

Artifacts in magnetic measurements of fluid samples

Z. Boekelheide and C. L. Dennis

Citation: AIP Advances **6**, 085201 (2016); doi: 10.1063/1.4960457 View online: http://dx.doi.org/10.1063/1.4960457 View Table of Contents: http://scitation.aip.org/content/aip/journal/adva/6/8?ver=pdfcov Published by the AIP Publishing

Articles you may be interested in

Spherical sample holders to improve the susceptibility measurement of superparamagnetic materials Rev. Sci. Instrum. **83**, 045106 (2012); 10.1063/1.3700185

Optimization of the first order gradiometer for small sample magnetization measurements using pulse integrating magnetometer Rev. Sci. Instrum. **80**, 104702 (2009); 10.1063/1.3239404

Design of a compensated signal rod for low magnetic moment sample measurements with a vibrating sample magnetometer Rev. Sci. Instrum. **79**, 035107 (2008); 10.1063/1.2901602

Vector vibrating-sample magnetometer with permanent magnet flux source J. Appl. Phys. **99**, 08D912 (2006); 10.1063/1.2170595

Anisotropy characterization of garnet films by using vibrating sample magnetometer measurements J. Appl. Phys. **93**, 7065 (2003); 10.1063/1.1540142





Artifacts in magnetic measurements of fluid samples

Z. Boekelheide^{1,2,a} and C. L. Dennis^{1,b} ¹Material Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA ²Department of Physics, Lafayette College, Easton PA 18042, USA

(Received 7 August 2015; accepted 24 July 2016; published online 1 August 2016)

Applications of magnetic fluids are ever increasing, as well as the corresponding need to be able to characterize these fluids *in situ*. Commercial magnetometers are accurate and well-characterized for solid and powder samples, but their use with fluid samples is more limited. Here, we describe artifacts which can occur in magnetic measurements of fluid samples and their impact. The most critical problem in the measurement of fluid samples is the dynamic nature of the sample position and size/shape. Methods to reduce these artifacts are also discussed, such as removal of air bubbles and dynamic centering. © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). [http://dx.doi.org/10.1063/1.4960457]

I. INTRODUCTION

Magnetic micro- and nanoparticles dispersed in fluids have many applications including damping in vehicle suspensions and landing gear,¹ and heat transfer materials.² In biomedicine, they can be used as contrast agents for magnetic resonance imaging (MRI)³ and magnetic particle imaging (MPI),⁴ as well as for magnetic nanoparticle hyperthermia.⁵ Magnetic fluids are even found in art, where they are used in certain art conservation processes.⁶ To optimize their behavior for this wide range of applications, a complete understanding of the magnetic behavior of these fluids is required. Therefore, there is a need for accurate magnetic measurements of magnetic micro- and nano-particles in solution.

The details of the magnetic hysteresis loop (magnetic moment m as a function of applied magnetic field H) can be very different for nanoparticles suspended in a fluid than for dried or immobilized nanoparticles.⁷ Nanoparticles suspended in fluid may rearrange with applied field, forming structures such as chains or loops due to their interaction with neighboring nanoparticles as well as with the applied magnetic field.^{8,9} Nanoparticles may also rotate to align their magnetic easy axis along the direction of the field.⁷ Both effects may change the effective magnetic anisotropy of the macroscopic fluid sample, which in turn affects the shape of the hysteresis loop. To capture these effects in magnetic measurements of fluids, it is necessary to measure the samples in their fluid form ("*in situ*"). Here we report on the magnetic characterization of magnetic micro- and nanoparticles in fluids. We describe artifacts which may arise due to the fluid nature of the samples and suggest methods to avoid them.

II. EQUIPMENT

Instruments for measuring the magnetic moment as a function of applied magnetic field include the alternating field gradient magnetometer (AGFM), the vibrating sample magnetometer (VSM)¹⁰ and superconducting quantum interference device (SQUID) magnetometer.¹¹ While these can be built in-house,¹² they are also commercially available.¹³ These commercial systems are wide-spread, with the measurement techniques and sample holders optimized for solid samples

^aboekelhz@lafayette.edu ^bcindi.dennis@nist.gov

2158-3226/2016/6(8)/085201/13

6, 085201-1

© Author(s) 2016.

like bulk crystals, thin films, and packed powders, but not for fluid samples. As a result, many researchers dry their fluid samples into powders or immobilize them in epoxy or another composite for measurement. Alternatively, some researchers are focused on measuring single nanoparticles with micro-SQUIDs¹⁴ or magneto-optical indicator films.¹⁵ However, these two single-nanoparticle methods are (respectively) limited by their (1) access only to magnetic properties (i.e. saturation magnetization) that do not depend on the presence of the fluid and (2) lack of good ensemble averaging on the effect of interactions on magnetic fluid properties.

To focus on the previously described dynamic effects that arise from magnetic nanoparticles in solution, we have used commercially available magnetometers, not single nanoparticle methods. Specifically, the results presented here are from an MPMS SQUID by Quantum Design and an MPMS3 SQUID-VSM by Quantum Design.¹³ Our results can be extended to other solid-sample magnetometers such as the vibrating sample magnetometer. We have chosen these two instruments to demonstrate the issues with fluid samples due to their access to the raw data which includes centering information.¹³

In all of these magnetometers, a sample is moved through or near a coil of wire. This coil of wire can be made of copper or a superconductor. The changing magnetic field from the sample moving induces a voltage in the coil (Faraday's Law). Figure 1(a) shows the geometry of the superconducting pickup coil which is common to both systems used. This coil configuration (aka a second derivative coil), is designed to eliminate contributions from magnetic fields which are either constant, such as the applied magnetic field, or linear, such as a gradient in the applied magnetic field. Thus, any signal is only due to the 2nd derivative or higher order terms of the changing magnetic field, i.e. the dipole field originating from the magnetic moment of the sample.¹¹

The SQUID and SQUID VSM systems use similar detection coil geometry, but the measurement techniques are quite different. Prior to either measurement, the sample is positioned in the middle of the coils horizontally (x-y plane) and vertically (z-axis). This position is called the "center". In a SQUID measurement, the sample is then stepped vertically through the entire coil and the induced voltage in the coil is measured at each step. This yields the "raw data", an example of which is shown in Figure 1(b). This induced voltage as a function of position f(z) is modeled as a single point dipole:

$$f(z) = P_1 + P_2 z + P_3 \left\{ 2[R^2 + (z + P_4)^2]^{-3/2} \\ -[R^2 + (\Lambda + (z + P_4))^2]^{-3/2} \\ -[R^2 + (-\Lambda + (z + P_4))^2]^{-3/2} \right\},$$
(1)

where the parameters Λ and R refer to the coil separation and radius, respectively, and P_1 , P_2 , P_3 , and P_4 are the four fit parameters of the dipole model. P_3 is the amplitude of the induced voltage, which is proportional to the magnetic moment of the sample, and P_4 is the center position. P_1 is a constant offset and P_2 is a linear offset to account for drift in the SQUIDs.¹⁶

In a SQUID VSM measurement, instead of stepping the sample through the entire coil, which is time-intensive, the sample is vibrated vertically about the center point of the coil with an amplitude of typically a few mm.¹⁷ The amplitude of the induced voltage is proportional to magnetic moment. (This is characteristic of a VSM measurement in general, although the coil configuration is different in an electromagnet-based system.)

In a typical SQUID VSM measurement, the sample center position is determined initially by a measurement similar to a SQUID scan: the vibrating sample is moved through the coils and a single maximum/minimum occurs where the sample is exactly centered between the coils. This center position is used for the rest of the measurement unless it is determined that the sample should be recentered, for example during a measurement that includes a temperature change and resulting change in length of the sample holder rod. "Dynamic centering" occurs when the sample is re-centered prior to every measurement, but requires additional time. Since the induced voltage is maximized at the center position, errors in vertical sample centering lead to a *decrease* in the magnitude of the measured moment. This error varies with the offset from the true center. For



FIG. 1. (a) Schematic of the pickup coil geometry in the SQUID and SQUID VSM systems used, where the arrows indicate direction of current. The orange box indicates the vertical (z-axis) center of the sample. The vertical arrows indicate approximate length and direction of sample travel during a measurement. (b) A typical response of the pickup coil to a single SQUID measurement. Also shown is the fit to the dipole model given by Equation (1).

the SQUID VSM, an error in the sample center of 0.5 mm corresponds to a 2% decrease in the measured magnetic moment of the sample.¹⁸

III. ARTIFACTS IN MAGNETIC MOMENT MEASUREMENTS OF FLUID SAMPLES

A. The central problem: Sample geometry is dynamic

The central problem in the magnetic measurement of fluid samples is that the sample geometry is not fixed but may change dynamically as a function of time and the applied magnetic field. The



FIG. 2. (a) Commercial liquid sample holder filled with a magnetic fluid sample.¹³ (b-f) A liquid sample that partially fills its sample space may assume various shapes. (g-i) Even if the sample space is completely filled, the nanoparticles within a fluid sample may be distributed in different ways. Here, the more concentrated regions are shown in dark brown and the more dilute regions shown in light brown.

geometry may also depend on the magnetic history of the sample. Changes in the sample size and shape, such as those in Figure 2, have two distinct effects. First, the sample center can change, reducing the measured moment from the actual value. This can also result in a change in the shape of the measured hysteresis loop, since the moment reduction can be a function of field. Second, a sample that (for example) splits in two due to an air bubble or elongates due to chaining, can violate the point dipole assumption inherent in Equation (1). A sample that is significantly larger than a point dipole will result in a decrease in the measured moment with respect to the actual moment due to increased breadth of the voltage curve. On the other hand a sample that is too small may have

a low signal to noise ratio, obscuring the signal. For typical SQUID geometries, the point dipole approximation is valid for samples <5 mm, but the details are specific to each magnetometer's geometry.^{13,19}

Figure 2(a) shows a photo of a commercially available liquid sample holder filled with a magnetic fluid sample. It can be logistically difficult to fill such a cup-style sample holder completely without incorporating an air bubble. Figure 2(a) shows an air bubble at the bottom of the sample space. Alternatively, it may be preferable to only partially fill the sample holder so that the sample is <5 mm in length. Either way, an air bubble in the sample space can cause significant issues because it allows movement of the sample within the sample space. For a partially filled sample holder, Figure 2(b) is the ideal scenario, and Figure 2(c)-2(f) shows different ways the sample can deviate from the single point dipole model, including an air bubble, a large meniscus, or normal instability in a ferrofluid causes a corrugated, spiked surface^{20,21} For these cases, in addition to the sample shape changing, the center position is also changed from the ideal case shown in (b).

Even if no air bubble is incorporated into the sample space, the nanoparticles within a fluid sample may assume different shapes. For example, when a magnetic field is applied, nanoparticles can form long chains in the direction of the field, creating regions of the sample which are more or less concentrated. The nanoparticles may also aggregate, either spontaneously or in response to an applied field history; aggregates then tend to sink to the bottom. These scenarios are shown in Figure 2(g)-2(i).

B. SQUID measurement

Figure 3 shows raw data from a SQUID measurement of a partially-filled sample holder, experimentally demonstrating both the shift in sample center position (peak position) and change in shape (peak width) that are a direct result of the dynamic physical nature of the sample. The sample was 30 μ L of a water-based magnetic fluid in a 60 μ L (partially filled) liquid sample holder. The magnetic fluid was a bionized nano-ferrite coated with a double dextran layer in a colloidal suspension in H₂O with solid content of 25 mg per mL.²² The initial sample shape approximated Figure 3(a)where some of the magnetic fluid adhered to the top of the sample holder space. After a series of ten scans at 300 K and 0.5 T, a change in the data between Scans 1-2 and Scans 3-10 is evident. When the sample was removed from the instrument immediately after the 10 scans, this change in sample shape from Figure 3(a) to 3(b) could be seen visually. The raw data from Scans 1 and 3 are shown in Figure 3(c) and fit to the dipole model. The differences are as follows: first, the sample center position shifts by about 2.5 mm, about what would be expected for a shift from the shape shown in Figure 3(a) to that in (b). Second, the width of the peak decreases, as the two point dipoles combine back into a single point dipole. A close up of the raw data from all ten scans is shown in Figure 3(d). Scan 1-2 overlap each other, and Scans 3-10 overlap each other; the significant change occurs between Scan 2 and Scan 3.

When analyzing the raw data from a SQUID measurement, the raw data is fit to the single dipole model (Equation (1)), shown as the solid lines in Figure 3(c)-3(d). The center position is a fit parameter, and therefore the exact center position does not have a significant effect on the resultant magnetic moment unless the center is so far to one side that the full dipole curve is not captured in the data. However, the deviation of the raw data from the dipole model fit in Scans 1 and 2 means that the dipole assumption is not as accurate as in Scans 3-10. This deviation can be seen clearly in the close up view of the data in Figure 3(d). The magnetic moment obtained from the fit to Scan 1 ($0.0306 \times 10^{-3} \text{ A-m}^2$) is 7% smaller than the moment obtained from the fit to Scan 3 ($0.0329 \times 10^{-3} \text{ A-m}^2$), where the sample shape better approximates the model assumptions of a single point dipole.

C. SQUID VSM measurements

In contrast to the SQUID measurement where the sample center position is a fit parameter, in a SQUID VSM measurement, the sample center position is much more critical. A shift in center must



FIG. 3. 10 successive SQUID measurements of a 30 μ L water-based magnetic fluid sample in a 60 μ L (partially filled) liquid sample holder. The sample shape and position shifts between Scans 2 and 3. The diagrams depict the expected shapes of the fluid sample during (a) Scan 1 and (b) Scan 3. (c) Raw data from Scans 1 and 3 with fits to the dipole model. (d) Close-up view of the raw data from Scans 1-10 with the fits to Scans 1 and 3.

be accounted for by re-centering the sample, otherwise significant effects on the resultant magnetic moment measurement can result, both in terms of the magnitude of the moment and the shape of the m(H) curve. This problem is shown in Figures 4 and 6.

1. Sample change due to normal field instability

Figure 4 shows data on 30 μ L of a mineral oil-based magnetic fluid sample in the 60 μ L sample holder (partially filled). The sample was a commercial magnetic fluid with a mineral oil base purchased from CMS Magnetics.¹³ The three hysteresis loops in Figure 4(a) were measured in the SQUID-VSM using three different centering schemes. For the blue curve, the sample was initially centered in the maximum field (0.5 T), while for the green curve the sample was initially centered in zero field (0.0 T). The third centering scheme (red curve) used a "dynamic center", i.e. the sample was re-centered at each magnetic field point.

Very clear disagreements between the curves are evident. Most obviously, the data which was taken with the zero-field center does not match the other two at high fields (44% decrease in measured moment). Also apparent is that the data taken with the high-field center does not match the other two at low fields. This can be seen in a close-up view in Figure 4(b). Because the magnitude of the measured moment is maximum when the sample is exactly centered between the coils



FIG. 4. (a) Hysteresis loops measured in the SQUID VSM for a 30 μ L sample of mineral oil-based magnetic fluid in the 60 μ L sample holder (partially filled). (b) Close up of low field data (c) Change in dynamic center position Δd . The diagrams depict the expected shapes and approximate center of the fluid sample at 0.0 T and 0.5 T. Error bars (1 σ) are included but may be smaller than the symbol.

in the vertical direction, if the errors are assumed to be due to incorrect vertical centering then the data with the highest moment is the most correct. In fact, the data taken with the "dynamic center" gives the maximum measured moment at all fields and matches the other two curves in the appropriate regimes. Also, for the green curve, the data for positive fields does not exactly overlap itself. This suggests that the shape of the sample changes from the beginning to the end of the measurement even under the same field and therefore there is some dependence on the sample's history. Therefore, the "dynamic center" is most accurate because it takes into account the changing center position of the sample.

These disagreements in magnetic moment in the different field regimes necessarily lead to the outcome that the hysteresis loop *shapes* differ significantly from each other in addition to the magnitude of the moment. Thus, these artifacts cannot be accounted for by a scale factor *post facto*. This type of hysteresis shape artifact is typically not seen with solid samples and is due to the dynamic nature of the center in the sample.



FIG. 5. (a) Normal field instability in a macroscopic quantity of the mineral oil-based magnetic fluid when placed next to a permanent magnet. (b) Microscope image of this magnetic fluid under a 0.07 T field supplied by an electromagnet. For clarity, the image shown is a section of the the magnetic fluid/water boundary. (c) Microscope image of this magnetic fluid under a 0.09 T field supplied by an electromagnet, showing that the surface assumes a spike shape (normal field instability).

The change in the dynamic center position (Δd) as a function of field is shown explicitly in Figure 4(c); the data points correspond to the center positions used for the hysteresis loop in Figure 4(a) (with the "dynamic center" scheme). This data shows how the sample moves dynamically with applied field over a range of approximately 2.5 mm. Thus, the sample sits at the bottom of the sample holder in zero field and moves upward with applied field. This is consistent with the sample displaying the well-known normal instability associated with ferrofluids.^{20,21}

This sample does display normal field instability, shown for a macroscopic quantity of this magnetic fluid in a vial placed next to a permanent magnet in Figure 5(a). To explore this further, Figure 5(b)-5(c) show a microscopic view of the normal field instability in a controlled, variable field supplied by an electromagnet with pole pieces. A drop of the mineral oil-based magnetic fluid was placed on a microscope slide along with a drop of water for contrast, and a cover slip was epoxied over it to avoid spillage or evaporation. Then a magnetic field was applied in the plane of the slide. The magnetic fluid, initially under zero applied field, assumed a shape determined by the various surface tensions for fields of 0.00 T to 0.07 T. Figure 5(b) shows a region at the edge of a water bubble at a field of 0.07 T. When the field was increased to 0.09 T (Figure 5(c)), the magnetic fluid moved and assumed a spike shape characteristic of normal field instability.²⁰ This is consistent with the field at which significant changes in the center position are seen in Figure 4(c). (Note: This field is dependent upon the magnetic properties of the sample and is not a general guideline.)

2. Sample change due to chain formation

Figure 6 shows data on 60 μ L of a water-based magnetic fluid sample in the 60 μ L sample holder (completely filled). The magnetic fluid was a bionized nano-ferrite coated with a dextran layer and an amine group in a colloidal suspension in H₂O with solid content of 25 mg per mL.²² The two hysteresis loops in Figure 6(a) were measured in the SQUID-VSM using two different



FIG. 6. (a) Hysteresis loops measured in the SQUID VSM for a 60 μ L sample of water-based magnetic fluid in the 60 μ L (full) sample holder. (b) Close up of low field data (c) Change in dynamic center position Δd . The diagrams depict the expected shapes of the fluid sample at 0.0 T initially, at 7.0 T, and at 0.0 T after a field has been applied and removed. Error bars (1 σ) are included but may be smaller than the symbol.

centering schemes. For the blue curve, the sample was initially centered in 7.0 T, while for the green curve, the sample was centered in 0.0 T. In this case, the sample space was entirely filled, thus we naively expect this sample to have negligible change in sample center resulting in a more accurate measurement. In reality, we observe a similar change in sample position due to re-organization of the nanoparticles in the solution. Again, the data taken using the high field center has a larger moment at high field, and the data taken using the zero field center gives a larger moment at low fields. A close-up of the low field data is shown in Figure 6(b). At 7.0 T, the error due to measuring using the zero field center is 22%.

Figure 6(c) shows the center position measured at a few field values. The data suggests a similar pattern as was seen in the mineral oil-based magnetic fluid. The center position varies over a range of approximately 2 mm, and changes rapidly at low field, flattening out at high fields. One major difference is that the center data shows history dependence. Initially, the sample center does not change at all upon application of a field. It is only once a field is applied and then removed that a change in center is seen. This leads Figure 6(c) to be non-single-valued at low fields. (Note that the magnetic moment data shown in Figure 6(a) (green curve) was measured with the sample centered in zero field *after* application and removal of a field.)

A microscopic investigation of this water-based magnetic fluid sample provides insight into this behavior. Again, a drop of the fluid sample was placed on a microscope slide, and a cover slip was mounted over it using epoxy (Figure 7(a)). Then, a magnetic field was applied by an electromagnet in the plane of the slide as it was viewed under a microscope. In zero field the nanoparticles within the sample appeared evenly distributed and no contrast was observed, however as the field was increased there was clear evidence of chain formation. Figure 7(b) shows the microscopic view of the sample at 0.09 T; the dark streaks in the direction of the applied field are highly concentrated "chains" of nanoparticles. Immediately after removal of the magnetic field, the sample was observed to have started separating; however, after 1.5 hours the sample had begun to redisperse (Figure 7(a)). It should be noted that sample separation depends not only on the strength of the magnetic field, but on the magnetic field *gradient*, which may differ between the SQUID environment and the electromagnet with pole pieces used in the microscopic study.²³



FIG. 7. (a) Water-based magnetic fluid sample on a microscope slide, with epoxied cover slip, for observation under the microscope. There is evidence of sample separation and redispersal after field application and chain formation. (b) Microscope image showing chain formation of nanoparticles under 0.09 T applied field.

This chaining and separation behavior of this water-based magnetic fluid can explain the measured center position of this sample. While well-dispersed to begin with, it is well-known that magnetic nanoparticles form chains upon application of a magnetic field in order to lower the magnetostatic energy of the system. When the field is removed, the chains are no longer the most energetically favorable; however, the nanoparticles do not necessarily quickly redisperse without shaking.²⁴ Instead, the chains may separate into loose collections which settle to the bottom of the sample holder; this settling changes the sample center from its original position. Schematics of this behavior are shown as insets to Figure 6(c) alongside the center position data.

D. Immobilization of nanoparticles

Another potential measurement concern for magnetic fluids is immobilization of some nanoparticles in the sample when sealing the holder. For holders which close using screw threads, the screw threads are sealed with epoxy to prevent the liquid portion of the sample from evaporating while in an evacuated sample space. It is difficult to fill the sample space and seal the screw closure without incorporating some of the magnetic particles in the epoxy. Some nanoparticles immobilized in epoxy this way can be seen in Figure 2(a).

Immobilized particles are of concern because they may display a nonzero remanence whereas the fluid samples will not due to Brownian rotation of the nanoparticles in the fluid, even if the individual particles are ferromagnetic.²⁵ This essentially leads to an inhomogeneous sample, measurement of which will indicate a larger moment at low field than would be seen in a sample that is completely in fluid form, and will affect a centering scan, which at low fields will indicate



FIG. 8. SQUID VSM measurement of magnetic moment of two samples ((a) mineral oil-based and (b) water-based), comparing the samples in liquid form and immobilized in epoxy. The magnetic moment for the liquid samples (red) is given on the left *y*-axis, while the magnetic moment for the samples immobilized in epoxy (black) is given on the right *y*-axis. Error bars (1σ) are included but may be smaller than the symbol. Note: What appears to be a negative coercive field in the liquid samples is actually systematic error in stated field due to flux trappage in the superconducting magnet.²⁶

that the center position is at the center of the immobilized particles only, ignoring the fluid portion of the sample. This would cause errors due to centering shifts as described previously.

Figure 8 compares hysteresis loops for the two magnetic fluids, in fluid form and immobilized in epoxy. The nanoparticles in both samples are magnetically soft enough that the potential sources of error described due to nonzero remanence are not significant. Essentially, the coercive field of the immobilized nanoparticles is smaller than the systematic error on the magnetic field measurement due to flux trappage in the superconducting magnet,²⁶ therefore the potential sources of error due to immobilized nanoparticles are not relevant for these particular samples. However, researchers working with magnetic fluids containing particles with large coercivity should be aware of this potential source of error.

IV. SUMMARY

Figures 3, 4, and 6 demonstrate artifacts in magnetic measurements of fluid samples. Artifacts arise from: (a) Change of sample center position during measurement, (b) change of sample shape during measurement, and (c) change in distribution of magnetic particles within sample fluid. Potential for error exists due to nanoparticles immobilized in the sample holder sealing process (e.g., epoxy), resulting in non-zero remanence due solely to immobilized particles. Awareness of these artifacts among the growing magnetic fluid community will improve the accuracy of reported measurements.

Our recommendations for accurate magnetic measurement of fluid samples include: (a) prevent large scale sample motion by minimizing air bubbles in sample container, (b) for measurement methods which rely on a predetermined center position, recenter before each measurement, or (c) use measurement methods which account for changes in sample center, (d) ensure sample size is within the recommended limits for the measurement system, (e) avoid immobilizing nanoparticles in sample sealing (e.g., epoxy), and (f) monitor raw data for violations in point dipole approximation.

ACKNOWLEDGMENTS

The authors thank Cordula Gruettner of micromod Partikeltechnologie GmbH for the waterbased magnetic fluid (BNF) samples.

- ¹ Y. T. Choi and N. M. Werely, "Vibration control of a landing gear system featuring electrorheological/magnetorheological fluids," Journal of Aircraft **40**, 432 (2003).
- ² P. J. Blennerhassett, F. Lin, and P. J. Stiles, "Heat transfer through strongly magnetized ferrofluids," Proc. R. Soc. Lond. A **433**, 165 (1991).

- ⁴ J. Weizenecker, B. Gleich, J. Rahmer, H. Dahnke, and J. Borgert, "Three-dimensional real-time in vivo magnetic particle imaging," Phys. Med. Biol. 54, L1 (2009).
- ⁵ C. L. Dennis, A. J. Jackson, J. A. Borchers, P. J. Hoopes, R. Strawbridge, A. R. Foreman, J. van Lierop, C. Gruttner, and R. Ivkov, "Nearly complete regression of tumors via collective behavior of magnetic nanoparticles in hyperthermia," Nanotechnology 20, 395103 (2009).
- ⁶ M. Bonini, S. Lenz, R. Giorgi, and P. Baglioni, "Nanomagnetic sponges for the cleaning of works of art," Langmuir 23, 8681 (2007).
- ⁷ H. Mamiya and B. Jeyadevan, "Hyperthermic effects of dissipative structures of magnetic nanoparticles in large alternating magnetic fields," Sci. Rep. 1, 157 (2011).
- ⁸ S. G. Sherman, D. A. Paley, and N. M. Wereley, "Parallel simulation of transient magnetorheological direct shear flows using millions of particles," IEEE Transactions on Magnetics 48, 3517 (2012).
- ⁹ A. P. Philipse and D. Maas, "Magnetic colloids from magnetotactic bacteria: chain formation and colloid stability," Langmuir 18, 9977 (2002).
- ¹⁰ S. Foner, "Versatile and sensitive vibrating-sample magnetometer," Review of Scientific Instruments **30**, 548 (1959).
- ¹¹ M. McElfresh, "Fundamentals of magnetism and magnetic measurements featuring Quantum Design's Magnetic Property measurement System," Tech. Rep. (Quantum Design, 1994).
- ¹² W. Burgei, M. J. Pechan, and H. Jaeger, "A simple vibrating sample magnetometer for use in a materials physics course," American Journal of Physics 71, 825 (2003).
- ¹³ Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

³ Y.-X. J. Wang, "Superparamagnetic iron oxide based MRI contrast agents: Current status of clinical application," Quant. Imaging Med. Surg. **1**, 35 (2011).

- ¹⁴ J. Xu, K. Mahajan, W. Xue, J. Winter, M. Zborowski, and J. Chalmers, "Simultaneous, single particle, magnetization and size measurements of micron sized, magnetic particles," Journal of Magnetism and Magnetic Materials **324**, 4189 (2012).
- ¹⁵ A. L. Balk, C. Hangarter, S. M. Stavis, and J. Unguris, "Magnetometry of single ferromagnetic nanoparticles using magnetooptical indicator films with spatial amplification," Applied Physics Letters **106**, 112402 (2015).
- ¹⁶ "MPMS Application Note 1014-213 Subtracting the Sample Holder Background from Dilute Samples," Quantum Design (2002).
- ¹⁷ Magnetic Property Measurement System SQUID-VSM User's Manual, Quantum Design, San Diego, CA, 13th ed. (2010).
- ¹⁸ "SQUID VSM Application Note 1500-010 Rev. A0 Accuracy of the Reported Moment: axial and radial sample positioning error," Quantum Design (2010).
- ¹⁹ "SQUID VSM Application Note 1500-015 Rev. A0 Accuracy of the Reported Moment: Sample Shape Effects," Quantum Design (2010).
- ²⁰ M. D. Cowley and R. E. Rosensweig, "The interfacial stability of a ferromagnetic fluid," J. Fluid Mech. **30**, 671 (1967).
- ²¹ A. R. Zakinyan and L. S. Mkrtchyan, "Instability of the ferrofluid layer on a magnetizable substrate in a perpendicular magnetic field," Magnetohydrodynamics 48, 615 (2012).
- ²² C. Grüttner, K. Müller, J. Teller, F. Westphal, A. Foreman, and R. Ivkov, "Synthesis and antibody conjugation of magnetic nanoparticles with improved specific power absorption rates for alternating magnetic field cancer therapy," Journal of Magnetism and Magnetic Materials **311**, 181 (2007).
- ²³ The magnetic field gradient next to a permanent magnet is larger than that of a solenoid producing the magnetic field in a magnetometer. However, a solenoid is necessarily finite and therefore also produces a gradient.
- ²⁴ G. Cheng, C. L. Dennis, R. D. Shull, and A. R. Hight Walker, "Influence of the Colloidal Environment on the Magnetic Behavior of Cobalt Nanoparticles," Langmuir 23, 11740 (2007).
- ²⁵ N. A. Clark, "Ferromagnetic ferrofluids," Nature 504, 229 (2013).
- ²⁶ "MPMS Application Note 1014-208 Remnant Fields in MPMS Superconducting Magnets," Quantum Design (2002).