An Approach to Monitoring of Magnetic Parameters of Cores of a Chain of Spheres. Diagnostics of Different Chain's Length and Core's Radius

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Abstract

The basic structural elements of the magnetized granular medium (effectively used, in particular, in apparatus of thin magnetic separation) are granule chains (according to channel-by-channel model), in connection with which there is a need to detail the features of their magnetization. The purpose of the work is to develop and implement an approach to measuring magnetic (micro)flows along the cores of different radius r in the chain of granules using a specially developed (by printed circuit board technology) sensor, with high radius R (15 and 20 mm) spheres available for such measurements.

From the data of measuring magnetic (micro)flows data of average induction in each of the quasi-continuous cores of the spheres chain are obtained, as well as data of magnetic permeability and susceptibility of these cores, their magnetization for different values of the intensity of the magnetizing field. It is shown that dependences of mentioned magnetic parameters from number n spheres in a chain are generalized on r/R for different R.

These relationships, increasing as n increases due to a decrease in the demagnetizing factor N of any of the cores and the chain as a whole, demonstrate the achievement of individually limiting values of magnetic parameters and corresponding auto-model regions where $N \to 0$. At the same time, the transition to each of these regions, manifesting almost independently of r/R and intensity, falls on the value of n = 10–12 = [n]. Thus, in fact, such a criterion value [n] distinguishes chains by sufficiently "long" – when $n \geq [n]$ and "short" – when $2 \leq n < [n]$. Data of demagnetizing factor for different cores of "short" chains of spheres are obtained and phenomenologically described.

Keywords: chain of granules, sensor contour on a printed circuit board, magnetic permeability, susceptibility, demagnetizing factor.

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Подход к контролю магнитных параметров сердцевин цепочки шаров. Диагностика разных по длине цепочки и радиусу сердцевин

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Базовыми структурными элементами намагничиваемой гранулированной среды (эффективно используемой, в частности, в устройствах для тонкой магнитной сепарации) являются цепочки гранул (согласно поканальной модели), в связи с чем возникает необходимость в детализации особенностей их намагничивания. Цель работы – разработка и реализация подхода к измерениям магнитных (микро) потоков по сердцевинам разного радиуса r в цепочке гранул при помощи специально разработанного (по технологии печатных плат) датчика, используя доступные для таких измерений шары повышенного радиуса R (15 и 20 мм).

По данным измерений магнитных (микро)потоков получены данные средней индукции в каждой из квазисплошных сердцевин цепочки шаров, а также данные магнитной проницаемости и восприимчивости этих сердцевин, их намагниченности для разных значений напряжённости намагничивающего поля. Показано, что зависимости указанных магнитных параметров от числа шаров n в цепочке обобщаются по r/R для разных R.

Эти зависимости, возрастая по мере увеличения n вследствие уменьшения размагничивающего фактора N любой из сердцевин и цепочки в целом, демонстрируют достижение индивидуально предельных значений магнитных параметров и соответствующих автомодельных областей, где $N \to 0$. При этом переход к каждой из этих областей, проявляющийся практически независимо от r/R и напряжённости, приходится на значение n = 10–12 = [n]. Тем самым такое, по сути критериальное, значение [n] разграничивает цепочки на достаточно «длинные» – когда $n \geq [n]$ и «короткие» – когда $2 \leq n < [n]$. Получены и феноменологически описаны данные размагничивающего фактора для разных сердцевин «коротких» цепочек шаров.

Ключевые слова: цепочка гранул, датчик-контур на печатной плате, магнитная проницаемость, восприимчивость, размагничивающий фактор.

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Introduction

The concept of the so-called effective medium is traditional in studies of any type of inhomogeneous magnets [1–8]. These magnets are used in various physical and applied problems. Effective medium is medium as a formally quasi-continuous volume of a magnet with its inherent magnetic parameters.

We used the concept of a quasi-continuous magnet for such types of inhomogeneous magnets as granular media (in particular, which are the key working bodies of fine magnetic separation devices). Concept could be efficient only to a chain of granules (and not the environment as a whole). This concept helped to study magnetic parameters. The model of channel-by-channel magnetization of a granular medium [9, 10] provided an information that a chain of granules was the basic structural element of this medium and a carrier of information about its magnetic parameters. At the same time, the chains of granules performed the function of a "bundle" of conductors-channels similar to each other for the generated magnetic flux. The example of comparing the corresponding magnetization curves proved the similarity of the magnetic parameters of the chain of granules and the granular medium as a whole [10].

The following must be said about the nature of the magnetization of such a quasi-continuous magnet as a chain of granules (for example, spheres). There was a pronounced redistribution of the magnetic flux over the cross section in contrast to the variant of magnetization of a solid (continuous) bar magnet. The flux density decreased as you moved away from the axis of the chain. Hence there was also a decrease in this density in one or another of its conditional core with an increase its radius r. This was due to an increase in the magnetic resistance of the "thickening" core of such a specific magnet due to decreasing volumes of metal in the core and increasing volumes of gaps between the surfaces of adjacent granules.

Direct measurements of magnetic fluxes proved that. We measured magnetic fluxes (with a microwebermeter) Φ through concentric loops of thin wire with different radii $r \leq R$, located in a hollow volume between the spheres in the chain, surrounding the contact point of the spheres with a radius R [9]. Thus, we obtained Φ in the corresponding in radius r cores of the chain of spheres. It became possible to obtain Φ values in the cores of even a small relative radius r/R by deeping the sensor loops into the inter-ball space. Use of chains with spheres of increased radius and loops of very thin wire was advisable here. The wire was so much thin as to place them as deep as possible in the thinning (when approaching the contact point of the spheres) volume between the surfaces of the spheres.

Then we had to develop ideas about the nature and features of the magnetization of chains of granules. It became necessary to expand the volume of this kind of labor-intensive research. Therefore, the issue of justified simplification in the manufacture and fixation of magnetic flux sensors (with the rejection of the traditional use for such purposes of a thin wire, which is not so practical here), became relevant. For example, by creating appropriate sensors. Printed-circuit technique could be sufficient to create appropriate sensors for such tasks [11–13].

Circular circuit on a thin printed board with a mounting hole like a magnetic flux sensor in the core of the chain of spheres

To measure the magnetic flux in one or another core of a magnetizable chain of spheres, we adhered to the classical principle. This was the principle of using a conductive sensor with a circular shape. A sensor in the form of a thin printed board with a conductive circular circuit or a block of concentric circuits made on it was preferable [11]. At the same time, each of the circuits had to have a small gap for the wire connection of its free ends with the microwebermeter.

With this approach to the implementation of the above magnetic measurements, which increases the reliability and quality of control, it is easy to ensure the required strict shape of the sensor circuit and/or each of the sensor circuits in the block (as geometrically ideal circles on a flat surface) and the concentricity of the sensor circuits with respect to the point of contact of the spheres and to each other.

It was also easy to ensure the correct positioning (Figure 1) of this working printed board 1 in the plane of symmetry of the volume between the contacting sphere 2 with radius R. The mounting hole ensured the correct positioning. The hole was made in the middle part of the working board concentric to the circuit-sensor or the block of circuits-sensors. The diameter d_0 corresponded to the recommendation: $d_0 = [\delta(4R–\delta)]^{0.5}$ [11], where δ was the board thickness. The edges of the board, formed around the circumference of the hole, fit snugly against the surfaces of the opposing spheres (without preventing their mutual contact). They fixed the working board in the required symmetry plane of the volume between the spheres.

Magnetic induction data in different cores of the chain of spheres, corresponding data on their magnetic permeability, susceptibility and magnetization

The board described above contained measuring circuits-sensors with a relative radius from $r/R = 0.2$ to $r/R = 0.9$, its positioning was in the middle of the studied chains of spheres (Figure 1). The board made it possible to obtain the necessary experimental data on the magnetic fluxes Φ in the cores of the chains of spheres corresponding in r/R. In this experiment, we used chains of different lengths, i. e. with a different (even) number n of spheres in one or another chain, namely from $n = 2$ to $n = 14$.

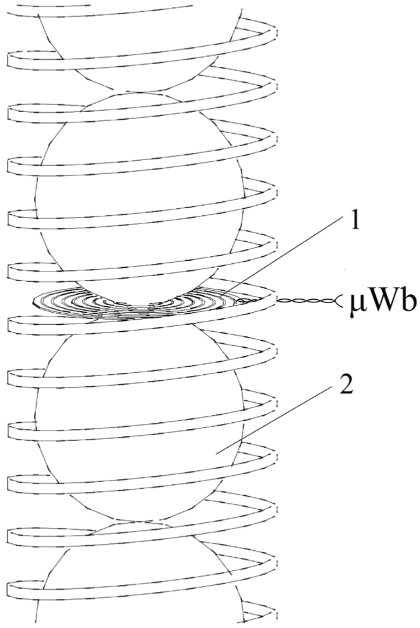


Figure 1 – The location of printed circuit board 1 with a sensor contour (sensor contours) of the magnetic flux values in the volume between the middle spheres 2 of the magnetized (in the solenoid) chain with even number n of contacting spheres

There were two identical series of experiments. In one of them, the chains consisted of spheres with a radius $R = 15$ mm, the other one contained spheres with a radius $R = 20$ mm (for subsequent comparison of the results of experiments on such a dimensionless parameter, which claims to be universal, as r/R). The spheres had an increased radius due to the need to place a sufficient number of measuring sensors as deep as possible in the volume between the surfaces of adjacent spheres. This volume thinned as it approached the contact point of the spheres, i. e. with the smallest possible relative radius r/R of the measuring circuit-sensor. The magnetization of the chains took place in a sufficiently long solenoid by a field strength from $H = 4.8$ kA/m to $H = 54.5$ kA/m.

According to the experimental data of the magnetic flux Φ, one could judge its density:

$$B = \Phi / \left(\pi r^2\right), \qquad (1)$$

i. e. about the data of the average induction B in each of the studied quasi-continuous cores of the chain of spheres. These data, obtained on the basis of formula (1), were shown in Figure 2 in the form of combined (for both series of experiments) families of dependencies B on the number of spheres n in chains at different values of r/R and H.

The resulting families of dependences B on n (Figure 2) were very informative for the qualitative and quantitative characteristics of the cores of chains of spheres as quasi-continuous magnets. This helped to visually illustrate the following notable features.

Firstly, the data of induction B in the cores of chains of spheres with a radius $R = 15$ mm corresponded to the data of induction B in the cores of chains similar in relative radius r/R with the same number n of spheres, but with a radius $R = 20$ mm. This can be seen in Figure 2 by the coincidence of the compared data B (points • and ○). This, quite expected (based on the principle of similarity), fact testified to the possibility of applying the obtained induction data (Figure 2) to the corresponding chains of spheres of a different identical radius.

Secondly, the larger the relative radius r/R of the core of the chain of spheres, the lower the values of induction B in the core were (Figure 2) due to a decrease in the proportion of ferromagnetic metal in the core and vice versa.

Thirdly, all dependences of the induction B (in the cores of the chain of spheres with different r/R) on the number n of spheres in the chain increased with increasing n due to a decrease in the demagnetizing factor N of each of the cores and the chain as a whole. Then they demonstrated the onset a characteristic self-similar region (Figure 2) with an individually limiting value B. This indicated the disappearance of the demagnetizing factor. The beginning of this region manifested itself almost independently of the relative radius r/R of the core and the intensity H of the magnetizing field, fell on the value $n = 10$–12 (starting from which $N \to 0$). Thus, such a transitional, but essentially criterial, value $n = 10–12 = [n]$ delimited both chains of spheres and their cores along the length (multiple of n) of the chain itself. They divided into quite "long" – when $n \geq [n] = 10$–12 and "short" – when $n < [n] = 10$–12.

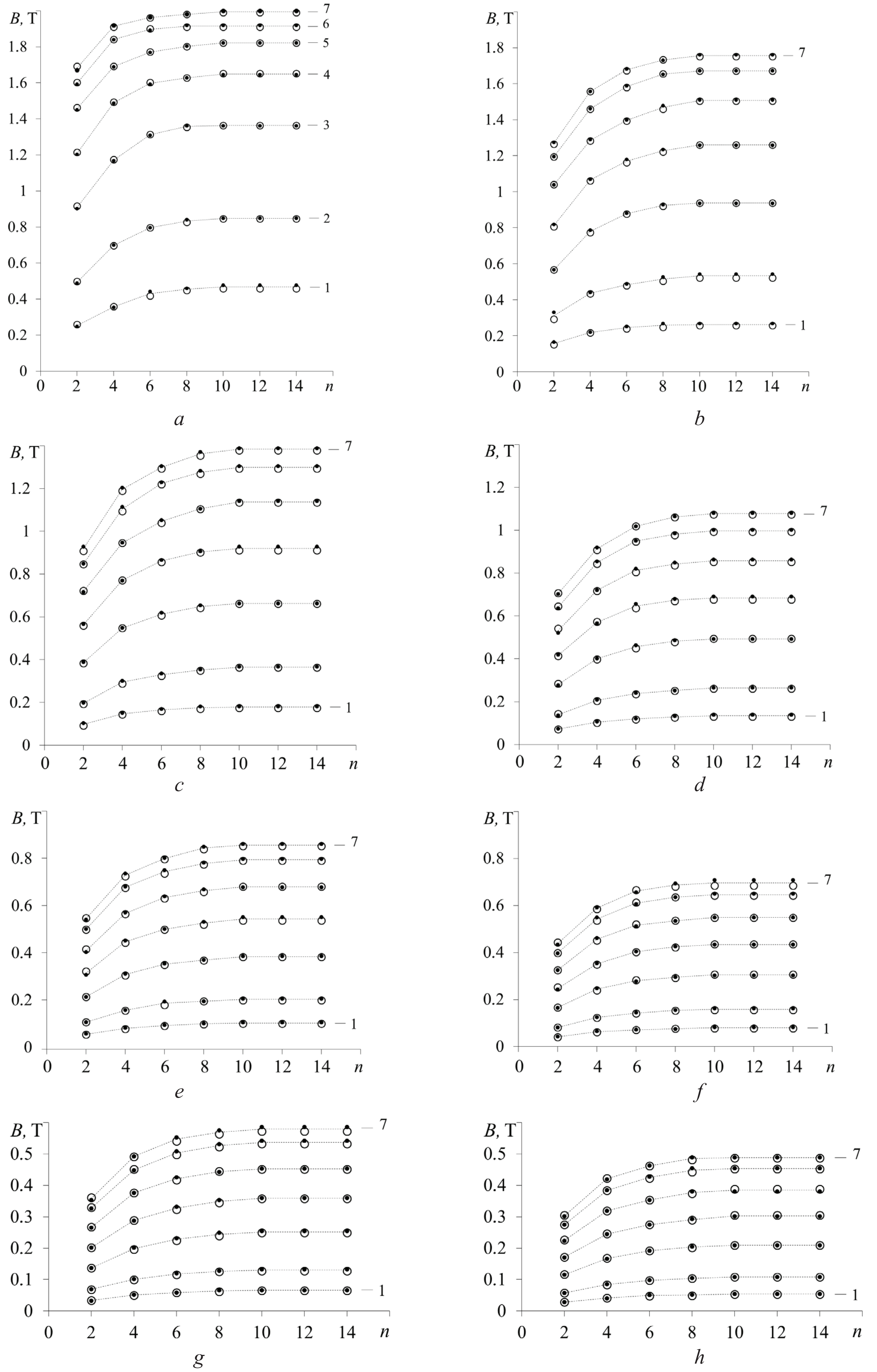


Figure 2 – Magnetic flux density in quasi-continuous cores of a chain of spheres, different in relative radius *r/R*, depending on the number *n* of spheres; *a* – *r/R* = 0.2; *b* – *r/R* = 0.3; *c* – *r/R* = 0.4; *d* – *r/R* = 0.5; *e* – *r/R* = 0.6; *f* – *r/R* = 0.7; *g* – *r/R* = 0.8; *h* – *r/R* = 0.9; 1 – magnetic field strength *H* = 4.8 kA/m; 2 – 10 kA/m; 3 – 20 kA/m; 4 – 29.7 kA/m; 5 – 39.5 kA/m; 6 – 48.7 kA/m; 7 – 54.5 kA/m; designations • and ○ are spheres with radius *R* = 15 mm and *R* = 20 mm, respectively

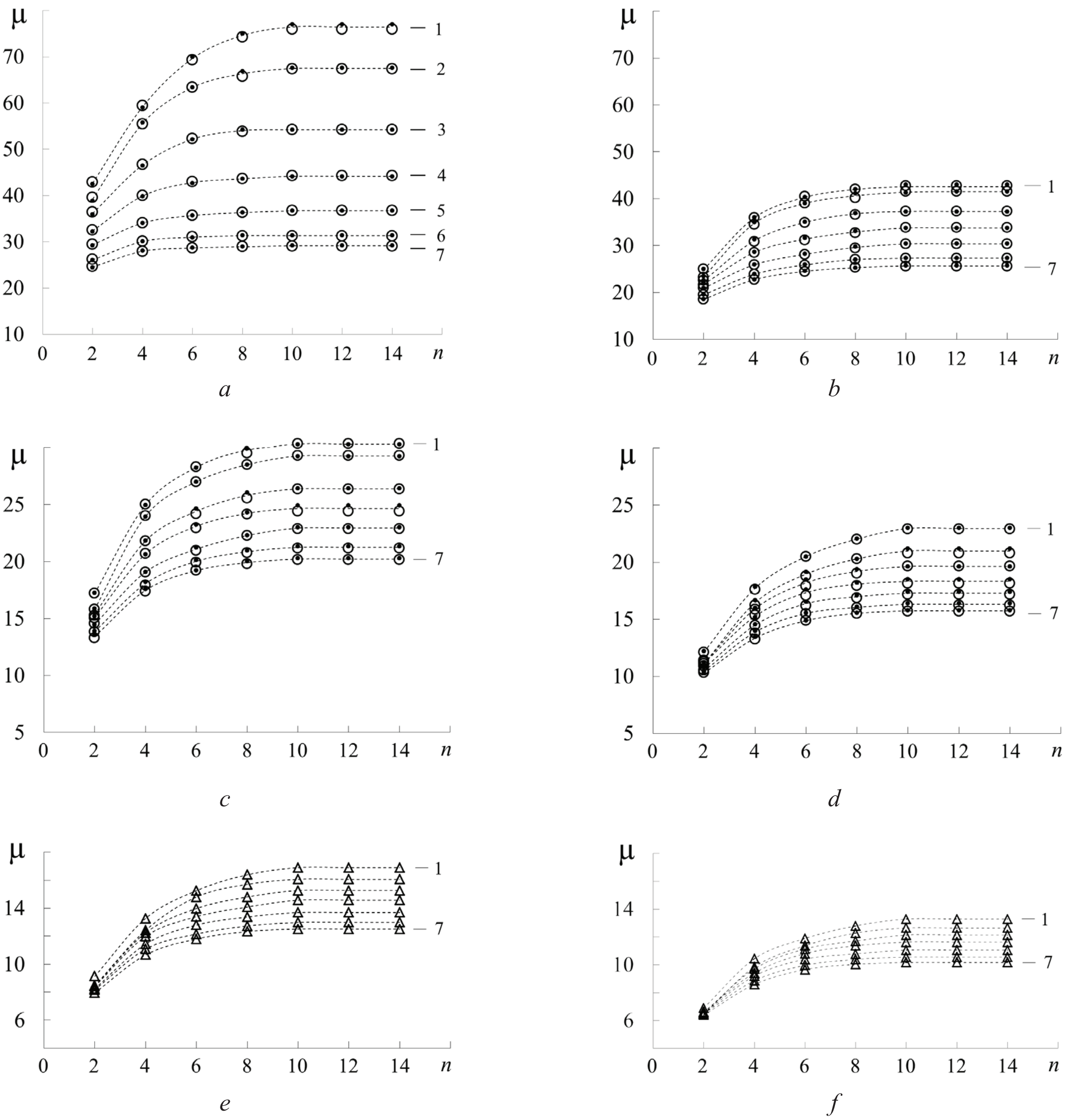
Mentioned specifics, including the fact of the manifestation of self-similar regions, which are fundamental here, were also valid with respect to other key magnetic parameters: magnetic permeability μ of the cores of chains of spheres (Figure 3), the magnetic susceptibility χ (Figure 4) and their magnetization M (Figure 5). The following relations were used to determine the values of μ, χ and M:

$$\mu = \frac{B}{\mu_0 H}; \tag{2}$$

$$\chi = \frac{\mu}{\mu_{N\to 0}}\left(\mu_{N\to 0} - 1\right); \tag{3}$$

$$M = \chi H, \tag{4}$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is magnetic constant; $\mu_{N\to 0}$ and $\chi_{N\to 0}$ are attainable limit individual values (in the corresponding self-similar region – according to Figures 3 and 4: at $n \geq [n] = 10$–12) magnetic permeability and susceptibility. Regarding the relationship (3), that is nonspecific and rarely appears in the literature, it was valid precisely with respect to "short" magnets (including the cores of chains studied here as quasi-continuous magnets). This was so because the parameters of susceptibility and permeability of the "short" and "long" magnets were, as is known, in the ratio $\chi/\chi_{N\to 0} = \mu/\mu_{N\to 0}$. The use of the well-known classical relation $\chi = \mu - 1$ was valid for a magnet devoid of a demagnetizing factor, for example, a classic toroidal or "long" cylindrical, but for a "short" magnet, this was not correct. Ignoring this circumstance, as, for example, in [14], turned out to be an unjustified simplification and led to the appearance of an error in the corresponding results.



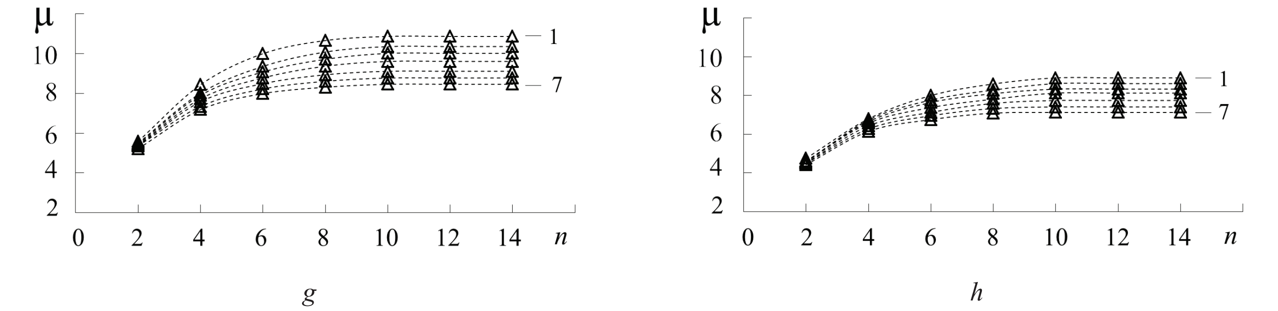


Figure 3 – Magnetic permeability μ of different (by relative radius r/R) quasi-continuous cores of a chain of spheres, depending on the number n of spheres; designations – according to Figure 2 (on *e*, *f*, *g*, *h* the designations Δ are generalized data for R = 15 mm and R = 20 mm); calculations – according to (2)

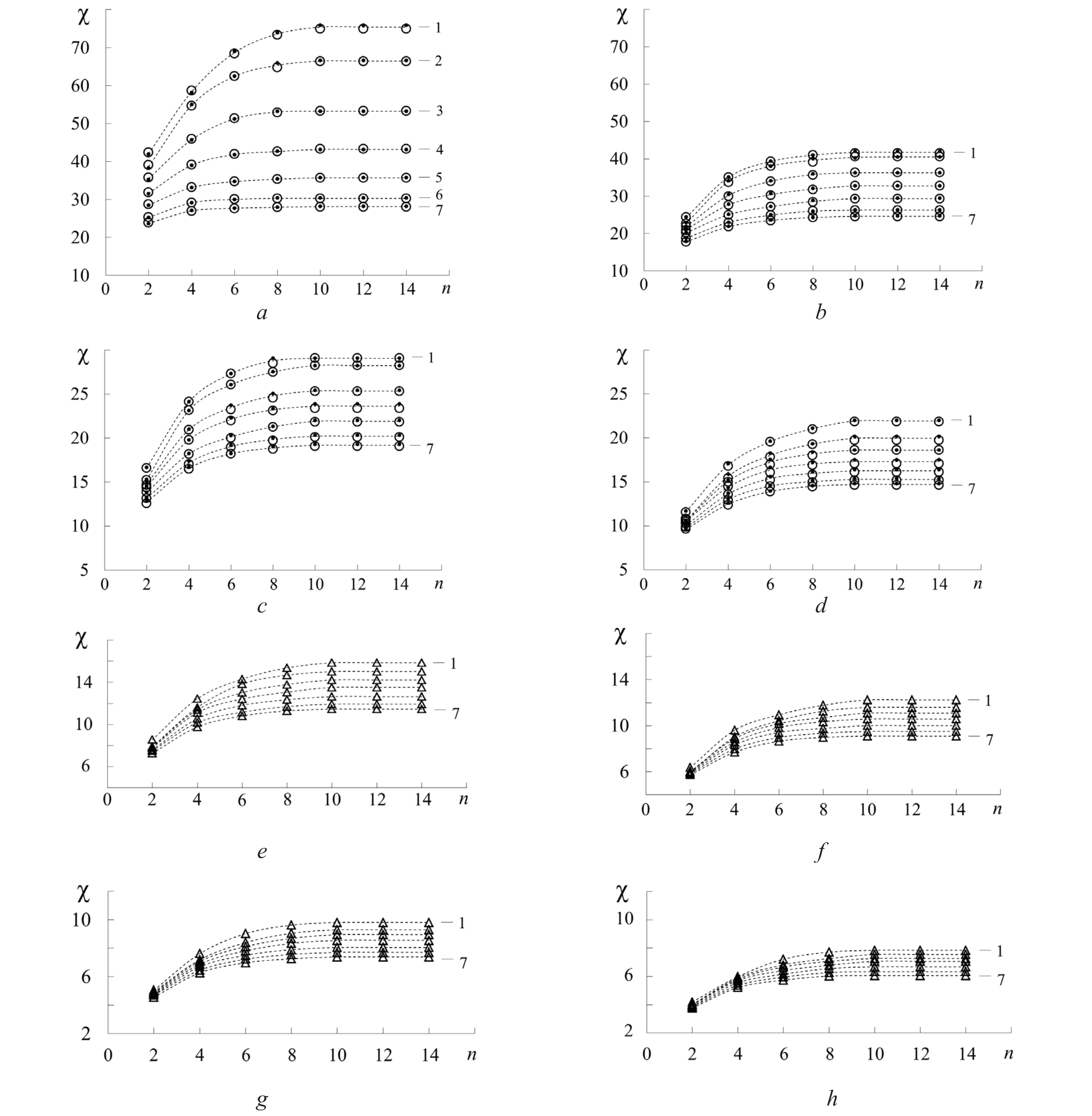


Figure 4 – Magnetic susceptibility χ of different (by relative radius r/R) quasi-continuous cores of a chain of spheres, depending on the number n of spheres; designations – according to Figure 2; calculations – according to (3)

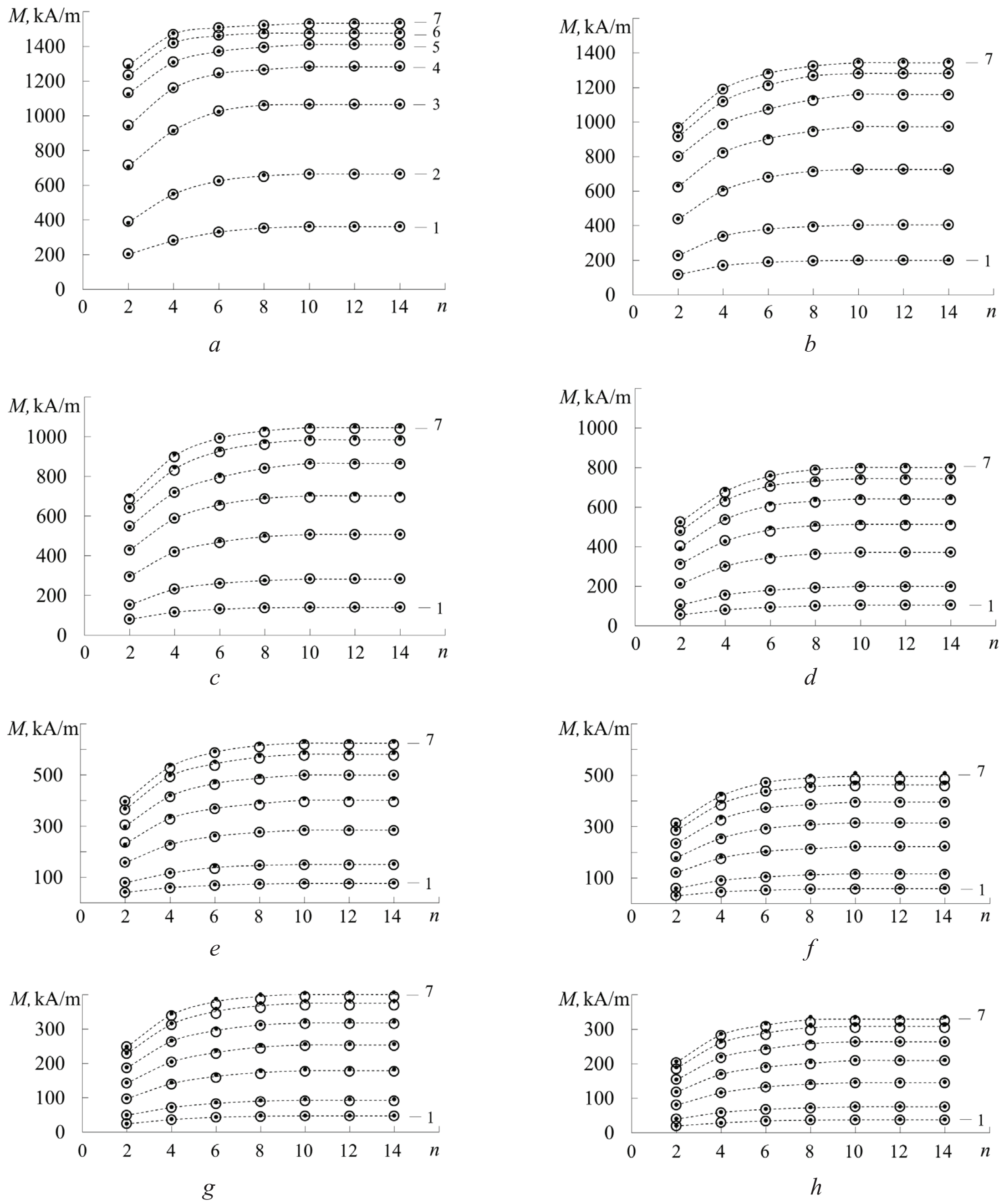


Figure 5 – The magnetization M of different (by relative radius r/R) quasi-continuous cores of a chain of spheres, depending on the number n of spheres; designations – according to Figure 2; calculations – according to (4)

Data of the demagnetizing factor of different cores of "short" chains of spheres. Functional approximation of these data

Figure 4 showed the values of the magnetic susceptibility χ of the cores of "short" chains of spheres with different relative radius r/R. These chains consisted of $n < [n] = 10–12$ spheres: $n = 2$, $n = 4$, $n = 6$, and $n = 8$. The individual limit values of the magnetic susceptibility $\chi_{N\to 0}$ for the cores of a "long" chain of spheres are also given. These chains consisted of $n \geq [n] = 10–12$ spheres. Therefore, it was possible to obtain data on the demagnetizing factor N of the cores of "short" chains, in particular, by the expression:

$$N = \frac{1}{\chi} - \frac{1}{\chi_{N\to 0}}, \quad (5)$$

depending on the number n of spheres in the chain, as in Figure 6a.

Each of the N values here is averaged for the entire studied range of field intensity $H = 4.8$–54.5 kA/m due to the fact that the influence of H (in this range) on the values of N was very weak. Here, in Figure 6*a*, it is shown that as the chain lengthened from $n = 2$ to $n = 8$, the demagnetizing factor N of its cores decreased. The decline was very significant – more than an order of magnitude.

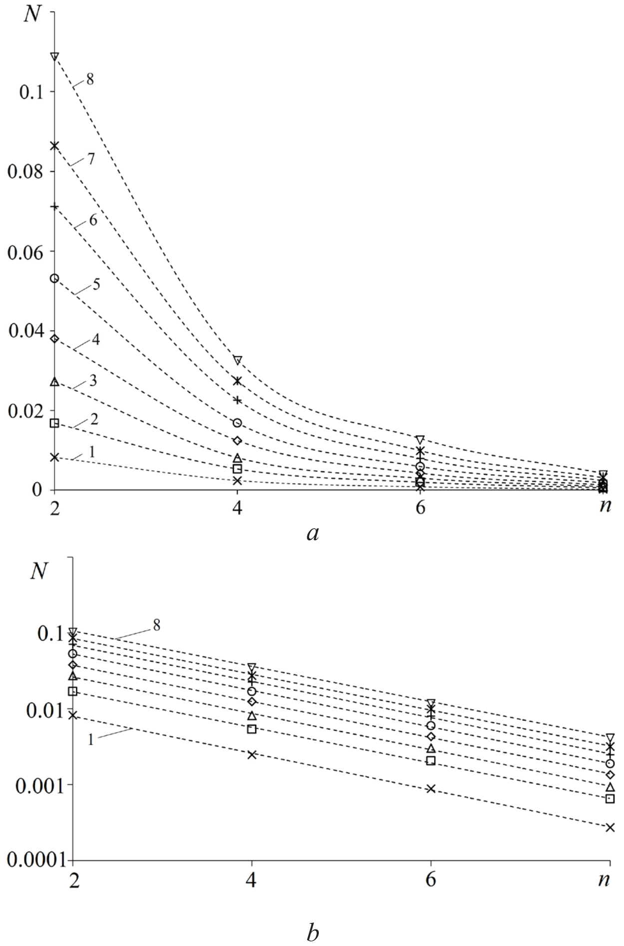


Figure 6 – Data of the demagnetizing factor of different (by relative radius r/R) quasi-continuous cores of a chain of spheres, depending on the number n of spheres: in ordinary (*a*) and semi-logarithmic (*b*) coordinates; 1 – $r/R = 0.2$; 2 – 0.3; 3 – 0.4; 4 – 0.5; 5 – 0.6; 6 – 0.7; 7 – 0.8; 8 – 0.9

The data N established according to (5) (Figure 6*a*) for the cores of "short" ($n < [n]$) chains of spheres succumbed to generalization by a functional (phenomenological) dependence. These data were presented in semi-logarithmic coordinates, as in Figure 6*b*. The fact of their quasi-linearization precisely in such coordinates testified to the exponential relationship between N and n:

$$N = A\exp(-kn), \tag{6}$$

moreover, with a practically constant phenomenological parameter $k = 0.54$. At the same time, the phenomenological parameter A in (6) is quasi-linearized in logarithmic coordinates (Figure 7).

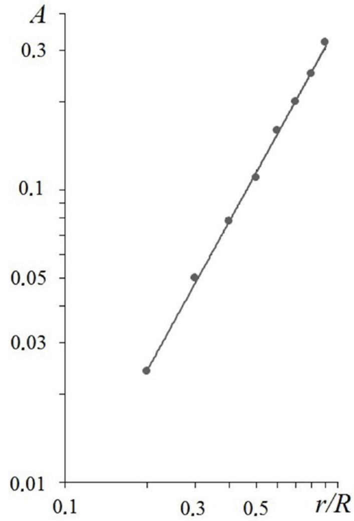


Figure 7 – On the power-law relationship (7) – due to the fact of quasi-linearization of the values of the phenomenological parameter A, which, in accordance with Figure 6*b*, depends on the relative radius r/R of the quasi-solid cores of the chain of spheres, in logarithmic coordinates

The parameter values were individual for one or another core (relative radius r/R). The fact of quasi-linearization of A parameter indicated a power-law relationship $A = a(r/R)^{1.7}$ with the value of the phenomenological parameter $a = 0.37$.

Then, taking into account this connection, expression (6) for the demagnetizing factor N of the cores of "short" ($n < [n]$) chains of spheres took the expanded form:

$$N = a(r/R)^{1.7}\exp(-kn), \tag{7}$$

representing the product of power and exponential functions for the values of the phenomenological parameters $k = 0.54$ and $a = 0.37$ aforementioned. Expression (7) made it possible to determine the demagnetizing factor of any (by the relative radius r/R) "short" core of a chain, i. e. consisting of $2 \le n \le 8$ spheres.

Conclusion

The relevance of direct control of the magnetic parameters of the cores of a chain of granules is noted as one of the basic structural elements of a granular medium (according to the model of its channel-by-channel magnetization). It contained information about the magnetic parameters of a granular medium that was the main working body of fine magnetic separation devices, particularly. For such control, a magnetic (micro) flux sensor Φ was preferable. It consisted of a circular circuit (a block of concentric circuits) on a thin printed circuit board that made it possible to carry out measurements in narrow slotted gaps between contacting granules-spheres. A clear fixation (positioning) of the board between the spheres was provided due to the presence in the board of a mounting hole of a certain diameter, depending on the radius of the spheres and the thickness of the board. In the experiments chains of spheres of different lengths were used, i. e. with a different number n of identical spheres in a chain (moreover, with spheres with a radius of R = 15 mm or R = 20 mm). Based on the results of measuring Φ in one or another core with a radius $r < R$, data on the average induction B in each of the quasi-continuous cores of the chain were obtained as well as data on the magnetic permeability μ and susceptibility χ of these cores, their magnetization M.

The resulting informative families of dependencies made it possible to establish the following. First, the data of the parameters B, μ, χ and M for the cores of chains of spheres with a radius R = 15 mm corresponded to the data of these parameters for the cores of chains similar in relative radius r/R with the same n, but with a radius R = 20 mm. This testified to the possibility of applying the obtained data to similar chains of spheres of a different radius, i. e. about their versatility. Second, the larger was the relative radius r/R of the core of the chain of spheres, the smaller the values of B, μ, χ and M were for it. This was due to a decrease in the proportion of ferromagnetic metal in the core and vice versa. Thirdly, all dependences of B, μ, χ and M (for different cores of the chain of spheres) on n initially increased as n increased due to a decrease in the demagnetizing factor N of each of the cores and the chain as a whole. Subsequently, they demonstrated the achievement of individually limiting values of these magnetic parameters and the corresponding self-similar regions (where $N \to 0$). In this case, the beginning of each of these regions, which manifested themselves almost independently of r/R and the field intensity H, fell on the value n = 10–12 (starting from which $N \to 0$). Thus, such an established, in fact, criterial, value n = 10–12 = [n] made it possible to distinguish both chains of spheres and their cores. The groups were as follows: sufficiently “long” – when $n \geq [n]$ and “short” – when $2 \leq n < [n]$. N data were obtained for different cores of “short” chains of spheres and described by a phenomenological expression. This expression was a product of a power (in r/R) and exponential (in n) functions.

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