; (e) 21.2 mm; (f) 24 mm; (g) 28 mm

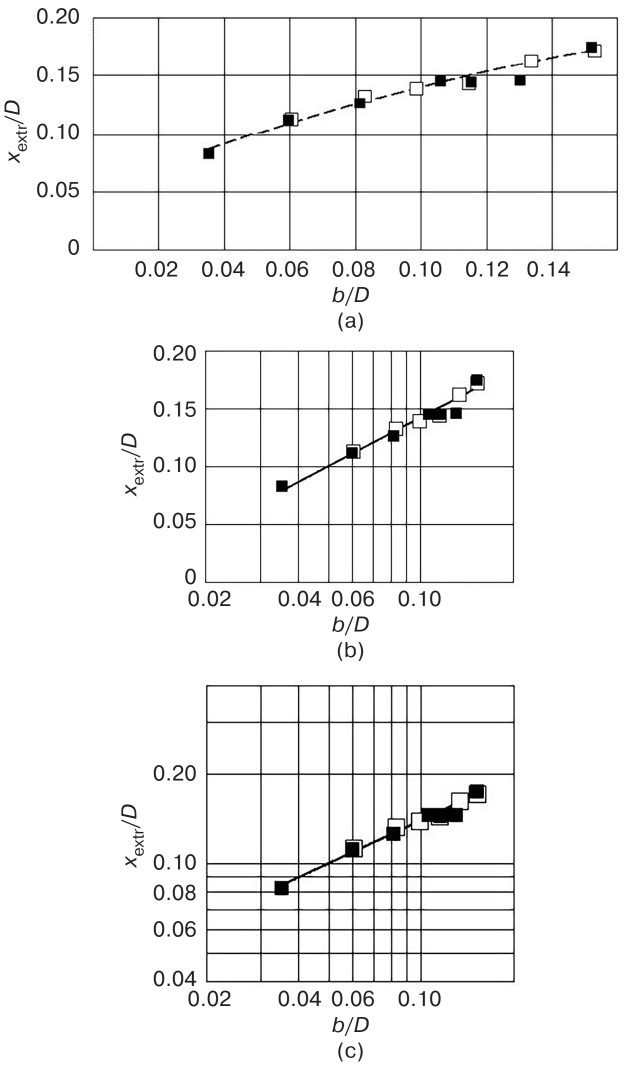


Fig. 8. Dependence of the relative coordinate of the dislocation of the working area of the magnetometer on the relative distance between its poles–hemispheres of the diameter D (□ 157 mm, ■ 184 mm) in ordinary (a), semi–logarithmic (b) and logarithmic (c) coordinates

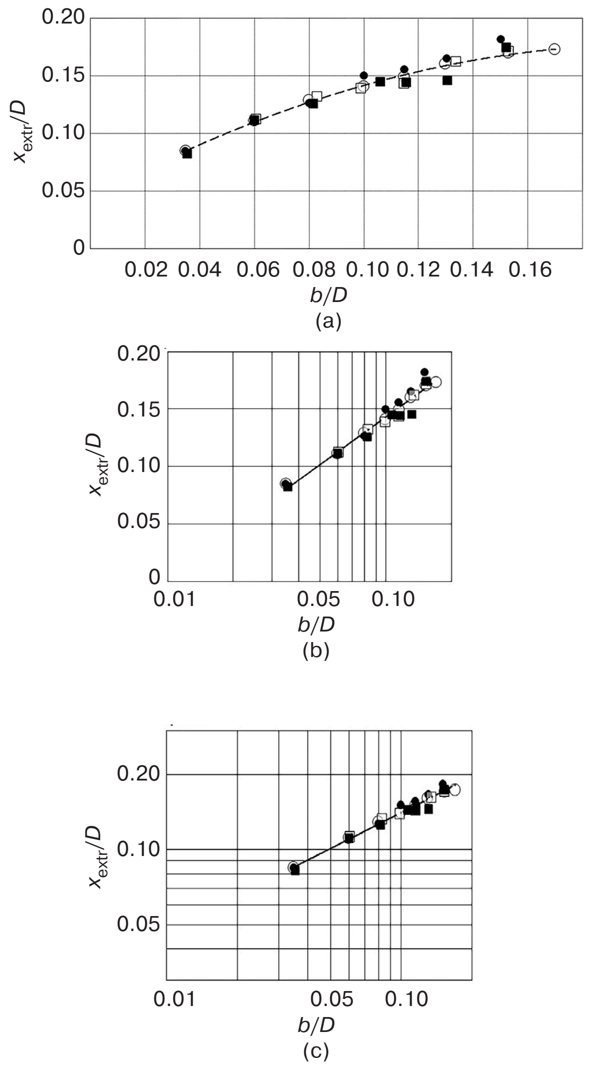


Fig. 9. Generalized dependence of the relative coordinate of the dislocation of the magnetometer working area on the relative distance between its poles–hemispheres with the diameter D (○ 100 mm, ● 135 mm, □ 157 mm, ■ 184 mm) in ordinary (a), semi–logarithmic (b) and logarithmic (c) coordinates

If to carry out joint processing of the data received for poles–hemispheres of the increased diameter, namely D = 157 mm and D = 184 mm, with the data received earlier for poles–hemispheres of the smaller diameter, namely D = 100 mm and D = 135 mm, the generalized dependence presented in Fig. 9, in semi–logarithmic (Fig. 9b) and logarithmic (Fig. 9c) coordinates, will take the form similar to (1) and (2), with the values of phenomenological parameters A = 0.061, k = 0.0094, G = 0.43, and z = 0.48.

CONCLUSIONS

The problem of expanding the capabilities of magnetometers of ponderomotor and magneto-rheological types designed to control the magnetic susceptibility of objects of small sizes, including both dispersed and individual particles, is considered.

In addition to the previously obtained data established using pole–hemisphere pairs of the diameters D = 100 mm and 135 mm, data are obtained for hemispheres of increased diameters D = 157 mm and 184 mm, mutually disconnected by one or another distance b.

The key dependencies of the magnetic induction B at the stepwise distance x from the center of symmetry of the interpole region (i.e., along the line of action of the ponderomotive force) have been experimentally determined to calculate the dependencies of the gradient grad$B \cong dB/dx$. This allows us to establish a characteristic inflection of each of the curves of dependencies of B on x and an extremum of each of the curves of dependencies of dB/dx on x, in the vicinity of which the values of dB/dx

are almost the same, which meets the requirement of constancy of the field inhomogeneity at the choice of the dislocation of the operating zone.

The coordinates of the dislocation of the operating zone are obtained from the determined and generalized dependencies of B on x and dB/dx on x. In order to calculate these coordinates, which depend on the values of D and b but not on the magnetizing force $I\omega$ of the winding of the electromagnetic system, analytical expressions of the power and logarithmic form are obtained.

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Authors' contributions

M.N. Polismakova—conceptualization, conducting a research and investigation process, writing and editing the text of the manuscript.

D.A. Sandulyak—methodology, data verification, applying mathematical methods to analyze data, preparation, writing and editing the text of the manuscript.

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

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

A.A. Sandulyak—methodology, editing the manuscript.

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

H.M. Basconus—data verification, collecting materials for the study.

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