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Research articles

Estimating saturation magnetization of superparamagnetic nanoparticles in liquid phase

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ABSTRACT

Superparamagnetic nanoparticles (SPMNPs), with unique physical and magnetic properties that differentiate them from their bulk magnetic materials, have been widely studied for potential applications in biomedical areas. With proper surface chemical functionalization, SPMNPs have found their applications in magnetic hyperthermia therapy, magnetic bioassays, drug delivery, magnetic manipulation, etc. These applications require elaborate tuning of the physical and magnetic properties of the SPMNPs such as saturation magnetization M_s and magnetic core size D. In this work, we present a search coil-based method to directly characterize the M_s of SPMNPs in the liquid phase. The nonlinear magnetic responses of SPMNPs under oscillating magnetic fields are exploited and the induced harmonic signals are used to analyze their M_s and D. Different combinations of M_s and D are assumed and their harmonic ratios R are summarized. Curve fitting shows that the harmonic ratio $R = 0.74 + 2.85 \times 10^9 \bullet D^{-4.41} \bullet M_s^{-1.44}$, with the coefficient of determination $R\text{-}square = 0.98$.

1. Introduction

Superparamagnetic nanoparticle (SPMNP) is an important nanomaterial that has been successfully applied in different biomedical areas such as hyperthermia therapy [1–6], drug delivery [3,7–11], magnetic manipulation and separation [12–16], magnetic biosensing [17–20], etc. In these applications, it is important to tune the magnetic properties of SPMNPs such as saturation magnetization M_s and the physical properties such as magnetic core size D. Herein, we report a search coil-based method for characterizing M_s and D of SPMNPs directly from liquid phase. The nonlinear magnetic responses of SPMNPs to external magnetic fields are unique for different types of SPMNPs regarding their M_s and D, and their response curves are described by the Langevin function. By placing SPMNPs under oscillating magnetic fields, the nonlinear magnetic responses induce odd harmonics that can be picked up by a pair of pick-up coils [21–24]. These harmonic signals contain the information about SPMNPs such as M_s and D [25–28].

As shown in Fig. 1(a), in a typical search coil system, two alternating currents (AC) are applied to outer coils 1 and 2, respectively, and two oscillating magnetic fields are generated inside each coil, respectively (see Fig. 1(a):(i) & (a):(ii)), one with high frequency f_H but small amplitude, the other with low frequency f_L but large amplitude (see Fig. 1(c)) [25,27,28]. The low frequency field periodically drives SPMNPs to saturation where harmonic signals are induced due to the nonlinear magnetic responses of SPMNPs (see Fig. 1(b)). In order to increase the signal-to-noise ratio (SNR), the high frequency field is applied to modulate harmonic signals into the high frequency region where the pink noise (1/f noise) is minimized. A pair of differentially winded pick-up coils (Fig. 1(a):(iii)) is placed in the center of two outer coils, the top half is winded clockwise while the lower half is counter-clockwise in order to cancel out the magnetic fields that come from two outer coils. During the measurement, SPMNP ferrofluid sample is confined in a tube and inserted in the upper half of pick-up coils (Fig. 1(a):(iv)), by canceling out the externally applied magnetic fields, this pair of pick-up coils can specifically pick the harmonic signals generated by SPMNPs.

2. Methods

2.1. Theoretical models

Under an external magnetic field, the magnetic moments of SPMNPs tend to align along the applied magnetic field, leading to a net magnetization. The magnetic response of an assembly of SPMNPs is a reversible S-shaped curve modeled by the Langevin function (in emu/cm³):

$$M_D = M_s L(\xi) \tag{1}$$

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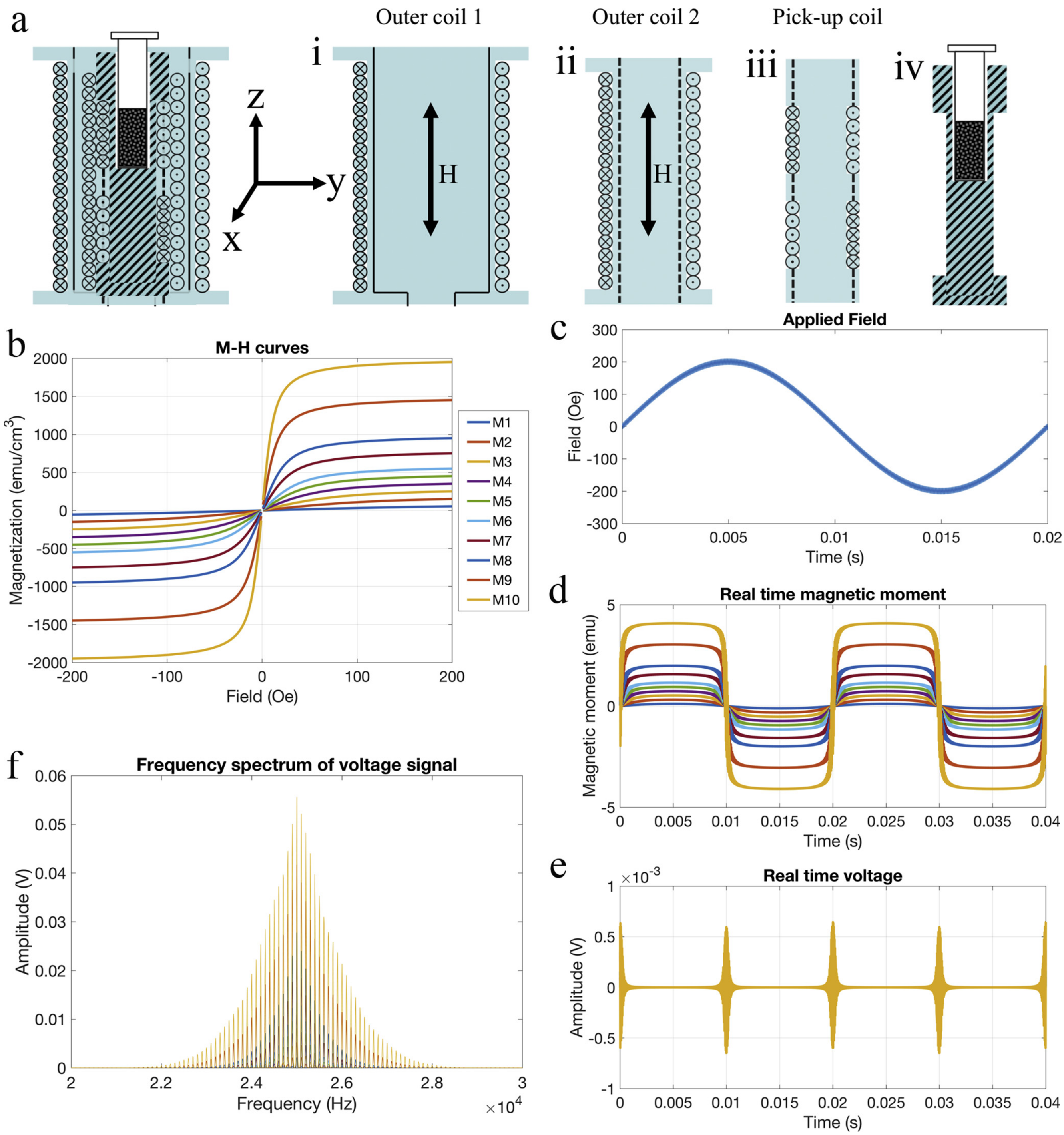

Fig. 1. (a) Search coil system setup. Two oscillating magnetic fields are generated by part (i) and (ii). Part (iii) is a pair of differentially winded pick-up coils, half of the coils are winded clockwise and the other half counter-clockwise to cancel out the external magnetic field from (i) & (ii). Part (iv) is a holder with a plastic tube containing liquid SPMNP sample. (b) Simulated magnetic response curves of 10 SPMNP samples M1–M10 with saturation magnetizations varying from 100 to 2000 emu/cm^3, assuming $D = 20$ nm, and $T = 300$ K. (c) Two oscillating magnetic fields in one $1/f_L$ period. Where $A_L = 200\ Oe$, $f_L = 50$ Hz, $A_H = 10\ Oe$, $f_H = 25$ kHz. (d) and (e) are the simulated magnetic moment and induced voltage from 10 SPMNP samples during two $1/f_L$ periods, respectively. Assuming $c = 500$ pM, $V = 0.5$ mL, $D = 20$ nm, $T = 300$ K. (f) Frequency spectrum of (e) shows odd harmonic signals at $f_H \pm 2nf_L$, where n is an integer.

and,

$$L(\xi) = \coth(\xi) - \frac{1}{\xi} \tag{2}$$

$$\xi = \frac{m_s H}{k_B T} \tag{3}$$

$$m_s = M_s V_c = M_s \pi D^3/6 \tag{4}$$

where D and V_c are the magnetic core diameter and magnetic core volume of SPMNP, m_s and M_s are the magnetic moment and saturation magnetization, respectively, H is the external magnetic field, k_B is Boltzmann constant, and T is temperature. Fig. 1(b) shows the simulated magnetic response curves of 10 SPMNPs based on the Langevin model, the M_s of 10 SPMNP samples varies from 100 to 2000 emu/cm^3, assuming $D = 20$ nm, and $T = 300$ K.

Herein, we apply two oscillating magnetic fields to SPMNPs, one