Metrological analysis of a magnetometer to measure the magnetization of magnetic nanofluids in strong magnetic fields

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Abstract. The successful application of magnetic nanofluids requires magnetometric instruments for studying their magnetization processes. The paper proposes a design of a mobile magnetometer with Hall sensors, which made it possible to take into account the features of the physical and mechanical properties of a wide range of laboratory and industrial magnetic nanofluids. Permanent magnets made of $SmCo_5$ alloy and magnetic cores made of soft magnetic steel form the device magnetic circuit. Magnetic fluxes add up in a magnetic fluid area and create a uniform field with an intensity up to $(2 \div 4) \cdot 10^5$ A/m. The magnetizing magnetic field intensity and the value of the magnetic field induction in a nanofluid are measured using Hall effect transducers, which are connected oppositely in a single measuring electrical circuit to determine the Hall EMF of the proportional magnetization of the material under study. A circuit method for correcting the non-equipotentiality EMF is used to improve the measurement accuracy. A comparative estimate of the relative error in measuring the magnetization of magnetic nanofluids was less than 2%. It has been established that the magnetometer methodological error is due to the fact that Hall effect transducers do not reflect the field in the substance correctly due to non-magnetic gaps. The device methodical error was estimated by numerical simulation of the magnetic field parameters in a real magnetic system of the MDM-P1 device using the Elcut computer program. Based on the results of a numerical analysis of the device magnetic system model, we have found the dependences of the methodological error in measuring the induction of the magnetic field in the substance and the magnetizing field intensity on the size of non-magnetic cavities in the device magnetic circuit and the magnetic properties of the materials under study. It is shown that the relative methodological error in determining the magnetization of magnetic nanofluids on the MDM-P1 device does not exceed 1%.

1. Introduction
The successful development of new promising magnetic nanofluids for scientific purposes and practical application is impossible without devices that measure their magnetization [1-5]. A distinctive feature of multifunctional magnetic nanofluids as compared to other colloidal materials is their relatively high magnetization. Nowadays, there are no simple design, mobile and accurate instruments that are able to measure the magnetization of magnetic nanofluids in a short period of time at low material cost [6-10]. There is a need for reliable test systems that enable the express analysis of saturation magnetization of magnetic nanofluids.
We propose a design of a mobile magnetometer with Hall sensors for studying the saturation magnetization of magnetic dispersed materials. Hall induction transducers make it possible to take into account the features of the physical and mechanical properties of a different laboratory and industrial magnetic nanofluids. An analysis of the additive and multiplicative components of the MDM-P1 magnetometer instrumental errors proves that high metrological characteristics of the device. However, a preliminary theoretical analysis of the magnetometer methodological error, which had been caused by the imperfection of the methods for measuring magnetic fields in the device, has revealed the need for additional research aimed at clarifying it.

The purpose of the work was to research the metrological analysis of a mobile magnetometer to determine the magnetization of the technical saturation of magnetic nanofluids and to assess the compliance of the device with international standards for magnetic measurements.

2. A device description
The magnetometer circuit is shown in figure 1. The device magnetic circuit is designed to create a uniform magnetic field of strength \((2 \div 4) \cdot 10^5\) A/m in the cuvette zone with the studied magnetic fluid. Permanent magnets made of \(SmCo_5\) alloy (1) together with the adjacent magnetic cores (2) made of soft magnetic steel form two symmetrical magnetic circuits. Magnetic fluxes created by permanent magnets add up in the working gap and double the magnetizing magnetic field strength.

![Figure 1. The diagram of the MDM-P1 device magnetic system.](image)

The cuvette (3) for a magnetic nanofluid (4) has a non-magnetic U-shaped frame made. The two cuvette surfaces facing the magnetic cores are covered with thin copper foil; it is filled with a liquid colloidal medium through the open part of the cuvette. The cuvette is tightly (without air gaps) placed in the magnetic system working cavity and is being magnetized.

A Hall transducer (5) is located under the cuvette with a magnetic nanofluid in its middle section. It is designed to measure the intensity of the magnetizing magnetic field \(H\). The transducer cannot be ruled out because the magnetizing field depends on the magnetic properties of the object under study.

It is known that the normal component of the magnetic field induction \(B\) remains constant when crossing the boundary of two media. If a thin non-magnetic interlayer is between two adjoining magnetic media, then the magnetic induction in it will be almost the same as without the interlayer. Based on this, the second Hall transducer (6) is installed in a rectangular cross-section slot and is located in the center of the cuvette magnetic fluid. Its purpose is to measure the magnetic field induction in a test substance.

The measuring circuit of the installation with Hall transducers includes the transducers themselves, as well as stabilized direct current sources for their power supply and measuring amplifiers in the measurement channels \(B\) and \(H\) (direct conversion schemes). A circuit method for correcting the non-equipotentiality EMF is used to improve the measurement accuracy.

Hall transducers have the same sensitivity and are oppositely connected in a single measuring electrical circuit to determine the Hall EMF proportional to the magnetization of the material under
study. The Hall sensors signal is amplified so that the digital value of the instrument readings is reflected in the absolute values of magnetization.

Initially, before the theoretical assessment of measurement errors, the device was calibrated using magnetic nanofluids with the magnetization previously determined on a precision vibration magnetometer. The relative magnetization measurement error for the device did not exceed 2 % (for magnetic nanofluids with magnetization in the range from 10 kA/m to 50 kA/m).

3. Estimation of the device methodical error using numerical simulation

The device methodical error [11] is associated with the fact that Hall transducers do not quite correctly reflect the field in the substance due to non-magnetic gaps. We solved the problem of calculating the magnetic field parameters in the real MDM-P1 device magnetic system (figure 1) numerically using the Elcut computer program [12] that was created for 2D finite element modeling and engineering analysis. The finite element method, in comparison with other numerical methods, makes it possible to solve nonlinear magnetostatics problems with high accuracy.

The first stage of solving the problem involves creating a flat geometric model of the studied magnetic system, which is shown in figure 2. A real magnetic system consists of two parts symmetric with respect to plane passing through the working gap center. Therefore, the geometric model reproduces only one of these parts to optimize the calculation process.

The next stage solves the problem through describing the medium properties in the corresponding blocks, indicating the field sources, and determining the boundary conditions. The field source is a KS37 permanent magnet made of $SmCo_5$ alloy with the properties (demagnetization curve) taken from [13]. A magnetization curve is set for magnetic cores made of steel (Steel 20). The objects of study are three magnetic nanofluids with magnetizations of 10, 30 and 50 kA/m, as well as a material with a high magnetization $13 \cdot 10^5$ kA/m that is Sch 24-44 cast iron for comparison. For the latter materials, it is enough to set the magnetization value and the corresponding magnetic field values in the saturation magnetization area. For the boundaries separating areas with different magnetic properties and for the outer boundary of the model, we set the Dirichlet or Neumann conditions. When the model properties

![Figure 2. The geometric model of a magnetic system with a finite element mesh.](image-url)
and the boundary conditions are specified, we build a mesh of triangular finite elements (see figure 2) and calculate the model.

Figure 3 presents the graphs showing the change in the magnetizing field in the working air gap along and across the lines of force (the origin is the center of the working gap). The magnetic field strength in the gap center (measuring cell) is 419 kA/m and significantly exceeds the field value required for magnetization to saturation of soft magnetic materials. The magnetic field strength in the longitudinal direction passes through a maximum in the gap center; in the transverse direction there is a minimum of strength in the center. The magnetic field inhomogeneity in the device working gap is \( \Delta H/H < 0.1\% \), which is much less than the permissible value equal to 1 % according to international standards for magnetic measurements. As applied to magnetic nanofluids, high field uniformity is necessary to exclude redistribution over the volume of dispersed magnetic particles under the action of magnetic forces, the magnitude of which is proportional to the magnetic field gradient.

A consequence of the high uniformity of the magnetizing magnetic field intensity is good uniformity of the magnetic field induction along the sample under study (see figure 4). For strongly magnetic materials (cast iron), the magnetic field induction inhomogeneity reaches 0.3 %, and for feebly magnetic materials (magnetic nanofluid), it is 0.1 %.

**Figure 3.** The change in the magnetic field strength in the working gap of the device magnetic system (counting from the working gap center): 1 – along the lines of force, 2 – across the lines of force.

**Figure 4.** The change in the magnetic field induction in the cast iron sample (along the lines of force).

Taking into account the small magnetization inhomogeneity of the materials under study in a magnetic field, all subsequent errors in determining magnetic characteristics were carried out for the material in the center of the magnetic nanofluid in the cuvette.

Measurements of the magnetic field induction in a substance are made using a Hall transducer installed in the magnetic circuit groove opposite the sample center. The non-magnetic cavity formed by the groove distorts the initial magnetic field topography, and this leads to a methodological error in the magnetization measurement. Hall transducers located in the groove record the underestimated value of the magnetic induction.

In addition, we studied the methodological error of measuring the magnetic induction depending on the groove transverse dimensions. Figure 5 shows the graphs of the relative error of the magnetic field induction \( \Delta B/B \) depending on the groove depth \( h \) for two groove width values. The magnitude of the error \( \Delta B/B \) increases sharply with increasing groove depth. Hence it becomes clear that with a constant groove depth equal to the Hall transducer thickness, the groove width should be increased up to the sample width (curve 2 in figure 5 reflects this case) or special thin-film Hall transducers should be used. It is especially important to choose the correct size of the groove when studying the properties of strongly
magnetic materials (see figure 5). The non-magnetic gap in the device magnetic circuit, which is formed by the cuvette copper wall, introduces a separate error in measuring \( B \) in the substance. Figure 5 (curves 1, 2) shows the graphs of the \( \Delta B / B \) error dependence on the non-magnetic gap thickness. The error obviously depends on the saturation magnetization of the material under study. For strongly magnetic materials, the error is a few percent for small gaps; for weakly magnetic materials, it is percent proportions. For example, when measuring the cast iron properties in a chain with a gap of 1 mm, the \( \Delta B / B \) error increases to 11 %, with a 2 mm gap it is 21 %. The area between the lines highlighted in red in figure 5 shows a small spread in the \( \Delta B / B \) error for magnetic nanofluids with magnetization in the range from 10 kA/m to 50 kA/m.

![Figure 5. The dependence of the measurement error of the magnetic field induction in a substance on the air gap size: a is a continuous gap between the magnetic circuit and a magnetic nanofluid sample (1) or a cast iron sample (2); b is the gap between the magnetic core and the cast-iron sample with the Hall transducer groove width \( l = 1 \) mm (3) and \( l = 2 \) mm (4).]

We now turn our attention to the methodological error in determining the strength of the magnetizing magnetic field using a Hall transducer installed under the sample in the middle section plane. As the transducer active zone moves away from the \( l \) sample surface, the relative error of the magnetic field strength \( \Delta H / H \) increases nonlinearly (figure 6). The \( \Delta H / H \) error increase rate depends on the magnetic properties of the sample, but its overall level is not high. The Hall transducers of the PKhE 607 series have their active zone at a distance of 0.5 \( \pm \) 1 mm and therefore the \( \Delta H / H \) error does not exceed 1 %. The curves in figure 5 at \( l = 0 \) mm tend to some finite value other than zero. This is due to the fact that the field strength at the center of the sample is less than at the edge. It should be emphasized that all the calculated data are valid only for the specified shape and size of the samples under study, but the general nature of the dependences is quite universal.

Using the graphs in figure 5 and 6, it is possible to show that the relative methodological error in determining the magnetization of magnetic nanofluids using the MDM-P1 device does not exceed \( \Delta J / J \leq 1 \% \). The small value of the device methodical error indicates that it has a correct design and measurement scheme. The correction factor \( k \) is defined as the ratio of the true magnetization of \( J \) substance to the experimental magnetization \( J_i^* \). The required \( k \) for recalculating the experimental results is \( k \approx 1.01 \).
Figure 6. The error in measuring the magnetic field strength depending on the $l$ distance from the sample to the active zone of the Hall transducer: 1 is cast iron, 2 is magnetic nanofluid.

The data of comparative magnetization measurements using the MDM-P1 device and a vibration magnetometer have shown that this coefficient has a similar value $\approx 1.015$. The given calculated data make it possible to easily estimate the methodological error of any other magnetometer with the same magnetic circuit as that of the MDM-P1 magnetometer under consideration. The obtained results show that the magnetometer can be used to study a wide range of materials including new promising magnetorheological fluids with magnetization up to $600$ kA/m [14–17].

4. Conclusion

There is a description of the developed principle measuring circuit and a design of a portable device for express measurements of magnetization of all existing laboratory and industrial magnetic nanofluids. It was found that the device has high metrological indicators, which enables accurate measurements of magnetization with low costs of the material under study. The results of a numerical analysis of the device magnetic system model give the dependences of the methodological error in measuring the magnetic field induction in the substance and the magnetizing field intensity on the size of non-magnetic cavities in the device magnetic circuit and the magnetic properties of the materials under study. It is confirmed that the magnetic field affecting the material samples under study has a high degree of uniformity. It is shown that the described magnetometer might become a good basis for developing sufficiently accurate instruments to measure the magnetization of strongly magnetic materials, for example, magnetorheological fluids.

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