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Study of Magnetofluidic Laser Scattering Under Rotating Magnetic Field

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Abstract. Magnetic field driven self-assembly of magnetic nanoparticles provides wireless programmable approach for tunable magnetofluidic laser scattering. In this work, we study magnetofluidic laser scattering from a commercial aqueous magnetic fluid (EMG 707) under an external rotating magnetic field. A set-up is developed to generate rotating magnetic field for the purpose. Self-assembled magnetic nanoparticle structures in the form of chains and bundles are formed along the magnetic field. This creates a linear streak formation in the forward laser scattering. Rotating magnetic field produces rotating linear streak. We report our initial results of rotating linear streaks at 3 rpm, 6 rpm and 10 rpm and our analysis of the patterns. The studies are useful for developing magnetic fluid based optical devices.

INTRODUCTION

Magnetic fluids (MFs) are smart fluids heavily explored worldwide for their novel optical properties [1, 2]. When external magnetic field is applied to MFs, it induces magnetic dipolar interaction among magnetic nanoparticles (MNPs) directing the motion of magnetic nanoparticles inside a liquid carrier resulting in the formations of chains of MNPs and their complex structures with time. Self-assemblies formed inside can switch back to their original state of individual particles upon the removal of external magnetic field and thus, show reversibility. Novel magneto-optical effects (MOE) are observed by controlling magnetic field driven self-assemblies and their interaction with light. Nature of magnetic nanoparticles, their surfactants and carrier medium govern the growth of self-assemblies along the magnetic field lines and mediate their response to the incident light. These self-assembly transitions have their characteristic time response dependent on the magnetic and hydrodynamic parameters of MFs [3]. Thus, it is possible to tailor these properties to design MFs for suitable optofluidic applications for which there is a growing interest [4].

Self-assembly dynamics of magnetic particles in MFs under rotating magnetic fields has been studied using techniques like optical microscopy by various groups [5, 6]. In the work presented here, we report magnetofluidic laser scattering (MFLS) from commercial aqueous magnetic fluid under rotating magnetic field. Low cost permanent magnet based assembly is developed to generate magnetic torque for rotating the self assemblies of magnetic nanoparticles inside a carrier liquid. It has been observed that passing a laser beam through self-assemblies of MNPs in aqueous medium generates anisotropic forward scattering in the form of a linear vertical streak perpendicular to the direction of applied magnetic field. We present our initial experimental investigations of magnetofluidic laser scattering from aqueous magnetic fluid in the form of periodic rotational movement of a linear streak due to rotating magnetic field.

EXPERIMENTAL

Commercial water-based ferrofluid EMG 707 (Ferrotec, Singapore) was used for the experiments. EMG 707 is monodisperse aqueous dispersion containing Fe_3O_4 nanoparticles with a solid diameter of 10 nm. As per the data provided by the manufacturer, values of other relevant parameters are: Viscosity, η : 1.84 ± 0.02 mPa.s, Saturation Magnetization, M_s : 11 mT, Magnetic Susceptibility, χ : 1.51. Our Nanoparticle Tracking Analysis (NTA) shows the Hydrodynamic Diameter, D_h of 40 nm. Our earlier studies have shown that EMG 707 has fast magnetofluidic laser scattering (MFLS) response to external magnetic field, thus quickly forming self-assemblies along magnetic field lines [3]. Figure 1 shows the schematic of the experimental set-up. A diode laser beam (630 nm, < 5 mW) is passed through a cuvette (path length: 1 mm) containing EMG 707 (volume fraction, Φ : 2×10^5). An electromechanical arrangement was made to make a permanent magnet rotate around a cuvette. The magnetic field at the center of a cuvette is 5 mT. MFLS patterns observed on a screen placed at a distance of ~ 30 cm from cuvette were recorded using a CCD camera. MFLS patterns were recorded at rotation speeds of 3 rpm, 6 rpm and 10 rpm. Matlab and ImageJ software were used to process images of forward scattering patterns.

FIGURE 1. (a) Schematic of experimental set-up, (b) Typical MFLS pattern observed on the screen (white arrow indicates rotation of the streak around the central spot with its axis perpendicular to the plane of the paper).

RESULTS AND DISCUSSIONS

To form magnetic field driven self-assemblies, magnetic interaction energy among induced dipole moments of MNPs must dominate thermal energy. The relative strength of two energies can be defined through the dimensionless magnetic coupling parameter (Γ) [7],

$$\Gamma = \frac{\mu_0 p_m^2}{2\pi D_h^3 k_B T} \quad (1)$$

where μ_0 is magnetic permeability, p_m is an induced a magnetic dipole moment in individual MNP, D_h is hydrodynamic diameter of MNPs, T is the temperature and k_B is Boltzmann's constant. In addition, evolution of self-assembly formation is also governed by volume fraction, (Φ) of MNPs inside a liquid carrier. $\Gamma \gg 1$ indicates strong magnetic coupling leading to the formation of MNP self-assemblies with their evolution being fast ($\Gamma\Phi \gg 0.1$) or slow ($\Gamma\Phi \ll 0.1$) [7]. Formation of MNP self-assemblies inside a liquid carrier creates optical anisotropy. In case of aqueous MFs, a linear streak perpendicular to external magnetic field is observed in forward scattering when laser beam is transmitted through aqueous MF having its direction perpendicular to external magnetic fluid. Linear streak is formed due to overlapping diffraction patterns from multiple MNP self-assemblies. Individual MNP self-assembly can be compared to a cylinder having and intensity distribution of its diffraction pattern is given by [8],

$$I(\theta) = I_0 \sin c(r_c k \sin n\theta) \quad (2)$$

where k is the wave vector, r_c is the radius of a cylinder, I_0 is the maximum intensity at the zero order of the diffraction pattern and θ is the observation angle (For a given experimental setup $\theta = 90^\circ$, as the beam direction is perpendicular to MNPs chains). As seen from Eqn. 2, the distribution of intensity is dependent on the width of self-assemblies.

When rotating magnetic field is applied, a magnetic torque acts on the self-assemblies formed inside a carrier liquid causing them to rotate in response to it. Rotation of applied magnetic field and rotating self-assemblies have phase angle between them due to hydrodynamic and magnetic interactions which control behavior of rotating self-assemblies. Mason number, Mn is a dimensionless number which provides the ratio of strength of hydrodynamic drag forces to magnetic forces [6],

$$Mn = \frac{32\eta\omega}{\mu_0\chi_p H_0^2} \quad (3)$$

where η is the viscosity of the fluid, ω is the angular rotation frequency of magnetic field, χ_p is the particle susceptibility, and H_0 is the magnitude of applied magnetic field. Mason number provides information about the state of rotating self-assemblies withstanding to external torque and viscous drag forces. Large Mn number indicates that hydrodynamic forces would dominate over magnetic forces breaking larger self-assemblies.

Figure 2 shows one cycle of MFLS patterns at 3 rpm, 6 rpm and 10 rpm, respectively. With increasing rpm, streak intensity reduces and there is a change in the profile of the streak. Streak becomes weaker with increasing rpm. This is shown in Fig. 3a, where the wing region represents streak component. This can be attributed to the fact that at higher rotations can break larger self-assemblies into smaller ones and therefore, decreasing the intensity of the streak. Our previous experimental investigations in dynamics of streak patterns at a stationary magnetic field, have shown that there is a strong correlation between the intensity of a streak and geometrical dimensions of MNP self-assemblies; fully grown assemblies provide a sharper streak [3]. Thus, at higher rotational speeds, the streak going weaker clearly indicates breaking of MNP chains. Shear forces arise due to magnetic torque and hydrodynamic drag which control the geometrical dimensions of self-assemblies and bring changes in the intensity profile of the streak as seen in the forward scattering.

FIGURE 2. One cycle of MFLS patterns under rotating magnetic field at (a) 3 rpm (b) 6 rpm (c) 10 rpm.

FIGURE 3. (a) Streak intensity profiles along the streak at different rpm (see text for details) (b) Intensity variation with time of a small region on the screen showing rotation of the streaks for different rpm.

Figure 3b shows streak rotations at different rpm obtained using image processing. Time duration between the streaks seems to be consistent over duration of 30 seconds. Small intensity modulation is observed in alternate peaks (~ 7 -8 A.U.) which may possibly due to asymmetry in the position of the magnet.

CONCLUSIONS

Our experimental investigations with MFLS from aqueous magnetic fluids under rotating magnetic field show that self-assemblies of MNPs formed along the magnetic field lines rotate along with rotating field. The results also show survival of self-assembly up to 10 rpm even in the presence of viscous drag. However, at higher rotations, a less intense linear streak implies that larger chain structures break into smaller ones due to hydrodynamic interactions. This suggests a limit on the average size of MNP self-assemblies that remain stable at a given rotational speed. More detailed measurements and analysis are being carried out to look for the details of dynamics of rotating MNP self-assemblies. Our results are useful for wireless manipulation of rotating MNP self-assemblies and developing optical devices using magnetic fluids.

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