APPARATUS AND DEMONSTRATION NOTES

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Assembling a magnetometer for measuring the magnetic properties of iron oxide microparticles in the classroom laboratory

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A compact magnetometer, simple enough to be assembled and used by physics instructional laboratory students, is presented. The assembled magnetometer can measure the magnetic response of materials due to an applied field generated by permanent magnets. Along with the permanent magnets, the magnetometer consists of two Hall effect-based sensors, a wall-adapter dc power supply to bias the sensors, a handheld digital voltmeter, and a plastic ruler. Here, a project-based exercise is described, where the objectives are as follows: (i) assemble the magnetometer, (ii) measure the magnetic response of the iron oxide microparticle sample, and (iii) obtain the magnetization of the sample from the measurements.

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I. INTRODUCTION

The Magnetic Properties of Materials (MPM) is a topic studied in most of Electromagnetism physics courses. However, most of these courses do not have an associated laboratory section, often due to budget or technical reasons. With the view that experiments are essential to improving the understanding of MPM, we designed a compact magnetometer to measure these properties. Our instrument is simple enough that undergraduate students can assemble and operate it at an instructional laboratory workbench with minimal supervision. Although the term *magnetometer* commonly is used to describe an instrument that simply measures magnetic fields,[1] this same term also refers to a more complete instrument, which is capable of measuring magnetic fields as well as obtaining the magnetic properties of a material. Recently, magnetometers aimed at undergraduate instructional laboratories have been described.[2–4] However, these instrumental designs include a bulky electromagnet and a lock-in amplifier for readout, thus limiting their appeal for use in instructional laboratories. The motivation of this work is to provide an accessible means by which students can conduct a quantitative magnetometer-based experiment to obtain the magnetic properties of a ferromagnetic material.[5]

Simple technology was intentionally used in the design of our magnetometer, so that students can understand every step of the measurement process. Our instrument is composed of two Hall effect sensors,[6] two NdFeB permanent magnets, a linear track, a handheld multimeter, a wall-adapter dc power supply, and a plastic ruler. For our investigation, an iron oxide microparticle sample was chosen, since this material is easily manipulated, inexpensive, and readily available. More importantly, these microparticles exhibit desired magnetic features such as saturation, remanence, and coercivity within our magnetometer measurement range and sensitivity. Furthermore, a comprehensive set of publications exists on iron oxide microparticles, and this material has all sorts of interesting industrial and biomedical applications.[7]

In this paper, a project-based exercise is described with the following three steps: (i) assembling the magnetometer, (ii) measuring the magnetic response of an iron oxide microparticle sample, and (iii) obtaining the magnetization of the sample from the measurements. At our institution, the project is executed in groups. Students are asked to research beyond the provided instructional materials, i.e., perform literature searches for datasheets and relevant journal papers. In the course of the project, each group acquires, organizes, and analyzes data. Each group then presents its results and compares them with the results of other groups in the classroom.

This hands-on exercise provides students with a different educational experience than in the lecture classroom. Characterizing the magnetic response of a material is a delicate measurement and, as with all measurements, has associated errors. During this process, students may find that many things do not work out as expected. As they work towards making good measurements, students may come to appreciate the value of patience and persistence.

Table I. Magnetometer components (refer Fig. 1 for labels).

Label	Component
1	Linear track, 45 mm × 45 mm 4-slot extruded aluminum, 450 cm long (Bosch Rexroth Corp./Part No. 8981004773)
2	Two "profiles," 10 cm long pieces of linear track, to position magnets (with slots 10 mm deep and 20 mm wide)
3	Two nylon threaded rods, 20 mm diameter and 4.0 mm pitch
4	Two nylon threaded nuts to keep the magnets at chosen distances from the sample
5	Two 40 mm × 20 mm × 10 mm NdFeB magnets, grade N42 (Neomagnete/Part No. Q-040-020-10 N)
6	Two acrylic pieces to support the magnets and threaded rods on top of the track
7	A 40 cm plastic ruler to record magnet positions
8	Acrylic "support," 45 mm × 45 mm × 6.0 mm plate with two 5.1 mm perpendicular slots
9	Acrylic "sample holder," 5.0 mm × 5.0 mm × 50 mm slab with a cylindrical cavity of diameter 3.0 mm, depth 3.0 mm near one end
10	Two Hall-based sensors (MLX-90215, Melexis Inc.), programmed with different sensitivities
11	5.0 Vdc, 100 mA wall-adapter power supply
12	Handheld multimeter
13	Melexis PTC-04 Programmer

II. ASSEMBLING THE MAGNETOMETER

The 12 components of the magnetometer are listed in Table I and are shown in Fig. 1. The first portion of our project consists of assembling the magnetometer as shown in Fig. 2(a) and measuring the applied field. In order to increase the applied field, the two magnets should be mounted such that one has its north pole and the other has its south pole facing the sample. This configuration is shown in Fig. 2(b), where the arrows indicate the sliding direction. Figure 2(c) displays details of the acrylic support, sample holder, and Hall sensors. Behind the sample holder, notice how screws and nuts (not shown in Fig. 1) hold the magnets fastened to the sliding profile. The two Hall sensors are mounted perpendicular to each other on the acrylic support, one for detecting the magnetic induction from the sample and the other for detecting the applied field. The sensors are labeled D_1 and D_2, respectively, in Fig. 2(c). The MLX-90215 was chosen from the Hall sensors available commercially because it is extremely versatile. This device contains a 0.2 mm × 0.2 mm Hall effect sensing element and an amplifier with programmable gain and offset; it has a ratiometric analog output. Once biased at 5.0 V, with no applied field, the MLX-90215 outputs 2.5 V. Magnetic fields entering the branded face of the sensor generate voltages between 2.5 and 5.0 V. Magnetic fields leaving the branded face generate voltages between 2.5 V and zero. The sensitivities of D_1 and D_2 were adjusted to about 60 and 3.0 mV/mT, respectively, using auxiliary calibration electronics (Melexis PTC-04 programmer).

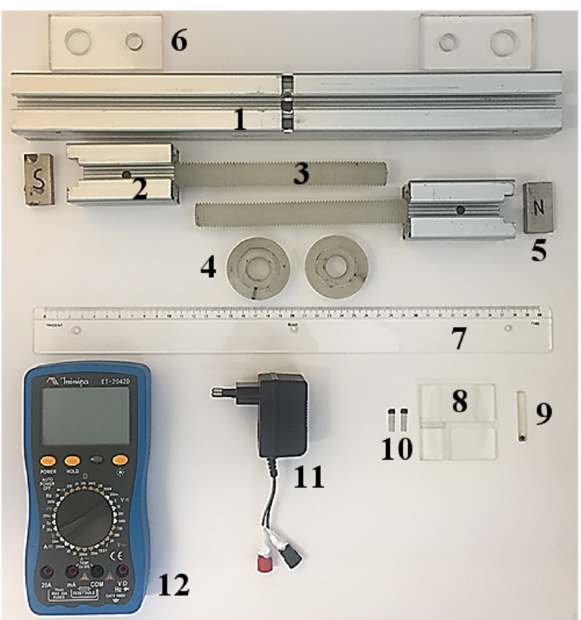

Fig. 1. Components of the magnetometer. A complete component list and labeling scheme are given in Table I.

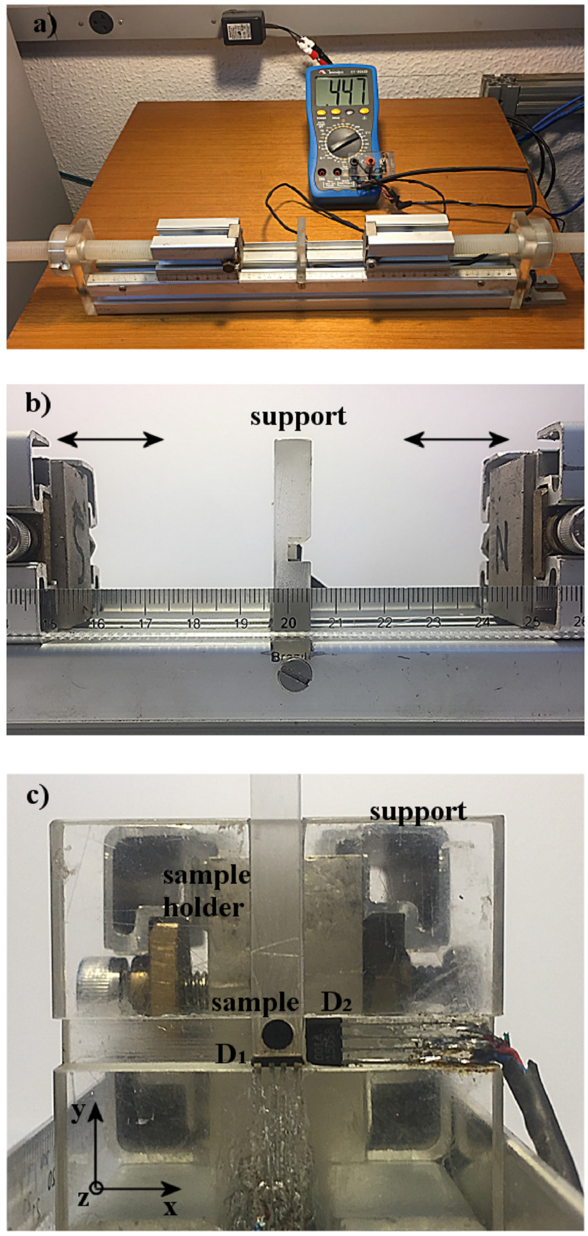

Fig. 2. (a) Assembled magnetometer; (b) details of the permanent magnets, acrylic support, and linear track; (c) details of the sample holder and the two Hall sensors (D_1 and D_2). The coordinate system used in the measurement is also shown.

We suggest giving the unassembled components of the magnetometer to a group of two students as shown in Fig. 1, together with two pairs of screws and nuts to secure the magnets. The sample holder and the iron oxide microparticles can be left aside at this point. Then, with Figs. 2(a)–2(c) made available, the students assemble the magnetometer. Besides the assemblage, the students can be tasked with finding the north and south pole of each magnet, so the magnets can be mounted appropriately in the profiles. Students can also be asked to correctly identify which Hall sensor is D_1 (60 mV/mT) and which is D_2 (3.0 mV/mT). If the PTC-04 programmer is made available, the Hall sensors can be bought unprogrammed and left for the students to program the sensitivity of these devices. For a challenging problem, students can be asked to determine the appropriate sensitivity for each sensor (with the reminder that at zero field, the multimeter reads 2.5 V). Appropriate gloves and glasses should be provided, since the magnets are strong and can hurt (e.g., sandwich fingers) if handled incorrectly.

Once the magnetometer is assembled, the range of magnetic fields it can apply to a sample is determined as follows. With the Hall sensor mounted on the acrylic support at the center of the linear track and the magnets on the sliding profiles, we measure the magnetic field as the magnet-sensor distance is decreased from 60 to 5.0 mm in 1.0 mm steps. Then, we measure the field as the magnet-sensor distance is increased back to 60 mm. In addition, in order to invert the applied field to obtain the coercivity of the material, the magnets should be flipped in their mounts (i.e., turned by 180° so that their field polarity is reversed) and the magnetic field should be measured as the magnet-sensor distance is decreased from 60 to 20 mm in 1.0 mm steps. Signals from D_1 and D_2 as the magnets approach the sensors are shown in Fig. 3. (We only show this figure to students at the end of the experiment when the comparison of results among group is being made.) In gathering these data, students will naturally ask why the signal from D_2 is not always exactly zero. The answer is that in the real world, *perpendicular* can only be approximated. Thus, if sensor D_1 has a small perpendicular component to the applied field, it will report a non-zero reading.

III. MEASURING THE MAGNETIC RESPONSE

Next, the cylindrical cavity of the sample holder is completely filled with iron oxide microparticles. The weight of the microparticles should be determined so that the sample density can be calculated. The microparticles that we use (Supermagna Magnetic Particle RW-222, Metal-Chek do Brasil, Ltda.) are shown in Fig. 4. According to the manufacturer's datasheet, these microparticles have sizes up to 44 μm and are commonly used in industrial nondestructive inspection to find small cracks in magnetic parts.[8] At the top of Fig. 4, the sample holder is shown with its cylindrical cavity filled with microparticles. The cavity holds about 15 mg of microparticles and, once filled, should be closed with a strip of adhesive tape.

Figure 5 shows a detailed view of the sample holder when placed on the acrylic support. Notice that the Hall element within sensor D_1 is placed at the back edge of the sample holder, so as to maximize the vertical component detection of the stray field generated by the sample. Students can be tasked with finding the exact position by checking the sensor's datasheet.

When a magnetic field is applied to a material, the magnetic induction $\vec{B}_{out}(x,y,z)$ measured outside the material is a function of the applied field, the material's magnetic response, and the measurement position relative to the sample. Thus,

$$\vec{B}_{out}(x,y,z) = \mu_0\left[H_{app}(x,y,z) + H_{stray}(x,y,z)\right], \tag{1}$$

where μ_0 is the permeability of free space, $H_{app}(x,y,z)$ is the applied field, and $H_{stray}(x,y,z)$ is the magnetic contribution of the material.

When placing the sample holder in the support, both the permanent magnets should be positioned as far away as possible from the sample. Next, the same measurement procedure done in Sec. II is repeated, so as to expose the sample to the applied field. Sensor D_1 should read the same as before but D_2 should read the contribution of the sample as well as some of the applied field displayed in Fig. 3. In order to obtain $\mu_0 H_{stray}(x,y,z)$, the first (without sample) D_2 measurement should be subtracted from the second (with

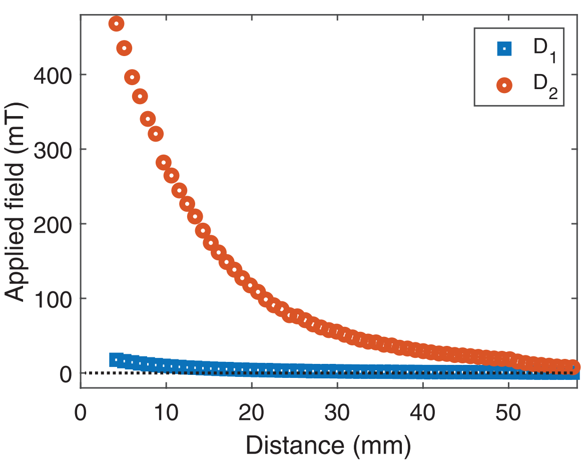

Fig. 3. Field generated by both the permanent magnets detected by sensors D_1 and D_2. The distance from each magnet to the center of the track varies from 59 mm to 5.0 mm in 1.0 mm steps.

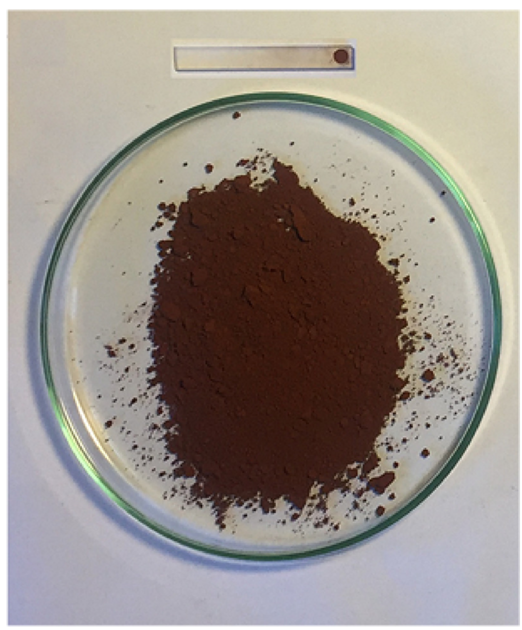

Fig. 4. Iron oxide microparticles with sizes up to 44 μm. At the top of the figure, the sample holder is shown carrying microparticles inside a cylindrical cavity of diameter 3.0 mm and depth 3.0 mm.

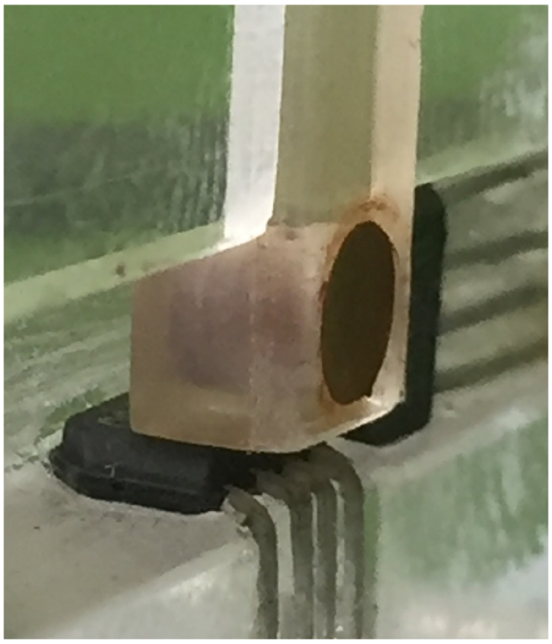

Fig. 5. Detailed view of the sample holder and sensor D_1. The Hall element inside D_1 is at the edge of the sample holder so as to maximize the vertical component detection of the stray field generated by the sample.

sample) D_2 measurement. The result of the subtraction is shown in Fig. 6. The stray magnetic induction due to the sample against the applied field is shown in milliTesla (mT). In the figure, the triangles pointing upward mean that the applied field is increasing (magnets moving towards the sample) and triangles pointing downward mean that the applied field is decreasing (magnets moving away from the sample). The average error bar corresponds to 0.15 mT.

Note that for applied fields bigger than 200 mT, the rate of change in the magnetic response against the applied field is drastically reduced. When the applied field is doubled, increasing to 400 mT, the stray field only increases about 1.0%. The magnitude of the saturation stray field is 3.4 mT. This field value is not a material property; it depends on the material magnetization but also on the sensor measurement position relative to the sample. Nevertheless, since the measurement position is not changed, it shows that, even when the applied field doubles, the material magnetic response stays about the same, indicating that the material is magnetically saturated. The inset of Fig. 6 displays a zoomed view, where a hysteretic response can be clearly seen. When the applied field is zero, there is a remanent field of about 0.4 mT. When the applied field is reversed, a coercive field of about −8.0 mT is measured. The coercive field is the field that must be applied to the sample to coerce its magnetic response to zero. This quantity is a property of the material, since it is independent of the measurement position and is evidence of a hysteretic response.

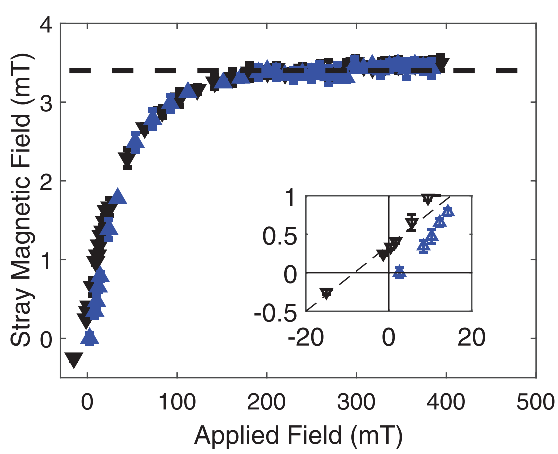

Fig. 6. Magnetic stray field as a function of the applied field. The sample contains about 16 mg of iron oxide microparticles with sizes up to 44 μm. Saturation and hysteresis can be seen in the inset. Triangles pointing upward (downward) indicate that the applied field is increasing (decreasing).

IV. OBTAINING THE MAGNETIZATION

The last portion of the project is a challenging exercise as it applies an abstract model to determine the material properties inside the sample. No new measurements are made; this exercise is the analysis of the data already collected.

The simplest model for our sample's magnetization assumes that a magnetic dipole is located at the center of the cylindrical cavity packed with iron oxide microparticles. A schematic drawing of this model is displayed in Fig. 7, where the magnetic moment $\vec{m}$ of the dipole is represented as a thick arrow. While carrying out this exercise, the instructor can lead a discussion on other possible models for a magnetic source given the size and shape of the sample.[9–11]

When a magnetic field is applied to a material, the magnetic induction inside it is given by

$$\vec{B}_{in} = \mu_0(\vec{H}_{in} + \vec{M}), \tag{2}$$

where $\vec{H}_{in}$ is a portion of the applied magnetic field that penetrates the material and $\vec{M}$ is the volume magnetization, i.e., the material response. The volume magnetization is defined as the magnetic moment of the sample divided by its volume.[12] Some approximations are made in order to use the magnetic dipole model: the sample is considered homogeneous and the

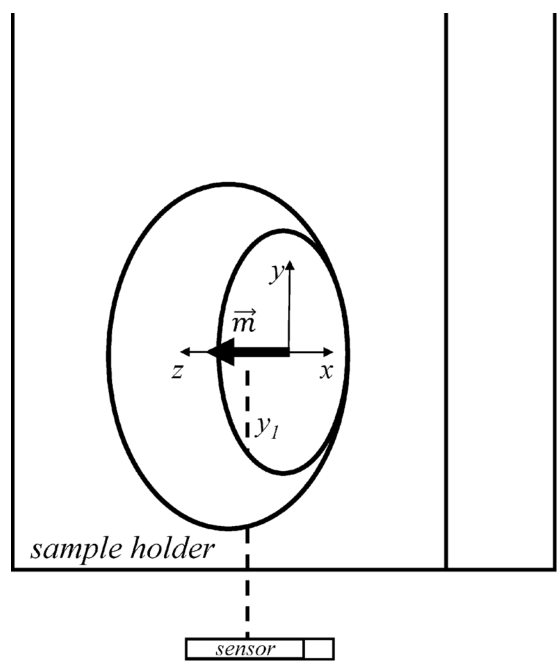

Fig. 7. The sample modeled as a single magnetic dipole, with magnetic moment $\vec{m}$, located at its center. The vertical distance from the sensor to the magnetic dipole is y_1.

fact that measurements are made very close to the sample is neglected. The field generated by a magnetic dipole depends on its magnetic moment $\vec{m}$ and the position $\vec{r}$ where the field is measured. Defining the origin of our coordinate system at the dipole position (i.e., the center of the cylindrical cavity), the dipole field generated is given by[13]

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\left[\frac{3(\vec{m}\cdot\vec{r})\vec{r}}{r^5} - \frac{\vec{m}}{r^3}\right]. \tag{3}$$

In this coordinate system, our setup applies a magnetic field along the z-axis and detects the y-component of the sample's stray field. Thus, in terms of the model, the sample generates a magnetic induction at the sensor given by

$$B_{y\,stray}(x_1, y_1, z_1) = \frac{3}{4\pi}\mu_0 m_z\left[\frac{y_1 z_1}{(x_1^2+y_1^2+z_1^2)^{\frac{5}{2}}}\right], \tag{4}$$

where x_1,y_1, and z_1 are the position coordinates of the Hall element inside D_1. Students should be encouraged to obtain Eq. (4) from Eq. (3) by considering the appropriate component of the magnetic induction detected by the sensor and also the component of the magnetic moment generated in the material by the applied field. Assuming a cylindrical geometry for the sample with radius a and length $2\,a$, the volume magnetization z-component can be written as $M_z = m_z/(2\pi a^3)$, yielding

$$B_{y\,stray}(x_1, y_1, z_1) = \frac{3}{2}\mu_0 a^3 \frac{y_1 z_1}{(x_1^2+y_1^2+z_1^2)^{\frac{5}{2}}} M_z. \tag{5}$$

With the aid of a digital caliper and using the sensor datasheet, the relative distances between the center of the sample holder (dipole position) and the position of the Hall element within sensor D_1 were obtained as follows: $x_1 = 0.0$ mm, $y_1 = 2.5$ mm, and $z_1 = 2.0$ mm. Students should measure the actual distances and consult the sensor datasheet. Using a equal to 1.5 mm, the following linear relation between the volume magnetization and the stray field can be obtained:

$$M_z = \frac{13.3}{\mu_0} B_{y\,stray}, \tag{6}$$

where $B_{y\,stray}$ is given in Tesla and M_z in A/m. From the saturation stray field measurement in Fig. 6 (3.4 mT), the sample saturation magnetization of about 36 kA/m is obtained using Eq. (6). From the measured remanent stray field (0.4 mT), the remanent magnetization for the iron oxide microparticles of 4.2 kA/m is obtained using the same equation. The literature results for pure bulk magnetite show the coercive field as −10 mT, similar to the value that we obtain, and the saturation and remanent magnetizations as 480 and 50 kA/m, respectively.[14] Note that the magnetization values of pure magnetite differ by 1 order of magnitude from the values that we find. This difference can be explained by noting that RW222 is a generic iron oxide (i.e., not pure magnetite) and that the density of our sample (760 kg/m^3) is about 7 times less than the density of pure magnetite.

V. CONCLUSION

The construction of a simple magnetometer using permanent magnets and Hall effect based sensors, suitable to be assembled and used on an instructional laboratory workbench, was demonstrated. In our project, the magnetometer is first assembled. The assembled magnetometer then is used to measure the magnetic response of iron oxide microparticles to an applied field, demonstrating the magnetic properties such as saturation, remanence, and coercivity. We find that the applied field needed to saturate our sample is about 200 mT, and the coercive field is −8.0 mT. Finally, the acquired data are analyzed based on a magnetic dipole model for magnetization. A saturation magnetization of 36 kA/m and remanent magnetization of 4.2 kA/m are obtained for our sample.

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