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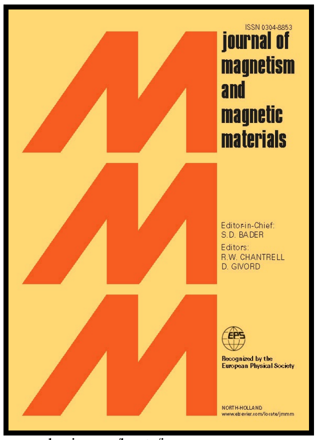

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PII: S0304-8853(16)32283-1
DOI: http://dx.doi.org/10.1016/j.jmmm.2016.09.094
Reference: MAGMA61875

To appear in: *Journal of Magnetism and Magnetic Materials*

Received date: 30 June 2016
Revised date: 16 September 2016
Accepted date: 20 September 2016

Cite this article as: Timur M. Batrudinov, Alexander V. Ambarov, Ekaterina A. Elfimova, Vladimir S. Zverev and Alexey O. Ivanov, Theoretical study of the dynamic magnetic response of ferrofluid to static and alternating magnetic fields *Journal of Magnetism and Magnetic Materials* http://dx.doi.org/10.1016/j.jmmm.2016.09.094

Theoretical study of the dynamic magnetic response of ferrofluid to static and alternating magnetic fields

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Abstract

The dynamic magnetic response of ferrofluid in a static uniform external magnetic field to a weak, linear polarized, alternating magnetic field is investigated theoretically. The ferrofluid is modeled as a system of dipolar hard spheres, suspended in a long cylindrical tube whose long axis is parallel to the direction of the static and alternating magnetic fields. The theory is based on the Fokker-Planck-Brown equation formulated for the case when the both static and alternating magnetic fields are applied. The solution of the Fokker-Planck-Brown equation describing the orientational probability density of a randomly chosen dipolar particle is expressed as a series in terms of the spherical Legendre polynomials. The obtained analytical expression connecting three neighboring coefficients of the series makes possible to determine the probability density with any order of accuracy in terms of Legendre polynomials. The analytical formula for the probability density truncated at the first Legendre polynomial is evaluated and used for the calculation of the magnetization and dynamic susceptibility spectra. In the absence of the static magnetic field the presented theory gives the correct single-particle Debye-theory result, which is the exact solution of the Fokker-Planck-Brown equation for the case of applied weak alternating magnetic field. The influence of the static magnetic field on the dynamic susceptibility is analyzed in terms of the low-frequency behavior of the real part and the position of the peak in the imaginary part.

Keywords: dynamic magnetic susceptibility spectra, ferrofluid, the Fokker-Planck-Brown equation

1. Introduction

Ferrofluids are highly functional materials, with physical properties that can be controlled by the magnetic fields. Applications of ferrofluids include targeted drug delivery, medical diagnosis, and localized cell destruction using field-induced hyperthermia. The application methods are based on ability of the ferrofluid to react to the external magnetic field. The efficiency of these methods depends on many factors such as the intensity, configuration, frequency of the magnetic field, and requires development of the theoretical basis. Many theoretical models of the dynamic response of the ferrofluids deal primarily with dilute systems, in which interparticle interactions can be completely ignored [1, 2, 3, 4, 5]. These models lead to very accurate results for nonconcentrated ferrofluids but cannot explain properties and behavior of ferrofluids where the interparticle interaction is significant. Several attempts are known to incorporate the dipole-dipole interaction into the theoretical description of dynamic spectra [6, 7, 8, 9, 10, 11, 12]. In addition, various configurations of the external field were investigated in the last decades [13, 14, 15].

In the present work we study theoretically the dynamic magnetic response of the ferrofluid to the simultaneously applied static and weak alternating magnetic fields. The theory is developed for the noninteracting dipolar particles with the Brownian mechanism of the relaxation of the particle's magnetic moment.

This paper is organized as follows. In Section 2 the theory is detailed, and new analytical expressioins for the dynamic response of ferrofluid to the static and alternating magnetic fields are presented. The results are in Section 3. Section 4 concludes the paper.

2. Theory

Consider the ferrofluid as a system of dipolar hard spheres (DHS), suspended in a long cylindrical tube whose long axis coincides with the laboratory Oz direction. The static and alternating magnetic fields are applied along the Oz-axis: $\mathbf{H} = (0, 0, h_s + h_a e^{i\omega t})$; h_s is the static field strength, h_a is alternating field amplitude, ω is oscillation frequency, t denotes time. Here we consider only the case of a weak alternating magnetic field when the amplitude h_a is sufficiently small. The orientation of each particle's magnetic moment $\mathbf{m}_j$ is defined by its polar angle θ with respect to the external field $\mathbf{H}$. The rotational motion of a single dipolar particle is described by the probability density $W(t, x)$, $x = \cos\theta$, determined by the thermal fluctuations and dipole-field interactions. For a randomly chosen particle this density is the solution of the Fokker-Planck-Brown equation [16, 17]

$$2\tau\frac{\partial W}{\partial t} = \frac{\partial}{\partial x}\left[(1-x^2)\left(\frac{\partial W}{\partial x} + \frac{\partial U}{\partial x}W\right)\right], \quad (1)$$

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